THE ACCURACY OF DEFLECTION-LINES DERIVED FROM DIGITAL ELEVATION MODELS

by

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Abstract

Long-reaching skyline cable yarding systems have seen increased use within the British Columbia coastal forest industry. Deflection-line analysis, which estimates the maximum yarding distance and locates the harvest boundary, is the key component in planning for skyline systems. Traