AN EXAMINATION OF ALTERNATIVE COMPENSATION METHODS FOR THE REMOVAL OF THE RIDGING EFFECT FROM DIGITAL TERRAIN MODEL DATA FILES

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AN EXAMINATION OF ALTERNATIVE COMPENSATION METHODS FOR THE REMOVAL OF THE RIDGING EFFECT FROM DIGITAL TERRAIN MODEL DATA FILES

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PREFACE

In order to make our extensive series of technical reports more readily available, we have scanned the old master copies and produced electronic versions in Portable Document Format. The quality of the images varies depending on the quality of the originals. The images have not been converted to searchable text.

PREFACE

This technical report is a reproduction of a report submitted in partial fulfillment of the requirements for the degree of Master of Engineering in the Department of Geodesy and Geomatics Engineering, September 1999. This work was supported by Service New Brunswick. The research was supervised by Dr. David Coleman.

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ABSTRACT

The province of New Brunswick began a systematic program of province-wide Digital Terrain Model (DTM) coverage in the late-1980's. Using 1:35,000-scale aerial photography, the DTMs were collected photogrammetrically as a series of profiles spaced 70 metres apart. No regard was given to breaklines along roads or water bodies.

The DTMs have gone through a series of stringent quality control checks to eliminate blunders and ensure the elevations of data points are blunder-free and all fall within specified accuracy tolerances. However, users of these DTM's have continued to express concern over perceived data quality based on the evidence of a regular "ridging" effect within many of the DTM files when viewed under certain conditions. Aware of similar phenomena found in DTMs produced by other organizations, Service New Brunswick (SNB) commissioned researchers in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick to investigate the respective requirements and alternatives for batch processing of the DTMs to remove this ridging effect.

This report presents research examining specific technical issues and compensation approaches associated with the quantification and removal of the ridging phenomena found in SNB's Enhanced Topographic Database digital terrain data. Further, the issue of ridging will be investigated from points of view ranging from a data limitation issue to a visualization issue. Finally, up to five specific solutions will be examined and compared.

ACKNOWLEDGEMENTS

As in any similar undertaking, there are many people to thank. First of all, I would like to thank my supervisor, Dr. David J. Coleman. His guidance and support have been crucial to the development and completion of this report. As a mentor, I can say of Dave that "they just do not get any better than that!" All his efforts are greatly appreciated.

This work would not have been possible without the financial assistance of the Province of New Brunswick, through Service New Brunswick. In particular, I would to thank Mr. Réjean Castonguay who sat patiently through what seemed like an endless stream of "progress meetings." He always showed a great interest in all our successes and equally in all our failures. Moreover, Réjean's advice, based on his many years of experience, was very helpful and very much appreciated.

I have always said that I am doing this degree for my children. Although, they are too young to realize it now, in the years to come I want them to know that all the sacrifice is intended to open future doors for them. I want them to reach for the stars.

Finally, I would like to acknowledge the sacrifice and efforts of my wife Shirley. Since her arrival in my life, she has provided the catalyst that allows me to achieve ever higher goals. I love her very much and look forward to our "continuing adventure!"

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INTRODUCTION

The terms digital elevation model (DEM) and digital terrain model (DTM) are often used interchangeably. In the late 1950's Miller and LaFlamme of MIT defined DTMs as:

> " simply a statistical representation of the continuous surface of the ground by a large number of selected points with known *xyz* coordinates in an arbitrary coordinate field"[1958].

The term DEM is defined by Bonham-Carter as a " digital computer file containing a grid or MATRIX of elevation models"[1994]. Although these terms are often confused in industry, these definitions will be used for this report. The term DTM is the more general term that can be used to describe any digital representation of terrain. The term DEM, as defined here, can only be used to define those digital representations of terrain that are collected as regularly spaced lattice of points or cells of elevation values. A DEM is a DTM but, a DTM is not necessarily a DEM. Except for specific instances, the term DTM will be used.

Digital Terrain Models (DTM) have proven useful to applications in hydrological modelling, geophysical data manipulation, spatial analysis within a Geographic Information System (GIS), viewshed analysis for forestry management systems, and GIS for transportation systems (GIS-T). Digital Elevation Models can be thought of as a fundamental set within the geomatics community - much like the topographic mapping produced by the large base mapping programs of the1970's. DTMs are utilized by most of the communities associated with geomatics including: civil engineering, forestry, surveying, planning, geology, geography and corporate strategic decision makers, although for very different purposes.

In order to promote development activities, governments across North America collect and sell DTM datasets. It is important that the quality of the DTM product is good in order that user groups develop a high regard for the data. A product perceived to have high quality will develop a good market for itself and this speeds recovery of the production costs.

Concern arises in government agencies when users perceive that the data sets being purchased are flawed. Such is the case with Service New Brunswick's (SNB) Digital Terrain Model Database. While the data was collected to a high accuracy (DTM points are within 2.5 metres of their true elevation) and have undergone rigorous quality control processes [NBGIC, 1995] , users have reported in certain 3-Dimensional perspective views a geometric effect in the DTM data which manifests itself as a series of ridges. The "ridging" runs in generally a north/south direction and is most prevalent in regions having little topographic relief. The magnitude of the ridges is less than 10 metres. Figure 1-1 illustrates the ridging within a SNB DTM dataset.

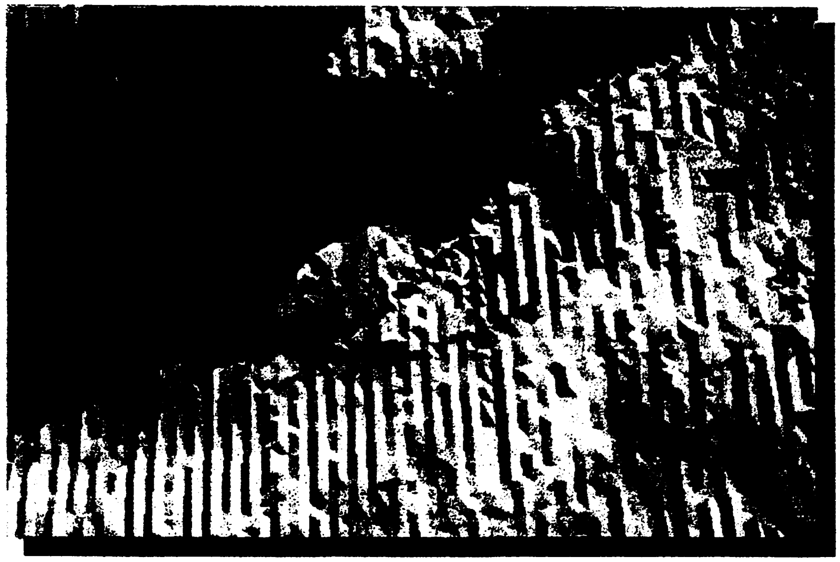

Figure 1-1: Example of ridging in SNB DTM dataset. Caraquet, New Brunswick.

The SNB DTM datasets are not the only DTM datasets contaminated by the ridging effect. Researcher has indicated that "banding" or, "striping" also exists in USGS 71/2-Minute DEM datasets- as shown in Figure 2-2 [Isaacson and Ripple, 1990].

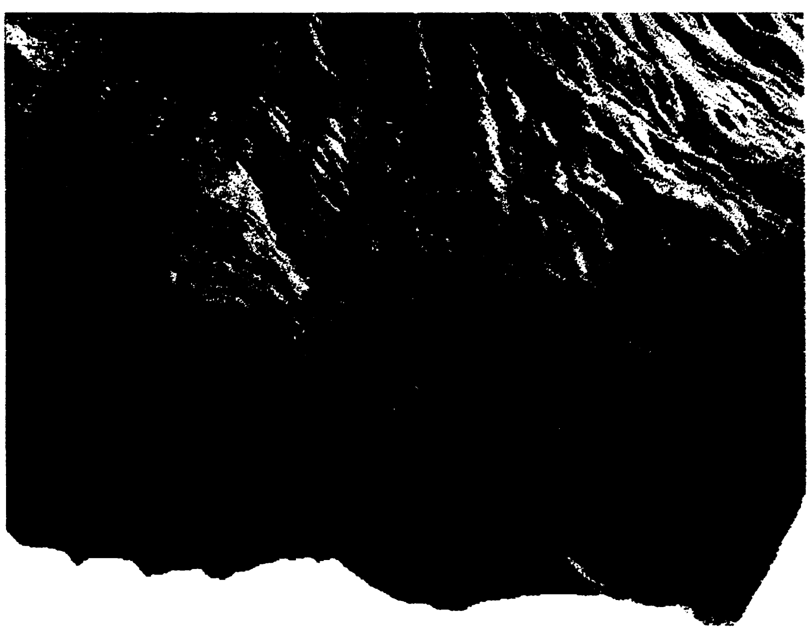

Figure 1-2: Example of Ridging in USGS datasets. Mount St. Helens, Washington State.

USGS and SNB DTM data were collected having the mass points sampled along regularly spaced profile lines. Moreover, the stereoplotter operator collected the lines in a "shuttlecock" manner. That is to say, the data was collected up the y-axis on one line and then down y-axis of the next - just as a field is plowed. The result is a DTM data set comprising row upon row of points of elevation values. The USGS believes that their "striping" or as it is called here, "ridging" is a "form of systematic error process which commonly affects photogrammetric digital elevation data"[Brown and Bara, 1994].

In order to find the solution to an effect such as ridging in DTMs, first the cause must be determined. At the earliest stages of research, it was postulated that ridging was an artifact of: (1) some combination of systematic errors incurred during the data collection process; (2) the pattern and/or distribution of DTM points along regularly-spaced profile lines; or (3) some combination of (1) and (2)[Coleman, 1998].

Moreover, there are those who subscribe to the philosophy that ridging is a data limitation problem. They believe that ridging is caused by systematic errors introduced by the operator when collecting the data along profile lines. At the other end of the spectrum, it has been proposed that the ridging is due solely to the linear arrangement of the point data. Proponents believe it is the linear alignment of the mass points which causes the visualization of the ridges and not some systematic error introduced at the time of data collection. Figure 1-3 graphically illustrates the range of philosophies.

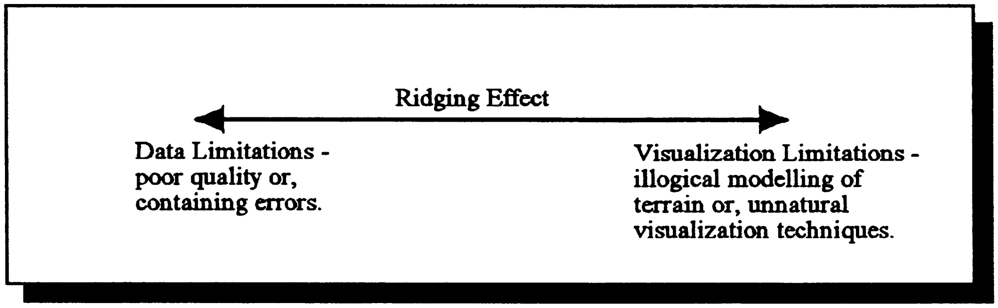

Figure 1-3: Competing philosophies in the cause of the ridging phenomena.

There was sufficient concern on the part of SNB that researchers at the Department of Geodesy and Geomatics Engineering at the University of New Brunswick were contracted to investigate the causes and removal methods of the ridging phenomena in SNB DTM datasets.

1.1 Project Objectives

The principal goal of this research is to find the cause and a method of removal for the ridging effect from Service New Brunswick DTM files. The secondary objectives of the project are:

(1) To establish the magnitude of "ridges" and to identify a criterion of testing for the DTM data;

(2) to test procedures to automatically identify the existence of the ridging effect within SNB DTM datasets;

(3) to test several alternative filtering procedures to remove or, diminish the ridging effect;

(4) to recommend on the most appropriate method of removal of the ridging and to develop a strategy for implementation of the necessary changes to the DTM data files [Pegler and Coleman,1998].

The purpose of this research is to first and foremost provide SNB with a method to detect and then remove ridging from contaminated DTM files. It is hoped that this will provide a cost effective alternative to recollecting all the data.

The research may also assist other agencies possessing DTM files with similar characteristics. Although the specifics of their problems may differ it is hoped that this research can provide a good starting point in solving their problems.

1.2 Proposed Approach

The proposed approach to this research is considered in four separate stages and presented below in outline form.

1.2.1 Background Research

The Background Research component of the project will cover five tasks, including:

- Meet with SNB personnel to establish lines of communication and begin the project;
- Review and summarize literature on the "ridging" effect in digital terrain models to identify existing research relevant to the SNB problem;

- Contact up to five (5) organizations across North America to obtain and compare, key lessons learned, specifications, and possible solutions with respect to the ridging effect found in digital terrain datasets.

1.2.2 Test Procedures to Identify the Existence of "Ridging" Within a Dataset

Prior to investigating alternative solutions to the problem, an automated detection scheme must be tested to determine if a particular dataset contains the "ridging" phenomena. This work involves:

- Data collection/conversion and software installation;
- Develop a model for the "ridging" effect;
- Investigate procedures for the automatic detection of ridging within a dataset.

1.2.3 Development of a "Testing Criteria"

In order to determine practical solutions to the problems resulting from ridging, a criteria must be developed defining the key indicators/tolerances for DTM data that would indicate practical improvements to the datasets in terms of user satisfaction and economics.

1.2.4 Test and Develop Alternative Solutions for the Compensation of Ridging Within a Dataset

The ultimate goal of the proposed research is the evaluation of a number of alternatives for compensating for "ridging" within DTM datasets. The ultimate solution must be cost effective and provide a practical means of automating a compensation algorithm. This will allow SNB to improve the quality of 1894 DTM datasets that cover the province.

The creation of a report on the findings of this research. A progress presentation at the end of Stage 2 will address the ability to effectively measure the phenomena. Finally, a presentation of the results to SNB staff will summarize key findings from all of the stages of the research.

1.3 Project Constraints

For the sake of simplicity, solutions will be developed using commercially available geomatics software packages. The majority of the work will be performed on a 200MHz Pentium personal computer having 128 megabytes of RAM, a 2.5 gigabyte hard drive, and 1 gigabyte JAZ drive. The operating system is Microsoft's Windows NT 4.0.

It should be reiterated that the goal of the project find the cause and a method of removal for the ridging effect from Service New Brunswick DTM files. Any software developed to help solve this problem will be developed and tested in prototype form only as a "proof-of-concept". It is not the intention of the researcher to develop a commercial software package or even an extension to existing commercial software.

1.4 Organization of the Report

The report will be organized in the following manner:

- Chapter 1 will provide the context and summarize the problem of ridging in SNB DTM datasets. The principal objective of the research is stated and secondary objectives are also described. In addition, the significance of the research is described. A summary of the proposed approach is presented along with the constraints of the project.
- Chapter 2 summarizes the relevant background research including the cause of ridging. In particular, various filtering methods are explored. These include; simple low pass filtering techniques, Fourier transform filtering, TIN Random densification and trend surfaces.
- Chapter 3 contains descriptions of the testing procedures to detect ridging, and the testing criteria for contaminated SNB DTM data. In particular, attention is paid to indicating practical improvements to the data sets. Further, based on the improvement criteria, various approaches to eliminate or, reduce ridging are discussed.
- Chapter 4 contains the summary of analysis, discussion and results obtained in the investigation undertaken in the previous chapters. In particular, the implications of the results, analysis decisions and recommendations are presented for the two phases of testing. Chapter 4 also describes the inclusion of a small pilot project

with Computer Terrain Mapping, Boulder Co., who provide a Fourier technique to filter out ridging primarily for USGS Level-1 DEMS.

- The final chapter will contain the summary of analysis, results, and conclusions obtained in the investigation undertaken in the previous chapters.

1.5 Chapter Summary

On behalf of the province of New Brunswick, SNB maintains a province-wide series of Digital Terrain Models (DTM).The DTMs were collected photogrammetrically as a series of profiles spaced 70 metres apart.

Users of these DTM's have continued to express concern over perceived data quality issues based on the evidence of a regular "ridging" effect within many of the DTM files. There was sufficient concern on the part of SNB that researchers the University of New Brunswick were contracted to investigate the causes and removal methods of the ridging phenomena in SNB DTM datasets.

The principal goal of this research is to find the cause and a method of removal for the ridging effect from Service New Brunswick DTM files. Further, a testing criteria for DTM data is to be identified. Based on the above findings, up to five alternative filtering procedures are to be developed to diminish the ridging phenomena.

The following reflect the outcome of this work including: background research, analysis - design and approach, summary analysis and discussion of results, and conclusions.

2

BACKGROUND RESEARCH

A review of the literature demonstrates that the ridging phenomena can be viewed from two perspectives: (1) that the ridging is due to some data limitation; or (2) that ridging is a problem due to data arrangement and visualization techniques. In addition, the background research on ridging identified that similar phenomena existed in other jurisdictions. Most notable of these is the ridging or, striping phenomena described in the literature regarding the USGS 7.5-Minute and 1-Degree Digital Elevation Models.

2.1 Manual Profiling - a DTM Data Collection Technique

The common thread between the USGS DTM and SNB DTM data sets that exhibit the ridging phenomena is the method in which the mass point data was gathered. In both cases, the mass point data was collected using a technique called manual profiling.

Figure 2-1 illustrates the manual profiling technique. In this technique, the stereoplotter operator, gathers the DTM mass points following along regularly spaced profile lines [NBGIC, 1995].

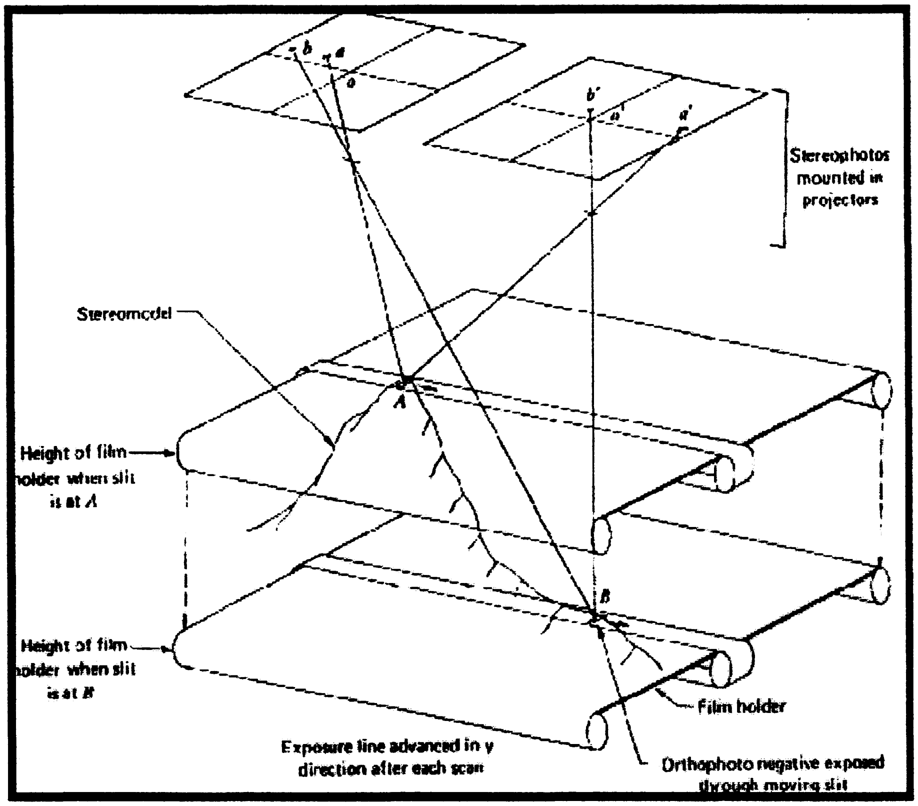

Figure 2-1: Manual Profiling (Lillesand and Kiefer [1979]).

At regular spacings along the profile line, the floating mark is placed on the what the operator interprets as the surface of the earth. For SNB data, the interval between the profile lines is 70 metres and where possible the points are spaced 70m apart.[NBGIC, 1995]. USGS Level 1, 7.5-minute DEMs have a line spacing of 90m and a point spacing approximately 30 metres [Russel and Ochis, 1996].

The USGS program of DTM data collection is much larger than the SNB program. The "Level 1" USGS data set collection began in the 1970s. In order to distinguish these early data sets from those collected with more modern techniques, they are described as the "Level 1" datasets. The majority of these data sets were collected using manual profiling techniques [Garbrecht and Starks, 1995]. It is interesting to note that the data sets collected with more advanced data structures (described as "Level 2" datasets) such as Digital Line Graphs don't exhibit the ridging phenomena [Garbrecht and Starks, 1995].

In both the USGS and SNB data collection specifications, the majority of the data was collected along the profiles lines in alternating directions. For example, if the mass points are being collected along the current profile line in a northerly direction then, upon completing the run along that line, the operator would move the required spacing to the next profile line and then begin sampling in a southerly direction. Of course, the operator's ability to accurately place the floating mark on the earth's surface may be inhibited by forest canopy cover, water, relief, or problems with the aerial photography [NBGIC, 1995].

2.2 Causes of the Ridging Effect - The Data Limitations Perspective

In general, the data limitations perspective believes the ridging effect is caused by some systematic error that is related to the DTM production methods [NBGIC, 1995] . A common explanation is that the ridging phenomena is due to errors introduced by the collection of data in a "shuttlecock" or alternate profiling manner [Garbrecht and Starks 1995], [Russel and Ochis, 1996].

Garbrecht and Starks, upon direct consultation with USGS staff, concluded that ridging is caused by a combination of "human and algorithmic" errors. The human error manifests itself as different operator perceptions when the floating mark is "set upon" the ground from between each alternating profile line. Algorithmic errors are introduced by the interpolation algorithm used to interpolate heights between the two profile lines.

Early research into the development of specifications for the production of DTM's using manual profiling indicated that excessive scanning speed during the collection of mass points along a profile caused an alternating datum error [Brunson and Olsen, 1980]. Brunson and Olson described the effect as a"herringbone" pattern in the contours derived from DTMs whose data was collected using "fast-velocity" profiling. It was reported that the herringbone pattern is more prevalent in areas of steep terrain. This type of error is often referred to as the "lag effect" [Russell, Kumler and Ochis, 1995]. The datum error represents a systematic tendency of the photogrammetric operator to allow the floating mark to "fly off" a crest of a hill and "dig in" at the base of a hill. The magnitude of this type of error increases proportionally with the speed of which the operator collects the data is areas of high relief.

Russell, Kumler and Ochis [1995] in their research suggest that the "lag effect" is not the sole cause for the systematic error that is said to be manifested by the ridging. If the lag effect is the sole cause of error in creating ridging, then no ridges would show up in flat areas. Clearly, Figure 2-2 dispels this notion.

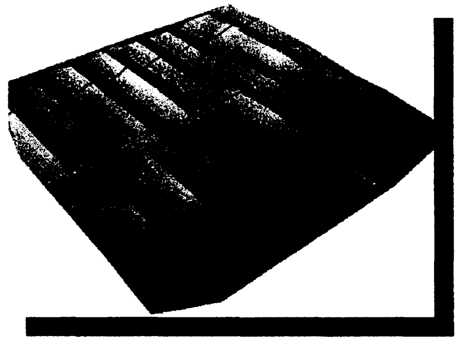

Figure 2-2: Example of ridging over a peat bog. Caraquet, N.B. Canada.

Contradicting the finding of Brunson and Olsen, others have found that ridging is often most prevalent in flat areas [Garbrecht and Starks, 1995] and [Pearson, 1998]. Further, Figure 2-2 also demonstrates that some profiles are consistently high or low, even where there is no significant change in elevation. However, the lag effect may explain why, in rarer instances, ridging is present in areas of steep terrain, as illustrated in Figure 2-3.

Figure 2-3. Presence of Ridging in Areas of High Relief. Hayesville, N.B., Canada.

The most recent research representing the data limitations perspective incorporates all the suggested causes of ridging as listed above. This current definition of the cause of the ridging phenomena is a function of several factors: manual profiling, algorithm errors, terrain, "lag effect", operator errors, and machine miscalibration [Russell and Ochis, 1995].

2.3 Causes of the Ridging Effect - The Visualization Limitations Perspective

Those supporting the belief that the ridging is due to limitations in visualization believe that, at the heart of the matter, it is the linear arrangement of the elevation data [Lee, 1998]. This raises the question, is it logical to attempt to model the earth's chaotic surface using simple linear arrangements of data? From a production point of view, this may indeed have merit. However, in terms of accurately representing the relief, it is not likely.

One may think of this as being similar to a pair of corduroy trousers. No matter how worn or smoothed the corduroy is, the lines of corduroy are still visible. Like the corduroy pants, the data patterns of the SNB DTMs are linear in nature and as a result visualization of the data will reveal this pattern [Pearson,1998]. In particular, when a TIN is used to create a DTM based on this data structure, the systematic creation of evenly spaced triangles of similar dimensions produces a linear pattern when viewed. Figure 2-4 shows the pattern of linear arrays of TIN triangle facets created from mass point data created in a linear manner. Although using TINs to build surfaces from nearly regularly

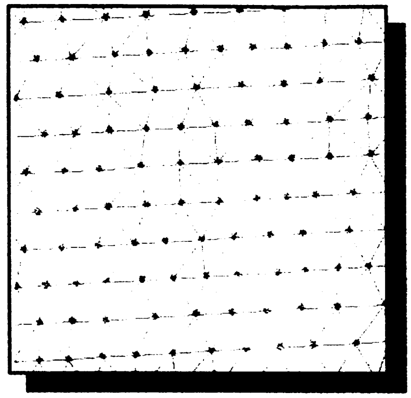

Figure 2-4: Horizontal linear array of TIN facets representing ridging.

sampled data is common, the TIN data model was not intended for this purpose. Rather, it was intended for use with points that clearly define the surface but are irregularly placed [Bonham-Carter, 1994]. In fact, the use of TINs for manually profiled data sets can compound the visualization problems.

There are four areas where research has been undertaken to address the ridging phenomena: spatial filtering, Fourier transformation, TIN random densification and surface interpolation schemes. The background behind each of these approaches will be discussed in turn.

2.4 Spatial Filtering

"Spatial frequency" is defined as the measurement of the spatial variation of a parameter [Schowengerdt, 1997]. For the purposes of this work, the parameter being measured is elevation within a DTM. Spatial frequency can be classified as either low or high. Objects that exhibit low frequency elevations have a slow change of elevation over a small distance [Leblon, 1997]. An example of an object exhibiting a low frequency are train tracks which exhibit only a very small change in elevation over a long distance.

An example of an object that exhibits a high spatial frequency in elevation would be a series of dykes. The dykes, when viewed in a cross-section, would have rapid changes in elevation over a short distance [Leblon,1997]. Ridging is an example of a high frequency phenomenon, as illustrated in Figure 2-5. The change in elevation is less than 10 metres over the distance between adjacent DTM profile lines which is approximately 70 metres [NBGIC,1995].

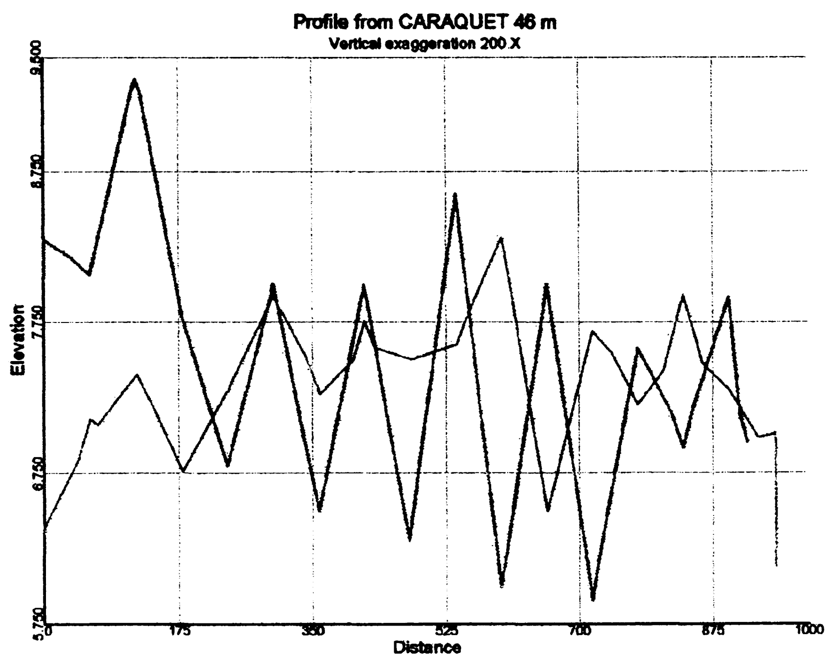

Figure 2-5: An Example of Ridging as a High Frequency Phenomenon.

Low pass filters (LPF) or, those filters that allow only the lower frequency objects through, are used to de-emphasize high frequency components of DTMs. Again, ridging can be reduced by a LPF because it is essentially a high frequency component of a DTM. Figure 2-6 illustrates how simple linear 3x3 LPF is implemented.

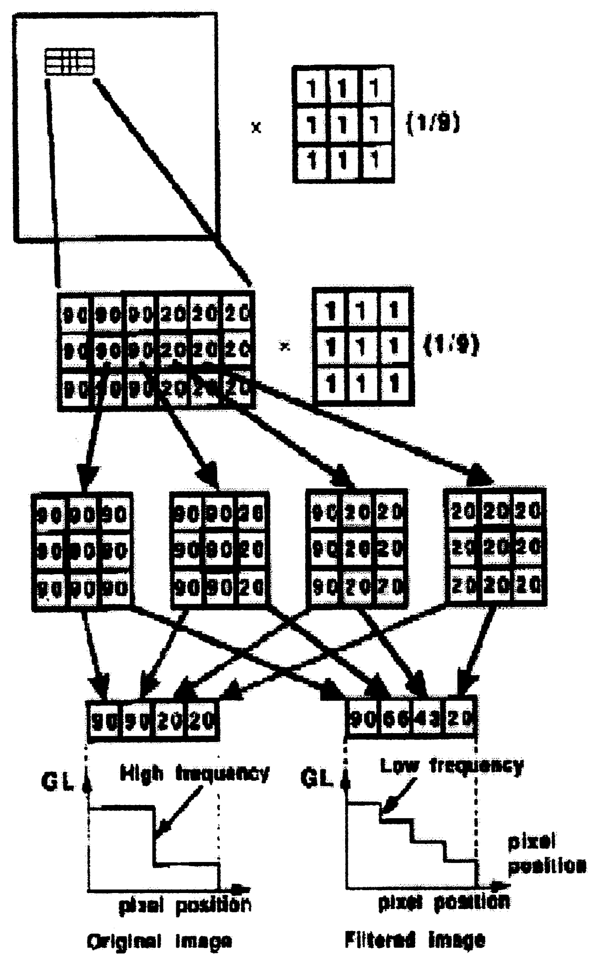

Figure 2-6: Operation of a Low Pass Filter (after Leblon, [1997])

The operation of 3x3 LPF is quite simple. A 3x3 kernel is centred over the pixel being operated on. The unfiltered value of the pixel is replaced by the mean of all nine pixels falling within the kernel. The result is a "smoothing" of the rapid changes in elevations - in the case of an image representing a DTM.

This technique of filtering, while a common approach, is known not to be sufficient to remove all the systematic errors in the DTMs [Brown and Bara, 1994]. Further, the smoothing effect of the filter will somewhat degrade the quality of the data by reducing the peaks and filling in shallow depressions. Of particular concern to many users is that the shallow depressions representing wetlands will be smoothed over. Those concerned with hydrological applications reject this ridging reduction method because of the reduction in the definition in the outline of drainage features and the introduction of artificial blockages to drainage channels [Garbrecht and Starks, 1995] Despite its shortcomings, however, 3x3 LPF spatial filters are often used due to their ease of implementation and simplicity.

There is an important relationship between cell size, filter size, and dimension of the feature to be smoothed. In the case of the ridging phenomena in SNB DTM datasets, the wavelength of the ridging (ie. crest-to-crest or trough-to-trough) is 140 metres. That corresponds to the perpendicular distance between three adjacent profile lines. In order for the filter to remove the ridge artifacts, it must extend over the three lines [Leese, 98]. In order for a 3x3 LPF filter to smooth the ridge then, the resolution (cell size) of the image must be resampled to 45 m. If another cell size is being used, then the dimensions of the filtering kernel (sometimes referred to as a "boxcar") must be altered to suit the problem.

Researchers suggest that a more robust technique is the use of "non-square, low pass" filtering techniques [Brown and Bara, 1994]. The non-square filter is oriented perpendicular to the direction of the ridging in DTM datasets. The filter works in a similar manner to the 3x3 LPF described above. However, having the kernel 5 pixels wide and perpendicular to the ridging allows the filter to smooth a longer wavelength (λ) of the ridge. In the case of SNB DTM data that is resampled to 45m resolution, the 3x5 filter would operate on approximately 1.5λ of a ridge. Orienting the filter perpendicularly to the ridge allows for greater smoothing across the ridges and less smoothing along the profile lines where no ridging exists.

Brown and Bara, in their research into the reduction of systematic errors in USGS DTMs, suggest the use of semivariograms and fractals in the detection of ridges in a DTM data set. Semivariance is a geostatistical measure which describes a DTM as "... the average squared difference of surface values" [Brown and Bara, 1994] which are a user defined distance apart. This separation between the values is known as the "lag distance". The formula for semivariance is as follows:

$$\gamma(h) = 1/2(N-h)\sum_{i=1}^{N-h} \left(z(i)-z(i+h)\right)^2$$

where N is the number of points on the surface, $z(i)$ is the elevation value of the surface at point i, and $z(i+h)$ is the value of the surface h distance away from point i.

A semivariogram is a plot of semivariance against lag. In general, the smaller the lag distance the smaller the semivariance and thus the similarity in elevation values. As reflected in Berry's application of Tobler's 1st law of geography that "all things are related, but nearby things are more related than distant things"[Berry, 1998].

Related to the slope of a log-log plot its semivariance, the fractal dimension of a surface is a number that ranges between 2 and 3. The formula for the fractal dimension is as follows:

$$D = 3 - m/2$$

where the D is the fractal dimension and m is the slope of the log-log plot of semivariance.

The fractal dimension is measure of the self-affinity of a surface [Polidori et al, 1991]. Perhaps self-affinity is best explained with an example. If a drumlin field is modelled by a DTM, a particular drumlin would possess self-affinity with the rest of the entire field - regardless of its dimension, scale, and location. It could be thought of as a single drumlin element in a set of drumlin elements. The quality of the affinity of the drumlin with the rest of the drumlin field is characterised by its fractal dimension.

In general, DTMs will exhibit self-similarity over short distances - on the order of hundreds of metres [Brown and Bara, 1994]. Using this property, systematic errors like ridging may be detected by calculation of the fractal dimension along specific cardinal directions ie. east/west and north/south. If the fractal number is higher along a particular direction than its perpendicular counterpart, then this is good evidence as to the existence and structure of ridging or other systematic errors [Polidori et al, 1991].

Once detected, low pass filters were used to reduce the systematic error [Brown and Bara, 1994]. However, this technique also degrades the quality of DEM by removing data values which were actually correct. The researchers state "...that the changes in elevation values with filtering appear to minor ... "[Brown and Bara, 1994]. An investigation into the contradiction regarding the amount of degradation of DEM will be performed.

2.5 Fourier Transforms

Spatial data or, other signals, can be represented in the "spatial domain" or in the "frequency domain" (also known as the power spectrum). The transformation between these two domains is managed by the Fourier transform [Pan and Chang, 1992]. Fourier transforms can be derived for 1 or 2 dimensions. Simply put, the 1-dimension Fourier transform fits a continuous function though a row spatial data. The function is constructed by combining sine and cosine waves. Each of the waves has individual amplitudes, phases, and frequencies. The resulting Fourier transformation is a measurement of the "amplitude and phase for each spatial frequency in the image" [Lillesand and Kiefer, 1994].

The Fast Fourier Transform FFT is the algorithm used in computers to model the discrete Fourier transform. The formula for the 1 dimension Fourier transform is as follows:

$$Z_n = \sum_{k=0}^{N-1} Z_k e^{2\pi i k n/N}$$

where Z_k is the range of elevations to be transformed, N is the total number of samples. The value for k ranges as follows:

$$k = 0,1,\ldots\ldots\ldots N-1,$$

and the value for n is as follows:

$$n = -N/2, \ldots\ldots, N/2$$

Frederikson [1980] explored the use of FFTs in the analysis and statistical description of DTMs. In his research, particular geological landforms were identified by analysing DTMs in the frequency domain. Hassan [1998] made use of Fourier transforms for the identification and filtering of the noise (ridging) within a DTM.

A periodogram is a graph of the power of a signal (or square of the elevation when transforming a DTM) versus the frequency. When dealing with DTM data, frequency refers to cycles (peak-to-peak or, trough-to-trough) per metre rather than cycles per second [Russell and Ochis, 1996]. The periodogram of a DTM having a smooth surface would exhibit large values at the low frequencies. At the higher frequencies the values would be extremely small because there would be no rapid change in elevation over a short distance that is characteristic of high frequency surfaces.

If, however, a sinusoidal wave was introduced to the smooth surface of the DTM, an interesting phenomena occurs. The sinusoidal signal that could represent undulating relief would produce a spike in the periodogram. This spike would occur at the frequency of the sine wave introduced to the surface.

The Fourier transform has no way of discriminating signal from noise. The noise in a DTM will be transferred into the frequency spectrum along with the elevation data. If, however, the noise (or systematic error) has a particular repeating pattern or wavelength then, just as with the sinusoidal signal, a spike or spikes will occur at the higher frequency or frequencies. If these spikes are removed and then the data inversely transformed back to the spatial domain, the systematic error component for the DTM will be removed. Hassan [1988] is careful to note that not all the random errors or noise will be eliminated because there may be minor contributions to the higher frequency components of the DTMs that are not eliminated by removing just the major spikes.

Filtering images using Fourier transformations differs from LPF spatial filtering because it attempts to only remove the systematic error component of an data value and return only the elevation component. The resulting filtered DTM will be restored with a minimum of distortions [Hassan, 1988] and will not suffer as great a degradation as occurs with LPF spatial filtering.

Figure 2-7 illustrates the steps used in the commercial implementation of this process. The DTM is first separated into individual profile lines that are perpendicular to the orientation of the ridging. Step 1 in Figure 2-7 illustrates a single profile line. Note the right hand portion of the profile line is obviously contaminated with ridging. In Step 2, in the figure, shows the periodogram of the same profile. Notice here that most of the signal is low-frequency in nature but, that there are two atypical spikes (highlighted by asterisks) in the higher frequencies. These spikes correspond to the ridging which has a wavelength of 180 and 90 metres. Note, that this corresponds to the 90 metre distance between DTM data profiles in USGS 7.5 Minute Level 1 DTMs.

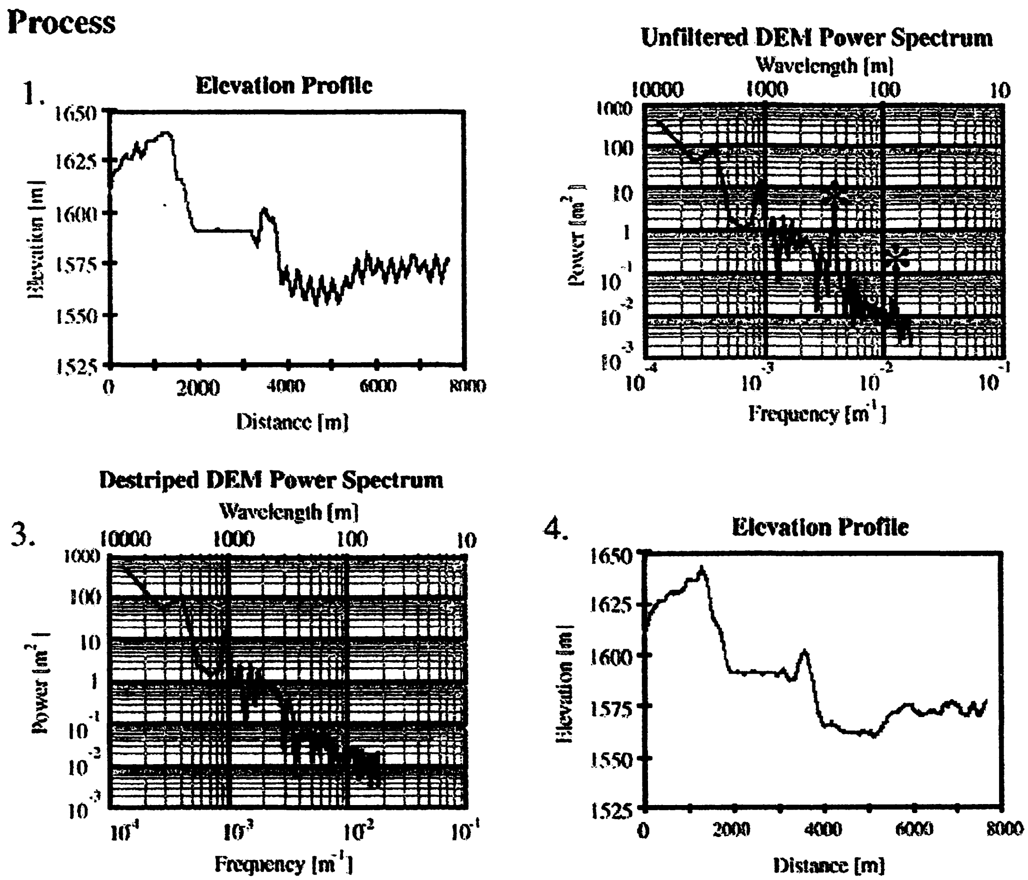

Figure 2-7: Ridging Removal Process using FFT's (After Russell et al., [1995]).

The atypical spikes in the high frequencies are then filtered out. Pan [1989] describes the use of a point filter to remove periodic noise in digital spatial data. The point filter is multiplied with the frequency domain data and the filtered result is then inversely transformed back into the spatial domain. The formula for the point filter is as follows:

$$H(u,v) = 1.0 - e^{\frac{r^2}{2\sigma^2}}$$

where (u,v) are the frequency coordinates, σ is the standard deviation of the Gaussian distribution and r is as follows:

$$r = \sqrt{\sqrt{(u-u')^2 + (v-v')^2}}$$

where (u',v') is the frequency of the spike to be removed.

Pan makes the point that, in order not to remove the good data, the user must have knowledge of the characteristics of the data. For instance, when filtering ridging from DTMs it is important to understand the wavelength of the ridging. In this way the only the noise will be separated from the signal.

Step 3 in Figure 2-7 illustrates the periodogram with the spikes due to ridging filtered out. Step 4 illustrates the filtered profile after it has been inverse transformed back to the spatial domain. All filtered profiles are united to created the filtered DTM.

Pan and Chang [1992] suggest that there are some restrictions to using FFTs to filter data: a large amount of data space required, "ringing" artifacts resulting from high-intensity discontinuities, and edge effects between filtered datasets. This last restriction could have serious ramifications when edge matching adjacent DTMs.

2.6 TIN Random Densification

During a discussion on the topic of causes and solutions to ridging, Lee [1998] proposed that - perhaps rather than a numerical solution to ridging such as the use of FFTs

- an alternative might be to rearrange the pattern of triangles making up the TIN. As mentioned earlier, it has been proposed that the ridging may be due to the systematic creation of evenly spaced, thin triangles produces a linear pattern when viewed. The solution proposed by Lee, which we call TIN Random Densification, is to interpolate values for randomly spaced points between the original profiles of data. By randomly breaking up the geometry of the triangles within the TIN, it is postulated that the ridging will be diminished.

2.7 Trend Surface

Surface functions are developed to create continuous surfaces from discrete sample points distributed throughout a study area. The points can represent measurements of elevation, concentration measures, or other measures of magnitude of some physical phenomena. Most commercial GIS software manufacturers include this functionality.

The variability of surfaces may be broken down into three components: trend, signal, and noise [Bonham-Carter, 1994]. The trend component is as known as drift. Trend surface interpolation constructs a surface based on a least squares regression fit through all the points. This can be thought of as fitting a plane (1^{st} order polynomial) through data points rather than the common 2 dimensional line. The resulting surface will represent a "best-fit" solution through the points that minimizes the squares of the residuals between the actual and estimated values [ESRI, 1997]. This type of surface fitting is best suited to continuous types of data such as elevation.

Increasing the value of the user defined polynomial increases the complexity of the surface. The value for the order parameter should range from 1, for a plane, to a maximum of 3. Caution should be exercised in using higher order polynomials because in certain data sets the interpolated maximum and minimum could exceed those of the original data set [ESRI, 1997]. Perhaps a medium order polynomial trend surface could be fit through the surface that would smooth the ridging but maintain the relief.

2.8 Chapter Summary

The purpose of this chapter was to examine the previous research on the causes of and solutions to, the ridging effect.

It is thought that the ridging effect is an artifact caused by some combination of the following factors: manual profiling, interpolation algorithm errors, "lag effect", machine miscalibration, operator errors, or the linear pattern of TIN facets caused by the regularly-spaced profile lines.

The research has suggested the following solutions for the ridging effect: low pass spatial filtering, Fourier filtering techniques, TIN Random Densification and trend surface generation. Testing and analysis using these four techniques will be explained in the next chapter.

3

ANALYSIS: DESIGN AND APPROACH

3.0 Analysis: Phase I

Chapter 3 contains the design and approach taken for the testing of the proposed solutions to the ridging phenomenon. The solutions are based on the information gathered in the background research. The testing was done in two phases. At a certain point during the testing, it became apparent that certain proposed solutions to the ridging problem were no longer worth continued exploration due to their poor performance. At this point, a second phase of testing was initiated whereby the testing was concentrated on comparing the remaining solutions. A good deal of the design decisions were tempered by time constraints imposed by a contract to deliver a consultant's report for SNB.

3.1 Approach

The general analysis approach taken was to select study areas and software, develop the testing criteria, investigate methods of detecting ridging, and then develop, implement and test the proposed ridging solutions.

3.1.1 Study Site Selection

Prior to starting the analysis, it was decided that three study sites should be selected that would allow testing of the various proposed ridging solutions in a variety of terrain conditions. Moreover, discussions were ongoing with Faye Cowie of the [1998] who was interested in the impact of this work on her studies into watershed delineation. These discussions resulted in the selection of a study site near Hayesville, N.B.

The numbers listed below correspond to the Service New Brunswick (SNB) map sheet index numbers. The mass point datasets and corresponding drawing exchange files (.dxf) are part of SNB's Enhanced Topographic Database. Figure 3-1 illustrates the location of the study sites.

	Map Sheet Number	Geographic Name	Feature
A.	4775646	Caraquet	- peat bogs, flat terrain
B.	4690675	Aroostook	- high relief
C.	4660666	Hayesville	- mixed relief, hydrological modelling

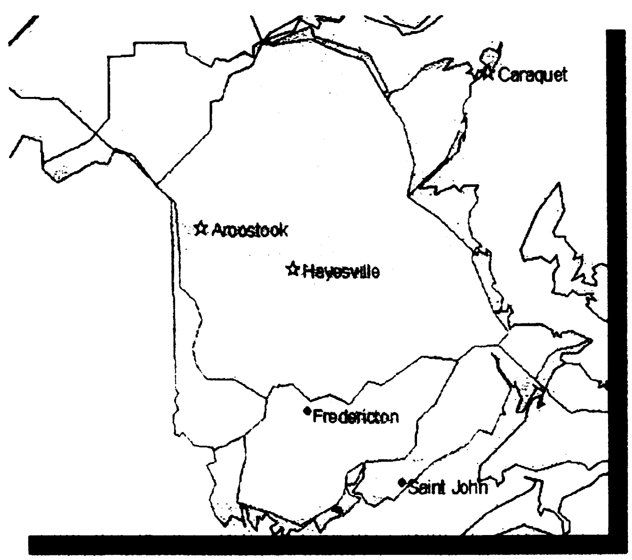

Figure 3-1: Study site locations. New Brunswick, Canada.

3.1.2 Software Selection

The software for this project was selected primarily for ease of acquisition, flexibility, and shortness of learning curve in order to have acceptable production. All the software was available through the Geodesy and Geomatics Engineering department at the University of New Brunswick except for some of the extensions to ArcView. However, these were promptly ordered after accessing their capabilities concerning this work. Moreover, previous training and industry experience made the learning curve shorter than with other software.

The software tools employed in this research include: PCI's Image Analysis v6.0 software and Environmental Systems Research Institute's (ESRI) ArcView v3.1. ArcView's functionality was enhanced by using ESRI's Spatial Analyst v.1.1, ESRI's 3D Analyst v.1.1, and Geokinetic Systems Inc. *theEngine*© for ArcView.

3.1.3 Test Patch Creation

For each of the three study site locations, a 1 km x 1 km test patch was created. This was done to help speed the initial processing and testing during first phase of the ridging analysis. The test patches were clipped from the SNB mass point files.

There are two data formats for DTMs: raster and vector. The raster data format is simply a lattice of cells. The value of the cell is the elevation of the surface at the cell. Resolution of raster DTM data reflects how well the DTMs may represent the relief.

The second data format, Triangulated Irregular Networks (TIN) are the most common vector data model for DTMs. TINs can be conceptualized as a mesh of three dimensional triangles, the vertices of which correspond to mass points. For this work, point data (either clipped or a whole map sheet) were then used to create a TIN. Since the SNB data were not exactly evenly spaced, particularly along the profile lines, the creation of a TIN ensured that all the mass point data were utilized.

The TIN data then was also copied and converted to a raster format having the desired resolution. Some of the proposed solutions, such as Fourier filtering or LPF spatial filtering, required working in raster rather then TIN format. The data was not converted first to raster because, in testing, this process created "holes" or areas that have a *NODATA* value. The NODATA values were assigned to cells that did not fall upon a mass point. Moreover, the documentation was not clear as to what elevation value was assigned to a cell that contained more than one mass point. Therefore, these difficulties were overcome by first creating a TIN data format from the SNB mass points,

3.1.4 Development of the Testing Criteria

In order to compare the merits of each of the solutions to the ridging phenomena, a basis for testing was created. These criteria were developed through discussions with SNB personnel, local contractors, and data users. The results of these discussions was the selection of five testing criteria: perspective viewing, profile creation, 100 random point comparison, hydrological analysis, and contouring. Only the first three criteria were used in the first phase of testing in order to streamline the analysis process.

At the outset, it was apparent that one of the primary concerns presented by users of the SNB DTM datasets was that the ridging became quite pronounced. Quite often, desktop GIS and viewing packages will automatically set viewing parameters for spatial data in order to emphasis outliers in the data. In terms of the DTM data, these parameters were set having a very low sun altitude and illumination angle perpendicular to the ridging. These default settings can lead to an un-natural emphasis of the ridging. It is almost certain that many users' concerns over perceived data problems would be minimized if they had a better understanding of the data and its limitations. Moreover, introduction of 3D visualization parameters that were tailored to the data would be beneficial. However, given that increasing numbers of non-specialized users will utilize SNB DTM data, it was felt that a robust ridging solution should be able to withstand users viewing the DTM in the most unflattering manner. All the perspective views in this work were generated in the most unflattering manner to fully test the solutions. All the perspective views were generated with a sun azimuth perpendicular to the ridging, having a sun altitude set at 30°.

The creation of profiles allowed for the examination of two concerns: the pattern of the ridging and the smoothing (or filling) in of the high or low points. It is important reveal the pattern of ridging that one is trying to filter. Certain filtering solutions, like Fourier transformation techniques require, that the user know the exact wavelength of the ridging present in the data being transformed. By knowing the exact frequency, the ridging can be tagged and filtered out in the frequency domain. Failure to do so could result in the removal of signal (elevation data) rather than noise (ridging).

Certain user applications of DTM data are very sensitive to any smoothing of the data. As was previously discussed, hydrological applications and in particular those associated with shallow wetlands are sensitive to any smoothing operations. Even very limited smoothing of the data could remove the shallow depressions representing wetlands. Still other applications are concerned with the removal of local and regional extremes in the relief. For example, the use of DTMs in creating aircraft flight corridors would be negatively impacted if the tops of mountains were smoothed over and not accurately represented by the DTM.

As a result, two profiles lines were created for each test patch. The lines were created having a direction being perpendicular to the orientation of the ridging. This allows for the best study of the pattern of the ridging. Moreover, one profile was placed so it crossed the highest point of elevation and the other line crossed the point having the lowest elevation allowing for study on the amount of smoothing by the filtering operation. Profiles were then created for each proposed solution for each study site's test patch.

Generally, the definition of aspect is the azimuth of the maximum slope [Bonham-Carter, 1994]. Extending this definition, aspect - relative to a TIN - may defined as the azimuth of the slope of an individual TIN facet. A TIN that is contaminated by ridging will have an unusably large number of TIN facets whose respective aspects were in one of two cardinal directions being 180° to each other. Recalling the previous example images of heavily contaminated DTMs, the ridges appear as row upon row of crests and troughs. The sides of these features are comprised of these opposite facing TIN facets.

Statistics were generated for the aspect map for each proposed solution for each study site's test patch. These statistics provide insight into the orientation of the ridging. Presumably, a dataset with the ridging removed would generate an aspect map having a lower number of TIN faces oriented perpendicular to the direction of ridging.

A common method for assessing the accuracy of a DTM is the comparison of elevation values from *randomly* generated points for a reference dataset with values for the same randomly generated points for another dataset [Brown and Bara,1994], [Polidori et al., 1991]. A variation of this kind of accuracy checking is to compare elevations for a random selection of the *original* mass points with interpolated elevation values for the same mass point locations for the other dataset.

For each study site's test patch, a theme was created containing 100 randomly selected mass points. The elevation values for the 100 points were compared for each of the proposed solutions. These values were analyzed using spreadsheet software. The basic descriptive statistics: mean, maximum elevation difference, and RMS (ie. standard deviation of the absolute height differences) were generated for each study site and proposed solution. Obviously, a suitable solution would remove the ridging and have the lowest RMS error between the original data and the "smoothed" surface.

In discussing the ridging problem with the user community, another testing criterion emerged. Those users involved in hydrological analysis were concerned with the generation of small " phantom streams" when using automatic stream generation program [Cowie, 1998]. Automatic stream generation is a common preliminary step in watershed delineation.

The automatic stream generation programs operate on raster data types. Typically, stream generation programs are based on the principle of "flow accumulation". The flow accumulation of a particular cell is the sum of all the contributions to flow from all the upstream cells. The algorithm assigns a value to the cell that corresponds to its direction of flow. This value is calculated through evaluating the elevations of all the surrounding cells, comparing those with its own elevation, and then determining the direction of flow. Working backwards from the cell in question, and utilizing the flow direction data, the total flow accumulation for a particular cell is determined [ESRI, 1997].

Users commented that these "phantom" streams were found in areas contaminated with ridging [Cowie,1998]. The streams clearly followed along the troughs between the ridges. The ridging has a negative impact on the flow direction of a cell causing its flow to follow in a trough. As a result the cell's flow direction is artificially altered by the ridging from its true flow direction. Therefore, in response to these concerns, and as an indicator of the removal of ridging, the percentage reduction in the number of phantom streams was calculated between the original dataset and the smoothed data set.

The final criterion of improvement was the comparison of contours generated from the contaminated data sets with those with the ridging removed. Contours are a common product of DTM datasets. Many users are more comfortable with contours than other types of surface representation. In addition, those who have limited computing facilities or software limitations may employ contours for simplicity.

Any recommended solution must create a DTM dataset that will produce acceptable contours. That is to say, the contours must not show the ridges. Figures 3-2 illustrates contours generated from a contaminated dataset. The ridging causes the contours to create unnatural, long, thin, parallel shapes. The ability to interpret and visualize the relief from this image is clearly hampered by the ridging.

Figure 3-2. Contours generated from DTM containing ridging (after Russell et al.[1995]).

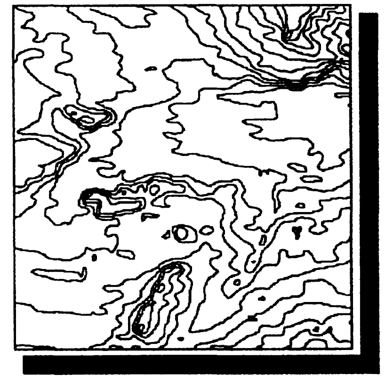

Figure 3-3. Contours generated from filtered DTM (after Russell et al.[1995]).

Figure 3-3 illustrates contours generated from a filtered dataset of the same region as that illustrated in Figure 3-2. It is clear that the contours have a more natural shape and it is much easier to interpret the relief in the filtered image. Contours images of this type will be generated for the various filtering solutions. For interpretation purposes, one representative area in each study site will be focussed on at a smaller scale.

3.1.5 Investigation into the Automatic Detection of Ridging

Figure 3-4 is an example of a TIN dataset that is contaminated by ridging. As was discussed earlier, it can be clearly seen that the majority of the TIN facets are facing in two cardinal directions which are perpendicular to the lines of point data. Figure 3-5, is a histogram of the aspect values of the TIN facets. In this example, the two large values on the right side of the graph represent TIN facets that face Southeast and Northeast.

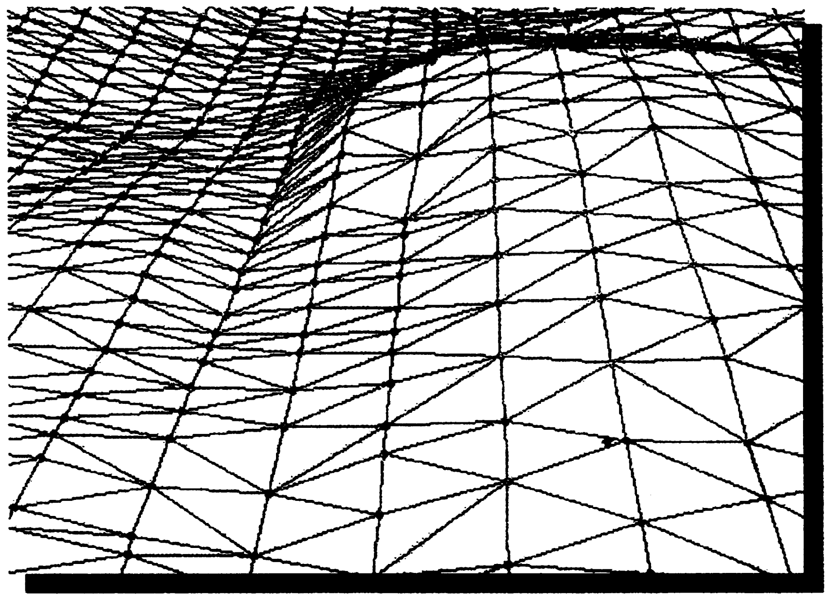

Figure 3-4: TIN facet alignment in the vicinity of ridging, Aroostook, New Brunswick.

These two large values indicate the presence of ridging. The large value on the left side of Figure 3-5 is due to a flat body of water.

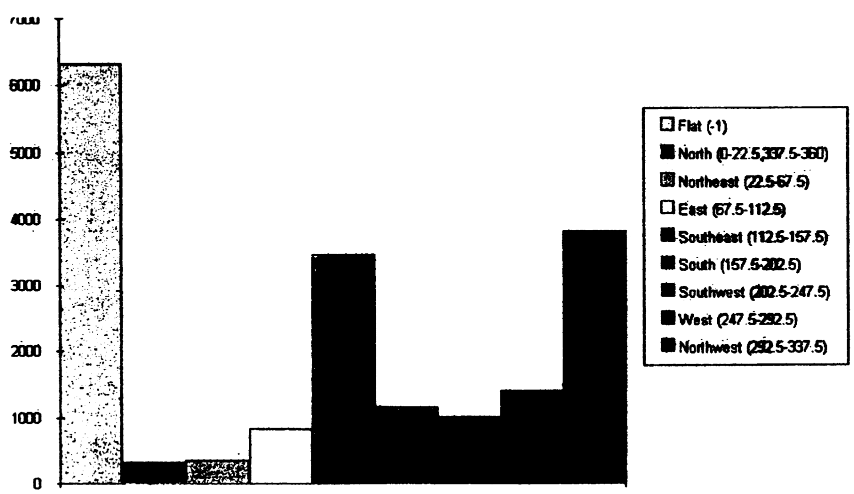

Figure 3-5: Histogram of Aspect Values.

A script was developed using Avenue which creates a histogram of an aspect map derived from a DTM. The script also reports the presence of ridging when the percentage of overall number of cell's aspect is in two cardinal directions and exceeds a user-defined tolerance. An example of the user interface is illustrated in Figure 3-6.

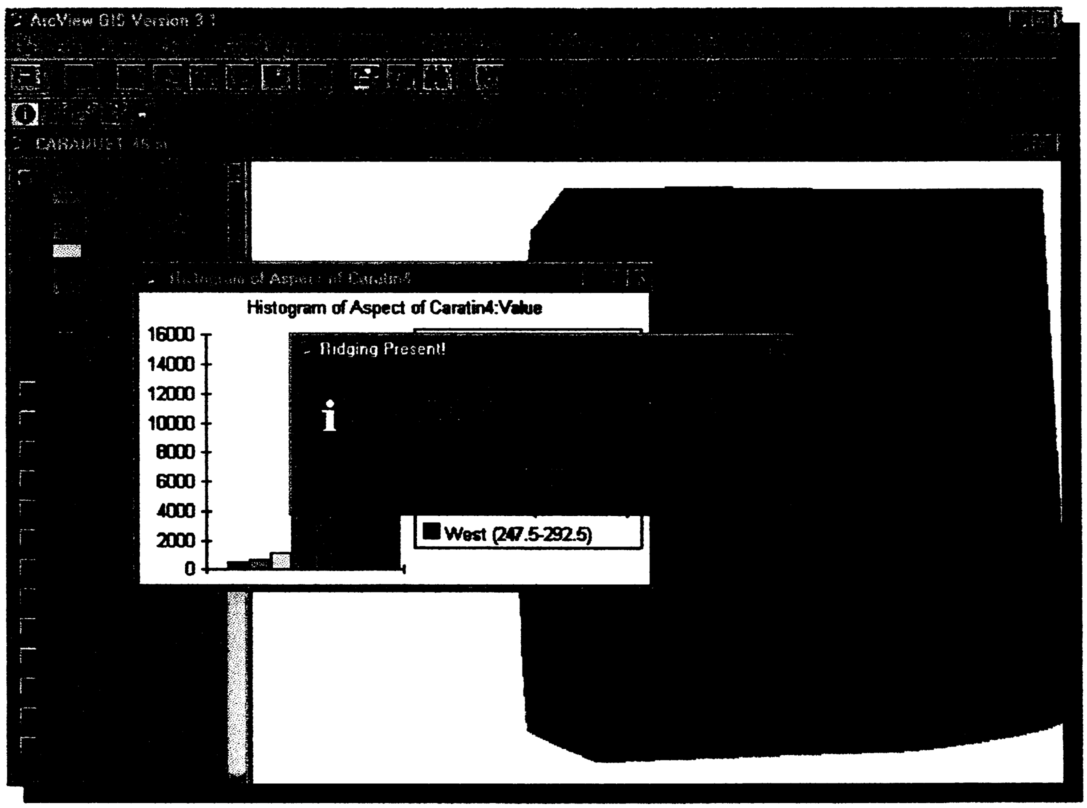

Figure 3-6: Ridging Detection - User Interface.

For example, if the mass point data was collected in lines running north/south, then one would expect that the aspect of the TIN faces, in a contaminated dataset, would be running primarily east and west. If, for example, the user tolerance was set at 52%, and the number of TIN facets exceeded this percentage, then the results of the script would indicate the presence of ridging as shown in Figure 3-6. The Avenue script is included in

Appendix A.

3.2 Development of Solutions for the Ridging Phenomenon

At this point, the following activities have been completed: background research, acquiring the test data, software selection, and development of the testing criteria, The next stage, is to determine and implement the functionality required to perform the various filtering and analysis techniques.

3.2.1 Spatial Filtering

Prior to exporting to PCI, the TIN data was converted to two separate files in raster format having resolutions 46 and 56m, respectively. These resolutions were chosen to optimize the spatial filtering. Given an average spacing between profile lines of 70m, then the optimal resolution for a filter with a width of three pixels is:

$$(70 + 70) \div 3 \doteq 46m$$

The second resolution of 56m was included in the analysis to investigate the impact of a change in resolution on LPF spatial filtering. The DTM data was imported into PCI's software where the spatial filtering was performed.

The DTM data was exported from ArcView as an ASCII text file. The header information had to be removed and saved as another ASCII file. Using the information in the header file, an empty image file was created using the correct number of rows and columns, resolution, and data type. The ASCII DTM data was then read into the first channel of the appropriate empty file in PCI using the EASI/PACE module command:

EASI> NUMREAD.

PCI has a simple programmable filter that allowed for the creation of various types of low pass spatial filters. The filters were created with kernel dimensions of 3x1, 3x3, 5x1, and 5x3 pixels. These dimensions mimic the work done by Brown and Bara [1994] in their investigation in low pass filtering of DTM data.

The concept of a low pass spatial filter is to emphasize low-frequency features. Those features with a high frequency are removed. In the case of a DTM, the results of a low pass filter would be the smoothing of the relief. However, features characterized by small rapid changes in elevation (such as a berm, ditch, or ridge) will be smoothed over and that detail would be lost.

As indicated in the background research, the size of the filtering kernel and its orientation affects the manner in which the DTM is smoothed. For this research using the SNB DTM data that is contaminated with ridging, there is *a priori* knowledge that the orientation of the ridging is in a specific direction i.e. north/south. As a result, the filter should be oriented perpendicularly, (in the east/west direction) to smooth out the ridges. Orienting the filter in the north/south direction would destroy the fine detail captured in the data in the north/south direction.

Conceptually, the user defined filter created in PCI using the Easi/PACE command, FPR (Filter, PRogrammable) is illustrated below:

1	1	1
1	1	1
1	**1**	1
1	1	1
1	1	1

The filter shown above is an example of how a 5x3 LPF is implemented by the user within PCI. The 15 cells in this filter kernel all have been assigned a value of 1. This represents a weighting factor to be applied to the value in the cell. The value of 1 indicates that no weighting factor is to be applied to the cell. The filtered value for the cell value being operated on (shown in bold), is calculated by the sum of all the individual cell values, multiplied by its weighting factor, divided by the total number of cells in the kernel. In this study, the weighting factor never changed, only the dimensions of the kernel had to be changed.

3.2.2 TIN Random Densification

As mentioned earlier, TIN Random Densification is premised on the introduction of random points into original linear lines of mass point data. The elevations of the random points are interpolated from the TIN created with the original points only. Finally, a new TIN is created by discarding the original data points and using only the new randomly densified points.

Figure 3-7 illustrates the algorithm implemented in the TIN Random Densification script. TIN random densification functionality was added by creating a customized "tool" in the ArcView project developed for this work. The Avenue script is included as

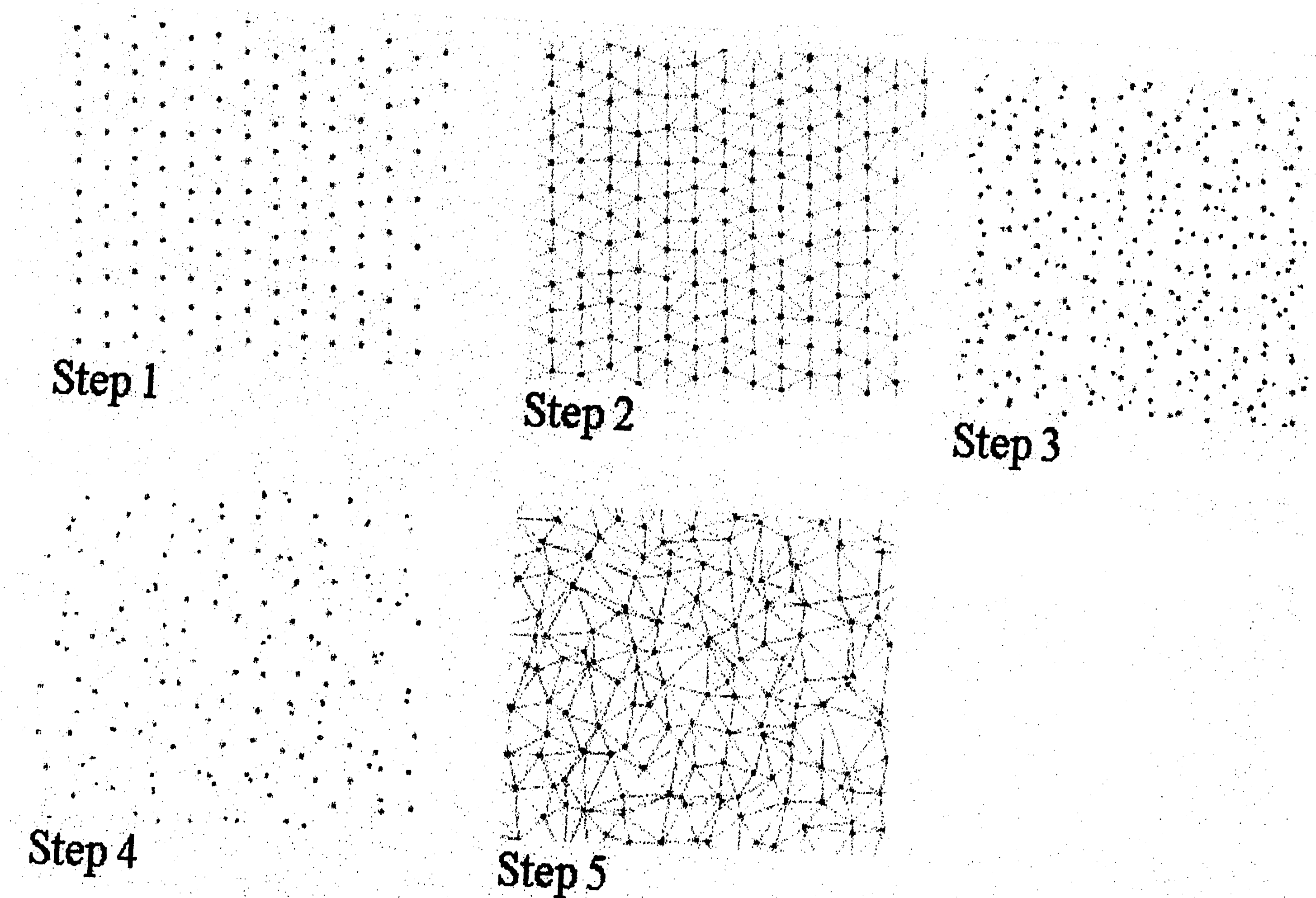

Figure 3-7: The process of TIN Random Densification.

Appendix B. Since this work may be described as testing for proof of concept only, it was not a priority to optimise the code for efficiency. It is more important that the algorithms were tested. Moreover, some of the functionality - in particular the interpolation of elevation for the random points, was called from routines in Geokinetics Inc. topology building extension for ArcView called, *theEngine*©.

Step 1, in Figure 3-7, is to open the mass point data set to be used in the creating the DTM. Notice that the data is collected along vertical profile lines. Moreover, the spacing between points along the lines is not uniform. This is the format of data a user would receive when purchasing SNB DTM data.

This raw mass point data is then used to produce the TIN shown in Step 2. The height value for each point is extracted from an "Elevation" item in the attribute table associated with the mass point file.

Step 3 shows the introduction of the random points. These random points have geometry created in the following manner:

- The script loops through each individual point in the point data coverage ;

- The user defines the number of points to be added per original point. Obviously, there is a tradeoff here in the ability to "break up" the pattern of triangles and the resulting file size;

- The user defines the minimum distance from the original point to which the new points are to be added from the original point. Again a tradeoff exists. If the minimum distance is set at a very small value, then a new triangle may be formed that is closely resembles the original. However, if the distance is set very at a value that closely approaching half the distance between the profile lines, then all the randomized points will be packed into "corridors" between the original mass points;

- Given that the approximate spacing between lines and points is 70m, then the maximum distance away that the new points may fall is 35m. This spacing parameter could be changed should different data be used.

The second part of Step 3 in Figure 3-6 is to assign an elevation value to the new points interpolated from the TIN produced in Step 2. Again, this interpolated value is generated from the original TIN surface. While this may seem illogical because it is the original surface that contains the ridging, it is not. Recall, that the background research suggested that one of the causes of the ridging effect is a limitations in the visualization and data arrangement. This perspective of the problem acknowledges that the original data was collected to a high accuracy - as per the original specifications - and that it passed satisfactory quality control measures. The basis of TIN Random Densification is to simply rearrange the pattern of points and interpolate the elevation values from the original surface.

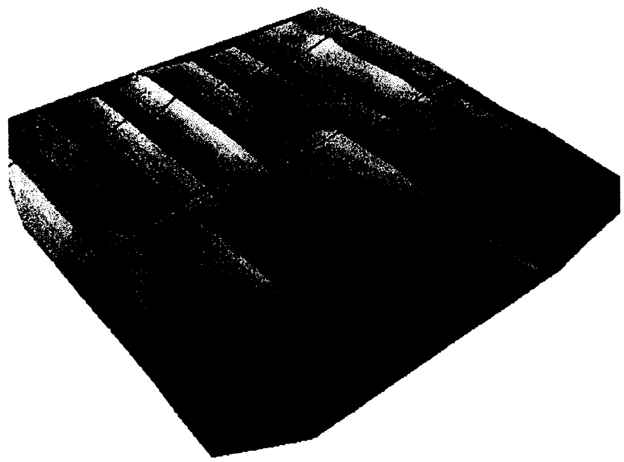

Figure 3-8: Unfiltered TIN. Peat Bog, Caraquet, N.B., Canada.

The original mass points are set aside in Step 4 in Figure 3-7, and all that remains is to construct a TIN from the random points as shown in Step 5. During the early stages of creating the algorithm for TIN Random Densification, the original mass point data were not discarded as illustrated in Step 4.

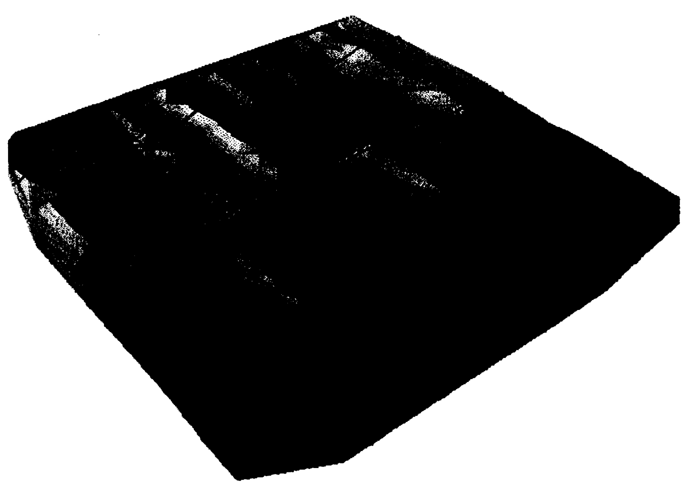

Figure 3-9: Randomly Densified TIN with the original mass point data included. Peat Bog, Caraquet, N.B., Canada.

The filtered TIN was generated with both the original mass points and the randomized points. An example of the unfiltered TIN is shown in Figure 3-8. Figure 3-9 illustrates a early TIN generated with the both the random and original mass points . Notice that the randomized points begin to break up the linear ridging pattern but, that pattern is still dominant and overpowers the random points.

Contrasting this is Figure 3-10 which illustrates a TIN built for the same study area, with the same 3D visualization parameters and with the original mass point data removed. Obviously, from a visualization point of view, this is an improvement over the previous image.

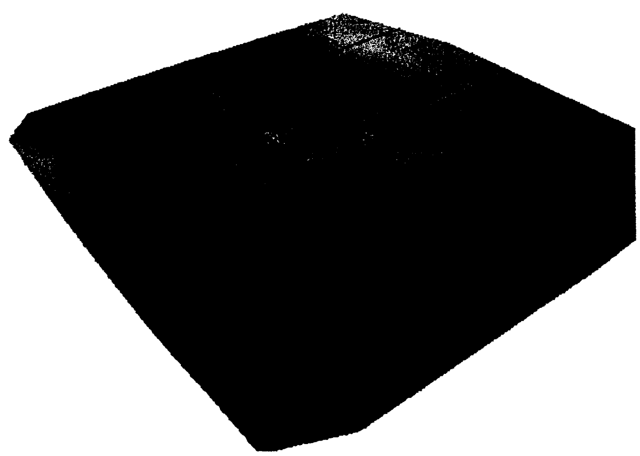

Figure 3-10: Randomly Densified TIN with the original mass point data removed. Peat Bog, Caraquet, N.B., Canada

It is important to note the very different configuration of the TIN as compared to the original illustrated in Step 2. The new TIN configuration does not display any of the linear pattern of TIN triangles that the original did. The theory is that, if the ridging is due to a visualization limitation, then the phenomena will be diminished.

Each study area's test patch was processed twice using the TIN densification program. After some experimentation, the user defined settings were a minimum point radius of 10m and, 2 and 5 points add per point, respectively.

3.2.3 Fourier Transformation

All three test patches were processed using PCI's Fourier transformation command, shown below:

EASI>FTF

PCI has the option of two types of Fourier transformations. The one that was used by those involved in the background research and by this author transformed from the spatial domain to magnitude and phase output. The second method is to transform to a real and imaginary output.

The magnitude output image is what will be filtered. It is an image of the magnitude of the frequency. The phase image cannot be altered; otherwise the spatial distribution of the data will be corrupted.

The magnitude image is filtered with the following command;

EASI>FFREQ

This command provides the user with several filtering options: Gaussian filter (low or high pass), Butterworth filter (low or high pass), and a user defined bitmap mask. The predefined radial filters each perform better in particular circumstances. The Gaussian filter is designed for creating a smooth cut-off of a particular frequency of the signal and it is useful for minimizing artifacts [PCI, 1997]. The Butterworth filter produces a much sharper frequency cutoff and is useful when the signal and noise are clearly separable [PCI, 1997]. After reviewing the software documentation and background research, it was decided that in order to have the maximum control, the user defined bitmap would be used.

One difficulty in handling DTM data transferred from ArcView to PCI is in the way the two programs handle *NODATA* DTM values. In ArcView, *NODATA* values are given the default value of -9999. PCI doesn't have a *NODATA* value. As a result, when performing any filtering operation, PCI will include values of -9999 in the filtering calculations. This can lead to some very strange results. In order to avoid this situation, a small modelling program must be written within EASI/PACE that replaces -9999 with 0. After the filtering in done, the process must be reversed.

One of the major limitations of PCI's implementation of the Fourier transform is that the input image must have dimensions which number as a power of 2 (ie. 46 rows x 64 columns). This required clipping a square out of the 1 km x 1 km test patch having dimensions that were on the order of 24 x 24 pixels. This process was tedious and time consuming as offsets from the origin had to be calculated. In addition, periodograms could not be produced as was done by those involved in the background research.

Figure 3-11 shows a DTM that is transformed into the frequency domain. The frequencies that correspond to the ridging manifest themselves as bright pixels at the far end of the X axis. Figure 3-12, shows a red bitmap mask placed over the "noise" or, ridging component. Any frequencies under the bitmaps are discarded. The noise will not contribute any signal when the DTM re-composed from the frequency domain back to the spatial domain. The Fourier filtered data was then imported back in ArcView for comparison with the other solutions.

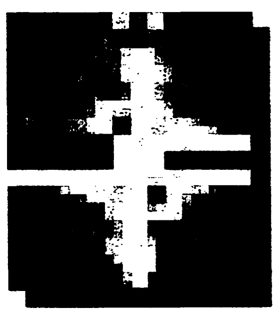

Figure 3-11: Magnitude image DTM transformed to the frequency domain.

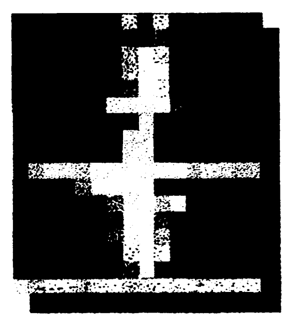

Figure 3-12: Bitmap editing in the frequency domain.

3.2.4 Trend Surface

The trend surface interpolation functionality was already incorporated as the request *MakeTrend* in ArcView's Avenue object oriented programming language. An Avenue script was created to incorporate this functionality. The script is included as Appendix C. A tool was added to the ArcView project used in this research that provided the necessary trend surface functionality tailored to this research. The test patches were then processed using the following parameters:

- polynomial orders of 3 & 4. This will create a slightly more complex surface to fit through all the data points. The software vendor does not recommend the use of any polynomial order higher than 4 [ESRI, 1997];

- the "useLogistic" parameter set to FALSE. This parameter is only used for categorical data and doesn't apply to elevations.

3.3 Analysis: Phase II

The second phase of analysis was begun once it was obvious which proposed filtering solutions did not perform satisfactorily. In short, all the filtering concepts except Fourier Filtering and TIN Random Densification were set aside and the remaining efforts were concentrated on these two solutions.

3.4 Approach Phase II

In addition to using different criteria to test the two remaining filtering techniques, one major change implemented in Phase II is the testing of the techniques on full map sheets. The test patches served the purpose of allowing for quicker initial assessment of the various filtering techniques in removing ridging.

Again, only the TIN Random Densification process and Fourier filtering techniques were tested in this phase. The criteria used in testing these solutions are additional 100 random point comparisons, hydrological analysis and contouring.

In addition, a small pilot study was undertaken as part of Phase II with staff from Computer Terrain Mapping Inc., of Boulder, Colorado, who commercially provide a service to eliminate systematic errors in USGS DEMs. Their technique involves using Fourier Transform for filtering [Russell et al, 1995]. It was felt that, the results obtained from Fourier filtering in PCI were hampered by operator inexperience and software difficulties, and that better results could be obtained by commercial vendors. Further, it was an important aspect of this research to get an idea of the cost involved in filtering systematic errors from DTM data. All three test site DTM datasets were sent to CTM as part of the pilot study.

3.5 Chapter Summary

The purpose of this chapter was to outline the design and approach taken for the testing of the proposed solutions to the ridging phenomena. Three study sites were selected for testing: Aroostook, Caraquet and Hayesville, in the province of New Brunswick, Canada. Five testing criteria were developed: 3 Dimensional visualization, profile examination, comparison of elevations for100 random points, contour comparisons and hydrological modelling.

In the first phase of testing, the four solutions to ridging that were developed in the previous chapter (LPF spatial filtering, Fourier techniques, TIN Random Densification, and trend surface generation) were tested against the criteria: 3 Dimensional visualization, profile examination, and 100 random point comparisons. LPF spatial filtering, and trend surface generation performed poorly in Phase I, and were dropped from the remainder of the testing.

In Phase II, TIN Random Densification and Fourier techniques were tested against the criteria: contour comparisons, further 100 random point comparisons, and hydrological analysis. The Fourier filtering was performed by CTM Inc, Boulder Co., as part of a pilot study.

The summary of analysis and discussion of results, for both phases of testing will be presented in the next chapter.

4

ANALYSIS AND DISCUSSION OF RESULTS

This chapter presents the summary of the analysis and discusses the results the two phases of the testing. In general, these analyses may be classified into "subjective" or, "analytical" categories.

4.1 Subjective and Analytical Analysis

Subjective analysis is meant here as assessing the quality of something based solely on user perception. This type of analysis is included here because many of the concerns of users of SNB DTM data are of this nature. This is particularly true when a user's perception of the quality of a DTM is influenced by 3-dimensional viewing in the most unflattering matter without making any statistical examination of the data. As a result, a major part of this analysis is to predict this kind of user subjective analysis and mimic its application to testing the proposed ridging solutions. The 3D visualization of the filtered surfaces and the examination of the profiles are both subjective analyses.

Contrasting the subjective analysis is the analytical analysis performed in this research. Analytical analysis is described here as assessing the quality of something by reducing it to basic descriptive statistics. The hundred random point comparison statistics are an example of an analytical analysis.

It was stated at the outset that three test patches would be used during Phase I of the analysis. However, it became apparent during the course of the project that there was not a significant benefit to carrying on with the Hayesville test patch given the time taken to process all the filtered surfaces and prepare files for analysis. For the criteria examined in Phase I, the relief was not significantly different between the Hayesville and Aroostook test patches. The test patch for Aroostook was favoured because it has the similar relief characteristics but, in addition, had profile lines originally collected in a east/west direction as opposed to the north/south profile lines in the Caraquet test site. The Hayesville study area was set aside in this phase of testing (except for the investigation into histogram of aspect values because the work was already completed) and was subsequently re-included in Phase II of the analysis. The DTM plots for Phase I are included as Appendix D. The DTM plots for Phase II of the analysis are included as Appendix E.

4.2 Phase I Results

4.2.1 Investigation into Histogram of Aspect Values

Attached as Appendix F are plots of histogram of aspect values for the Caraquet and Hayesville test sites. In order to have sufficient sampling of facets, the analysis had to be performed on full map sheets.

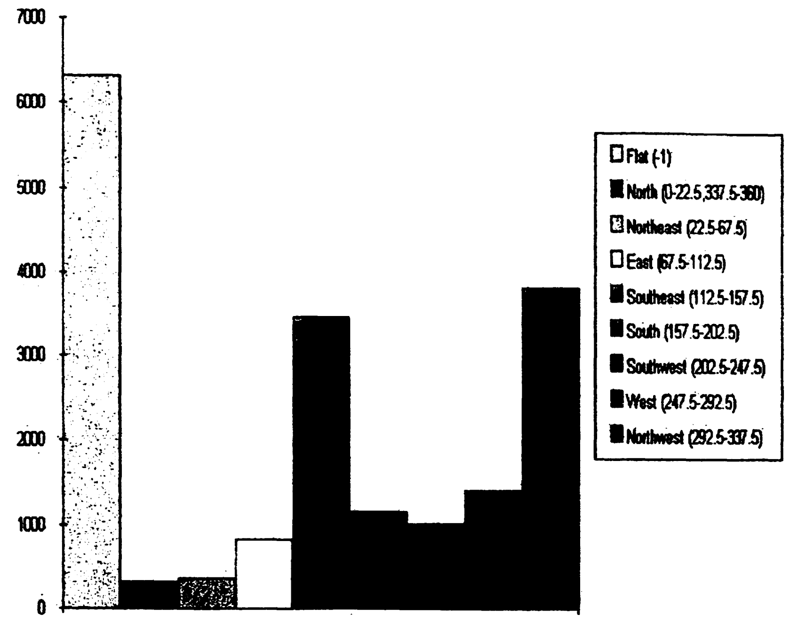

Figure 4-1: Histogram - Aspect of Unfiltered DTM, Caraquet, N.B.

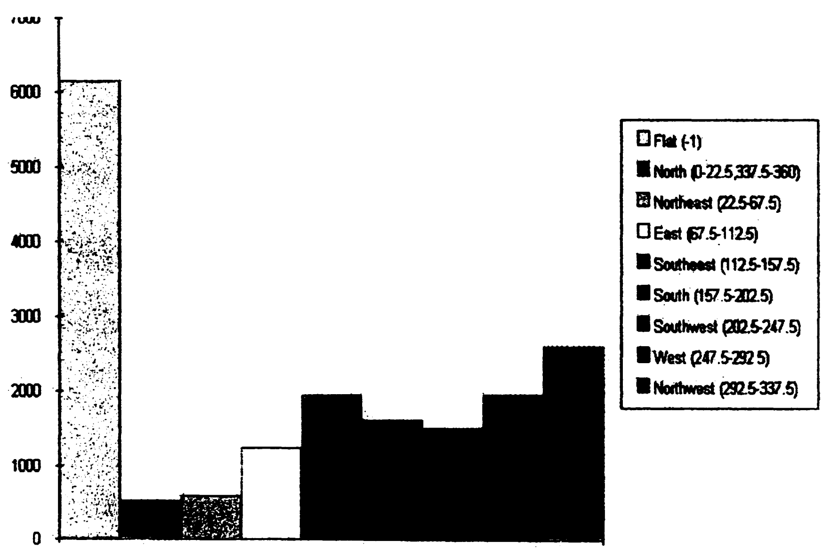

Figure 4-2: Histogram - Aspect of TIN Random Densification, Caraquet, N.B.

The histogram in Figure 4-1 illustrates that, in the Caraquet study site, most of TIN facets, possess an aspect in one of two directions, northwest and south east thereby indicating the presence of ridging. The large spike on the left side of the histogram is a result of large water body. Figure 4-2 is a histogram of the aspect value of a DTM processed using TIN Random Densification for the Caraquet study site. The two large spikes that indicate ridging have been diminished.

Contrasting this are the histograms for the Hayesville study site. Figure 4-3 is a histogram of aspect for the contaminated DTM. The distribution of aspect values is Gaussian in nature. As a result, it was concluded that the detection of ridging using histogram of aspect values fails in regions of higher relief. As has been stated, in areas of higher relief, a greater portion of the digital number (DN) value is signal and less in due to the noise caused by ridging. Therefore, the ridging is not as predominant. The aspect will be controlled by the larger elevation component of the DN and not the ridging. This makes detection by histogram difficult.

Figure 4-4 is a histogram of aspect value for a randomly densified TIN for the Hayesville study site. The histogram is very similar to the original. Again this is due to the predominance of elevation in the DN value.

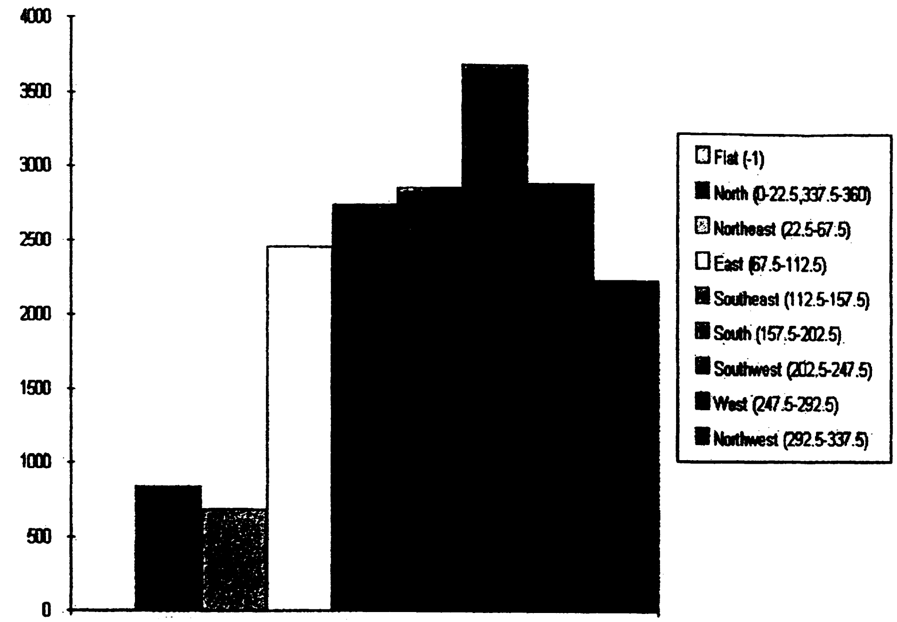

Figure 4-3: Histogram - Aspect of Unfiltered DTM, Aroostook, N.B.

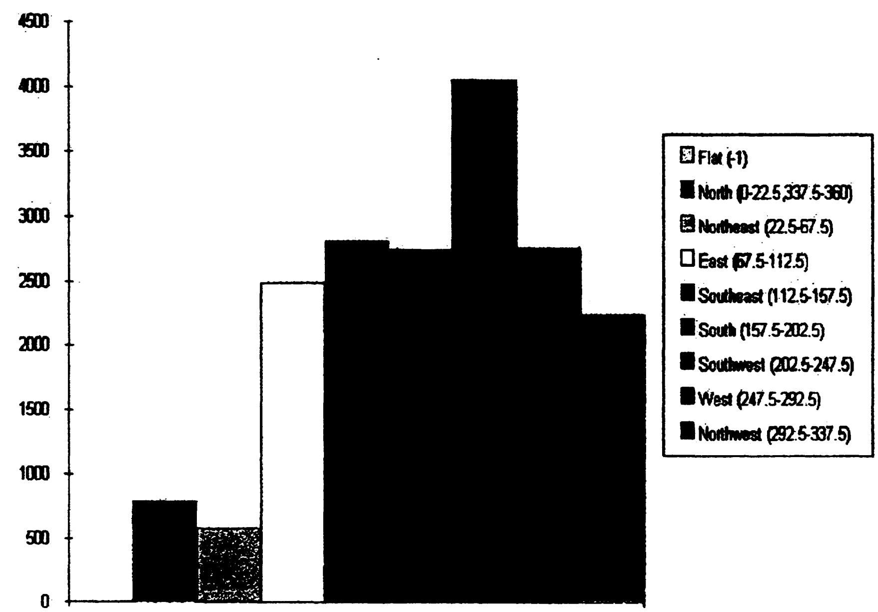

Figure 4-4: Histogram - Aspect of TIN Random Densification, Aroostook, N.B.

4.2.2 3D Visualization Analysis

Table 4-1 indicates the results for the subjective analysis component for Phase I of the analysis. Included in the table are the results of the performance of the filtered DTMs in 3D visualization.

In order to make rational comparisons, the subjective analysis must be quantified in a clear and simple manner. To this end, the 3D visualization of each of the filtered images was assessed, albeit subjectively, on a scale of 1 to 5. A ranking of "1" indicates that the ridging was not diminished, and the topographic detail was severely degraded (smoothing is an example of topographic degradation) when viewed 3-dimensionally. A ranking of "5" indicates the ridging was completely removed when visualized in 3D, and the topographic detail was not at all degraded. The next sections will expand on the results of the 3D visualization testing for the four proposed solutions on the two study sites.

Filtering Method	3D Visualization	Profile	
Test Patch Aroostook			
5x1 Low Pass Spatial Filter	**2**	**1**	
Fourier Filtering	**3**	**3**	
Tin Random Densification 10-2	**4**	**3**	
Tin Random Densification 10-5	**4**	**3**	
Test Patch Caraquet			**Total Score**
5x1 Low Pass Spatial Filter	**3**	**2**	**8**
Fourier Filtering	**3**	**2**	**11**
Tin Random Densification 10-2	**4**	**3**	**14**
Tin Random Densification 10-5	**4**	**2**	**13**
Trend Surface	**1**	**1**	**2**

Table 4-1. Summary of Phase I Subjective Analysis.

4.2.2.1 LPF Spatial Filtering

Table 4-1 includes the results for 3D visualization of the 5x1 LPF spatial filtering. Early on in processing the various solutions it became apparent that the LPFs performance would in all likelihood not withstand the rigours of the remaining testing criteria. It was decided that in the interest of time savings, that only one of the LPF filters would continue to be included in the analysis. The 5x1 LPF was selected to continue since the published research [Brown and Bara, 1994] indicated that it would obtain the best results. Moreover, the testing of the spatial filters on DTMs having a resolution of 56 metres was abandoned in favour of concentrating the analysis on the recommended resolution of 46 metres [Leese,1998].

As was described earlier, some of the proposed solutions to the ridging phenomenon require the DTM data be converted from vector (TIN) to raster data type. While in general the results of this conversion were satisfactory, some generalization took place.

The 5x1 LPF spatial filtering scores ranged from 2 to 3. The higher score was assigned for the Caraquet study site. In this area of extremely flat relief, the characteristic smoothing didn't affect the degradation of detail as much because there was little to begin with. In the Aroostook study site where there are greater changes in relief, the filter clearly degraded the detail and thus was given a lower score. The filtered image could loosely be described as illustrating only the major changes in relief. All the small peaks and valleys have been removed.

4.2.2.2 Fourier Filtering

Results of 3D visualization for Fourier filtering are slightly improved over those for LPF spatial filtering. The primary improvement was in the preservation of the relief detail. However, this seemed to be at the expense of preserving some of the ridging. In particular, the 3D image of the Caraquet study site (Appendix D) illustrates that not all of the ridging has been removed. The ridging is more evident in this study site as the noise due to the ridging makes up a greater percentage of the total DN assigned to each cell.

The absence of periodogram functionality within PCI's FFT module made it very difficult to pick out the exact frequency due to ridging and filter it out. Perhaps the results would improve if it were possible to place less reliance on "eyeballing" the frequency due to ridging in the frequency domain image.

4.2.2.3 TIN Random Densification

The analysis of TIN Random Densification were performed using two sets of user parameters on the Caraquet and Aroostook study sites. The first parameter is minimum distance a random point would be place from the original mass point being operated on. This was set to 10 metres for both sets. The second parameter was the number of points added per original point. This was set at 2 and 5.

The nomenclature for file naming is as follows:

< abbreviated study site name> Minimum Distance - # Points added per original point

For example, the file name Aroo10-2 indicates a DTM in the Aroostook study site processed using the TIN Random Densification with a minimum distance of 10 metres and two points added per original point.

The results for TIN random densification were in general excellent from a 3D visualization point of view. The ridging was completely removed in the Caraquet study site and only a minimal amount remained in the Aroostook study site. In addition, the relief in the Aroostook was preserved from the original image to the processed image. For both study sites, the local peaks and valleys were preserved with this process.

One of the advantages of this method of filtering is that it operates on vector data sets and doesn't require the conversion of the TIN to a raster DTM data set. As a result, there is no degradation of detail inherent in vector to raster DTM conversion.

Table 4-1 shows that TIN Random densification was given the highest scores for 3D visualization evaluation criteria. The table also shows that, from a visualization point of view, no difference was perceived between adding 5 points per original point and adding 2 points per original.

4.2.2.4 Trend Surface

The results for the production of a trend surface from the original mass points were very poor. None of the original relief was preserved no matter what order of polynomial was specified. It would seem that this techniques basis in least squares produces a surface of "best fit". The algorithm estimates a generalized surface based on all the data. The result is a surface that definitely has no remnants of ridging but, also little of the relief detail remains. The results were so poor that testing was not continued beyond those performed on the Caraquet test site.

4.2.3 Profile Analysis

The results for the analysis of profiles for the solutions are also found in Table 4-1. A similar kind of ranking was employed when assessing the profiles (or cross-sections) of the various filtered surfaces. A ranking of "1" indicates that the profile was significantly altered from the original. A ranking of "5" indicates a profile that resembles the original profile but, with the local variation due to ridging removed. Moreover, the filtered profile must retain the variation in terrain not ridging.

4.2.3.1 LPF Spatial Filtering

The profile resulting from the Caraquet DTM filtered using LPF spatial filtering performed moderately well although, it clearly showed that some of the ridges remained after filtering. However, in the Aroostook test site, where there is significantly more relief than found in Caraquet, the resulting profile showed major degradation of the relief detail. The resulting score of 2 reflects this degradation. However, the results demonstrate that LPF spatial filtering will easily remove the ridging at the expense of some relief detail.

4.2.3.2 Fourier Filtering

The profiles for the Caraquet study site clearly shows that the frequency due to the ridging phenomenon was not removed. The sinusoidal nature of the ridging is quite distinct and as a result these profiles were only given a score of 2.

The profiles for the Aroostook study site reflects a very smooth surface. The local high and low points have been completely removed. More over, the profiles show that there has been an introduction of relief where there originally was none. Due to its poor performance score of 1 was assigned to these profiles.

4.2.3.3 TIN Random Densification

TIN Random Densification also had the performance for this testing criteria. The profiles generated for the Caraquet study area show that some remnants of ridging remain. However, the magnitude of the ridges have clearly been diminished.

Included in Appendix D are, profile plots having no vertical exaggeration. Examination of these plots shows a flat profile - particularly in the Caraquet study site. Only when the profiles are vertically exaggerated by 200 times does the ridging appear. These plots are included to educate users of the effect of software generated parameters. When creating the profile graphs for the Caraquet study site, ArcView automatically set the vertical exaggeration parameter to 198X. The idea is to emphasize trends in the data. Of course, when dealing with DTMs that contain ridging, this can mislead user opinion on the quality of the data. If the users were first to view profiles with little or no vertical exaggeration, a more favourable opinion regarding the quality of the DTM data would be formed.

The profiles for the Aroostook study site reflect minimal generalization. Table 4-1 shows that the introduction of more random points didn't improve the quality of the profile. Examination of the profiles indicate that TIN random densification performed the best in terms of preserving the local maximum and minimum elevations.

4.2.3.4 Trend Surface

Again the trend surface performed very poorly in the profile analysis receiving the lowest score 1. The profile was significantly altered from the original profile.

4.2.4 100 Random Point Comparison

The results for the 100 randomly selected point comparison are contained in Table 4-2.

Summary Of Statistics for the Caraquet Study Area					
	Fourier	5x11LPF	TIN_RD 10-2	TIN_RD 10-5	Trend Surface
Mean	-0.0523	0.402	-0.120	-0.114	0.121
Max Diff	4.102	6.687	3.848	3.975	3.391
RMS	1.101	1.555	0.685	0.600	0.779
Summary of Statistics for the Aroostook Study Area					
Mean	7.815	7.898	0.049	0.107	
Max Diff	82.8	39.9	2.2	3	
RMS	20.254	17.978	0.489	0.479	

Table 4-2: Phase I, 100 Random Point Comparison.

Prior to investigating the results for the individual solutions being tested, it is appropriate to address the accuracy of the original DTM mass point data. The specifications required that the collected data would be accurate to ±2.5 metres of their true elevation [NBGIC,1995]. Therefore, when examining the results from the 100 random point comparison, situations where the root mean square error (RMS) values exceed ±2.5 metres are unacceptable.

Further, it is useful to comment on the results from the 100 randomly selected point comparison. In general, the results are very good. However, in areas where elevation changes rapidly over a short distance, the results are not as good. Where changes in local relief are small, then the surface generated from the randomly generated points is very similar to the original surface - which is desirable. However, where the relief rapidly changes, the geometry of the random points can cause the two surfaces to differ and thus they produce a higher RMS value. It is important to review the results of the 100 random point comparison with respect to the degree of relief change for the data set and triangle geometry resulting from the pattern generated by the random points.

While the comparison of elevation values between surfaces is a common method of DTM accuracy assessment [Isaacon and Ripple, 1990][Li,1991] there are those who do not agree with this method. In particular, Polidori et al. [1991] suggest the use of fractal dimensions at different scales and orientations for the assessment of DTM accuracy. It is suggested that generation of an RMS error from random check points is not "sensitive to interpolation artifacts ... and directional tendency [Polidori et al., 1991] ". Certainly, the research indicates that fractals may be used in detecting the presence of ridging, and accuracy assessment. The research undertaken here will make use of the more classical accuracy assessment technique of generating RMS values. Fractals are very useful in assessing the quality of DTMs without a reference surface. Further, since we are using aspect as a detection method, the use of fractals is not necessary.

Scatter plots of the 100 random points comparing filtered and unfiltered elevations for all the study sites are included in Appendix F.

4.2.4.1 LPF Spatial Filtering

Table 4-2 contains the results for comparing 100 randomly selected points between the unfiltered SNB DTM and a LPF spatial filtered DTM. The results for Caraquet are reasonable given the accuracy of the data. However, the results were very poor in the Aroostook test site having the higher relief. Figure 4-5 illustrates a scatter plot for the Aroostook study site.

Examination of the point where the maximum difference is located shows a small localized peak(s) that was completely smoothed out by the averaging inherent in LPF filtering. A resolution of 46 metres means that features that are smaller than 230 metres by 30 metres are subject to major degradation - particularly if the feature is a local maximum or minimum.

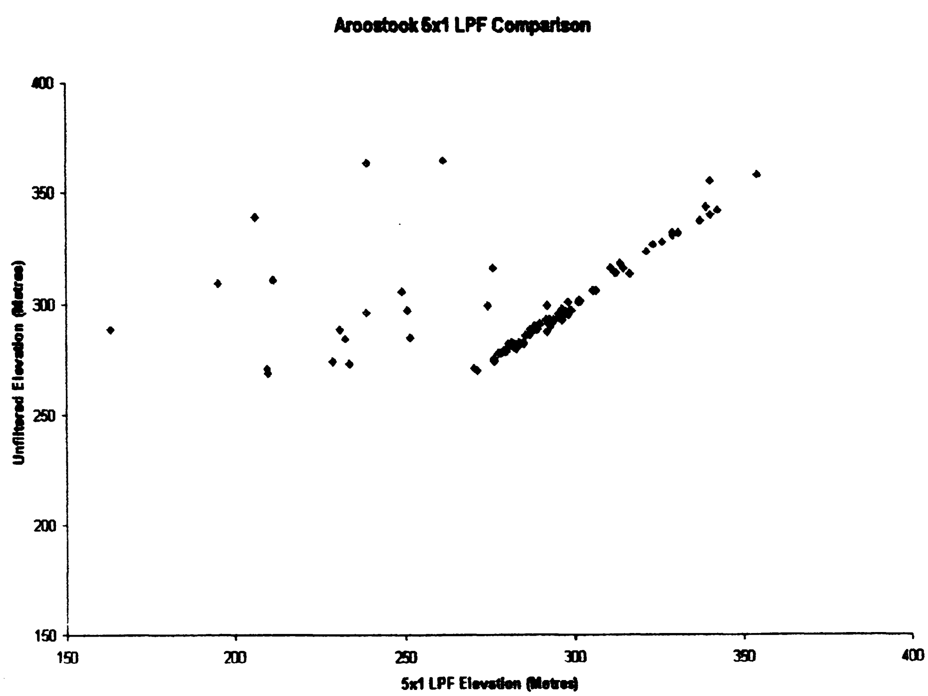

Figure 4-5: Scatter Plot of LPF v. Unfiltered Elevations, Aroostook, NB.

Figure 4-5 is a scatter plot that compares the elevations derived from LPF spatial filtering and the unfiltered elevations for the same 100 randomly selected points. The plot shows that, for the Aroostook study site, there is a strong linear correlation between the elevation values except for those elevations where the filtered smoothed out the surface. The linear correlation indicates that the elevation value for the points was similar between the filtered and unfiltered DTMs. The points affected by the smoothing are shown as outliers on the upper left hand portion of the graph. Results of this type are similar for all the study sites.

4.2.4.2 Fourier Transformations

The Fourier techniques performed satisfactorily in the Caraquet study site but did not perform adequately in the Aroostook study site. Figure 4-6 illustrates comparison of Fourier techniques for the Aroostook study site.

The results demonstrate it was easier to separate the noise from the signal in the Caraquet study site than in the Aroostook study site. Examination of the frequency (magnitude) image for this study site demonstrated that this was indeed the case. Since such a relatively large portion of the total DN value is noise (because there is low relief relative to the magnitude of the ridging), only a small contribution to the DN value is from elevation. This makes it simpler to pick out the noise.

When relief represents a larger contribution to the DN value, however, it is much more

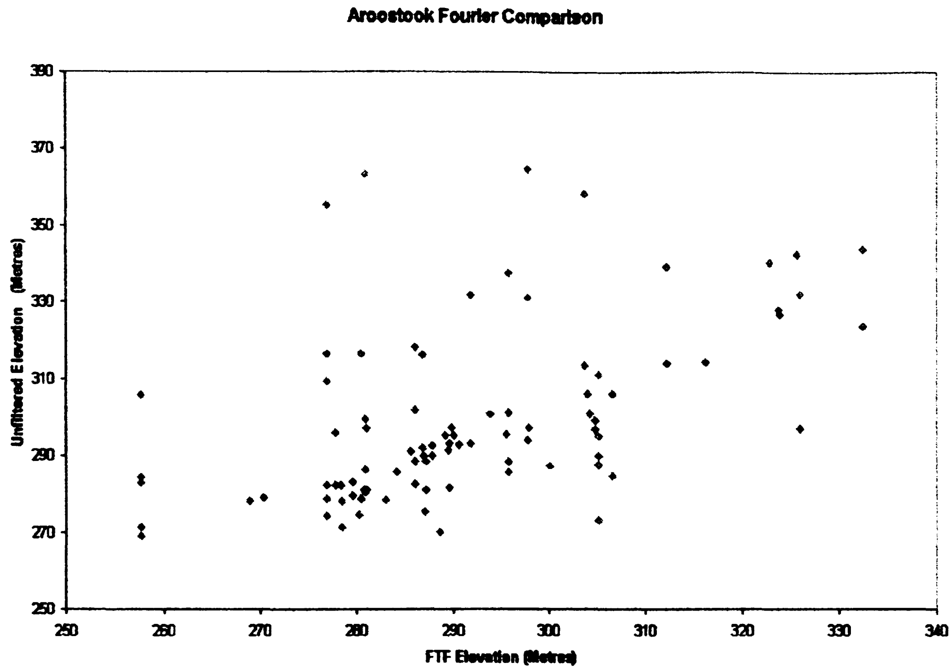

Figure 4-6: Scatter Plot of Fourier v. Unfiltered Elevations, Aroostook, NB.

difficult to separate the noise from the signal. The results for the Aroostook study site reflect this. The poor results are due to filtering out some noise and signal in the frequency domain. When the image is transferred back to the spatial domain and tested, the results indicate excessive smoothing of the DTM

Figure 4-6 shows that very little correlation exists between the Fourier filtered elevations and the unfiltered elevations. The scatter plot has so many outliers that it has the appearance of a random generated graph. This is the result of excessive smoothing of the elevation values. Moreover, the scatter plot indicates that part of the signal, in addition to the noise, was filtered in the frequency domain. Similar plots were found for the other study sites (Appendix G).

4.2.4.3 TIN Random Densification

The results for the 100-point comparison of randomly-densified TINS are very satisfactory for both study areas and both user defined parameters. In contrast to the other solutions, TIN random densification actually performed better in the higher relief study site. Examination of the data reveals no conclusive explanation of the better performance in the Aroostook data.

However, it was found that the maximum differences occurred when the check point falls in an area having a very steep slope. As a result, it is more difficult to interpolate an accurate elevation value for the random point.

Figure 4-7 illustrates the scatter plot for the Caraquet study site. The plot exhibits a positive linear correlation between the derived elevation values. This plot is representative of the results achieved for all the study sites. For the most part, the outliers fall in the lower right hand quadrant of the graph. These outliers are caused by an increase in the elevation interpolated during the TIN random densification process. A possible cause of this is that the original point was a local minimum "pit") that was surrounded by higher elevations and, when the point's elevation was is interpolated it is assigned a higher value.

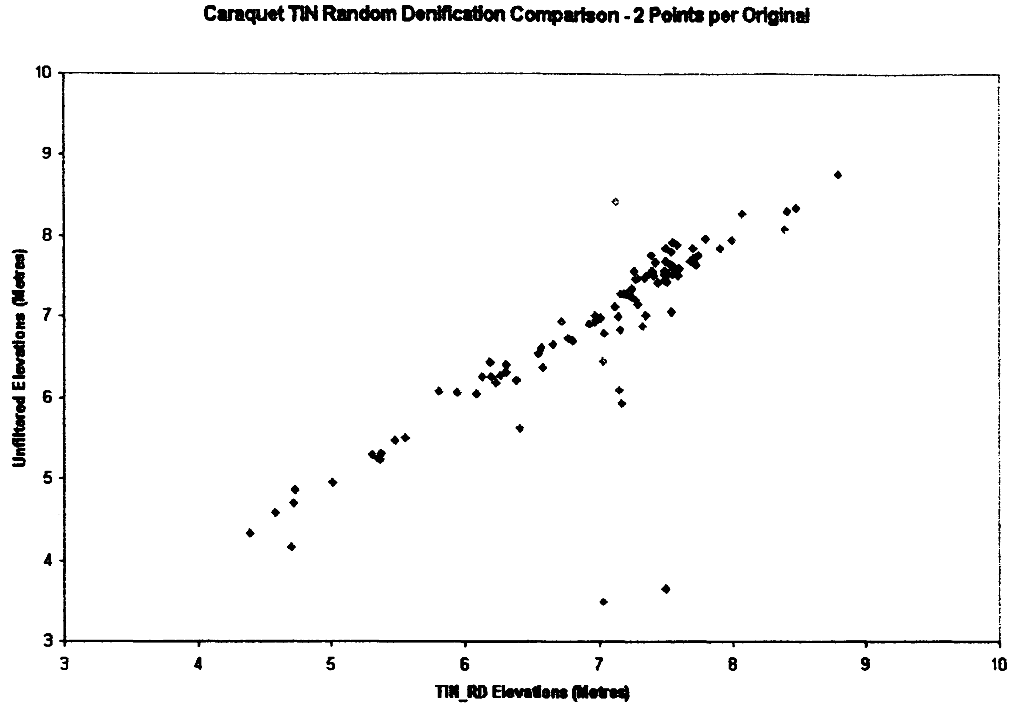

Figure 4-7: Scatter Plot of TIN Random Densification v. Unfiltered Elevations, Caraquet, NB.

4.2.4.4 Trend Surface

The results for the trend surface are misleading. The performance in the 100 random point comparison was deceivingly strong. The Caraquet study area is very flat and the generalized surface is statistically close to the original data. This is reflected in these results. However, it should not be forgotten that the trend surface completely breaks down in area of significant relief. Figure 4-8 illustrates the scatter plot for the Caraquet site analysis. The scatter plot illustrates the lack of correlation between the surfaces.

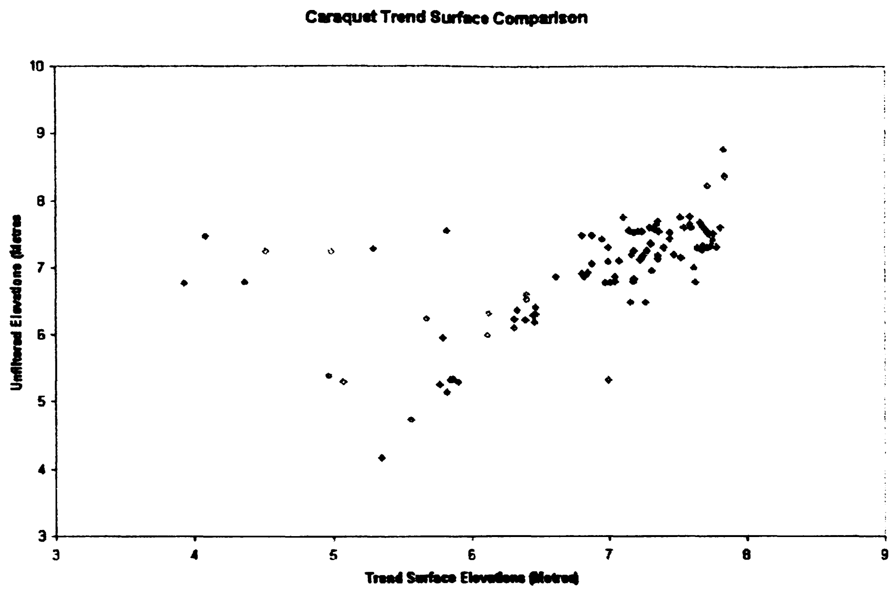

Figure 4-8: Scatter Plot of Trend Surface v. Unfiltered Elevations, Caraquet, NB.

4.2.5 Implications of the Results

- *Spatial Filtering removes the detail of relief, therefore, shallow depressions such as wetlands will be eradicated;*

- *The Fast Fourier Transform approach is dataset specific - each DTM dataset must be evaluated and processed individually as opposed to a single "universal" solution being applied on a jurisdiction-wide basis;*

- *The FFT approach is complex and may require specialized personnel to maximize its potential;*

- *Smoothing of the detail (spatial filtering) may be the simplest option when performing landscape rendering where loss of relief detail is not critical.*

Examination of the results of the 3-D visualization and profiles in Phase I clearly demonstrates that the TIN Random Densification process and the Fourier filtering are better solutions then either the Trend Surface or the Spatial Filtering. Examination of the 100 random point comparison revealed similar results. The TIN Random Densification process has the two lowest RMS errors. Of particular note is the lower RMS error in the Aroostook test patch which has a much higher relief. The Fourier filter performed poorer in this high relief test patch.

One concern arising out of discussions with SNB personnel was the effect of file size by the various solutions.

Figure 4-9 illustrates the relative file sizes in ArcView of the various filtering techniques employed in Phase I. There is a dramatic increase in file size when add five points per original point (i.e. Aroo10-5) as compared with only adding two points per original point (i.e. Aroo10-2).

Reviewing the previous results indicates TIN Random Densification specifying 5 points is only marginally superior to specifying 2 points. However, when file size is considered, the TIN Random Densification approach specifying 2 points per original point is superior to TIN Random Densification specifying 5 points per original point.

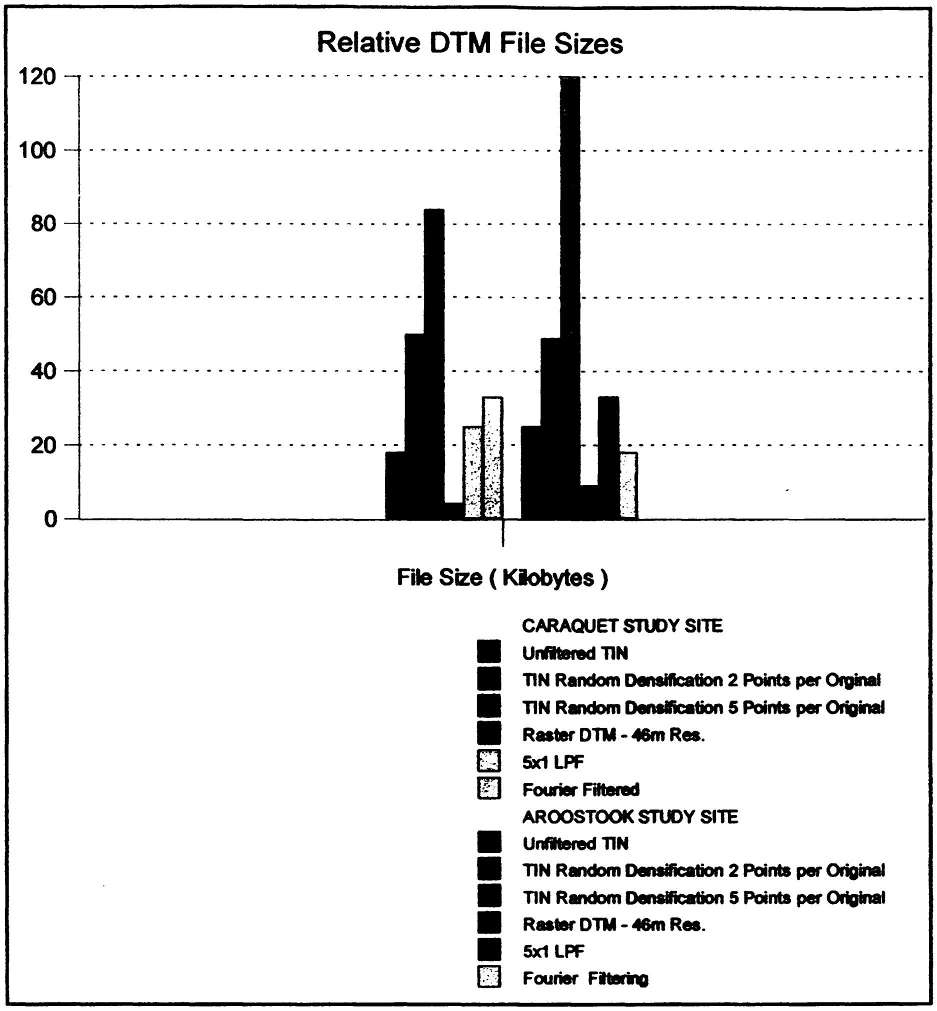

Figure 4-9: Relative File Sizes for Phase I.

4.2.6 Phase I Analysis Decisions and Discussion

The following is a list of conclusions and recommendations to carry into phase II.

- *The results of phase I analysis demonstrate that TIN Random Densification - specifying 2 points per original point - produced the best results based on the* *criteria specified for Phase I;*

- *By its very random nature, any DTM processed by TIN Random Densification is a unique solution, that is to say if the same DTM was reprocessed, a slightly different result would be obtained;*

- *The results from the Fourier filtering were not as good as was expected in comparison to results obtained by other researchers as described in the background literature;*

- *Fourier filtering is more complex than the other solutions and warrants carryover to Phase II in order to fully explore its possibilities.*

4.3 Phase II Results

Phase II of the testing saw the reintroduction of the Hayesville test site. In addition, the use of the 1 km x 1 km test patches were abandoned in favour of testing solutions on full map sheets.

Only the TIN Random densification and Fourier filtering solutions were tested in this phase. All the other proposed solutions performed so unsatisfactorily in Phase I testing that it was decided that they didn't warrant carryover into Phase II. Further, under this writer's direction, Fourier filtering solutions were performed on the three test sites by CTM Inc., Boulder Colorado, as part of a pilot study. The criteria of comparison employed in this phase included: contouring, 100 random point comparison, and hydrological analysis.

4.3.1 Contouring

Contours were generated for each map sheet in each of the three study areas. Plots of the generated contours are attached as Appendix G. Moreover, for each study area, contours generated from the unfiltered and filtered data sets were compared in order to ascertain whether the ridging (which is readily detected when a contaminated dataset is contoured) can be detected when the filtered DTM is contoured. Figure 4-10 illustrates a small contoured portion of a contaminated DTM. The ridging is reflected in the contouring by the long narrow parallel contour lines. Figure 4-11 represents a contoured DTM filtered using the TIN Random Densification Process. Clearly, the pattern of the ridging is diminished in the DTM filtered using the TIN Random Densification process.

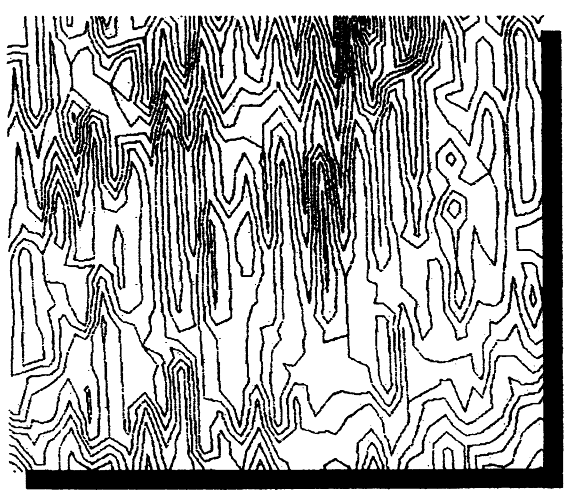

Figure 4-10. Caraquet, 0.5m Contours from Unfiltered TIN.

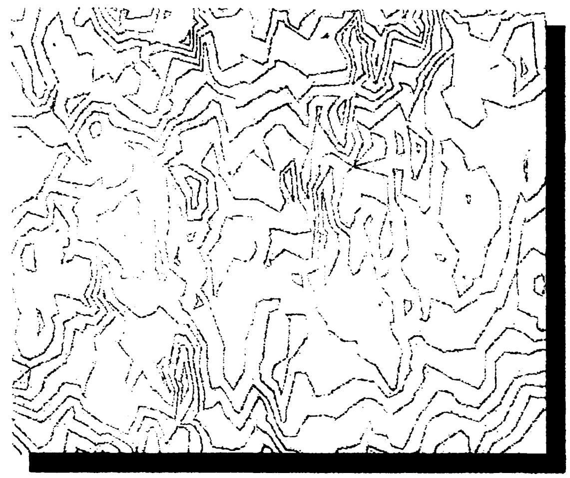

Figure 4-11: Caraquet, 0.5m Contours from TIN processed with TIN Random Densification.

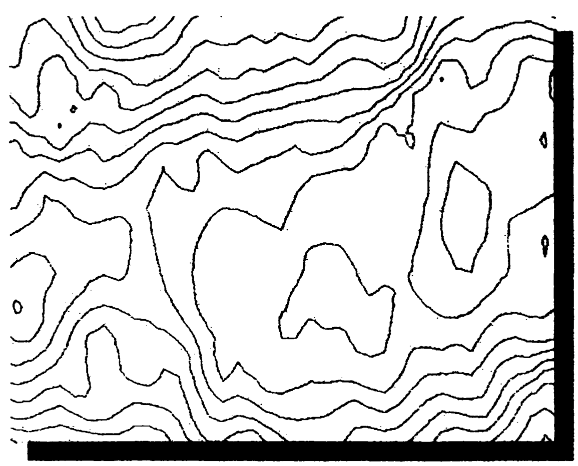

Figure 4-12. Caraquet ,0.5m Contours from CTM Fourier Filtering.

Figure 4-12 illustrates contours derived for the same area as shown above from the DTM created by Computer Terrain Mapping (CTM) using their Fourier filtering technique. The results indicate that significant smoothing of the data has taken place. Undeniably, the ridging has been removed and the contours are more aesthetically pleasing than those contours in the previous two figures. However, since the extent of the smoothing is a concern, the 100 point comparison was also performed on the CTM filtered image in an attempt to quantify the overall "distortion" of the modified DTM's.

The results from the contouring analysis are summarized in Table 4-3. The individual results of the contouring are assessed on a scale of "1" to "5". A score of "5" indicates that the generated contours contain no remaining trace of the ridging. A score of "1" indicates that the ridging still remains in the contoured image.

Image Name	Contouring Score
Caraquet: Unfiltered	1
Caraquet: TIN_RD 10-2	3
Caraquet: Fourier - CTM	5
Aroostook: Unfiltered	2
Aroostook: TIN_RD 10-2	3
Aroostook: Fourier - CTM	5
Hayesville: Unfiltered	1
Hayesville: TIN_RD 10-2	3
Hayesville: Fourier - CTM	4

Table 4-3: Summary of Contouring Analysis.

The contours generated by Computer Terrain Mapping's Fourier techniques scored the best results for all the study sites. In general, the contours for CTM's filtered DTMs showed little or no trace of ridging and they also had an aesthetically pleasing shape. Contrasting this are the contours generated from the randomly densified DTM. These contours definitely show a reduction in ridging but, they have an unpleasing angular quality to them. Certainly, a thinning or, contour generalization program should be used to produce a better contour map.

4.3.2 100 Random Point Comparison

The data sets processed by CTM were analysed and compared with TIN Random Densification process by comparing interpolated values for the same 100 randomly selected points used in the previous analysis.

Summary Of Statistics [illegible] Study Area			
	[illegible]	[illegible]	[illegible]
Mean	-0.120	-0.114	**0.121**
Max Diff	3.848	3.975	**3.649**
RMS	0.685	0.600	**0.796**
Summary Of Statistics for the Aroostook Study Area			
Mean	0.049	0.107	**1.839**
Max Diff	2.2	3	**18.1**
RMS	0.489	0.479	**3.982**
Summary Statistics for the Hayesville Study Area			
Mean	0.185	0.149	**-0.143**
Max Diff	3.9	4.9	**6.7**
RMS	0.730	1.114	**1.525**

Table 4-4: Phase II, 100 Random Point Comparison.

Table 4-4 shows the results of this investigation. The results of the 100 random point comparison show that the images filtered by Computer Terrain Mapping (CTM) have higher RMS errors in test sites having higher relief than the results achieved using TIN Random Densification. These results are due to excessive smoothing by the process used by CTM.

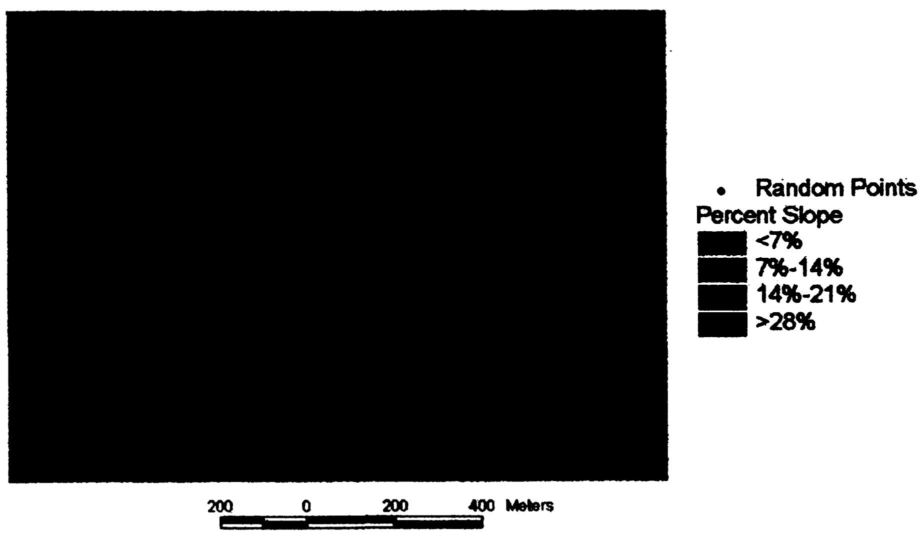

Figure 4-13: Slope based 100 Random Point Comparison, Aroostook, NB.

	slope<7%	7%>slope<14%	14%>slope<21%	21%>slope
Summary Of Slope Statistics TIN Random Densification: Hayesville				
Avg	0.163	-0.193	-0.213	-0.100
Max Diff	2.500	3.900	1.100	0.400
RMS	0.574	0.881	0.396	0.141
Summary of Slope Statistics for CTM Filtered: Hayesville				
Avg	-0.890	0.483	0.393	-5.450
Max Diff	5.900	5.700	6.100	6.700
RMS	2.314	2.260	3.567	1.626
Summary of Slope Statistics TIN Random Densification: Aroostook				
Avg	-0.009	-0.030	-0.236	0.000
Max Diff	0.800	2.100	2.200	0.100
RMS	0.249	0.509	0.892	0.141
Summary of Slope Statistics for CTM Filtered: Aroostook				
Avg	0.291	1.055	7.314	9.900
Max Diff	14.9	11.000	18.1	10.500
RMS	4.439	6.073	9.407	0.849

Table 4-5: Phase II: Slope Based 100 Random Point Comparison.

The results in Table 4-4 indicated that the performance of the TIN random densification and CTMs Fourier techniques were affected by the relief. To investigate this, statistics were generated for 100 randomly selected points that were classified by its surrounding slope, as illustrated in Figure 4-13. Table 4-5 shows the results of this investigation.

The slope based analysis shows that the amount of smoothing, as indicated by the maximum difference, increases with slope, for DTMs processed by CTMs Fourier techniques. Moreover, the RMS error generally increased with slope for these DTMs. No such conclusion can be drawn for DTMs processed by TIN Random Densification. The statistics show a random pattern in the statistical measure over the range of slope classes.

4.3.3 Hydrological Analysis

Caraquet Study Area

Change in # of flcara10-2strm N/S Streams

Direction	Cardinal	Diff of Cells	% Change
1	East	281	
4	**South**	**-1175**	**-11.5%**
16	West	841	
64	**North**	**-1535**	**-15.1%**

Change in # of flcaraCTM N/S Streams

Direction	Cardinal	Diff of Ce	%Change
1	East	1122	
4	**South**	**2811**	**27.60%**
16	West	6138	
64	**North**	**768**	**7.50%**

Aroostook Study Area

Change in # of flaro10-2strm E/W Streams

Direction	Cardinal	Diff in Cells	% Change
1	**East**	**-43**	**0.19%**
4	South	-1003	
16	**West**	**-279**	**-1.3%**
64	North	-607	

Change in # of arooctm10str E/W Streams

Direction	Cardinal	Diff in Cell	%Change3
1	**East**	**1945**	**8.82%**
4	South	1490	
16	**West**	**1175**	**5.33%**
64	North	754	

Hayesville Study Area

Change in # of flhay10-2strm N/S Streams

Direction	Cardinal	Diff in Cells	% Change
1	East	290	
4	**South**	**-219**	**-0.8%**
16	West	-1094	
64	**North**	**-591**	**-2.3%**

Change in # of hayCTM10str N/S Streams

Direction	Cardinal	Diff in Cell	%Change
1	East	2806	
4	**South**	**3343**	**13%**
16	West	2723	
64	**North**	**-335**	**-1.20%**

Table 4-6. Summary of Hydrological Analysis.

The results of the hydrological analysis are summarized in Table 4-6. The Table shows the results of the hydrological analysis for the three study sites. The upper half of the table is for the DTM's that were filtered using TIN Random Densification. The lower half is for those DTMs processed in the pilot study with CTM Inc.'s Fourier techniques. For each study site and filtering method, the difference in the number of cells representing streams was calculated between the unfiltered and filtered DTM. The table has columns for the cardinal direction (*Cardinal*), difference in the number of cells representing streams (*Diff of Cell*), and the percentage change for the total number of cells. The rows that are in bold indicate the cardinal direction along which the mass point profiles were collected. These are the values of greatest interest as a good filtering process will reduce the number of streams running along the troughs between the ridges.

The results of the hydrological analysis demonstrate that, in general, only TIN Random Densification reduced the number of cells representing streams running in the same direction as the original mass point profile lines. CTM's Fourier filtering actually increased the number of generated phantom streams in all except one case. It is important to note that, in the Aroostook study area, we are interested in the reduction of cells representing streams in the east/west directions because the original mass point profile lines also run in the east/west directions. The final generated stream network coverages may be found in Appendix I.

4.3.4 Phase II Analysis Decisions and Discussion

The following represent the decisions and recommendations for the analysis carried out in Phase II.

- *Any contamination of a DTM by ridging will bias automatically generated stream paths.*

- *Fourier Filtering techniques and TIN Random Densification both have the advantage of minimal alteration of the original data, or restoration of the original data, as opposed to spatial filtering or trend surfaces which degrade the detail of relief.*

- *Fourier Filtering has been implemented commercially which reflects the complexity of this solution.*

- *TIN Random Densification DTMs can produce contours with a "jagged" appearance, which may cause another concern with user groups. These contours could be smoothed to produce more realistic results.*

- *TIN Random Densification DTMs have larger file sizes than the original unfiltered datasets.*

4.4 Implementation Considerations

Where legacy data is contaminated by the ridging phenomena, filtering solutions may be implemented in three ways: project by project basis, as required basis, or on a program basis.

Implementation on a project by project basis means that the agency in charge of the legacy datasets informs its users of alternative solutions and provides a list of consultant's having the expertise to commercially perform ridging filtering services. Once provided with this information, users are then left to solve their own ridging problems

The agency in charge of the contaminated DTMs may opt to provide an executable program in which users could acquire. Users would then install and use the programs to filtered their contaminated DTMs. If TIN Random Densification is implemented in this "as- required" basis, then users must be told to expect slightly different results with each filtered DTM. Moreover, users may encounter problems when comparing results with others filtering the same DTM using TIN Random Densification. The major benefit of these first two options is the lowcost of implementation.

The final implementation scheme is to take a program based approach. This is the most expensive implementation solution. In this scenario, TIN Random Densification (or what ever solution is utilized) is used to process all the DTMs for a particular jurisdiction such as province or state. The benefits of a program based approach are increased user confidence and sense of goodwill in the agency and its datasets. Further, tighter quality control procedures will produce more consistent results.

4.5 Chapter Summary

Based on the testing criteria in the two phases of testing, TIN Random Densification had the best performance as a method of removal of the ridging effect from SNB DTM files. Fourier filtering had the second best performance in the testing.

The primary strengths of TIN Random Densification are that it is a "reorganization" of the original data rather than a smoothing filter. In addition, TIN Random Densification is unaffected by the degree of relief in the file and it is a "batch" filtering operation.

The weaknesses inherent in TIN Random Densification are that it produces unique solutions with each implementation, generates poor contours and increases file size.

TIN Random Densification, or any other solution to the ridging effect, may be implemented in three ways: project by project basis, as required basis, or on a program basis.

5

CONCLUSIONS

The final chapter of this report will review and summarize the work done herein. First the project objectives and the analysis approach will be reviewed. Next, the results from the two phases of testing will be summarized. In particular, the testing results from TIN Random Densification and those obtained from a pilot study with Computer Terrain Mapping Inc. will be discussed. Based on the analysis performed in this report, the best solution to minimize the ridging phenomena in SNB DTM datasets will be presented. Finally, areas for future research and concluding remarks will be given.

5.1 Review of Project Objectives

The objective of this research was to find the cause and a method of removal for the ridging effect from Service New Brunswick DTM files. To accomplish this a number of secondary objectives were studied. These included:

(1) *To establish the magnitude of "ridges" and to identify a testing criterion for the removal of ridging from DTM data.* Four testing criteria were developed, as described in Chapter 3, to provide a foundation for the analysis of solutions to the ridging effect.

(2) *To test procedures to automatically identify the existence "ridges" within datasets.* Chapter 3 outlined the investigation into the automatic detection of ridging and the results of this work were presented in Chapter 4.

(3) *To test several alternative compensation procedures to remove or, diminish the ridging effect.* Chapter 2 outlines the background research used to determine four compensation procedures. Chapter 3 describes the testing design and approach for the proposed compensation procedures. Chapter 4 presents the result obtained, over two phases of testing, of the proposed compensation procedures.

(4) *Make a recommendation on the most appropriate method of removal of the ridging and to explore strategies for implementation of the necessary changes to the DTM data files.* Based on the results from the testing, the most appropriate removal method was identified and suggestions were made towards its implementation.

The report was structured in the following manner. Chapter 1 provided the context and summarizes the problem of ridging in SNB DTM datasets. The principal objective of the research is stated and secondary objectives were also described. In addition, the significance of the research is described. A summary of the proposed approach is presented along with the constraints of the project.

Chapter 2 summarized the relevant background research including the cause of ridging. In particular, various filtering methods were explored. These included; simple low pass filtering techniques, Fourier transform filtering, TIN Random densification and trend surfaces.

Chapter 3 contained descriptions of the testing procedures to detect ridging, and the testing criteria for contaminated SNB DTM data. In particular, attention was paid to indicating practical improvements to the data sets. Further, based on the improvement criteria, various approaches to eliminate or, reduce ridging were discussed.

Chapter 4 contained the summary of analysis, discussion and results obtained in the investigation undertaken in the previous chapters. In particular, the implications of the results, analysis decisions and recommendations were presented for the two phases of testing. Chapter 4 also describes the inclusion of a small pilot project with Computer Terrain Mapping, Boulder Co., who provided a Fourier technique to filter out ridging primarily for USGS Level-1 DEMS.

5.2 Summary of Testing Results

The testing was broken up into two phases. The first phase was designed to quickly eliminate proposed solutions whose performance clearly was unsatisfactory based on the testing criteria. The second phase of testing was undertaken to focus on the solutions whose performance in early testing indicate that they may possibly exhibit the best overall performance based on the criteria of improvement. Conclusions on the best solution to the ridging effect will also be presented.

5.2.1 Phase I Testing Results

The four proposed solutions: LPF spatial filtering, Fourier transformation techniques, TIN Random Densification, and Trend surface generation were tested against three criteria of improvement. These criteria were: 3-Dimensional visualization, profile analysis, and 100 randomly generated point comparison. In addition, concerns raised by SNB personnel on the file sizes of the filtered DTMs were addressed. In addition, the testing was performed using a histogram of aspect values to detect ridging.

The testing revealed that the use of histogram of aspect value of a DTM to detect the presence of ridging is not a suitable detection method for most types of terrain. While the results were good for area having low relief, the method failed in test sites with more variable terrain. The failure is due to the inability of the histogram to detect the proportionally smaller contribution of ridging to the DN values of the DTM and thus the contribution to aspect.

Filtering solutions based on LPF spatial filtering, Fourier filtering techniques, and trend surface generation performed poorly with respect to the testing criteria for Phase I. However, software limitations and perhaps user inexperience contributed to the poor performance of the intriguing Fourier filtering approach. As a result, TIN Random Densification and Fourier filtering techniques were carried over into the second phase of the testing. LPF spatial filtering, and trend surface generation were not carried over into the second phase of testing.

5.2.2 Phase II Testing Results

TIN Random densification and CTM's Fourier filtering techniques performance were tested against three criteria: contouring, 100 random point comparison, and hydrological modelling. CTM's solution produced better contours than did TIN Random densification. However, the contours produced by TIN Random densification were an improvement over those derived from the contaminated datasets.

TIN Random Densification showed better performance in the hydrological modelling. DTMs generated from randomly densified datasets showed a greater percentage reduction in the creation of phantom streams than DTMs processed using CTM's Fourier techniques.

In the 100 random point comparison criteria, TIN random densification performed better than CTM's solution. Further, the statistics show that significant smoothing results from CTM's Fourier solution. Moreover, breaking down the results of 100 random point comparison based on slope demonstrated that CTM's solution performed poorly in areas of higher slope. No such trend was discovered for TIN Random Densification.

Therefore, based on the results for both phases of testing, and in particular giving a greater weighting to visualization and statistical performance, the most appropriate method of removal for the ridging effect from Service New Brunswick DTM files is TIN Random Densification followed closely by Fourier filtering as a viable alternative.

5.3 Future Research

The research performed in this report has suggests that future areas of research could include:

- TIN Random Densification has been implemented in this report as a " proof of concept" only, and any industrial implementation will require several improvements. For Example: (a) implement the algorithm in a lower level programming language (i.e. C) to increase processing speed; (b) address the addition of breakline data; (c) mask or clip any densified points that fall within water bodies: and (d) set a minimal proximity tolerance for all points (ie no two points shall be closer than X metres apart), to name a few.

- Any useful implementation will require the investigation of edgematching issues among randomly densified DTMs. Once a more robust algorithm is produced, it would be beneficial to undertake a small pilot study to investigate just how adjacent filtered DTMs would behave. Further, methods must be developed to edgematch adjoining randomly densified DTMs.

- Any solution should be examined in light of a cost benefit analysis. Given that some degradation of the data occurs no matter what filtering solution is used, what are the benefits and costs associated with filtering DTM datasets. In short, is it a worthwhile endeavour?

5.4 Concluding Remarks

No solution to the ridging phenomena will remove all remnants of the ridging. This research addressed the problem from a data visualization point of view by creating a solution based TIN Random Densification. However, the data visualization point of view suggests that the cause of the ridging phenomena is the original method of mass point data collection. Collection of mass point data along parallel profile lines is seen as fundamental cause of ridging by supporters of this view of the problem. Any DTM filtered or not, that is derived from data collected in this manner is contaminated with ridging. At some point, consideration must be given to discarding this data and recollecting it using a better method.

The results of this report have demonstrated that TIN Random Densification is the best technique, followed closely by Fourier Filtering as a viable alternative.

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APPENDIX A

Avenue Script: Ridge_Detector.ave

```
'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
' Ridge_Detector
' A simple script to detect the occurance of
' "Ridging" in a data set utilizing the
' % of a TINs Aspect

' January 16, 1999
' By: Kevin H. Pegler

' Requires that the TIN theme in question
' to be the active document

'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

' Get the active TIN document

' Inform the user that the TIN theme
' must be the first theme in TOC

AnswerChar = MsgBox.YesNo ( "Is the TIN Theme first in the TOC & is it Active
?","Warning!", True )

if ( AnswerChar = False ) then
  Exit
end

' get the user defined tolerance
tolerance = MsgBox.Input ("Input as a decimal value","User defined % of Parallel TIN
Facets Representing Ridging", "0.52")
'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

' Convert the TIN to an aspect GRID

' including => Spatial.Aspect

' Spatial.Aspect

theView = av.GetActiveDoc

' get active theme
t = theView.GetActiveThemes.Get(0)

' turn grid or tin into slope grid
```

```
if (t.GetClass.GetClassName = "GTheme") then
 g = t.GetGrid
 r = g.Aspect
elseif (t.GetClass.GetClassName = "STheme") then
 theTin = t.GetSurface
 box = Rect.Make(0@0,1@1)
 cellSize = 1
 ce = AnalysisPropertiesDialog.Show(theView,TRUE,"Output Grid Specification")
 if (ce = NIL) then
  return NIL
 end
 ce.GetExtent(box)
 ce.GetCellSize(cellSize)
 r = theTin.AspectAsGrid(cellSize,box)
else
 return NIL
end

' set name of data set, triggers evaluation
aspectFN = av.GetProject.GetWorkDir.MakeTmp("aspct", "")
r.Rename(aspectFN)

' check to see if output is valid
if (r.HasError) then
 return NIL
end

' create a theme
gthm = GTheme.Make(r)

' create appropriate legend for theme
theLegend = gthm.GetLegend
theLegend.Interval(gthm,"Value",9)
flatColor = Color.Make
flatColor.SetRgbList({175,175,175})
nColor = Color.Make
nColor.SetRgbList({255,0,0})
neColor = Color.Make
neColor.SetRgbList({255,165,0})
eColor = Color.Make
eColor.SetRgbList({255,255,0})
seColor = Color.Make
seColor.SetRgbList({0,255,0})
```

```
sColor = Color.Make
sColor.SetRgbList({0,255,255})
swColor = Color.Make
swColor.SetRgbList({0,165,255})
wColor = Color.Make
wColor.SetRgbList({0,0,255})
nwColor = Color.Make
nwColor.SetRgbList({255,0,255})
labelList = {"Flat (-1)","North (0-22.5,337.5-360)","Northeast (22.5-67.5)","East
(67.5-112.5)","Southeast (112.5-157.5)","South (157.5-202.5)","Southwest
(202.5-247.5)","West (247.5-292.5)","Northwest (292.5-337.5)"}
rangeList = {"-1","0 - 22.5,337.5 - 360","22.5 - 67.5","67.5 - 112.5","112.5 -
157.5","157.5 - 202.5","202.5 - 247.5","247.5 - 292.5","292.5 - 337.5"}
theColorList =
{flatColor,nColor,neColor,eColor,seColor,sColor,swColor,wColor,nwColor}
theLegendClasses = theLegend.GetClassifications
count = 0
for each c in theLegendClasses
  c.SetLabel(labelList.Get(count))
  c.SetRangeString(rangeList.Get(count))
  count = count + 1
  if (count > 8) then
    break
  end
end
theLegendSymbols = theLegend.GetSymbols
count = 0
for each s in theLegendSymbols
  s.SetColor(theColorList.Get(count))
  count = count + 1
  if (count > 8) then
    break
  end
end
gthm.UpdateLegend

' set name for theme
gthm.SetName("Aspect of " + t.GetName)

' add theme to the View
theView.AddTheme(gthm)
'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

```
'make the aspect theme the active doc etc.

thecurrentThemes = theView.GetThemes
thecurrentThemes.Get(0).SetActive (True)
thecurrentThemes.Get(0).SetVisible ( True )
thecurrentThemes.Get(1).SetActive ( False )
thecurrentThemes.Get(1).SetVisible ( False )
theView.InvalidateTOC(nil)

'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>


' histogram of the  for the aspect data

' Spatial.Histogram

theView = av.GetActiveDoc

' create histogram for each active GTheme
for each t in theView.GetActiveThemes
 if (t.Is(GTHEME).Not) then continue end

 ' apply mask
 theMaskGTheme = theView.GetExtension(AnalysisEnvironment).GetMask
 if (theMaskGTheme = NIL) then
  valueTheme = t
 else
  valueGrid = t.GetGrid.ExtractByMask(theMaskGTheme.GetGrid)
  valueTheme = GTheme.Make(valueGrid)
  if (valueGrid.HasError) then
   return NIL
  end
  valueTheme.SetLegend(t.GetLegend)
  valueTheme.SetName(t.GetName)
 end

 ' create histogram
 if (theView.GetGraphics.HasSelected) then
  if (theMaskGTheme = NIL) then
   theChart = valueTheme.Histogram(TRUE, NIL, TRUE)

  else
   theView.AddTheme(valueTheme)
```

```
   theChart = valueTheme.Histogram(TRUE, NIL, TRUE)

   theView.DeleteTheme(valueTheme)
  end
  theChart.SetName("Histogram of " + t.GetName + " Within Selected Graphics")
 else
  theChart = valueTheme.Histogram(TRUE, NIL, FALSE)
  theChart.SetName("Histogram of " + t.GetName)

 end

 ' set chart properties
 theChartDisplay = theChart.GetChartDisplay
 theChartDisplay.SetGroupGap(0)
 theChart.GetWin.Activate


end

'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

 tstVtab = theChart.GetVtab

 numrecs = tstVtab.GetNumRecords


 '>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>


 cntr = 0

 theClassList = List.make

 theCountList = List.make

 theClassLabelList = List.make


 for each record in tstVtab

   countField = tstVtab.FindField ( "Count" )

   subcntr = tstVtab.ReturnValue ( countField , record )
```

```
    cntr = cntr + subcntr

    classField = tstVtab.FindField ( "Class" )

    theClassList.Add ( tstVtab.ReturnValue ( classField , record ))

    theCountList.Add ( tstVtab.ReturnValue ( countField , record ))

    Class_labeField = tstVtab.FindField ( "Class_labe" )

    theClassLabelList.Add ( tstVtab.ReturnValue ( Class_labeField , record ))

 end



'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

'Loop through the lists and test for ridging


 i = 1

 while ( i < 5 )


   theRidgeNum = theCountList.Get(i) + theCountList.Get(i + 4 )


   thePercntRidgNum = theRidgeNum/cntr


   if (thePercntRidgNum > tolerance.AsNumber ) then

     MsgStr = "The ridging is running: " + theClassLabelList.Get(i) ++
theClassLabelList.Get(i + 4)
     MsgBox.Info ( MsgStr , "Ridging Present!")
     Exit
   end
     i= i + 1
 end
```

APPENDIX B

Avenue Script: TIN_RD.ave

```
'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

'TIN Random Densifier : TIN_RD.ave
'By Kevin Pegler. Dec12,1998

'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

theView = av.GetActiveDoc
for each t in theView.GetThemes
  if (t.IsVisible) then
  t.SetVisible(FALSE)
  end
end
'##########################################################
'Dec 22 '98
'Create a automatic random point graphic generator
'msgBox.Info ("Auto Random Point Generator", "Info")



theThemes=theView.GetThemes


 ' Make the first theme active

ptFTheme = theThemes.Get(0)
ptFTheme.SetActive( TRUE )
ptFTheme.SetVisible ( TRUE )


'*********************************
 'get user inputs

  labels = { "number of points to add per point", "minimum distance" }
  defaults = { "2", "10" }
  userList = MsgBox.MultiInput( "User Input", "TIN_RD", labels, defaults )
  'MsgBox.ListAsString( order, "Here is your order", "LOOK" )

Npoints = userList.Get( 0 ).AsNumber
Mindist = userList.Get( 1 ).AsNumber

'**********************************
```

```
'get the max min coords for the selected theme

boundingRect = ptFTheme.ReturnExtent

minBigXNum = boundingRect.GetLeft
minBigYNum= boundingRect.GetBottom

maxBigXNum = boundingRect.GetRight
maxBigYNum =boundingRect.GetTop

ptfeaturesToCheck = ptFTheme.GetFTab
total =ptFTheme.GetFTab.GetNumRecords

'setup a decent symbol size


'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'top o the looper for each point in the theme

X_coordField = ptfeaturesToCheck.FindField ("X_coord")
Y_coordField = ptfeaturesToCheck.FindField ("Y_coord")
for each rec in ptfeaturesToCheck

   currentXNum = ptFTheme.GetFTab.ReturnValue( X_coordField, rec)
   currentYNum = ptFTheme.GetFTab.ReturnValue( Y_coordField, rec)

  'create the local 35m kernal around the current point

  kernalMinXNum = currentXNum - 35

 kernalMinYNum = currentYNum - 35

  kernalMaxXNum = currentXNum + 35

 kernalMaxYNum = currentYNum + 35

  'test the kernal values

  if ( kernalMinXNum< minBigXNum ) then
    kernalMinXNum = minBigXNum
  end
  if ( kernalMinYNum <minBigYNum ) then
    kernalMinYNum = minBigYNum
```

```
 end
 if ( kernalMaxXNum >maxBigXNum ) then
  kernalMaxXNum = maxBigXNum
 end
 if ( kernalMaxYNum >maxBigYNum ) then
  kernalMaxYNum = maxBigYNum
 end

 randptCounter = 1

'**********************************
 while (randptcounter < Npoints) ' puts n points into each point's kernal

  XcoordNum = Number.MakeRandom( kernalMinXNum, kernalMaxXNum )
  YcoordNum = Number.MakeRandom( kernalMinYNum, kernalMaxYNum )
  distNum = ( (XcoordNum - currentXNum)^2 + (YcoordNum - currentYNum)^2 ).Sqrt

  if (distNum > Mindist ) then
   thePoint = Point.Make(XcoordNum, YcoordNum)
   theGShape = GraphicShape.Make ( thePoint )
   theView.GetGraphics.Add (theGShape)
   theView.Invalidate
   randptCounter = randptCounter + 1
  end
 end 'botton of randpt loop
'**********************************

end
'bottom of the pointlooper
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'##########################################################


'Graphic.SelectAll
theDoc=av.GetActiveDoc
theDoc.GetGraphics.SelectAll

msgBox.Info("Convert Graphics to a Shapefile","Info")

' From theEngine=>start.commit

calledScriptreturn = av.run ( "start.commit", "" )
```

```
'Make Firstlegendin the  TOC the activetheme


 theView = av.GetActiveDoc
 theThemes=theView.GetThemes


 ' Make thefirst theme active
 theThemes.Get(0).SetActive( TRUE )
 theThemes.Get(0).SetVisible( TRUE )
 theThemes.Get(1).SetActive( FALSE )
 theThemes.Get(1).SetVisible( FALSE )

theView.InvalidateTOC(nil)

msgBox.Info ("Convert from 2D to 3D", "Info")

'From the Engine =>3D.ConvertTo3DShape

calledScript2return = av.run("3D.ConvertTo3DShape", "" )

' Make thefirst theme active
 theThemes.Get(0).SetActive( TRUE )
 theThemes.Get(0).SetVisible( TRUE )
 theThemes.Get(1).SetActive( FALSE )
 theThemes.Get(1).SetVisible( FALSE )

msgBox.Info ("Convert 3D to 2D & Elev item", "Info")


'++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++
'Convert 3D Theme toa 2D theme with an elevation item

' Name:  3D.To2D
'
' Title:  Convert a 3Dfeaturetheme to 2D
'
```

```
' Topics: 3DAnalyst
'
' Description: Converts a 3D point, line, orpolygon theme into 2D by removing the
' z values from thevertices. If theinput is a 3D pointtheme the user is requested
' for an output field name that willbe added asan attribute to storethe feature
' height. This will not occur for lines or polygons.Attributevalues from visible
'fields will be copied for all feature types. This script can be runfromviews and
' scenes through a button or menu choice. This script assumesthere is oneactive3D
' point, line, or polygon theme.
'
' Requires: 3D Analyst
'
' Self:
'
' Returns:


'
'  Initialsetup
'
theDoc =av.GetActiveDoc
theTheme =theDoc.GetActiveThemes.Get(0)
theInFTab=theTheme.GetFTab
theInShape =theInFTab.GetShapeClass.MakeNull
thePrj=Prj.MakeNull

'
'  Clone visible fields sovalues can be copied over to output
'
outFields={}
for each f in theInFTab.GetFields
  if(f.IsVisible and f.IsTypeShape.Not) then
  outFields.Add(f.Clone)
  end
end

'
'  Get outputname and create file
'
def =av.GetProject.GetWorkDir.MakeTmp("thm","shp")
def =SourceManager.PutDataSet(ftab, "Output2D & Elevation ShapefileName", def, true)
if (def= NIL) then
  exit
```

```
end
inClass =theInFTab.GetShapeClass
if(inClass.IsSubclassOf(Point))then
  outClass = Point
  zFldNam= MsgBox.Input("Name ofnew attribute field used to storeheights:", "Elevation
Item","Elevation")
  if (zFldNam =NIL) then
    exit
  end
  if (theInFTab.FindField(zFldNam) <>NIL) then
   MsgBox.Error("Field name is alreadyused by another attribute", "Field Exists")
    exit
  end
  zFld = Field.Make(zFldNam,#FIELD_FLOAT, 5, 4)
 outFields.Add(zFld)
elseif(inClass.IsSubclassOf(Polygon)) then
 outClass =Polygon
elseif(inClass.IsSubclassOf(PolyLine)) then
  outClass=Polyline
end
theOutFTab=FTab.MakeNew(def,outClass)
theOutFTab.SetEditable(TRUE)
theOutFTab.AddFields(outFields)

'
' Loop through and write out selectedfeatures
'
theBitMap =theInFTab.GetSelection
if(theBitMap.Count = 0) then
 theBitMap.SetAll
  unsetBitmap =TRUE 'reset flag for end of loop
else
  unsetBitmap =FALSE
end
shapeField =theInFTab.FindField("Shape")
done =FALSE
offset = -1
while(not done)
  recNum =theBitmap.GetNextSet(offset)
  offset =recNum
  if (recNum <> -1)then
   theInFTab.QueryShape(recNum, thePrj,theInShape)
    rec =theOutFTab.AddRecord
```

```
  if(outClass.GetClassName = "Point")then
   theOutShape =theInShape.AsPoint
      elseif (outClass.GetClassName ="Polyline") then
   theOutShape =theInShape.AsPolyLine
  else
   theOutShape=Polygon.Make(theInShape.AsPolyLineZ.AsPolyLine.AsList)
  end
theOutFTab.SetValue(shapeField, rec, theOutShape)
  for each f in outFields
   inField=theInFTab.FindField(f.GetName)
    if (inField <> NIL) then
     attVal=theInFTab.ReturnValue(inField, recNum)
      theOutFTab.SetValue(f, rec, attVal)
  else
     theOutFTab.SetValue(f, rec, theInShape.GetZ)
    end
  end
 else
  done =TRUE
 end
end

'
'  Clean up
'
if(unsetBitmap) then
theBitmap.ClearAll
end
theOutFTab.Flush
theOutFTab.SetEditable(FALSE)

'
' Optionally add output astheme
'
if (MsgBox.YesNo("Add 3D shapefile astheme?","Convertto 2DShapefile",TRUE)) then
 fthm =FTheme.Make(theOutFTab)
theDoc.AddTheme(fthm)
end

'>>>>>>>>>>>>>>>>>>>>>>>

'Clean up
```

```
' Make thefirst theme active
 'theThemes.Get(0).SetActive( TRUE )
' theThemes.Get(0).SetVisible( TRUE )
' theThemes.Get(1).SetActive( FALSE )
' theThemes.Get(1).SetVisible( FALSE )
' theThemes.Get(3).SetActive( TRUE )

'msgBox.Info("Merge 2D & Elev Shapefiles", "Info")

'calledScript3return = av.run("Merge.append", "" )

theView = av.GetActiveDoc

for each t in theView.GetThemes
  t.SetVisible(FALSE)
  t.SetActive(FALSE)
 end

theThemes.Get(0).SetActive( TRUE )
theThemes.Get(0).SetVisible( TRUE )

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

msgBox.Info("Building TIN","Info")
calledScript4return = av.run("3D.CreateTIN", "" )
```

APPENDIX C

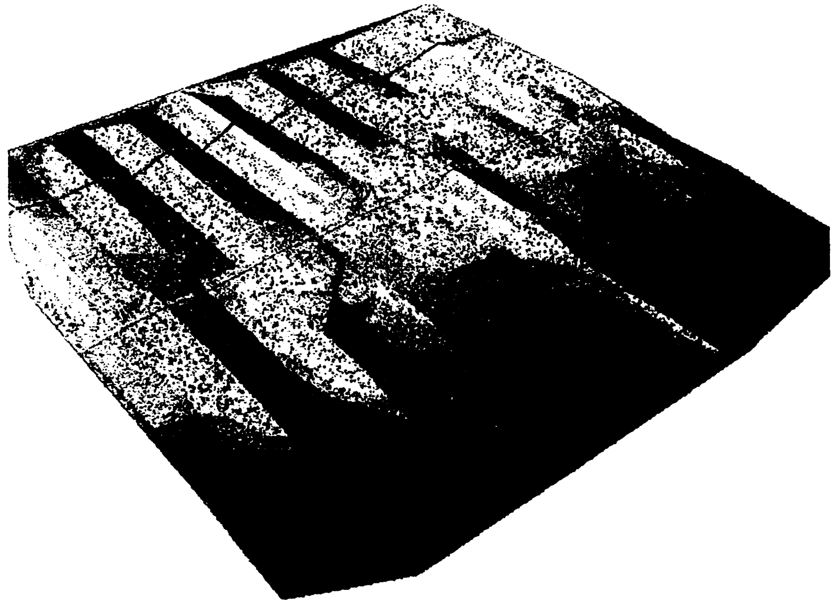
Avenue Script: TREND.ave

```
'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
'Trend.ave
'A script to interpolate a point surface using
'the trend request - based on least squares.
' By Kevin H. Pegler
'February 7th, 1999

'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
' Get the active Point Coverage

' Inform the user that the POINT cover
' must be the first theme in TOC

AnswerChar = MsgBox.YesNo ( "Is the POINT Theme first in the TOC & is it Active
?","Warning!", True )

if ( AnswerChar = False ) then
  Exit
end


theView = av.GetActiveDoc

' get active theme

pttheme = theView.GetActiveThemes.Get(0)

'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

' obtain parameters for the interpolated grid to be created

theCellSizeNum = 46

ExtentRect = pttheme.ReturnExtent

gridsizeList = { theCellSizeNum,ExtentRect }


polyorderNum = msgbox.Input ( "Enter the Order of Polynominal", "Trend Surface
Interpolation", "3" )


zField = ptTheme.GetFTab.FindField("Elevation")
```

```
anInterp = Interp.MakeTrend ( polyorderNum.AsNumber, FALSE)
aPrj = Prj.MakeNull
theResultGrid =
Grid.MakeByInterpolation(ptTheme.GetFTab,aPrj,zField,anInterp,gridsizeList)

' create a theme
theGTheme = GTheme.Make(theResultGrid)
' check if output is ok
if (theResultGrid.HasError) then
  return NIL
end
'add a name for the GRID

theResultGrid.SetName("Trend surface of: " + pttheme.Getname)



' add theme to the view
theView.AddTheme(theGTheme)

'that's all folk's
'>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

APPENDIX D

Analysis: Phase I - DTM Plots



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

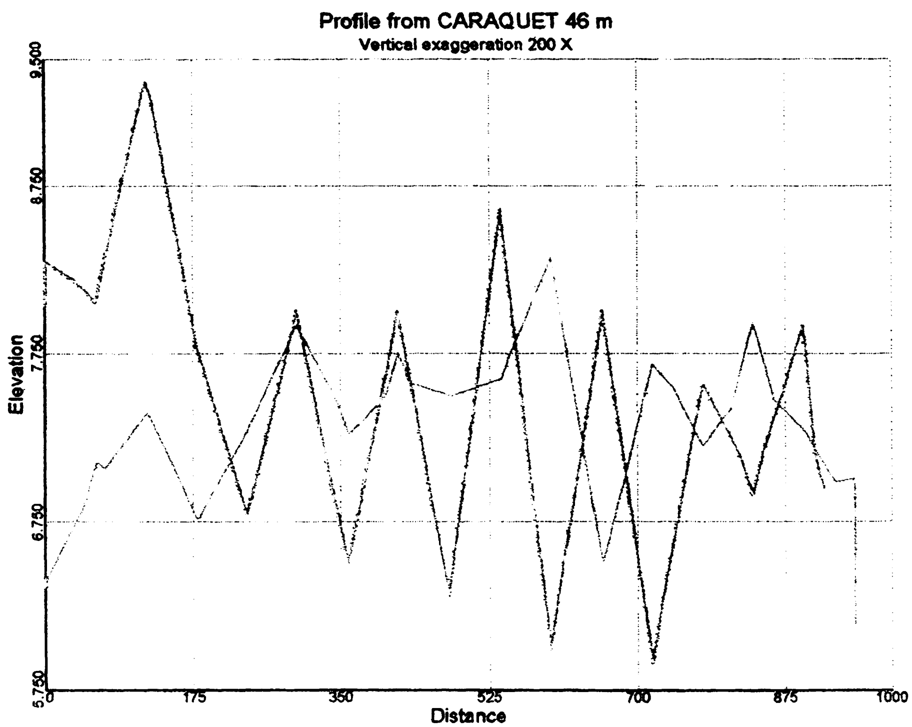
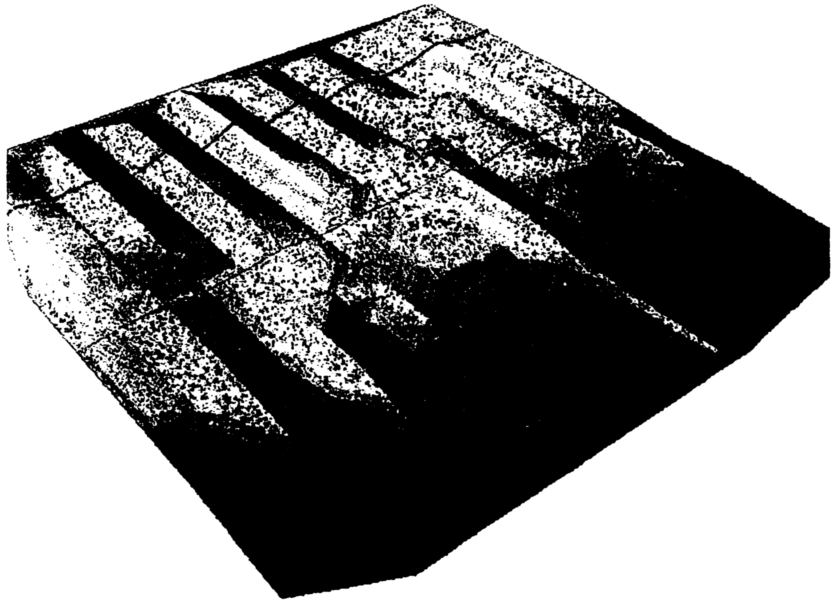


Figure: Caraquet, TIN



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

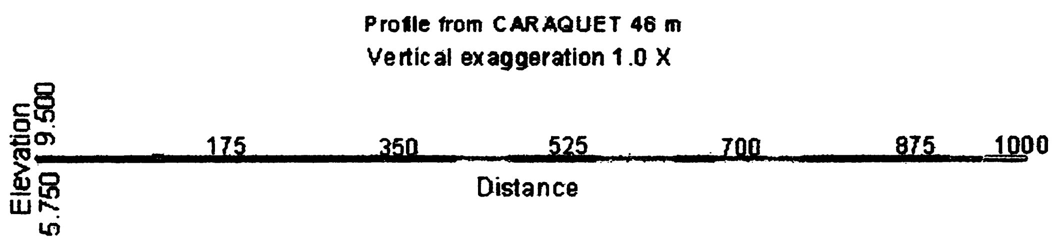
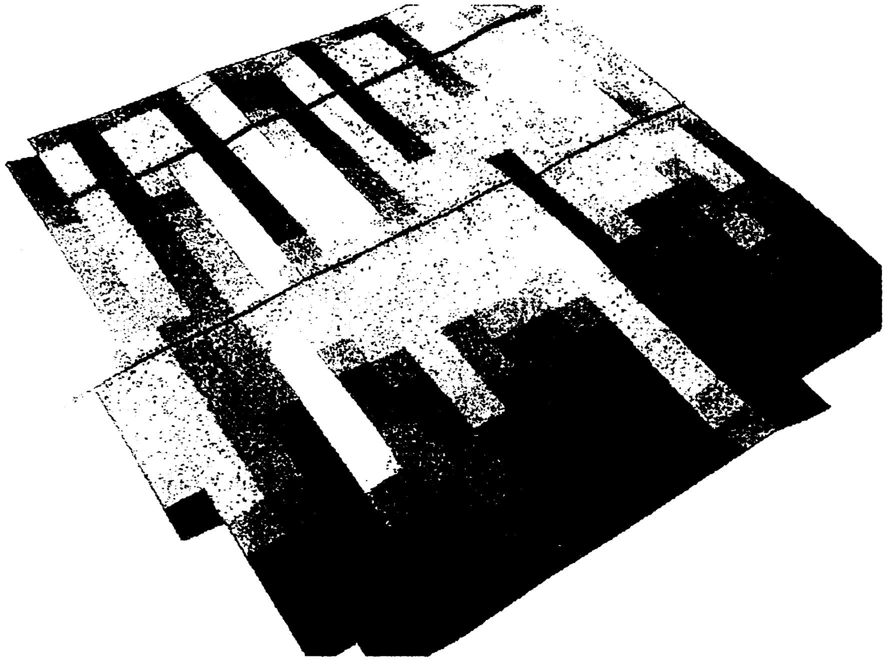


Figure: Caraquet, TIN



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

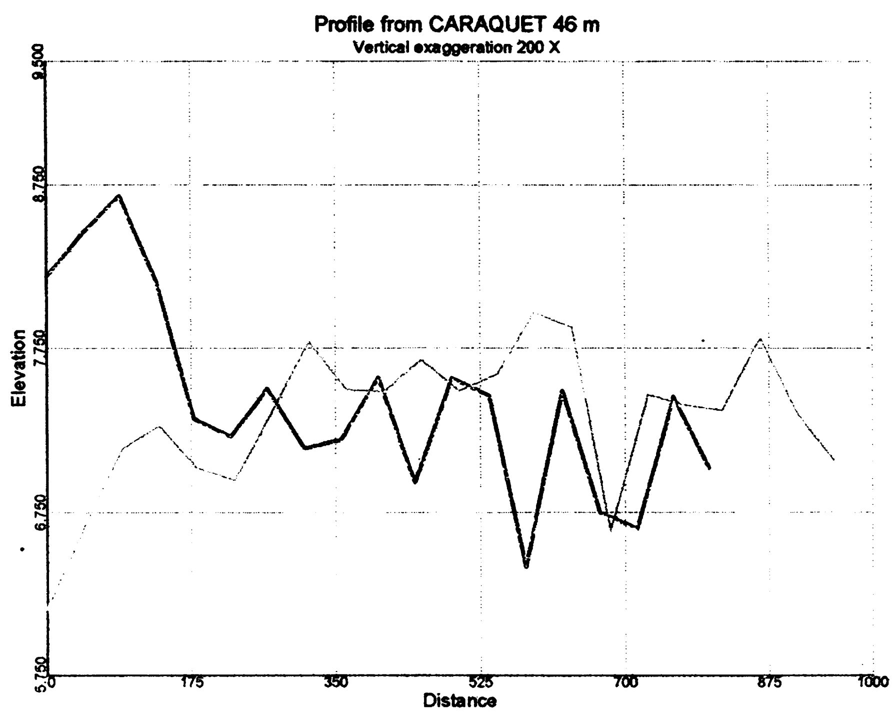
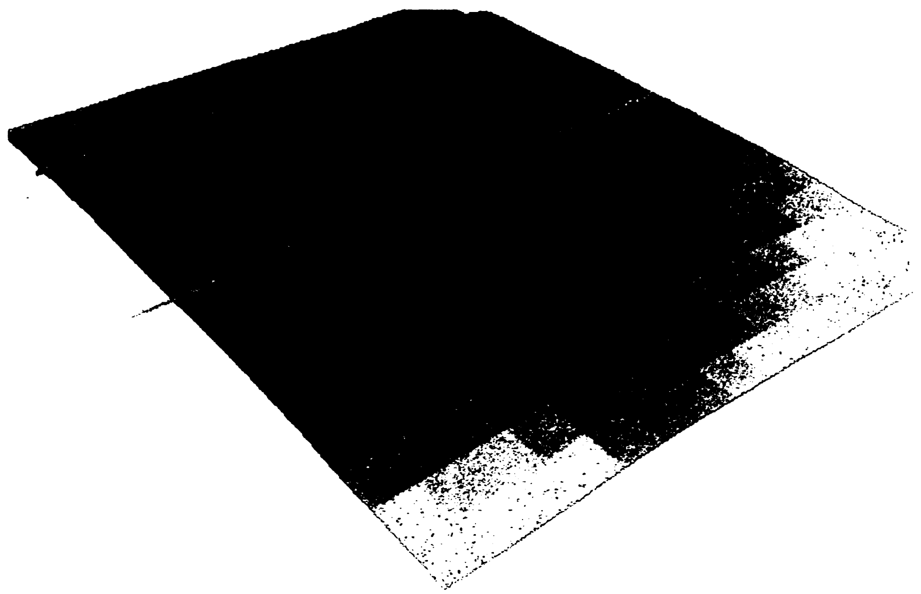


Figure: Caraquet, 46m Res.



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

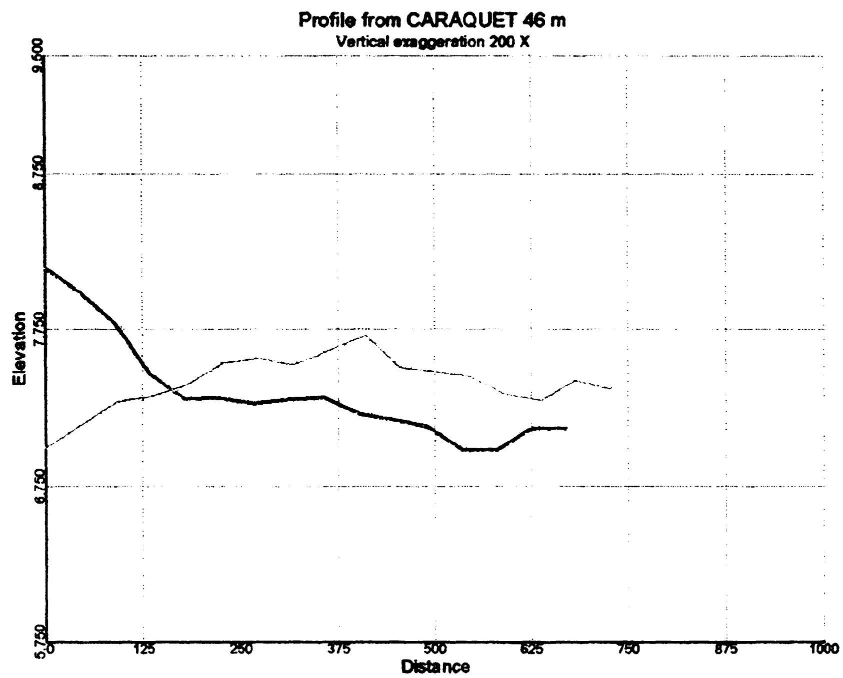
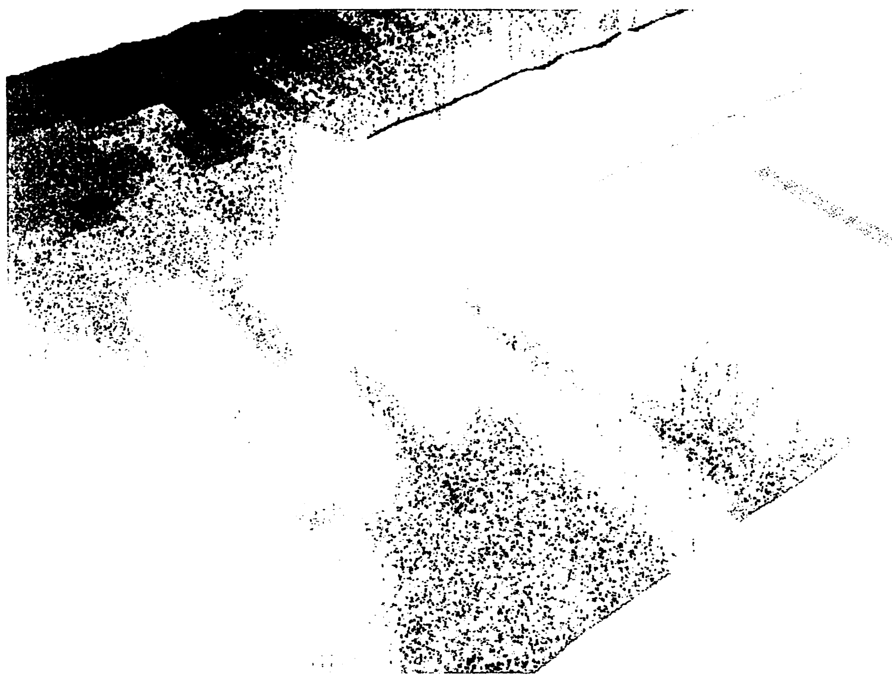


Figure: Caraquet, 46m Res. 5x1 Low Pass Filter



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

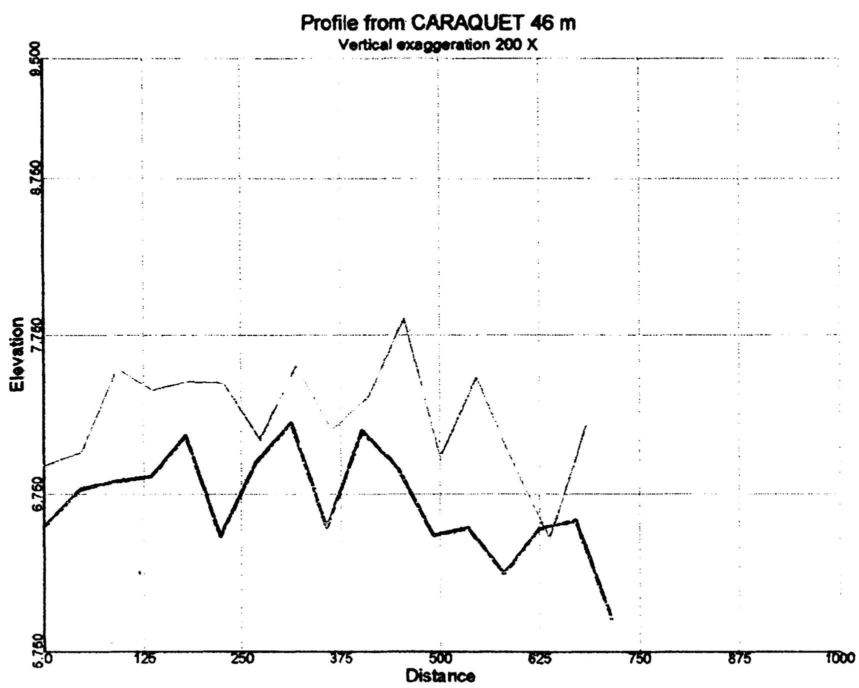
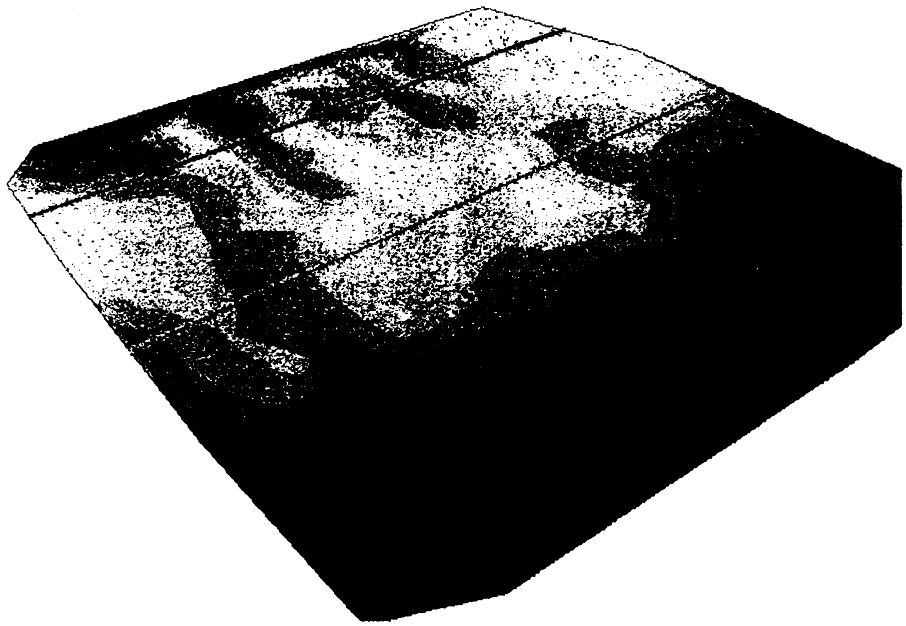


Figure: Caraquet, 46m Res., Fourier



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

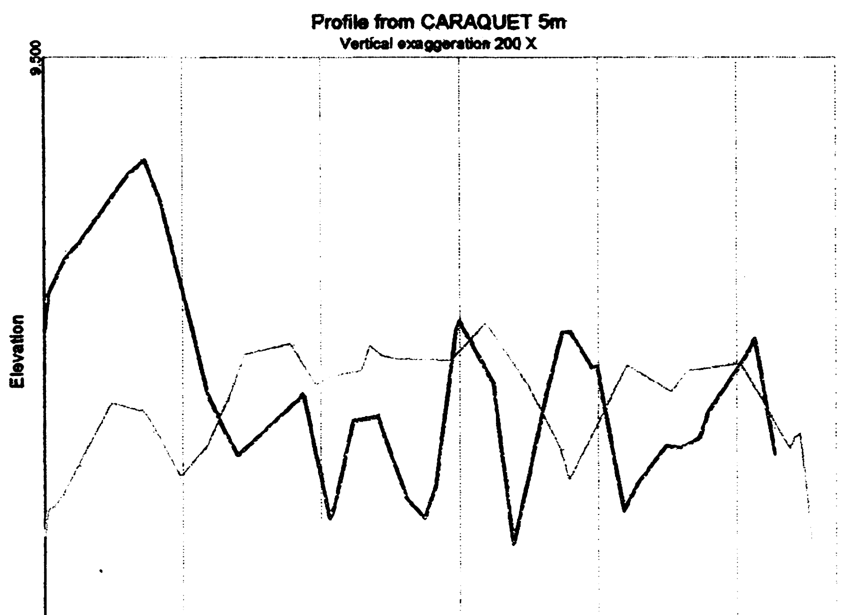
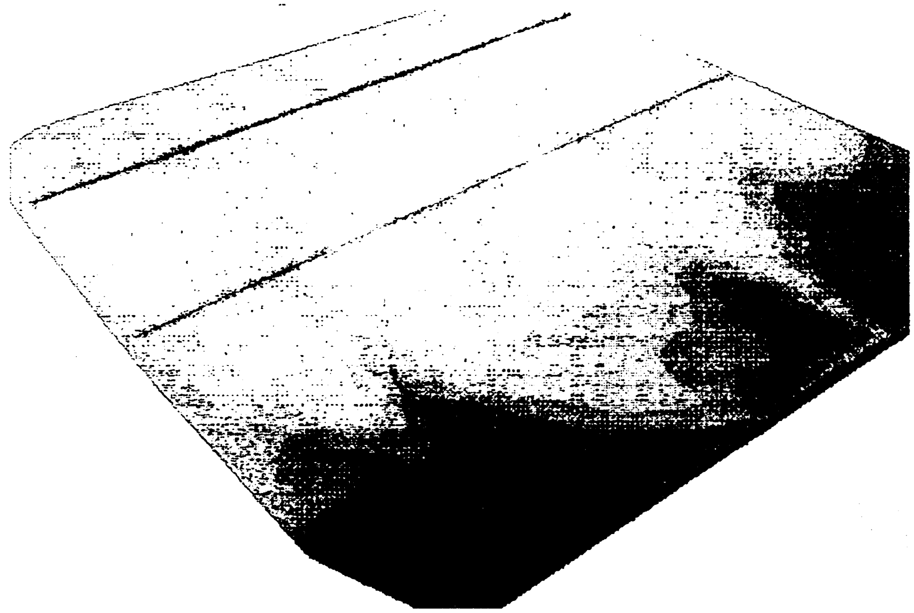


Figure: Caraquet, Random TIN Densification, 10-2



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

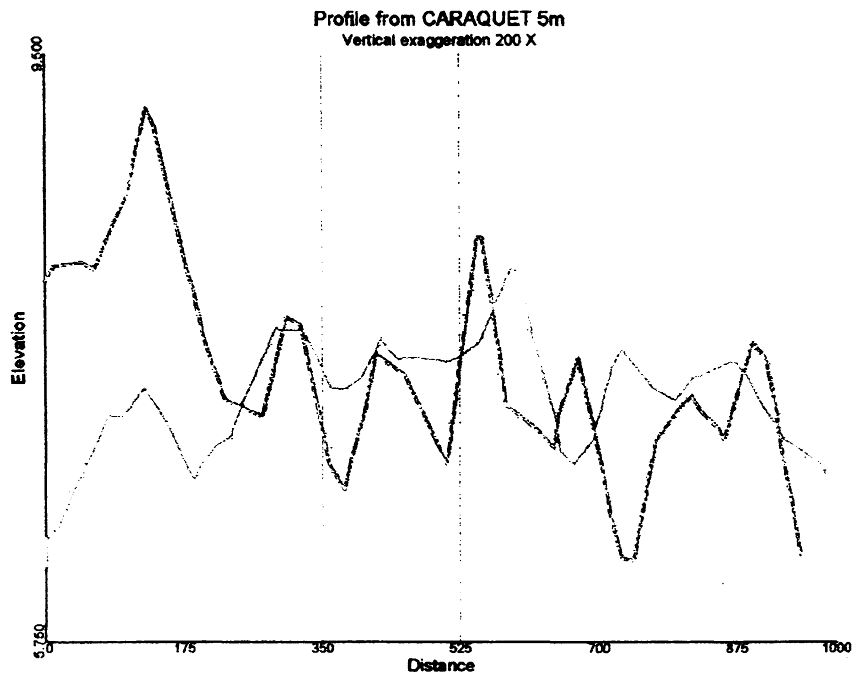
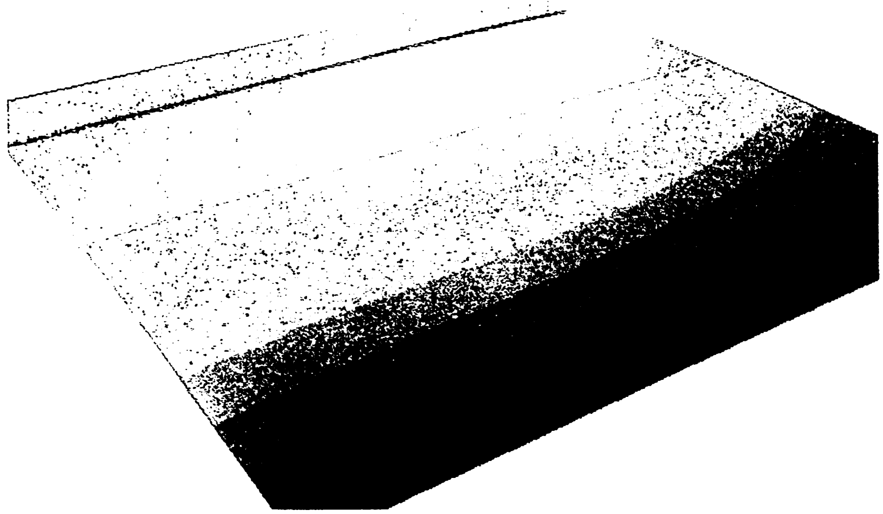


Figure: Caraquet, Random TIN Densification, 10-5



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

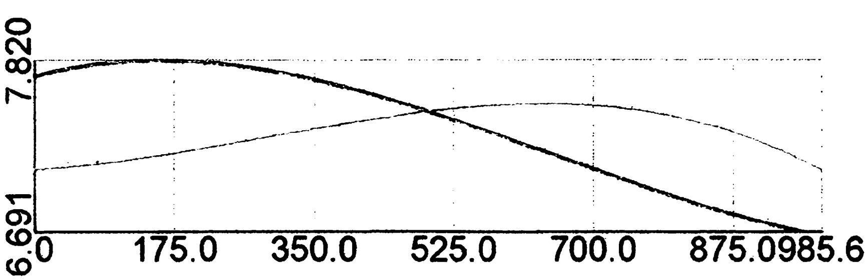
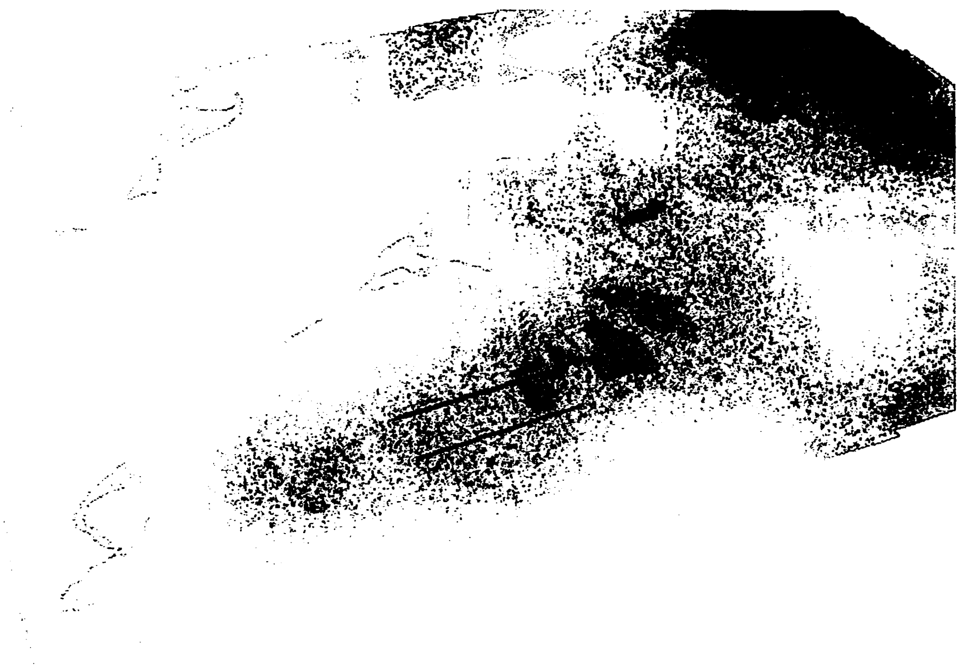
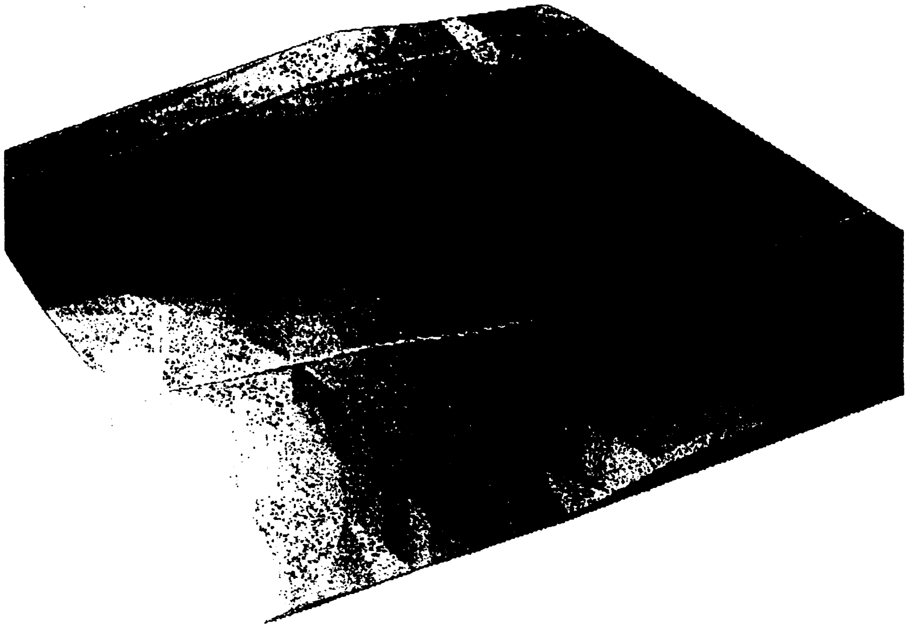


Figure: Caraquet, Trend Surface, Order = 3
Vertical Exaggeration = 200x



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 10x

Figure: Caraquet, 46m Res., Filtered by Whitestar Inc.



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

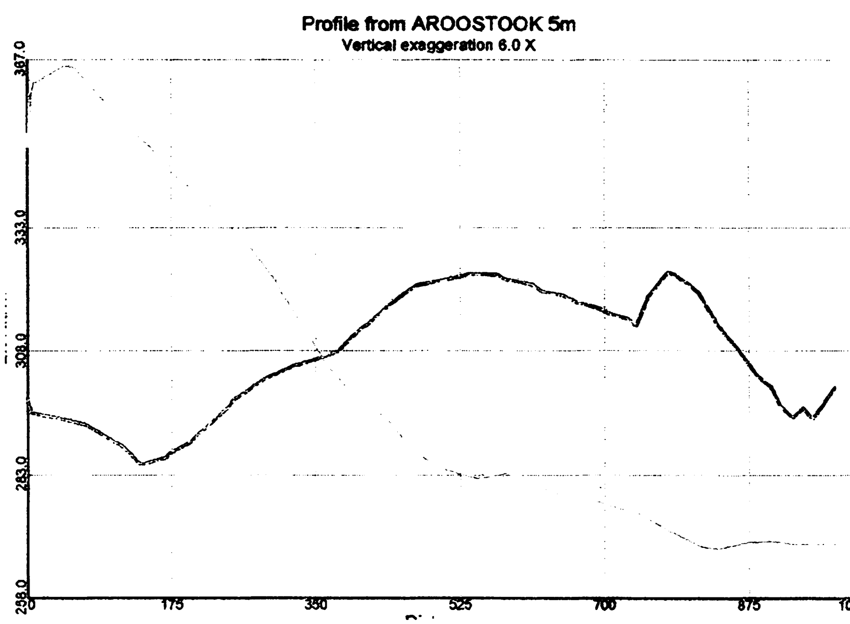
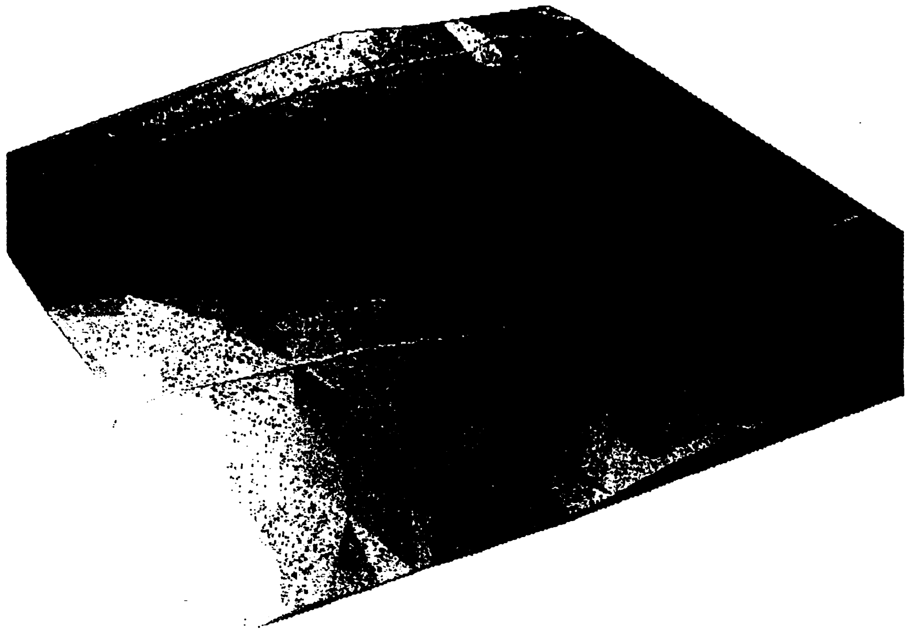


Figure: Aroostook, TIN



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

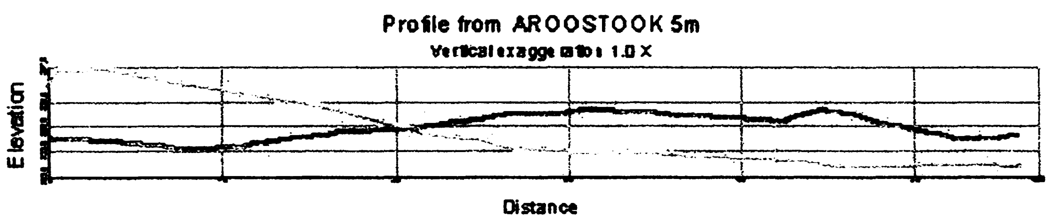
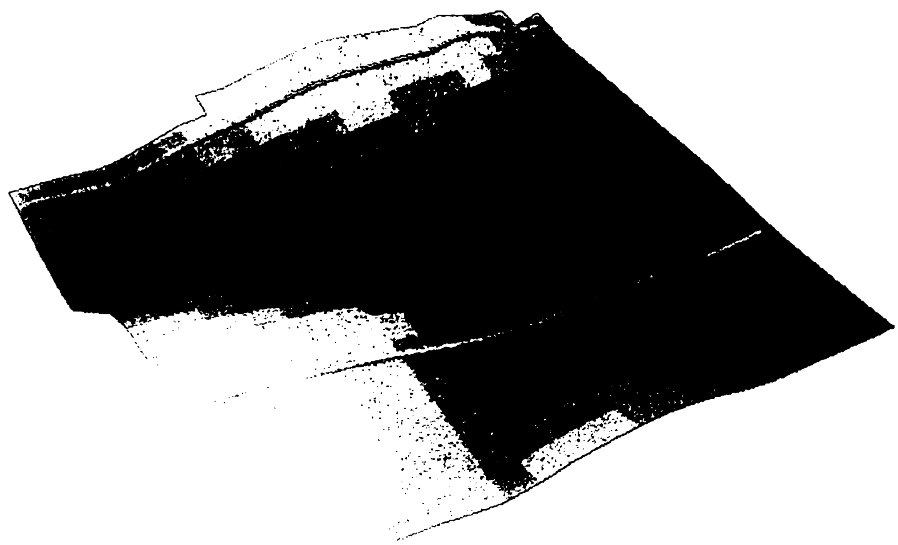


Figure: Aroostook, TIN



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

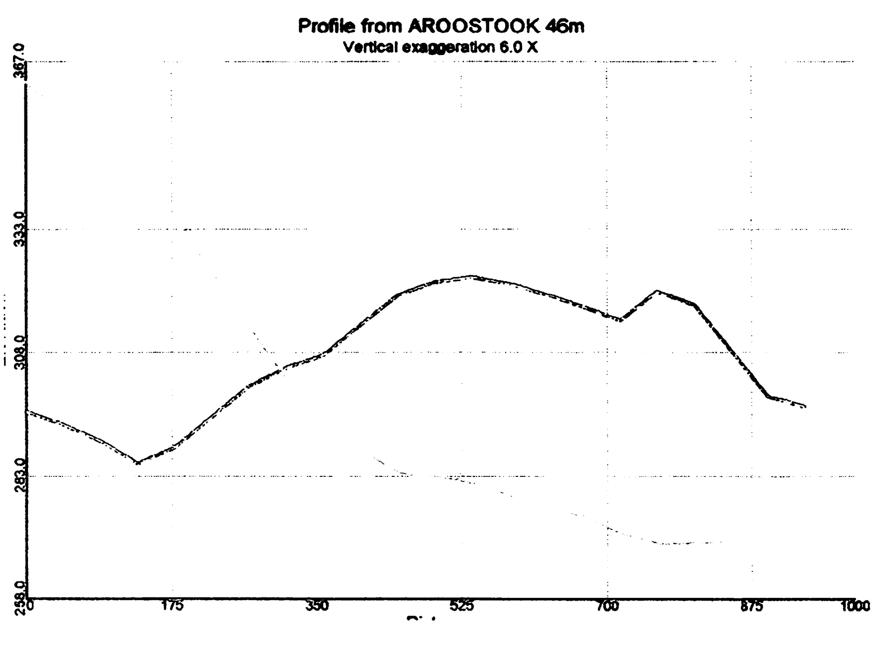
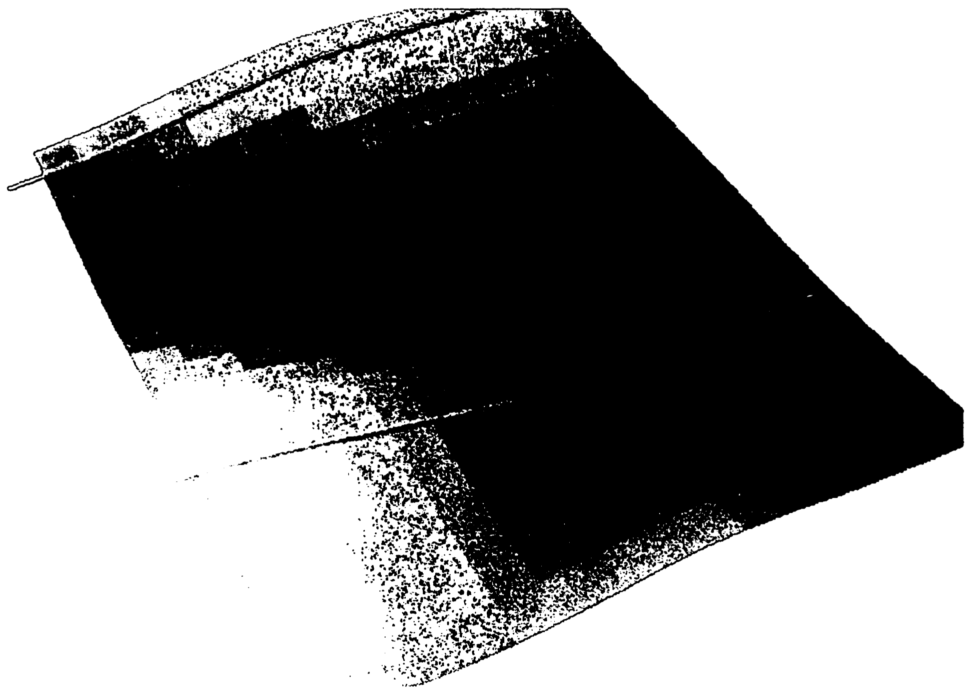


Figure: Aroostook, 46m Res.



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

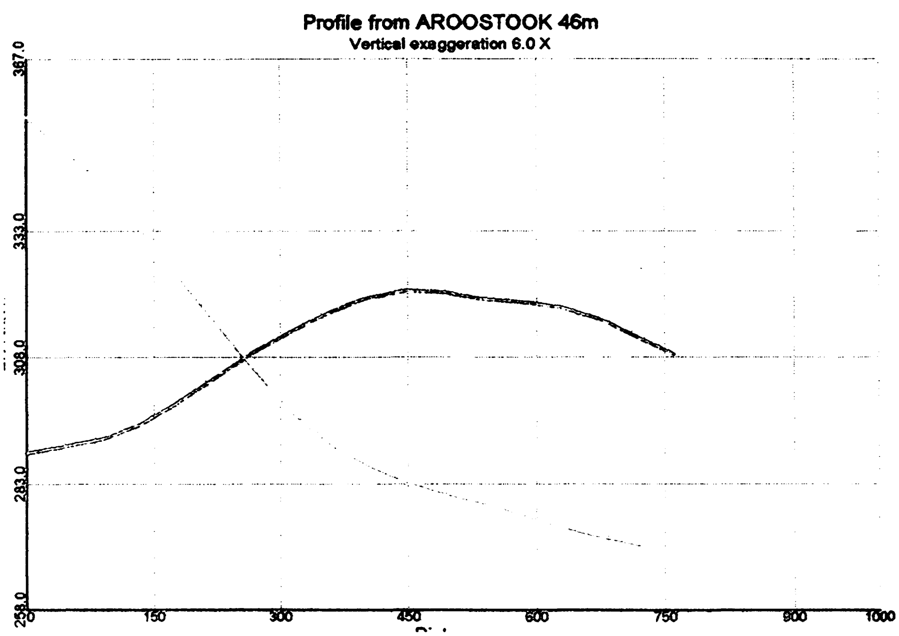
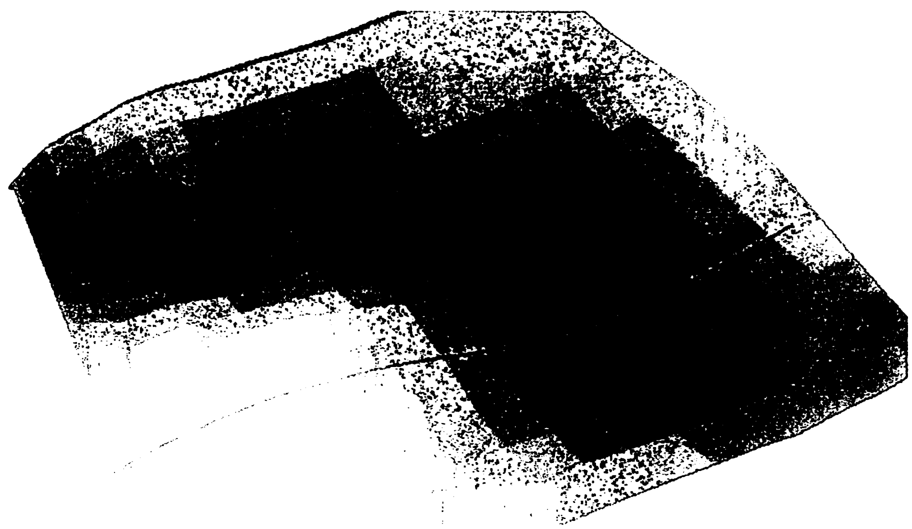


Figure: Aroostook, 5x1 Low Pass Filter



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

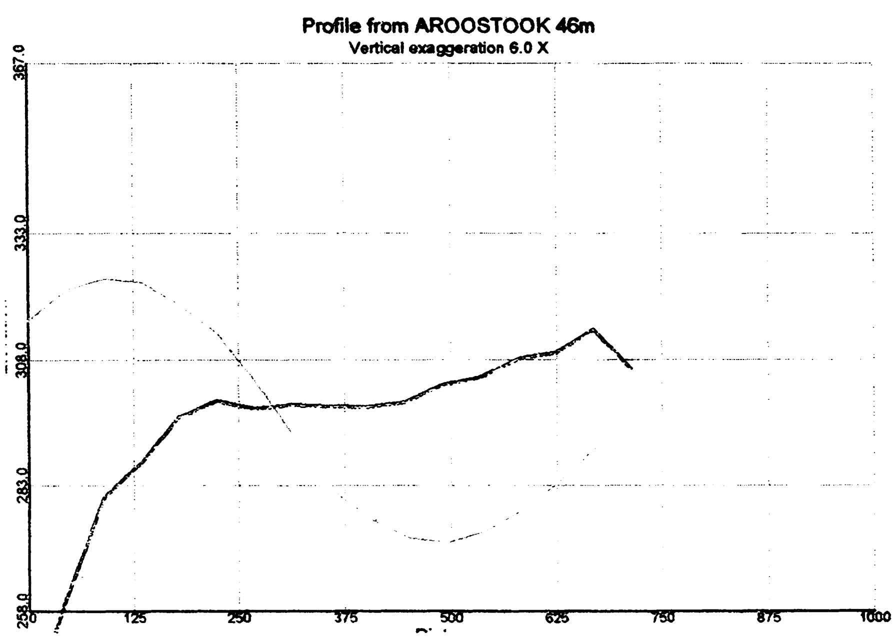
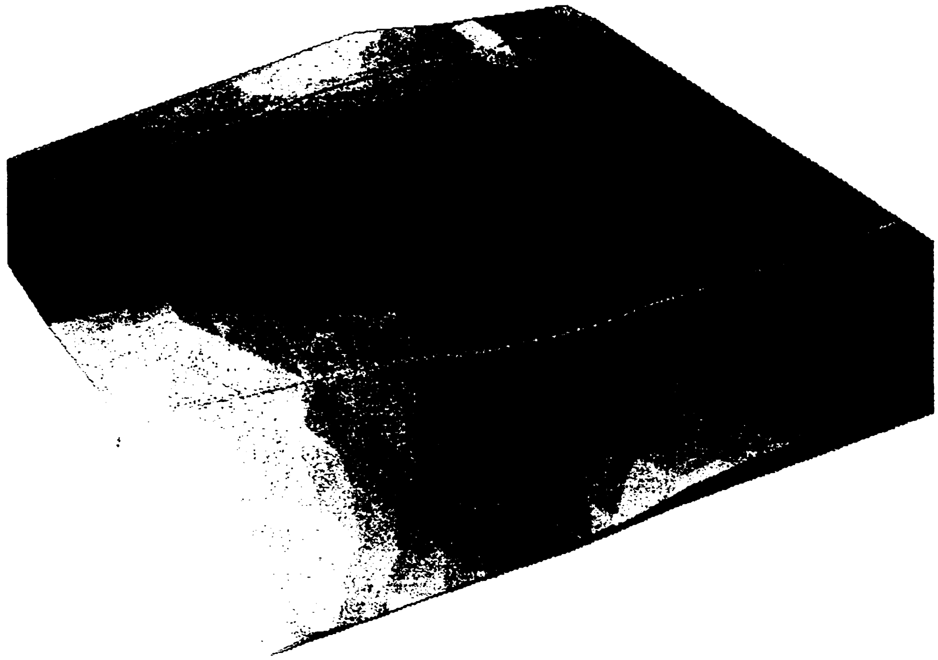


Figure: Aroostook, Fourier Transform



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

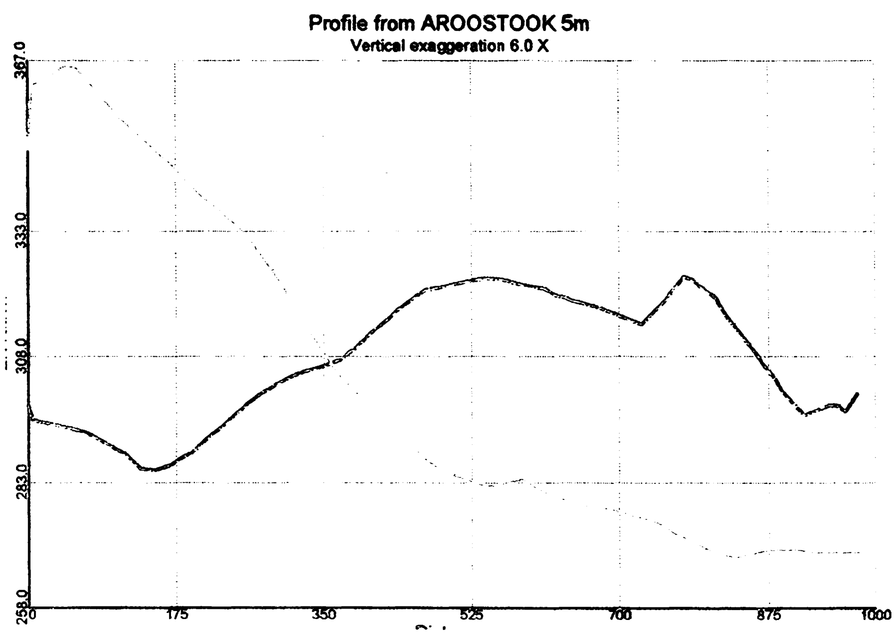
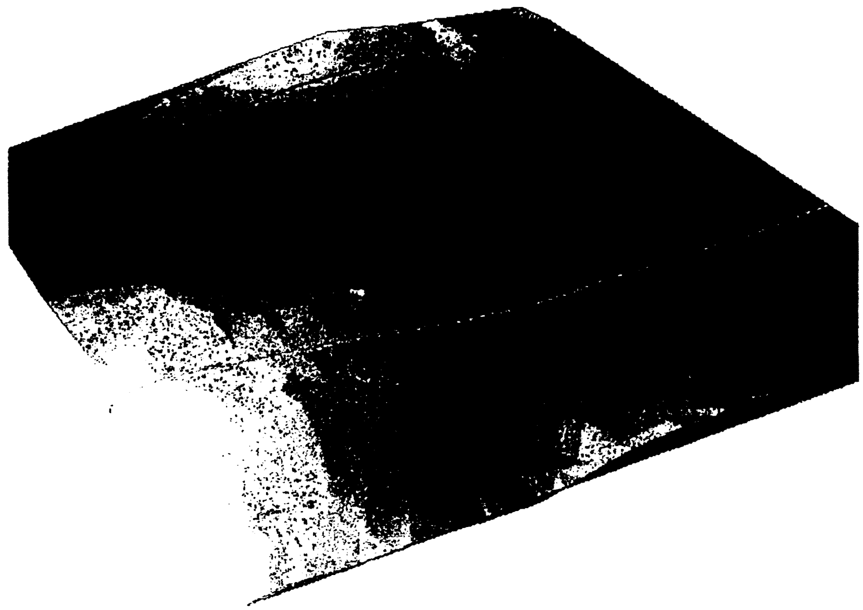


Figure: Aroostook, Random TIN Densification, 10-2



Not to Scale. Sun Az = 270° Altitude = 30° Vertical Exaggeration 1.5x

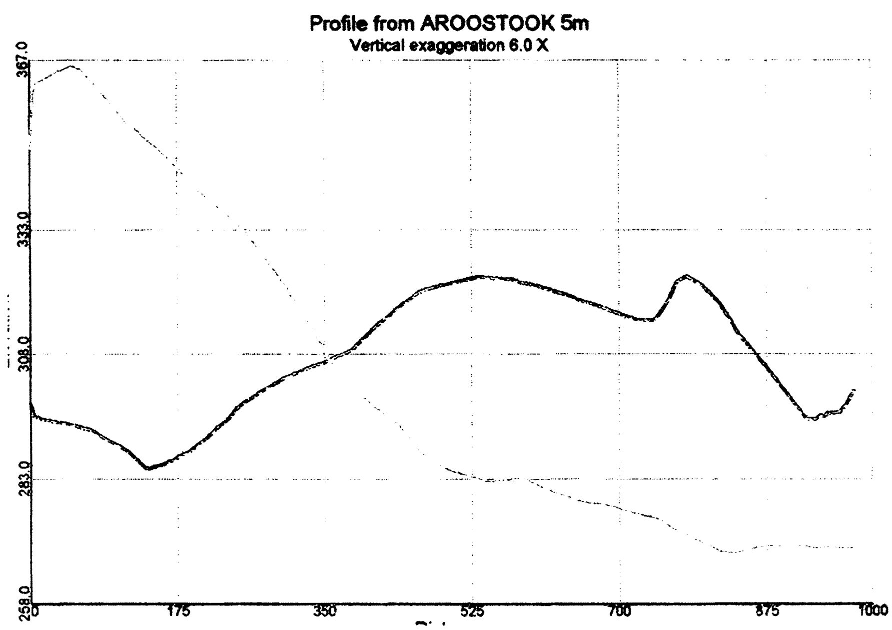
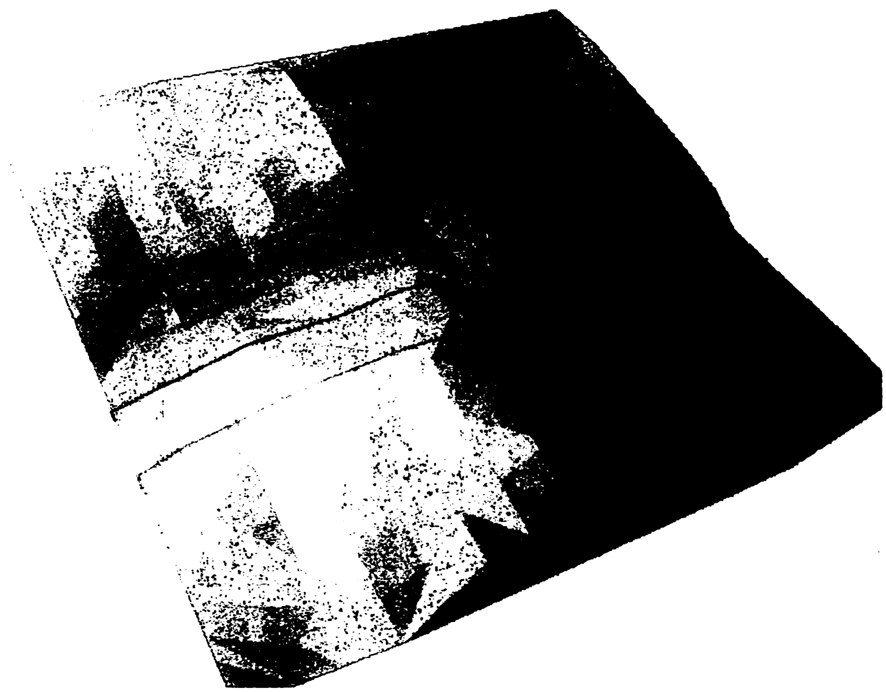


Figure: Aroostook, Random TIN Densification, 10-5



Not to Scale, Sun Az = 270° Altitude = 30° Vertical Exag = 1.5x

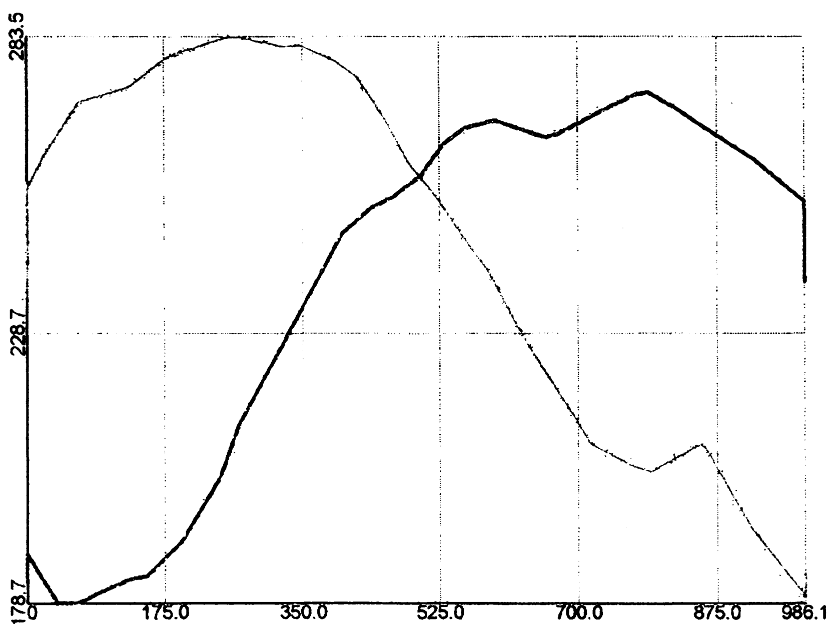
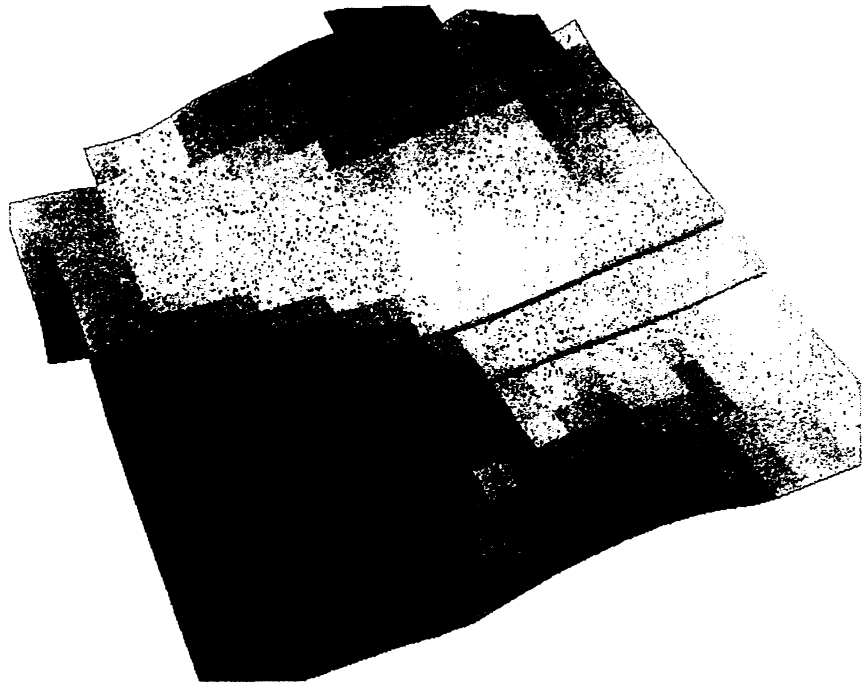


Figure: Hayesville, TIN



Not to Scale. Sun Az = 270° Altitude = 30° VE = 1.5x

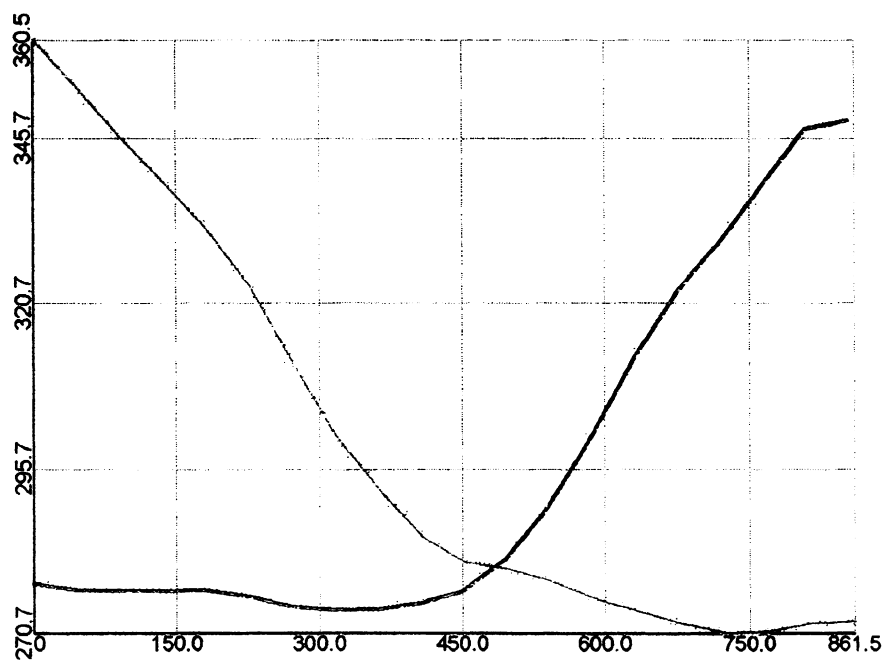
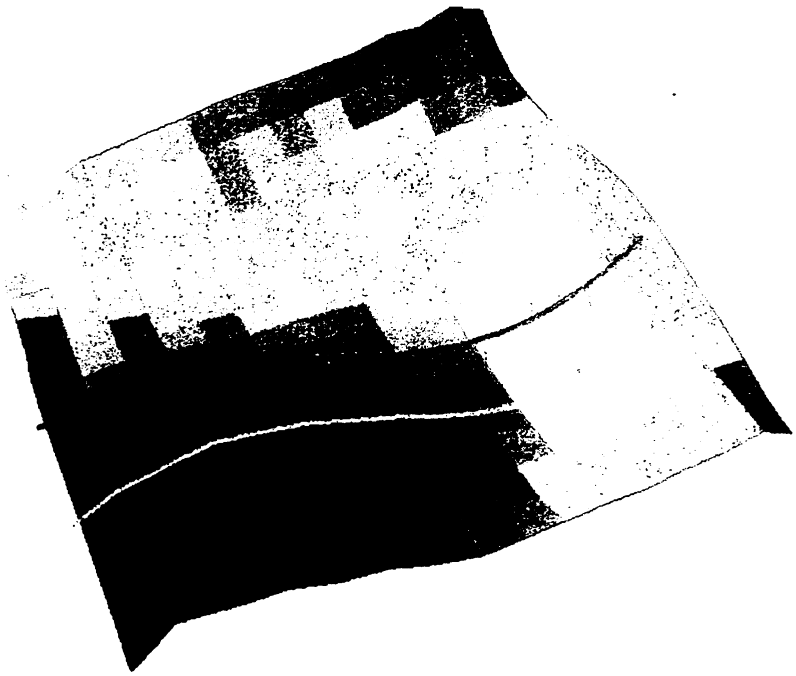


Figure: Hayesville, 46m Res.



Not to Scale. Sun Az = 270° Altitude = 30° VE = 1.5x

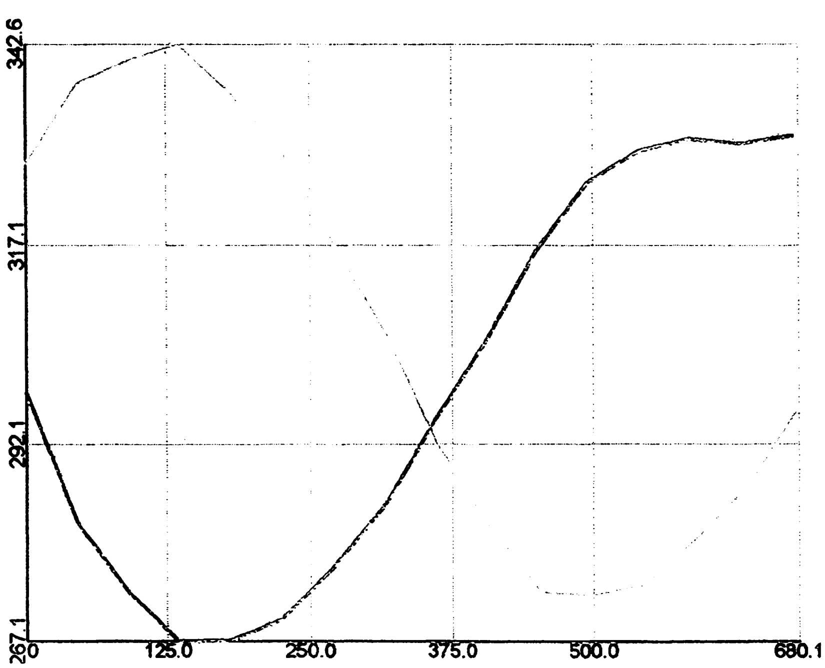
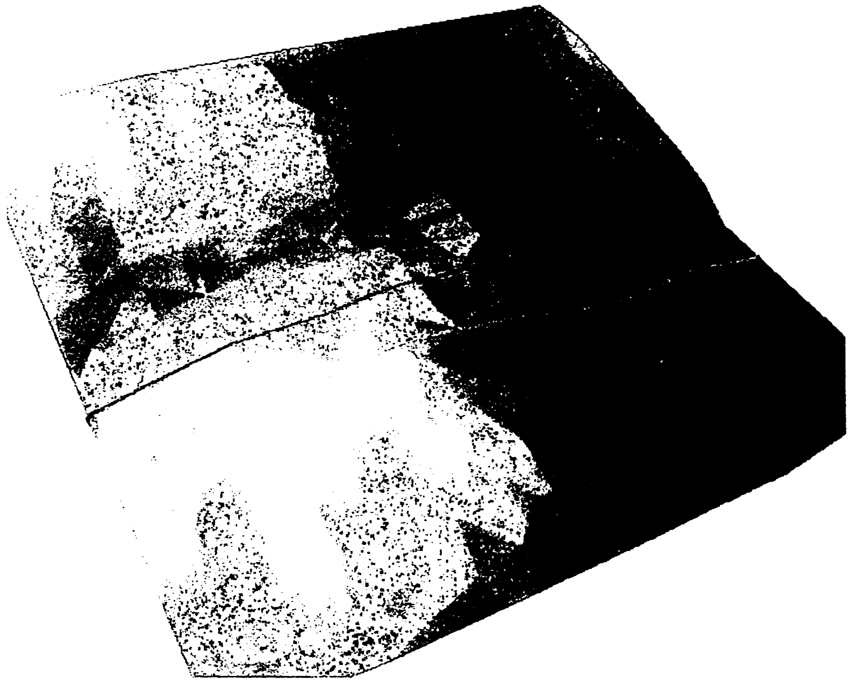


Figure: Hayesville, FFT.
Vertical Exaggeration = 7x



Not to Scale. Sun Az = 270° Altitude = 30° VE = 1.5x

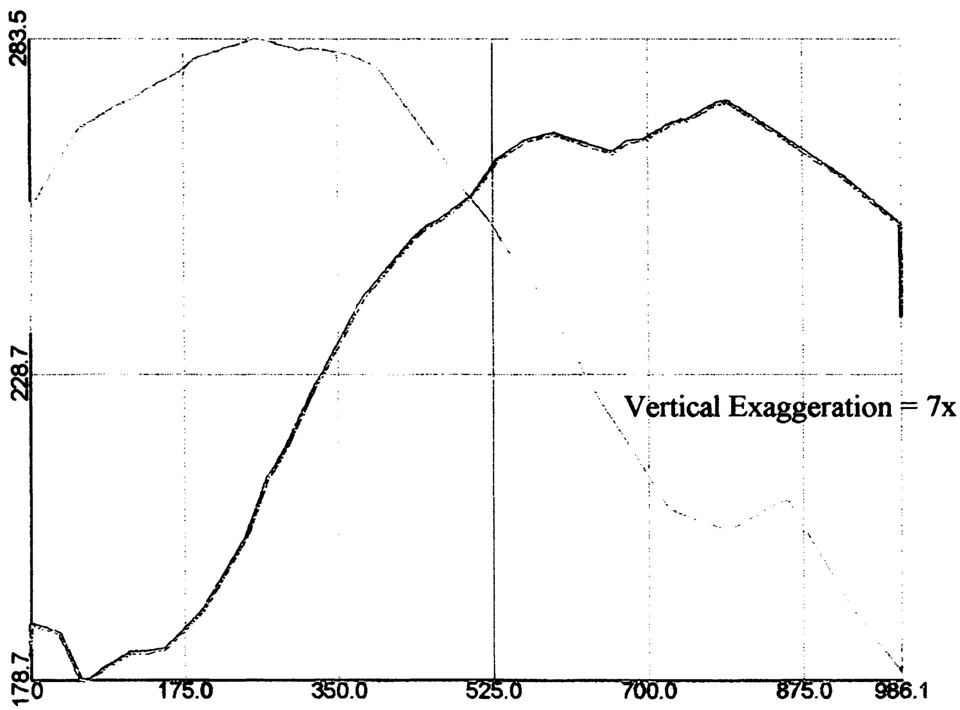
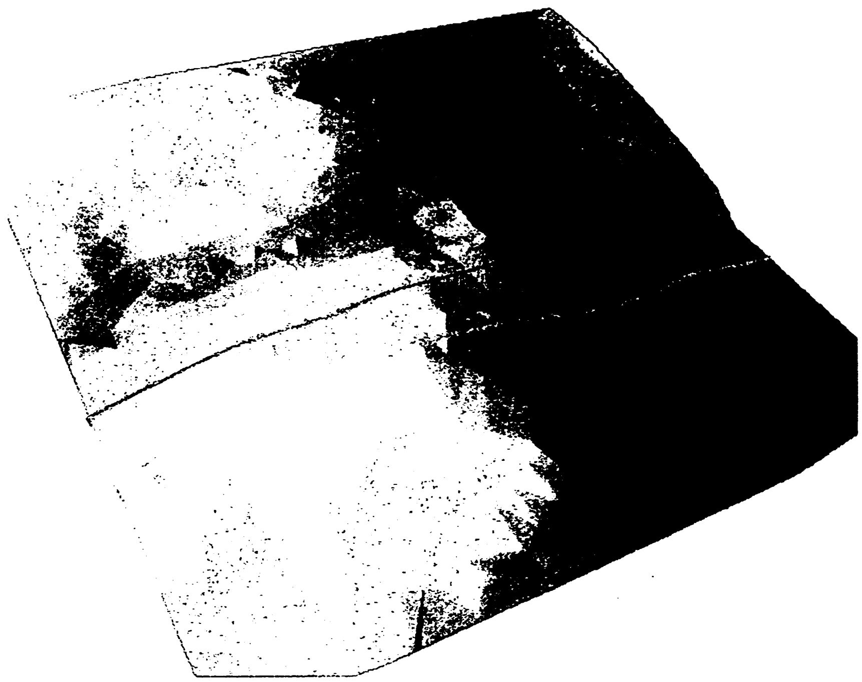


Figure: Hayesville, Random TIN Densification 10-2.



Not to Scale. Sun Az = 270° Altitude = 30° VE = 1.5x

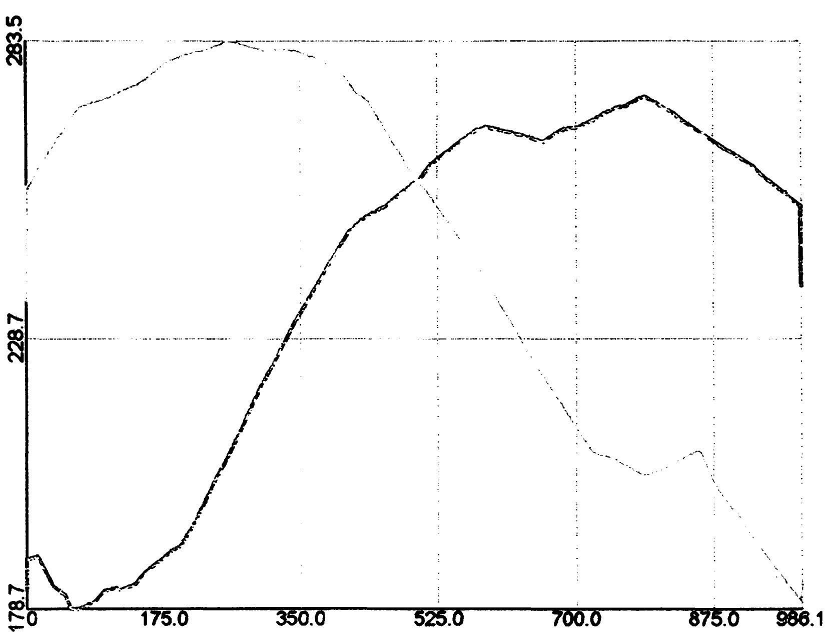


Figure: Hayesville, Random TIN Densification 10-5.
Vertical Exaggeration = 7x

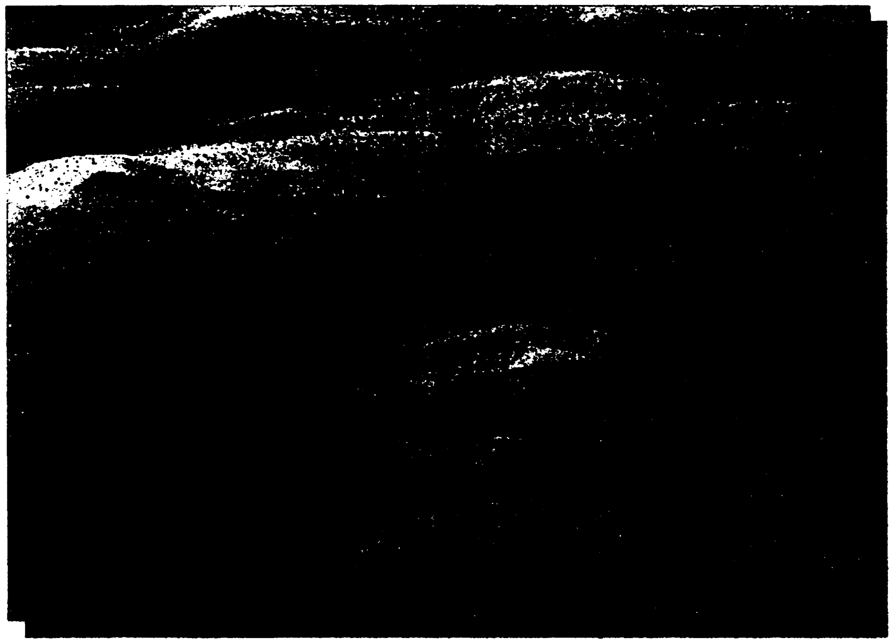


Image A: Aroostook Study Site - TIN contaminated with Ridging.

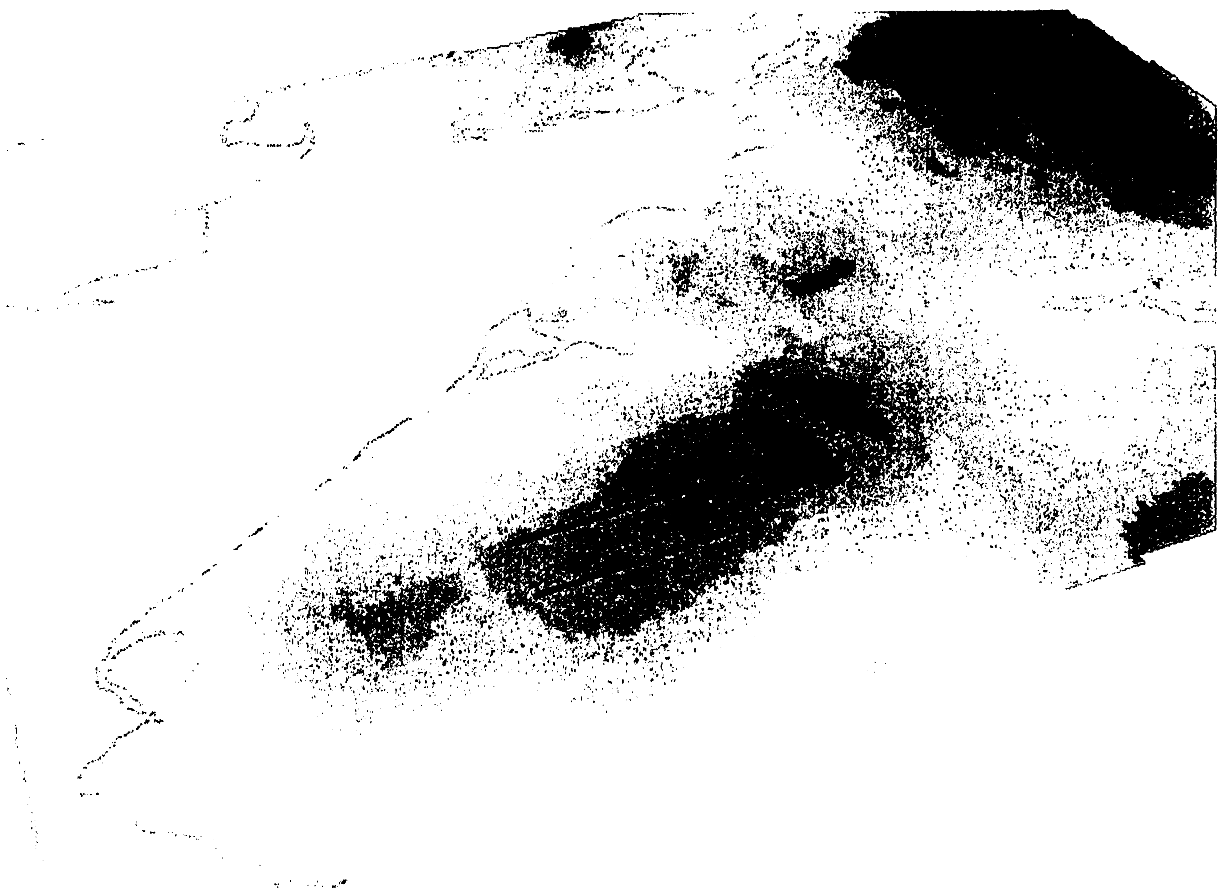
Image B: Aroostook Study Site - Randomly Densified TIN.

Figure: Random TIN Densification, Testing:
Comparison in Region of High Relief.

APPENDIX E

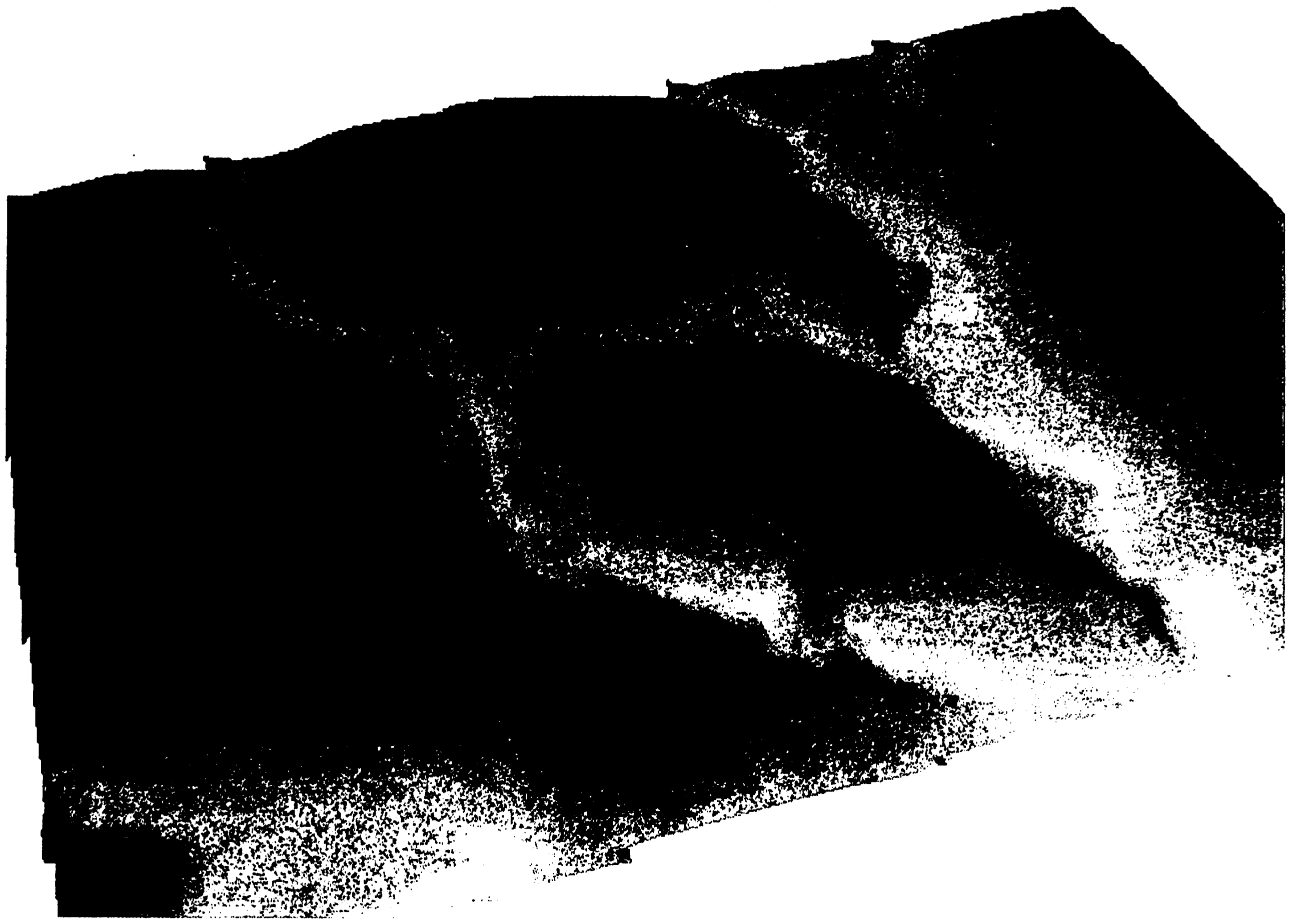
Analysis: Phase II - DTM Plots

Caraquet: CTM Fourier Filtering



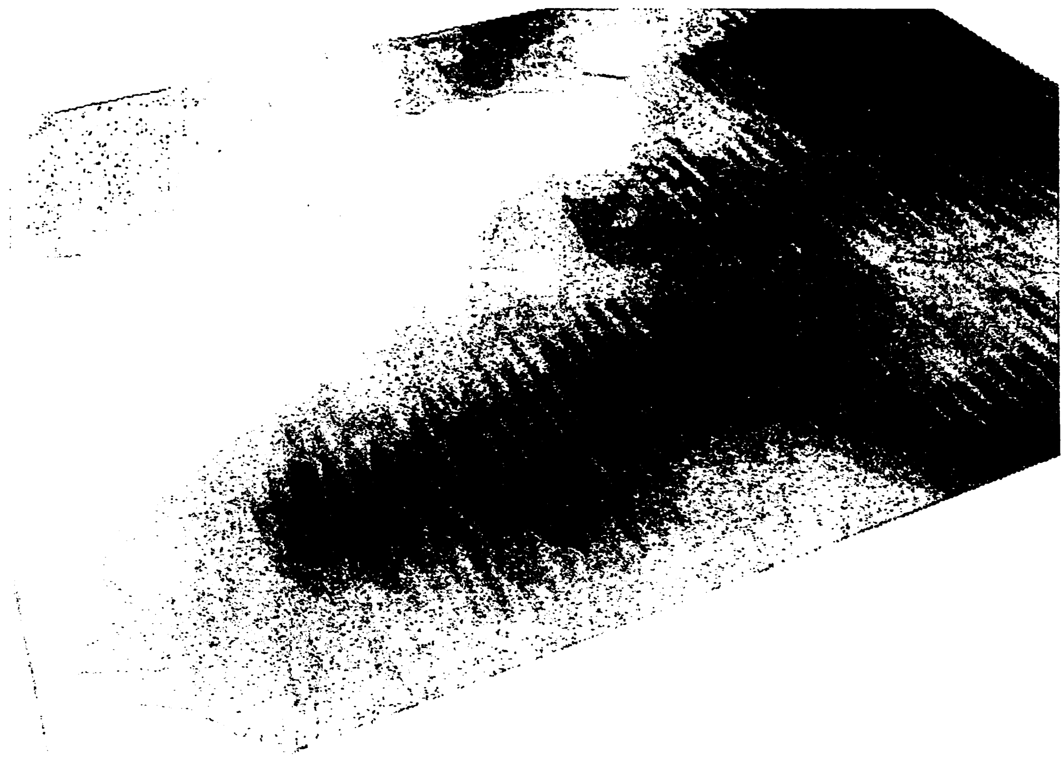
Aroostook: CTM Fourier Filtering

Hayesville: CTM Fourier Filtering



APPENDIX F

Histograms



Not to Scale. Sun Az = 270° Altitude = 30°

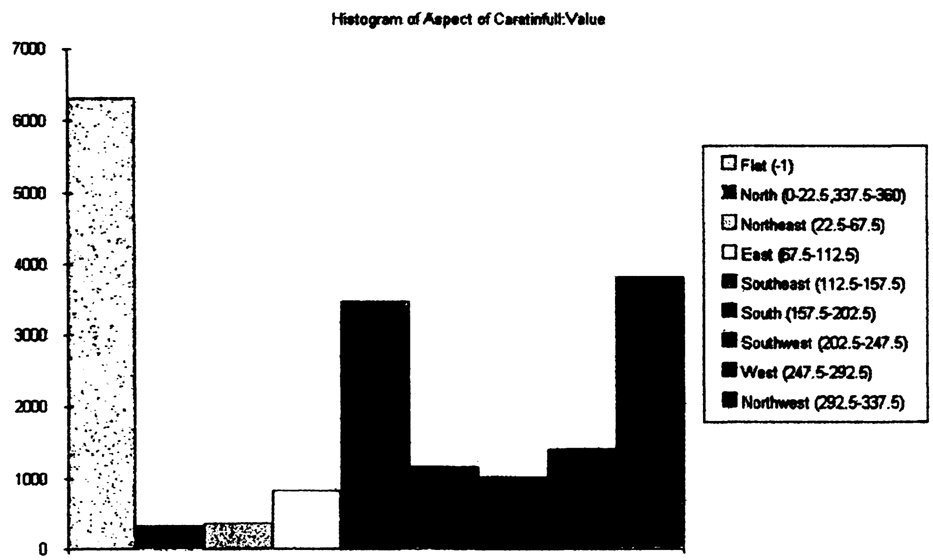
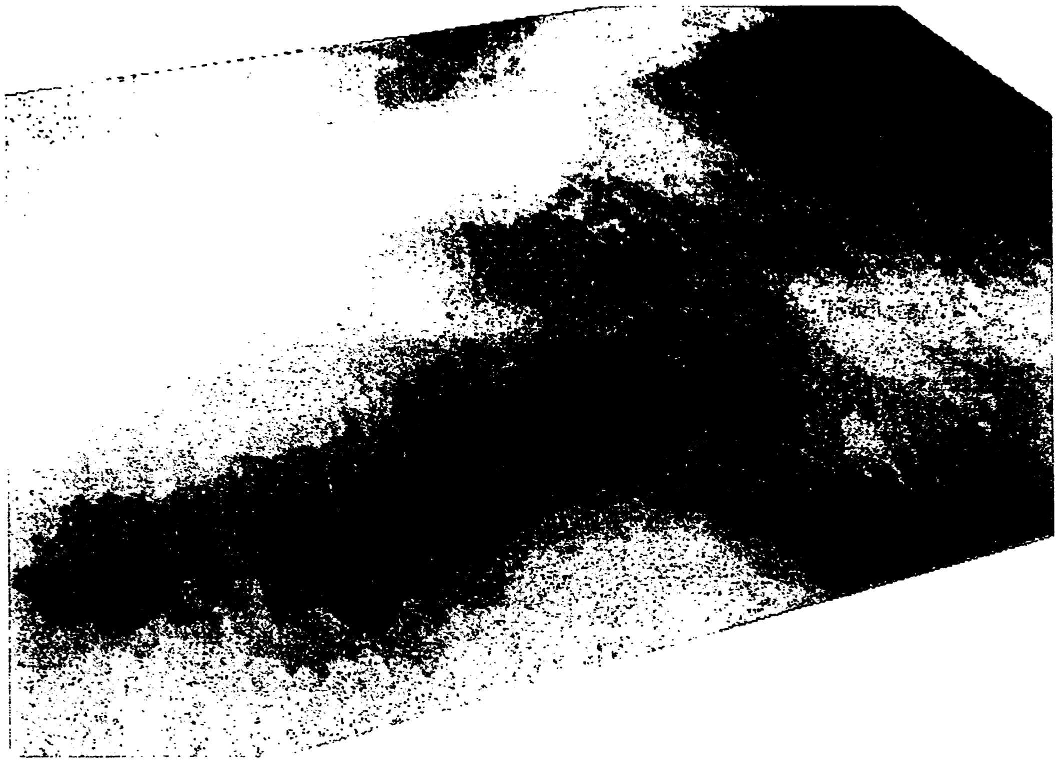


Figure: Caraquet - Full Sheet, TIN with Histogram of Aspect Values



Not to Scale. Sun Az = 270° Altitude = 30°

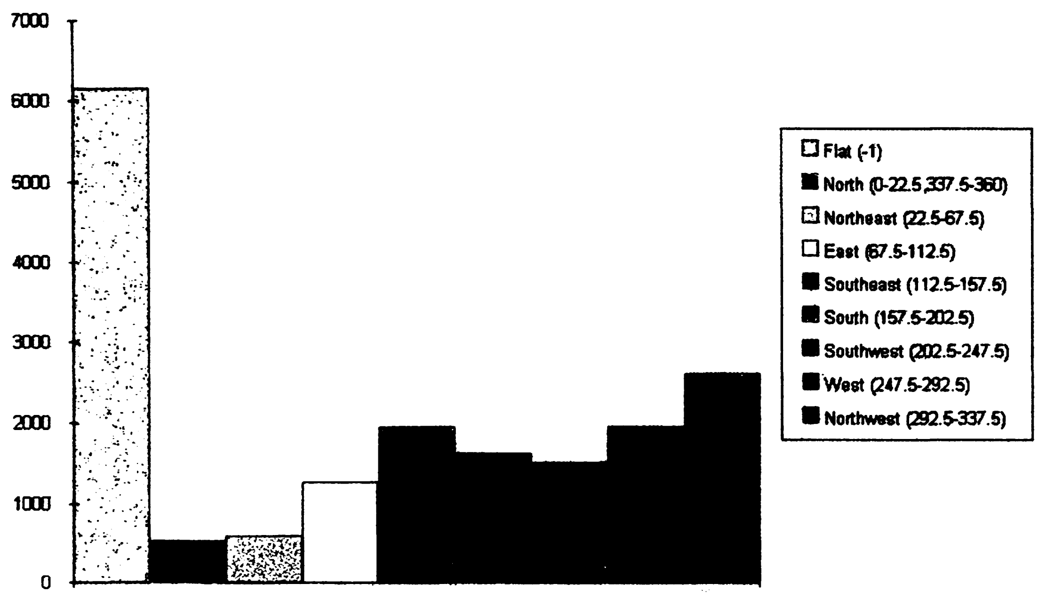
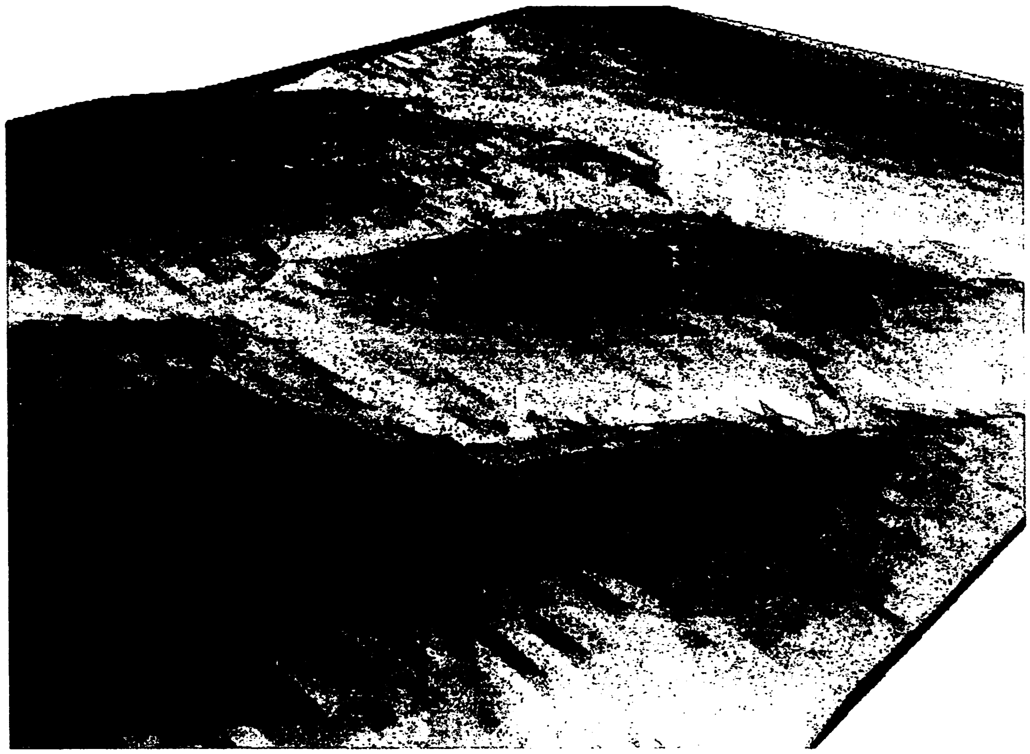


Figure: Caraquet - Full Sheet, TIN Random Densification 10-2, with Histogram of Aspect Values.



Not to Scale. Sun Az = 270° Altitude = 30°

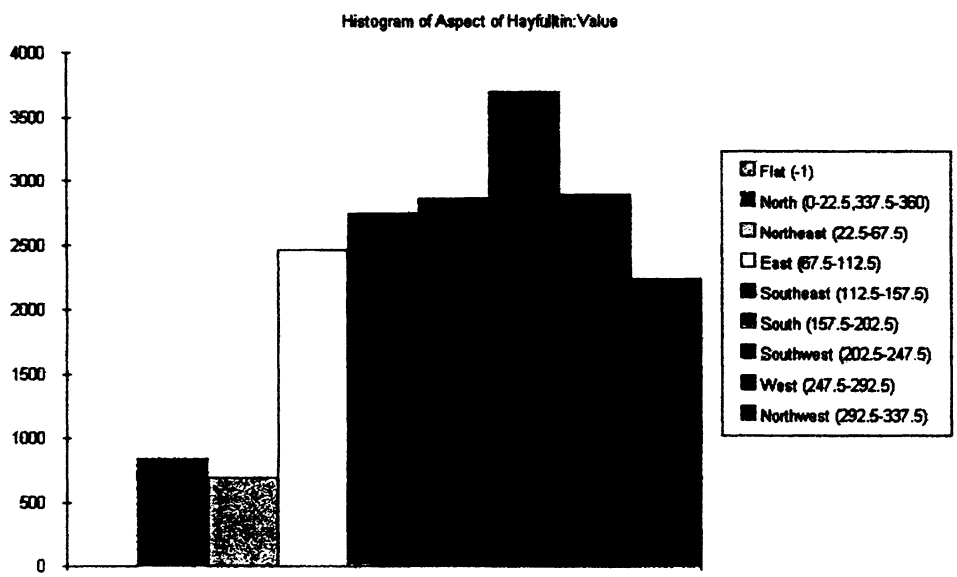
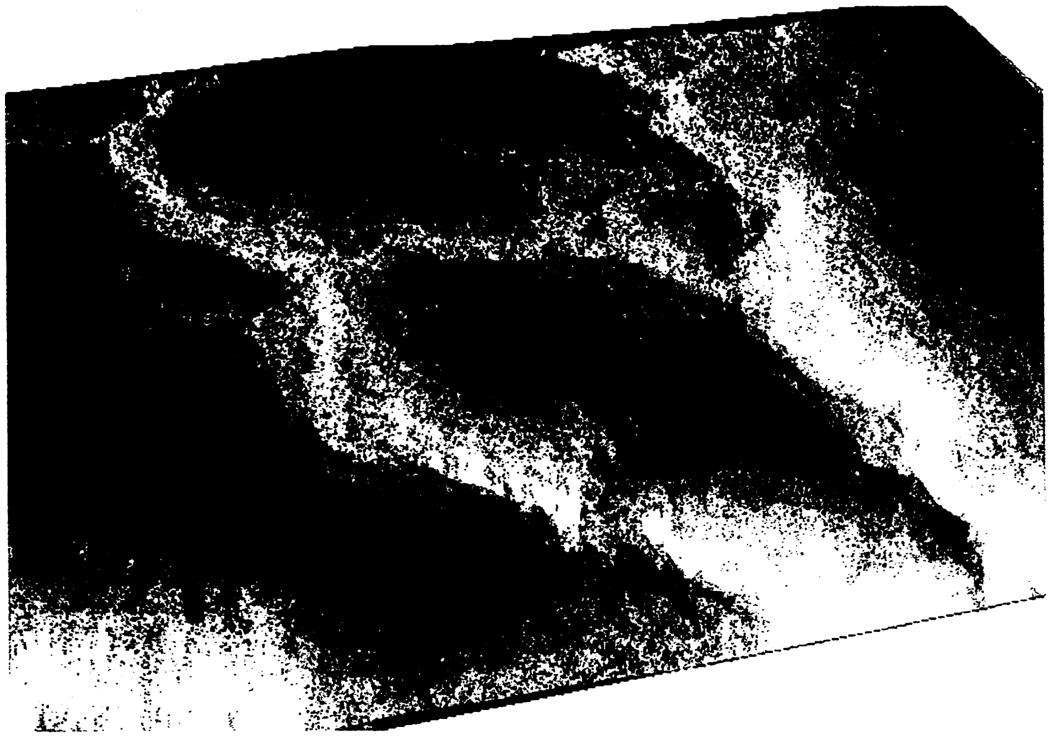


Figure: Hayesville - Full Sheet,TIN, with Histogram of Aspect Values.



Not to Scale. Sun Az = 270° Altitude = 30°

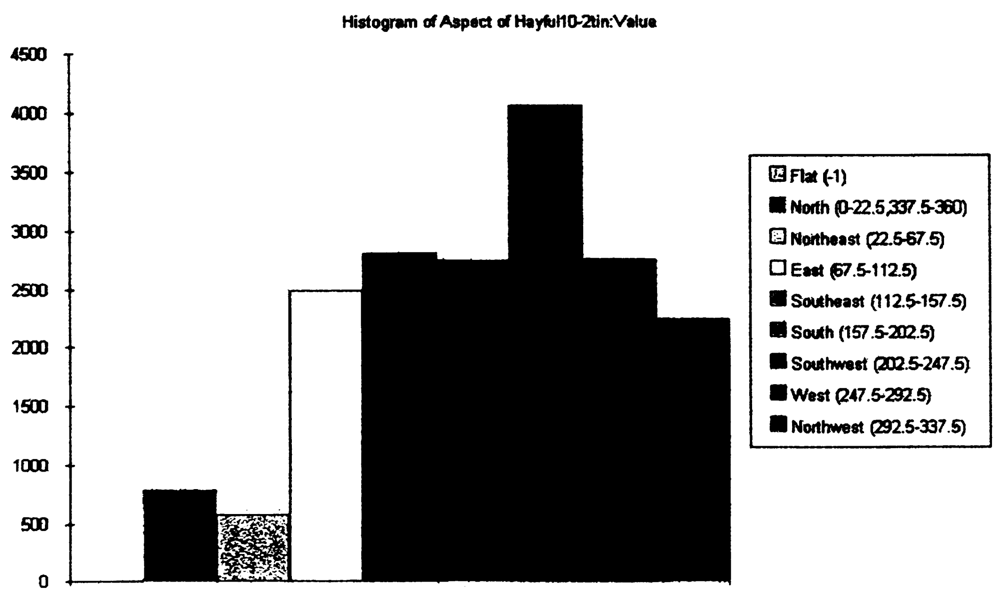
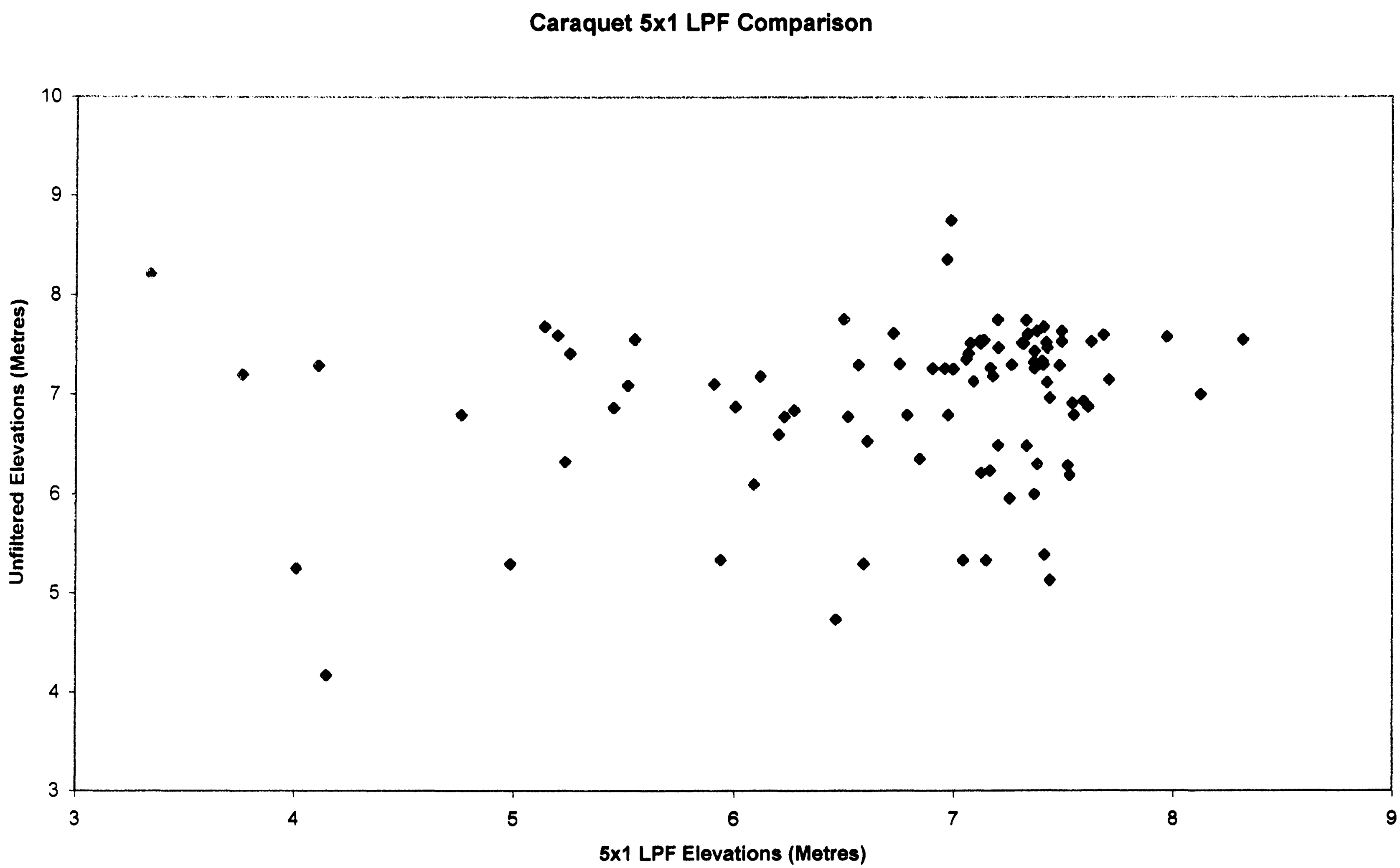
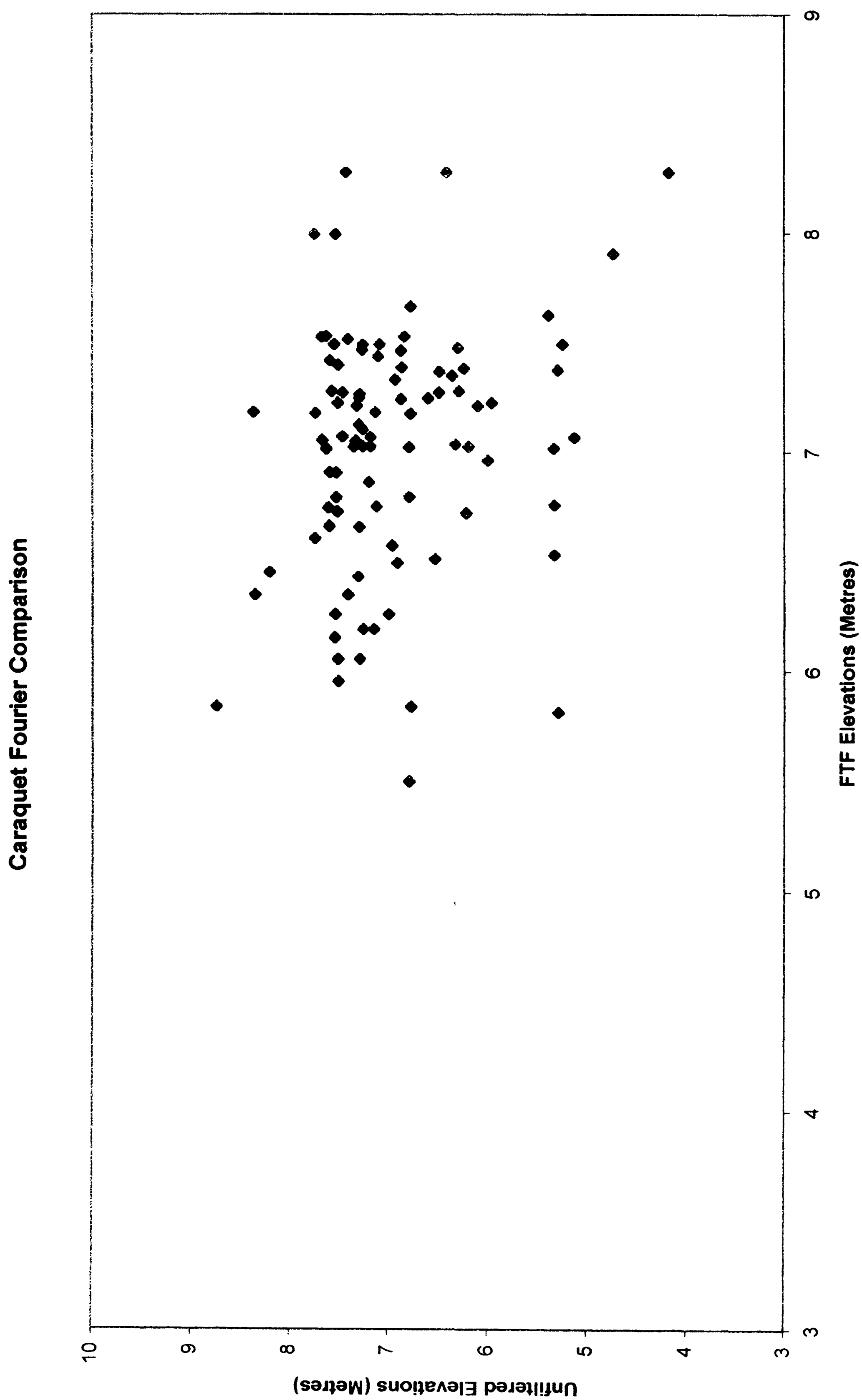


Figure: Hayesville - Full Sheet, TIN Random Densification 10-2, with Histogram of Aspect Values.

APPENDIX G

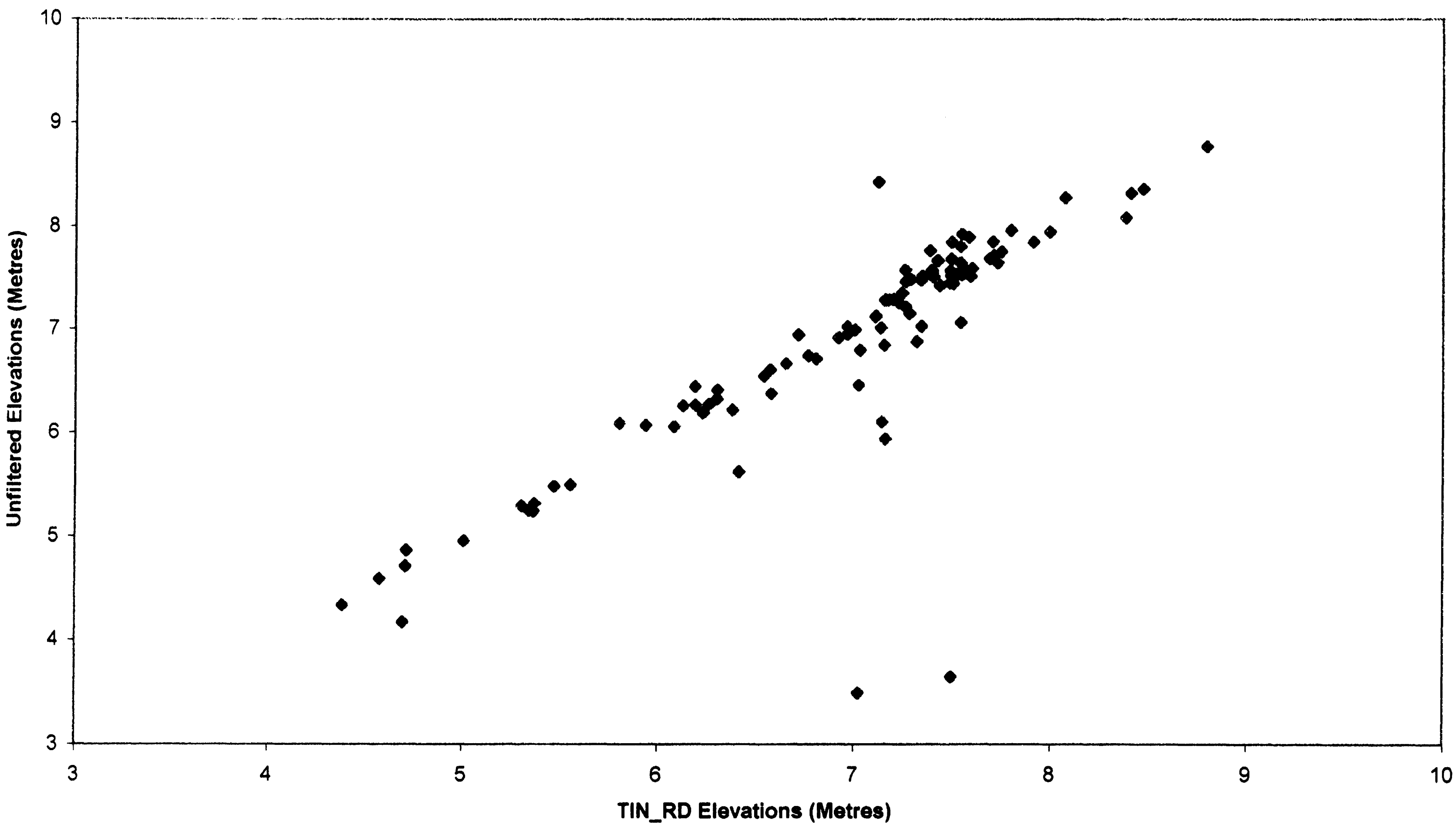
Scatter Plots


Caraquet 5x1 LPF Comparison
Unfiltered Elevations (Metres)
5x1 LPF Elevations (Metres)
10
9
8
7
6
5
4
3
3
4
5
6
7
8
9

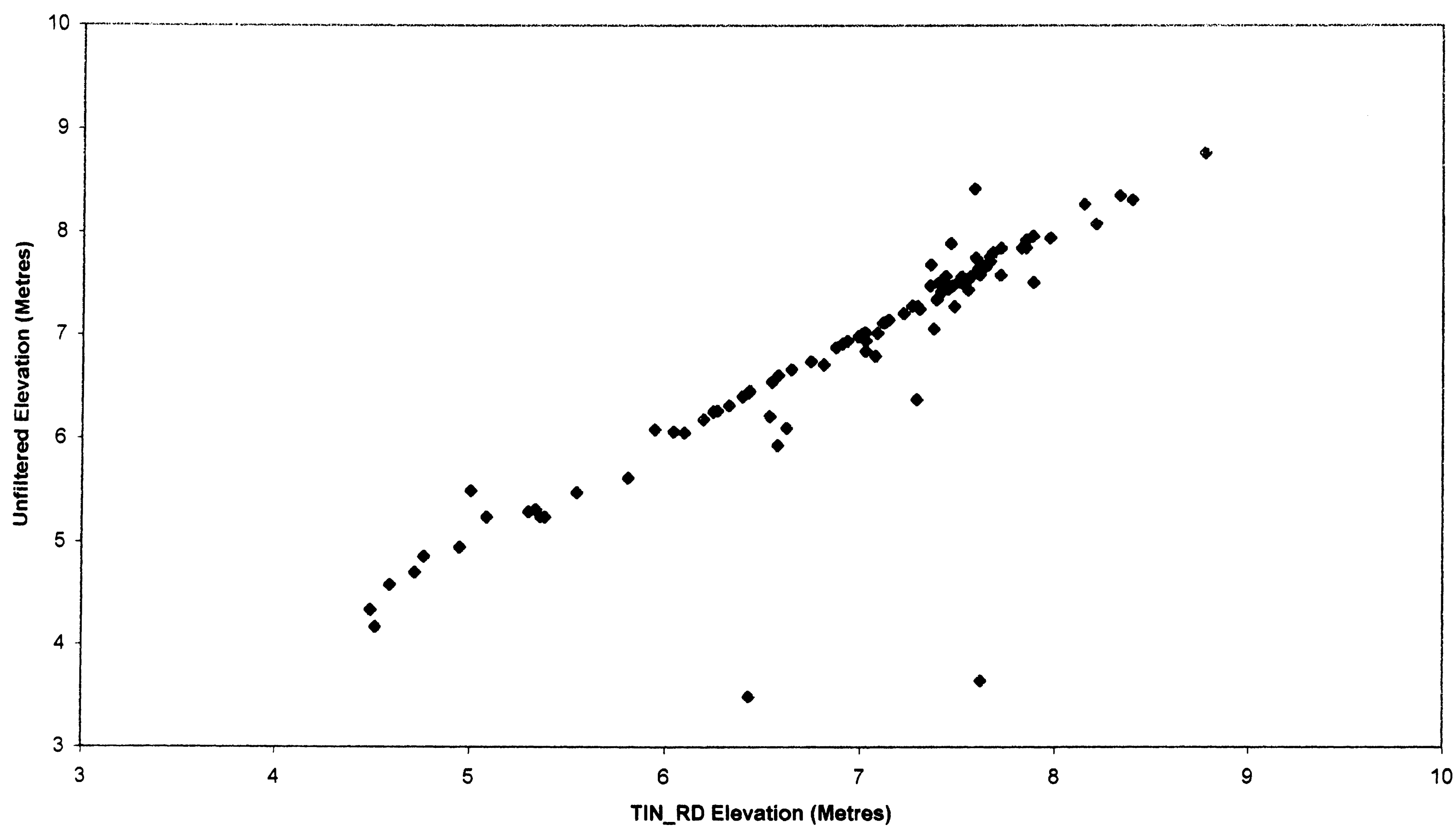


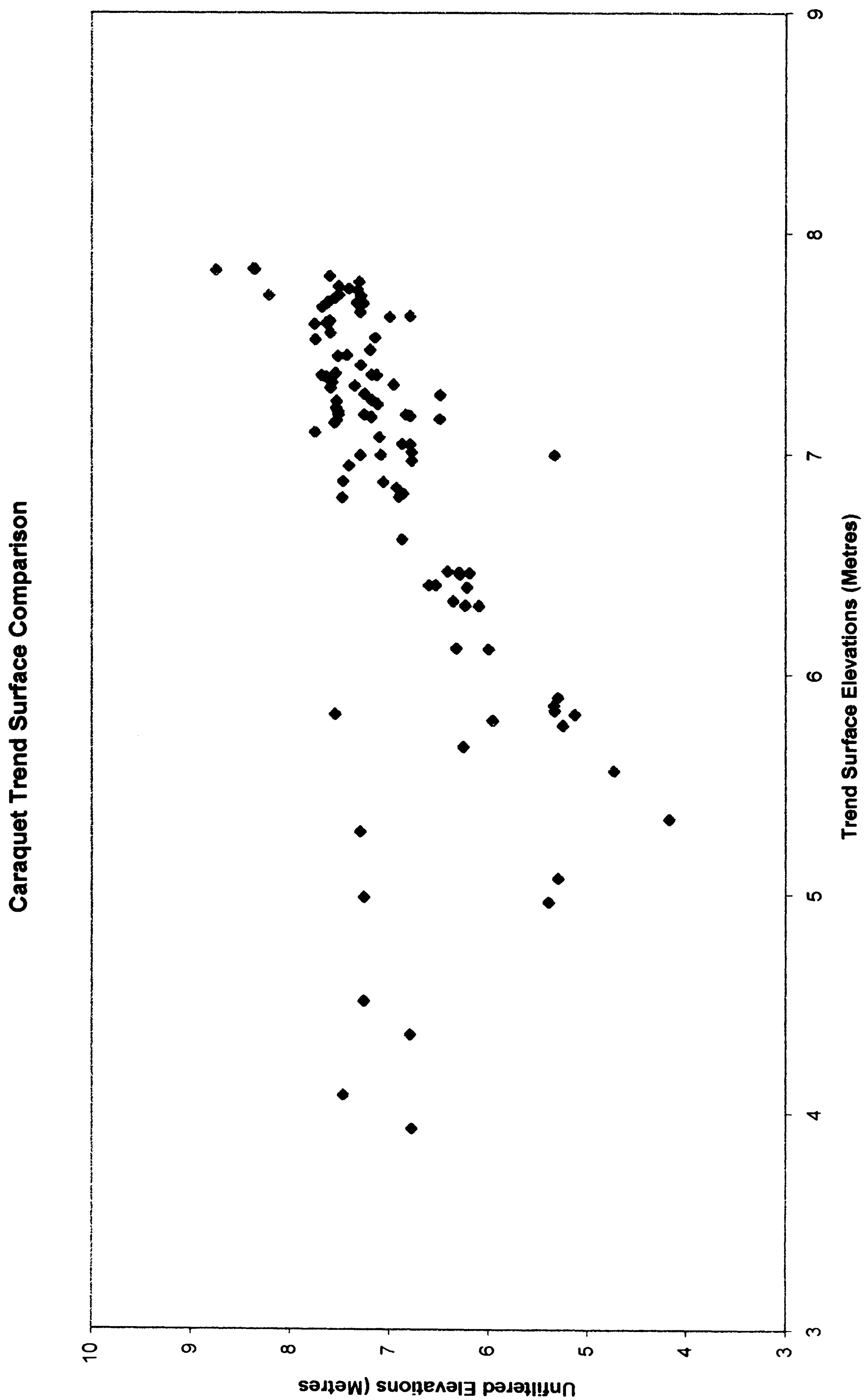
Caraquet Fourier Comparison
Unfiltered Elevations (Metres)
FTF Elevations (Metres)
10
9
8
7
6
5
4
3
3
4
5
6
7
8
9

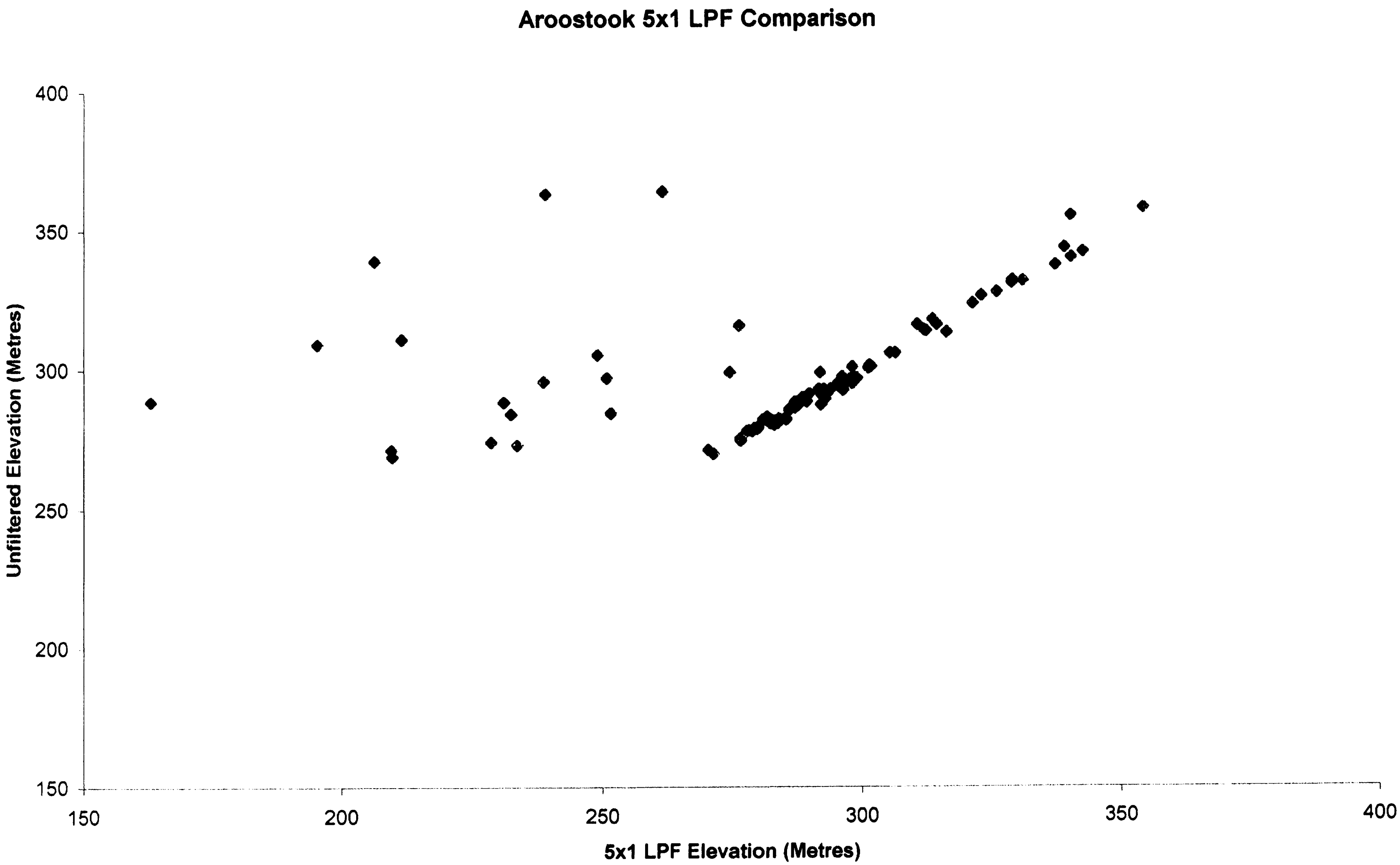
Caraquet TIN Random Denification Comparison - 2 Points per Original

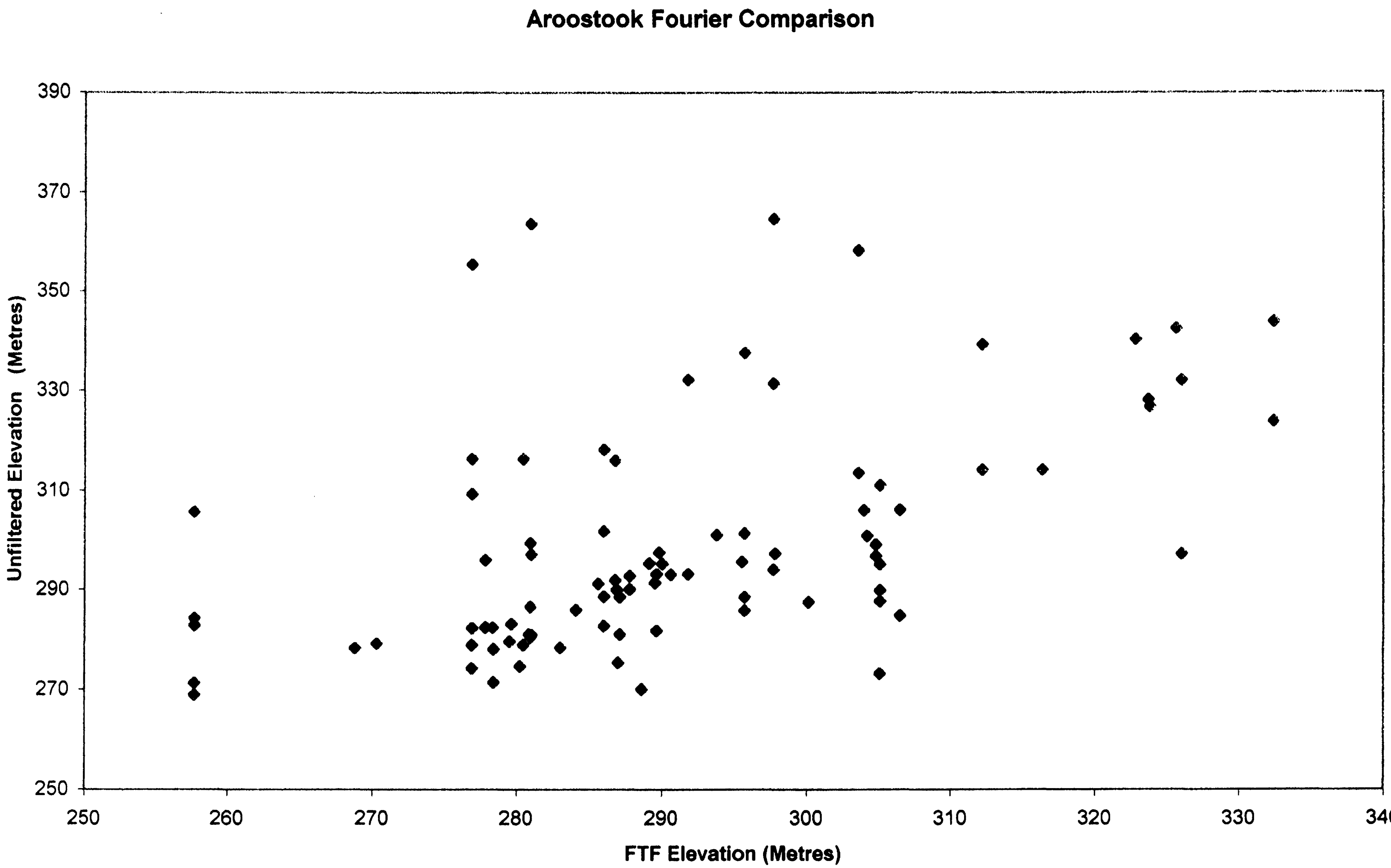


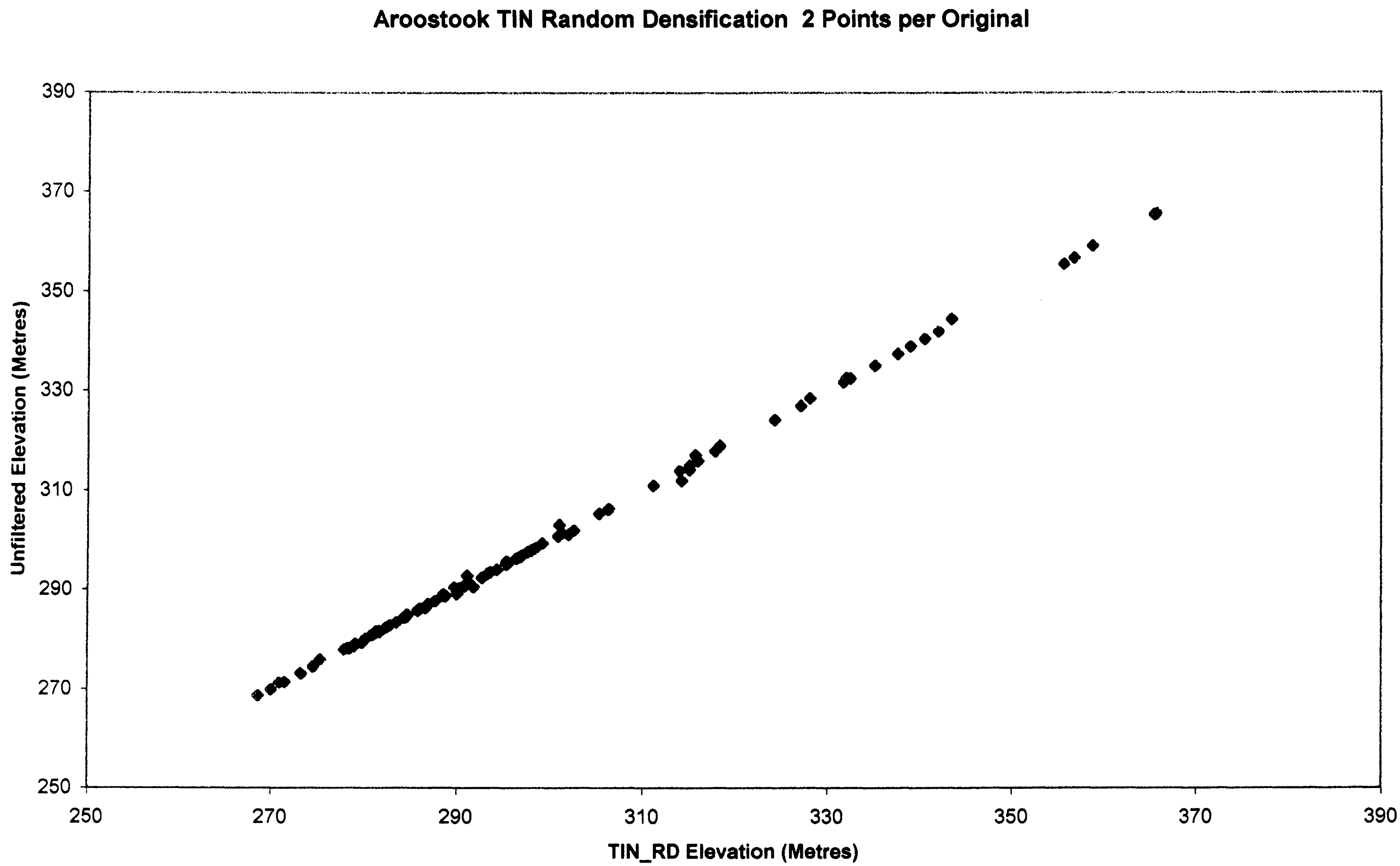
TIN Random Densification - 5 Points per Original



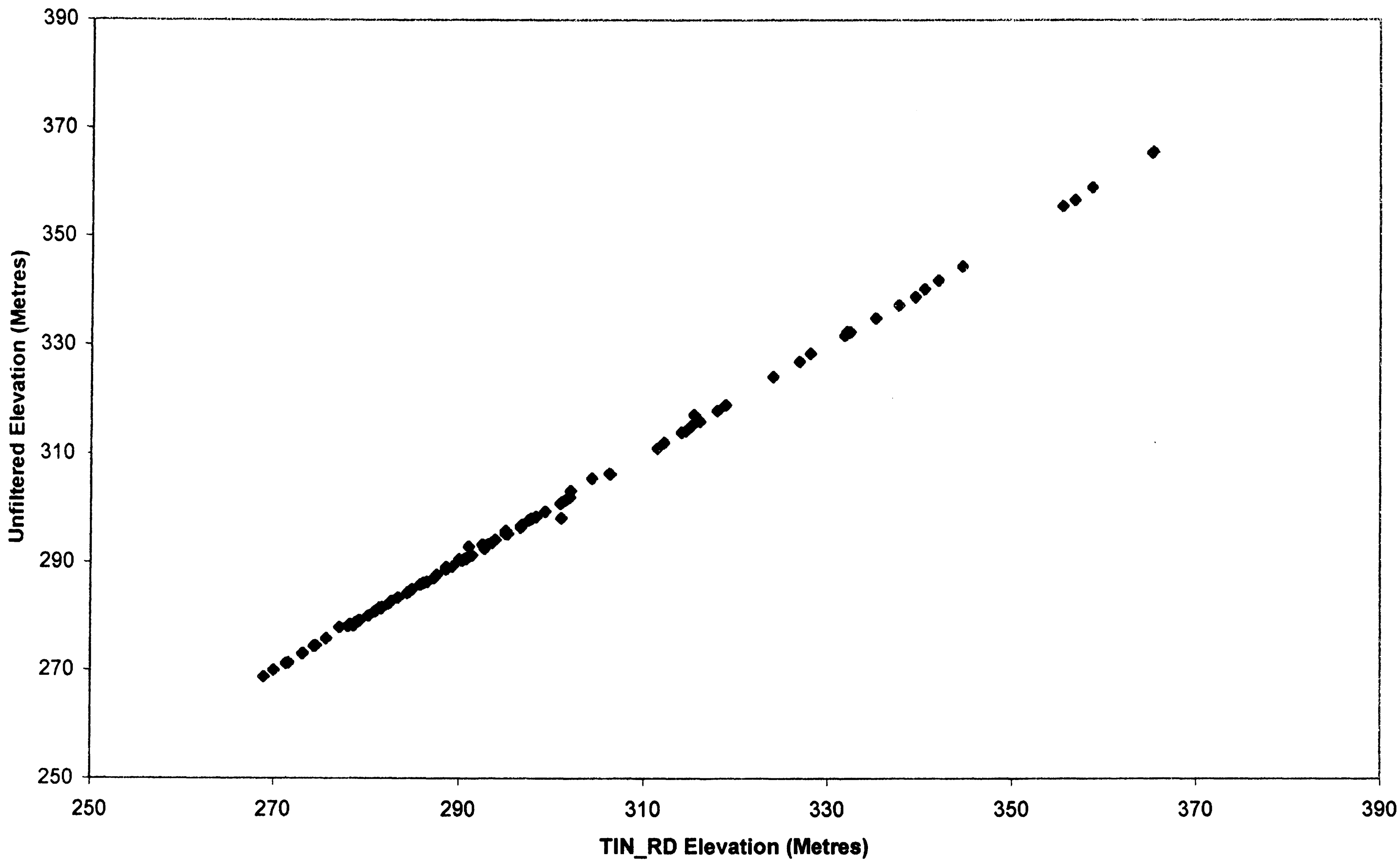

Caraquet Trend Surface Comparison
Unfiltered Elevations (Metres
10
9
8
7
6
5
4
3
Trend Surface Elevations (Metres)
3
4
5
6
7
8
9


Aroostook 5x1 LPF Comparison
400
350
300
250
200
150
Unfiltered Elevation (Metres)
150
200
250
300
350
400
5x1 LPF Elevation (Metres)


Aroostook Fourier Comparison
Unfiltered Elevation (Metres)
390
370
350
330
310
290
270
250
250
260
270
280
290
300
310
320
330
340
FTF Elevation (Metres)


Aroostook TIN Random Densification 2 Points per Original
Unfiltered Elevation (Metres)
TIN_RD Elevation (Metres)
390
370
350
330
310
290
270
250
250
270
290
310
330
350
370
390

Aroostook TIN Random Densification 5 Points per Original



APPENDIX H

Analysis: Phase II - Contour Plots

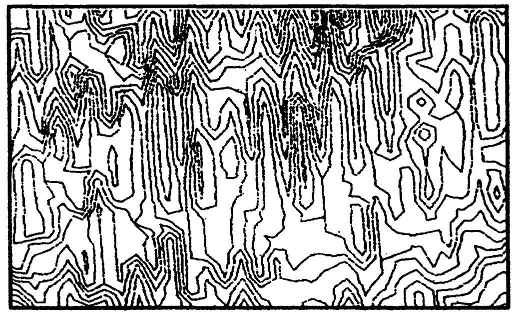


Image A: Contours generated from a TIN that is "Contaminated" with Ridging.

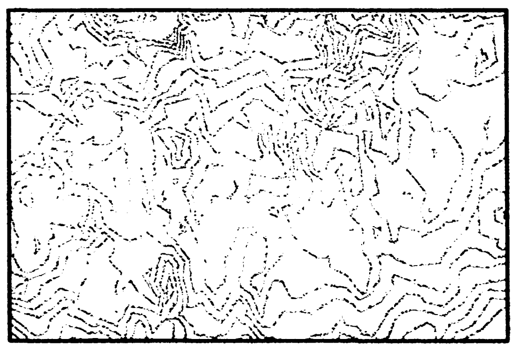


Image B: Contours generated from a randomly densified TIN.

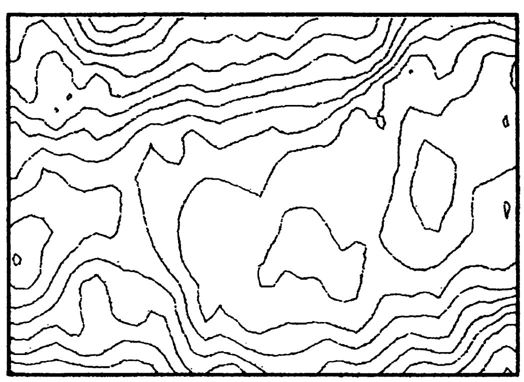


Image C: Contours generated from CTM Fourier Filtering.

Figure: Caraquet. 0.5m Contour Comparison

Image A: Contours generated from a TIN that is "Contaminated" with Ridging.

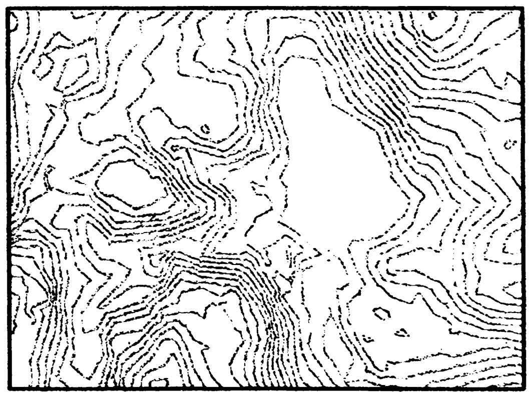


Image B: Contours generated from a randomly densified TIN.

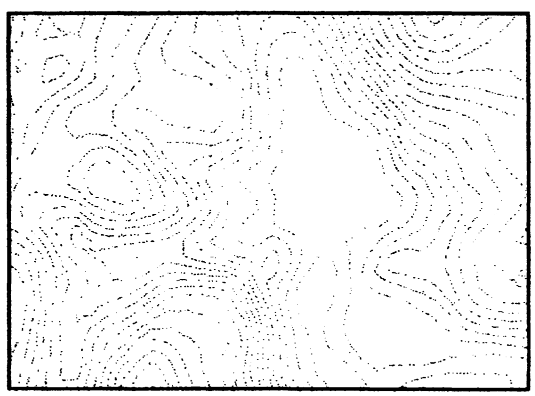


Image C: Contours generated from CTM Fourier Filtering.

Figure: Aroostook. 3.0m Contour Comparison

Image A: Contours generated from a TIN that is "Contaminated" with Ridging.

Image B: Contours generated from a randomly densified TIN.

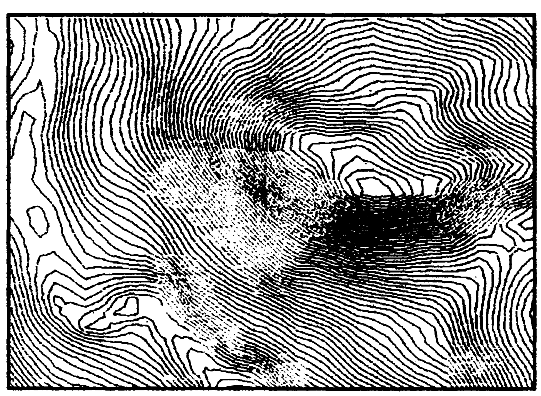


Image C: Contours generated from CTM Fourier Filtering.

Figure: Hayesville. 3.0m Contour Comparison

APPENDIX I

Analysis: Phase II - Hydrological

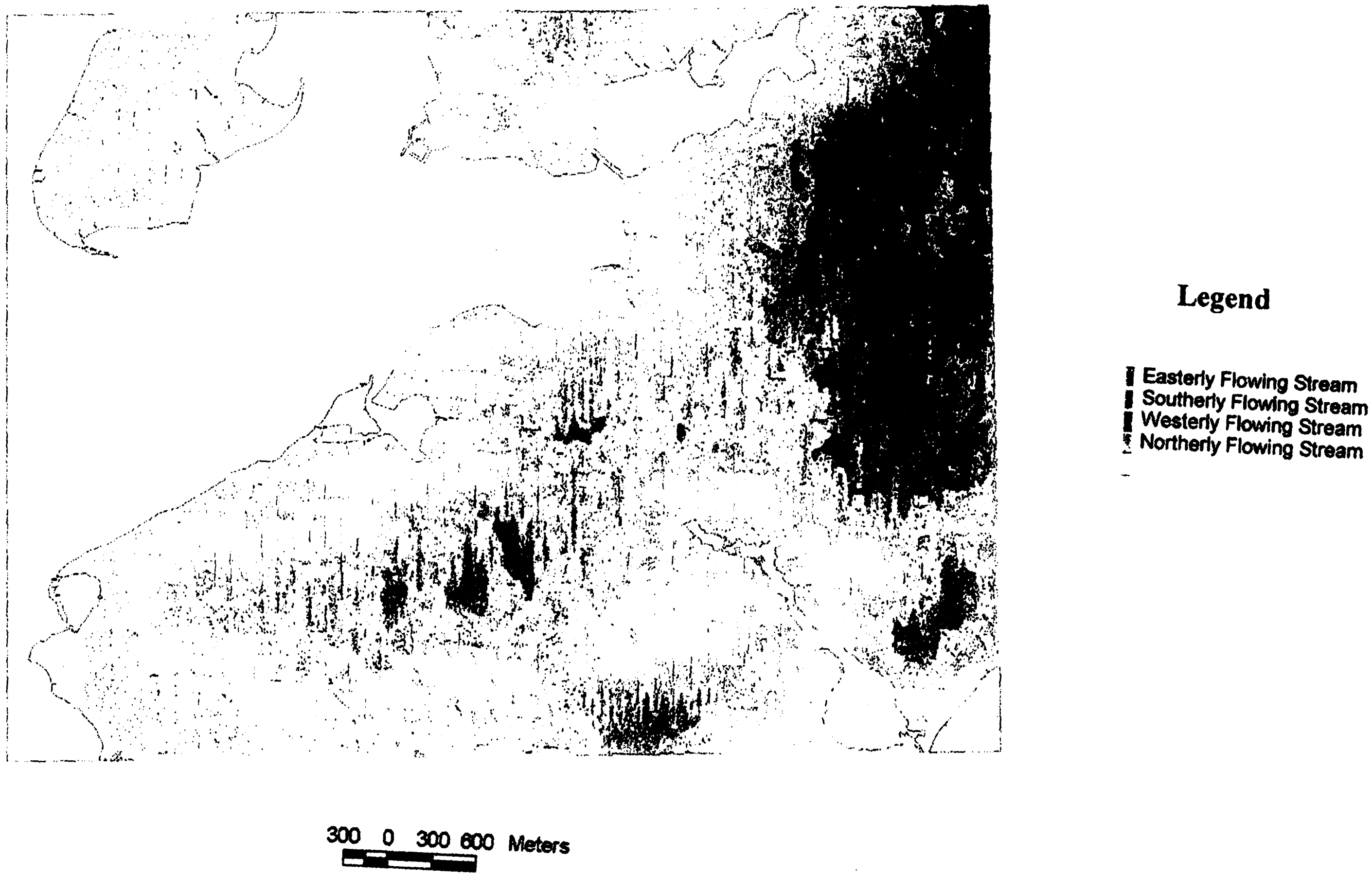


Figure: Hydrological Analysis
Caraquet: Unfiltered DTM

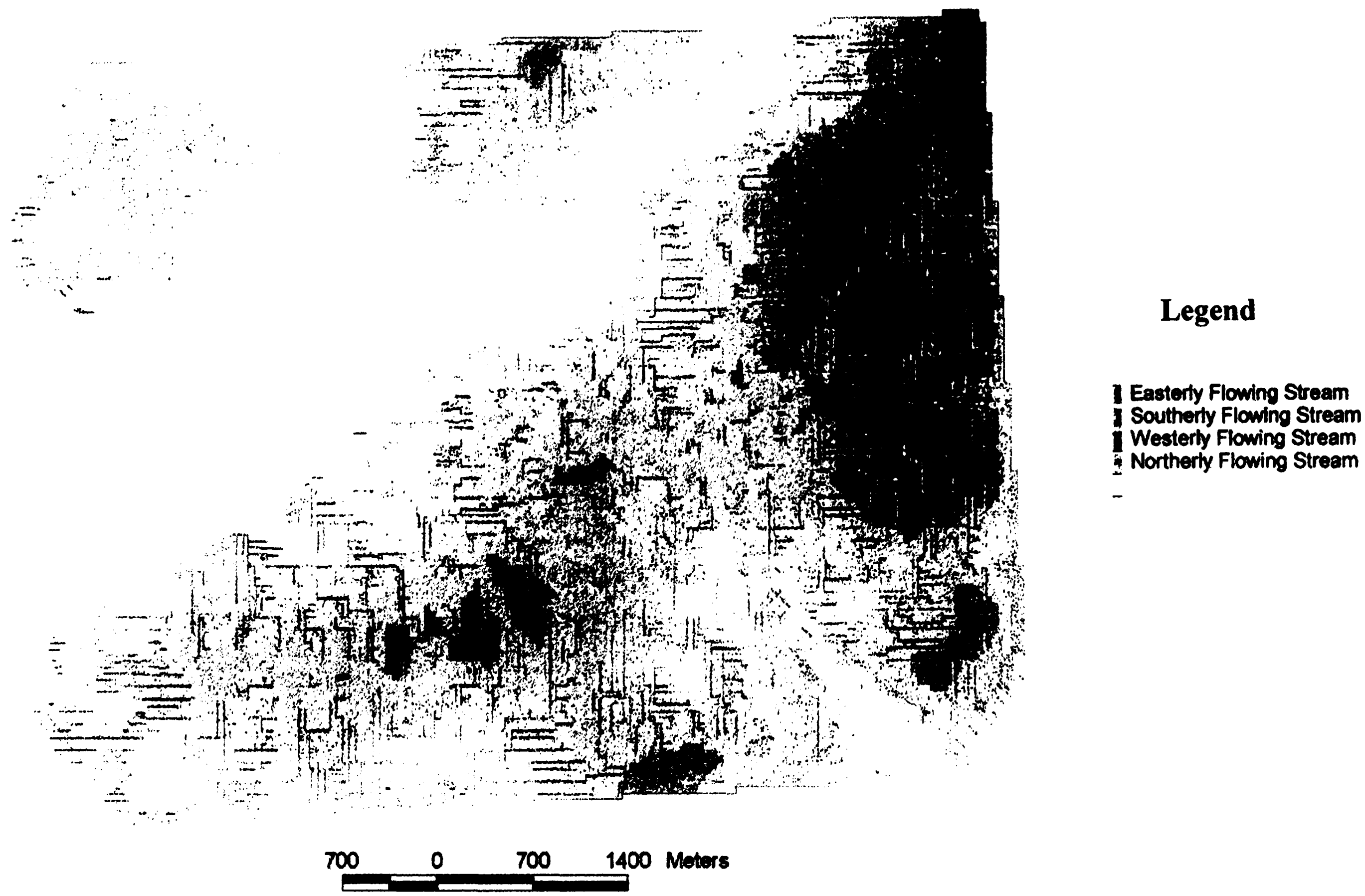


Figure: Hydrological Analysis
Caraquet: TIN Random Densification 10-2

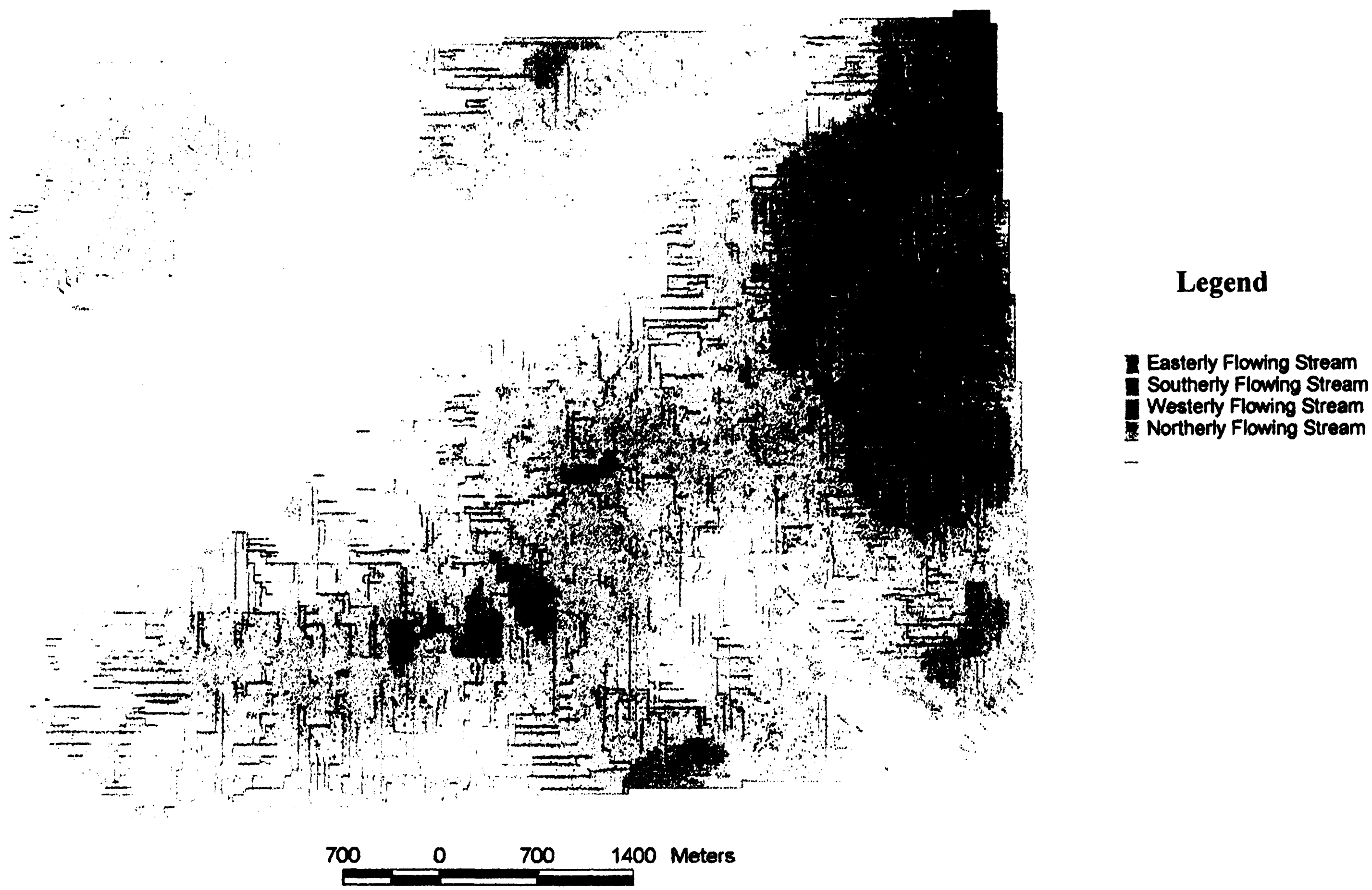


Figure: Hydrological Analysis
Caraquet: CTM Fourier Filtering

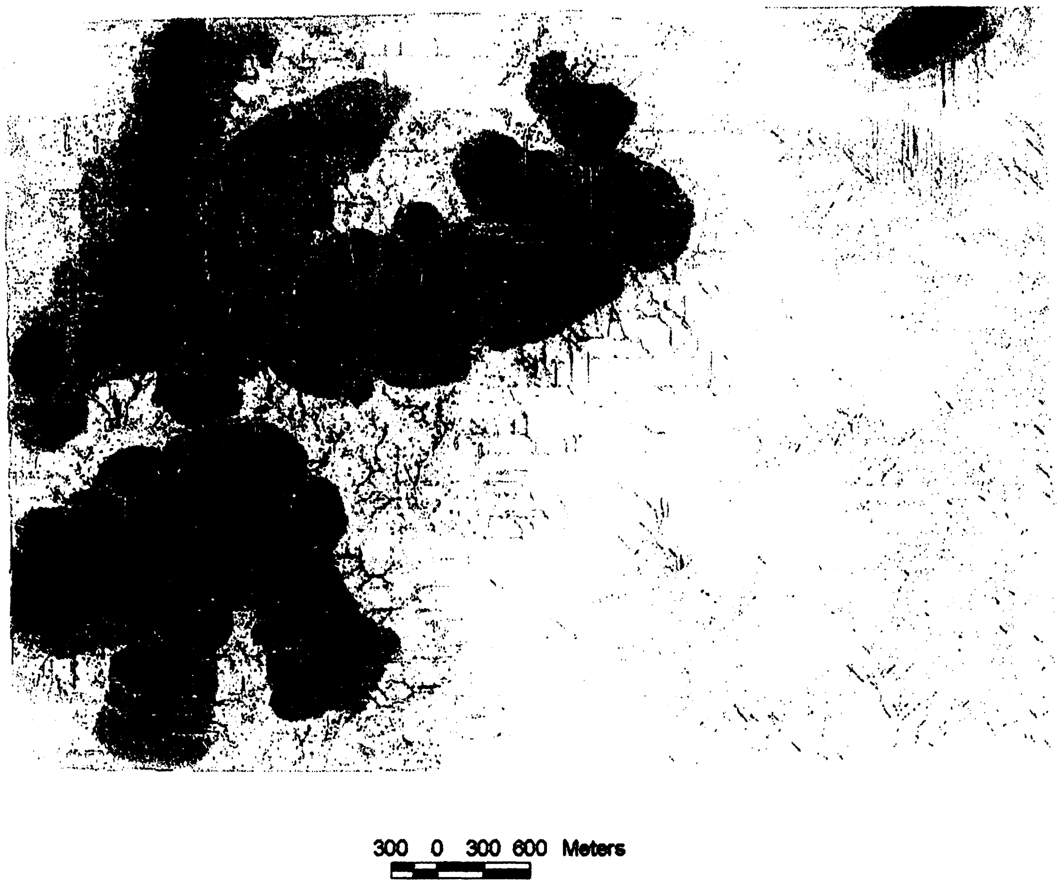


Figure: Hydrological Analysis
Aroostook: Unfiltered DTM

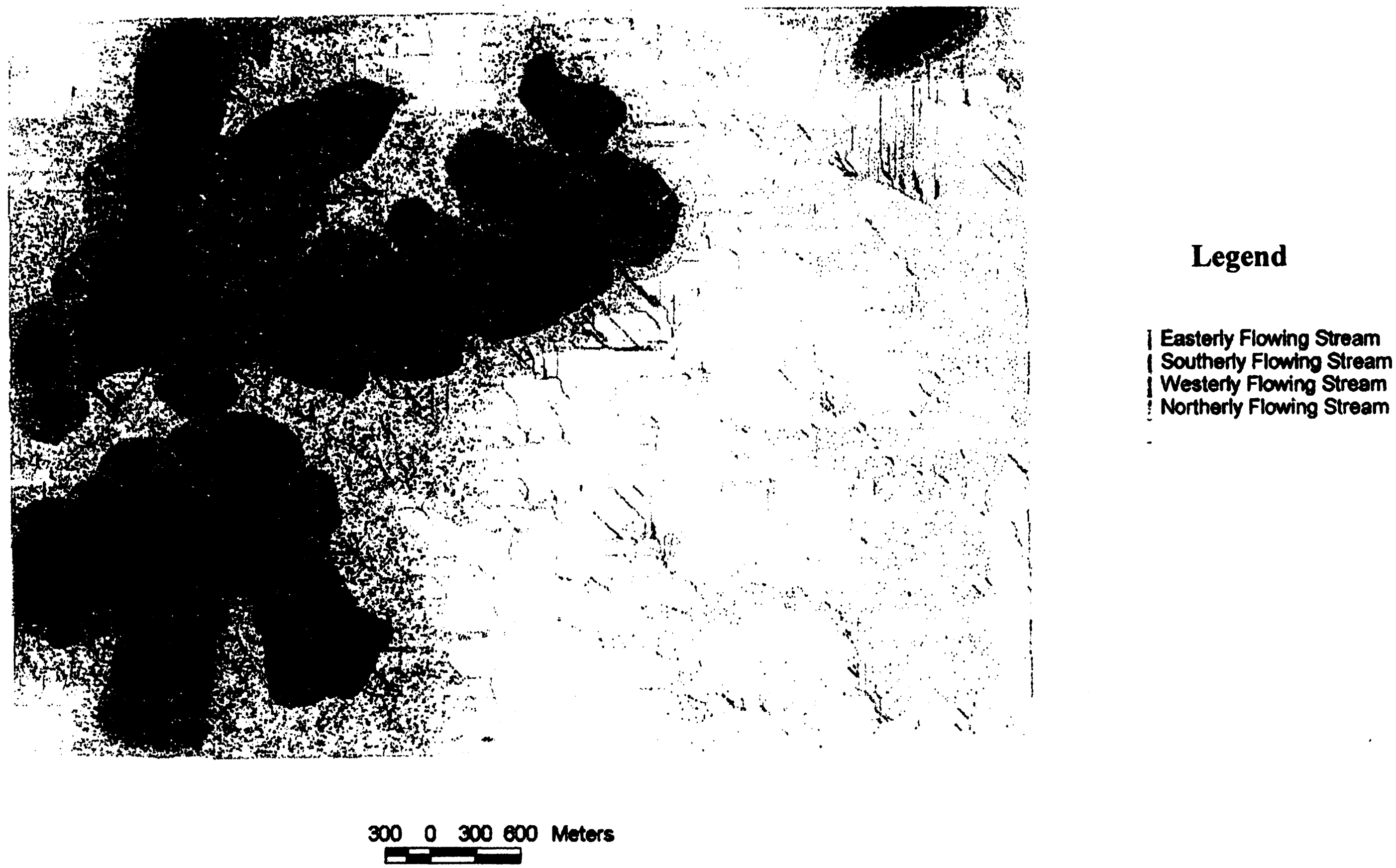


Figure: Hydrological Analysis
Aroostook: TIN Random Densification 10-2

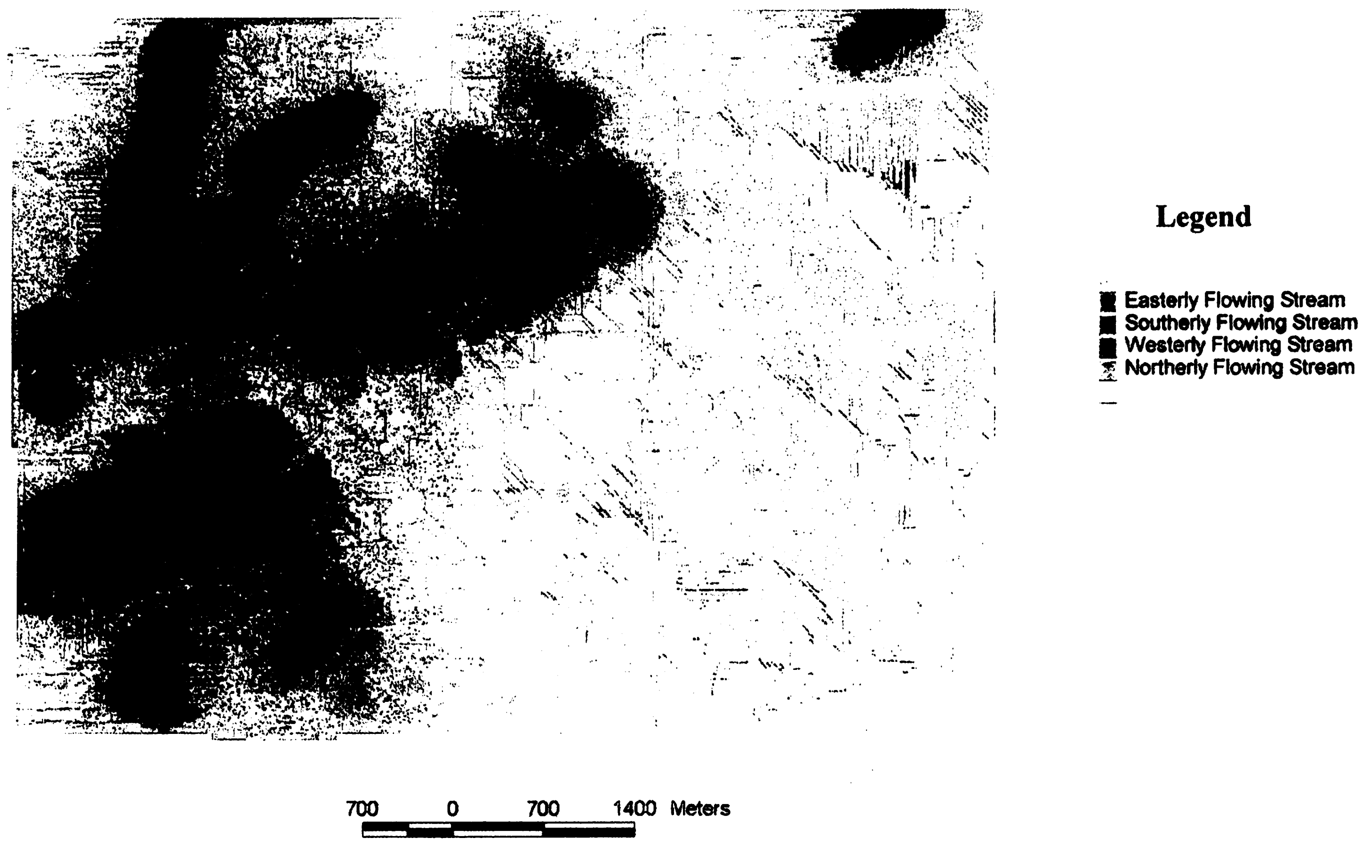


Figure: Hydrological Analysis
Aroostook: CTM Fourier Filtering

Figure: Hydrological Analysis
Hayesville: Unfiltered DTM

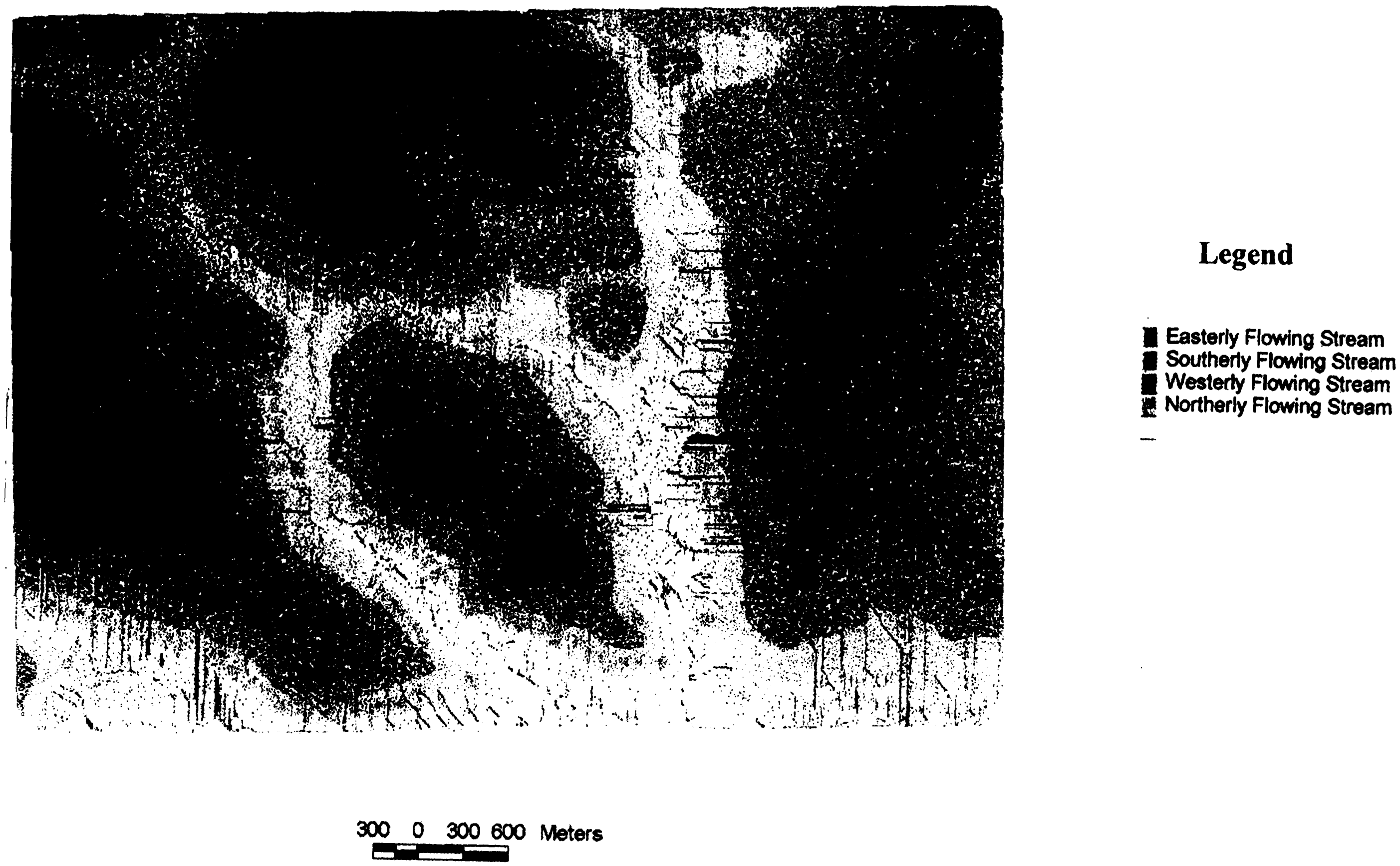


Figure: Hydrological Analysis
Hayesville: TIN Random Densification 10 -2

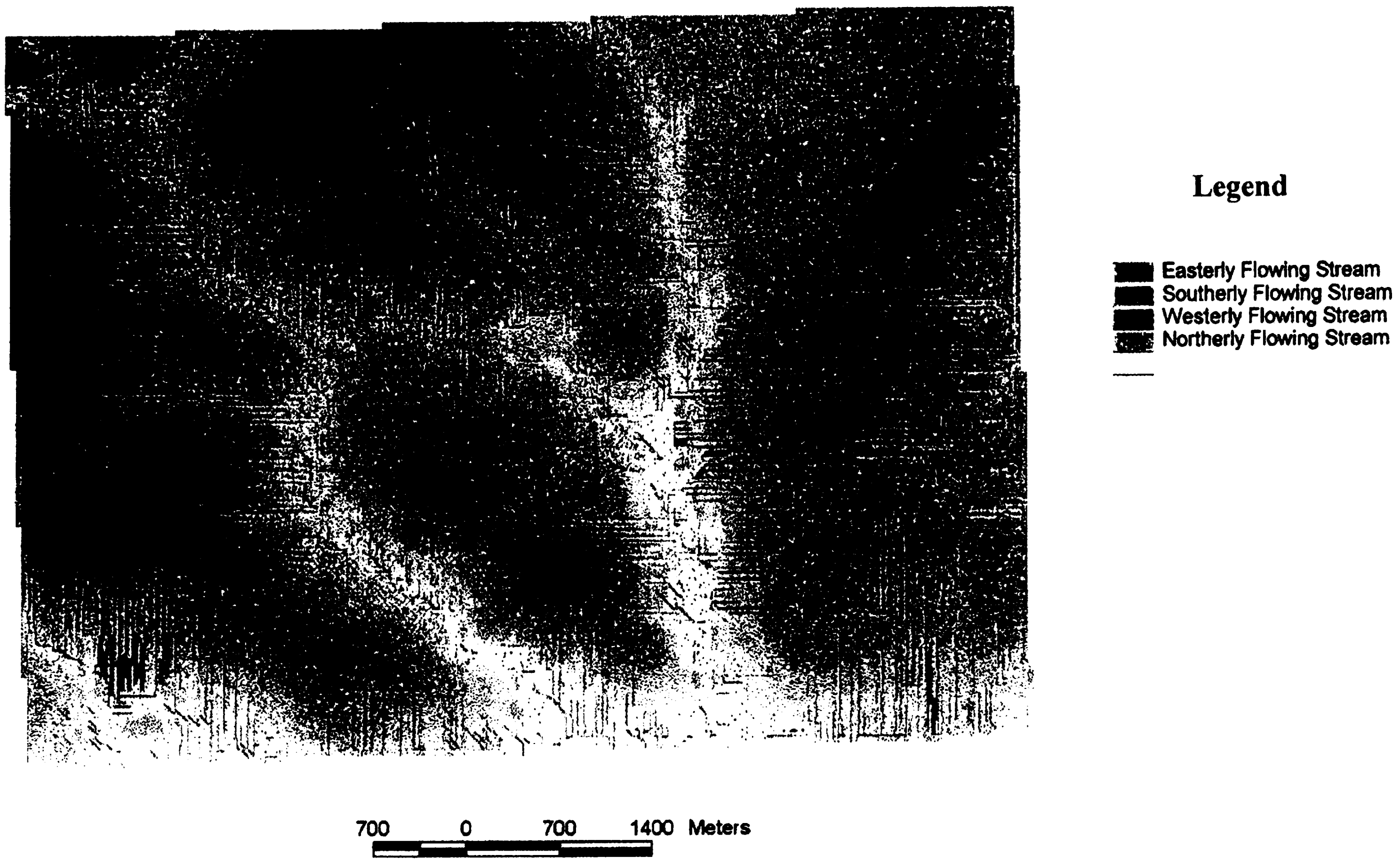


Figure: Hydrological Analysis
Hayesville: CTM Fourier Filtering

Vita

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Publications: Pegler, K., D. Coleman, and R. Castonguay (1999). "TIN Random Densification: A Process to Minimize the Ridging Phenomenon in DTMs." *Proceedings of the 1999 URISA Annual Conference*, Chicago, Illinois. (August 20-26) pp. 223-230.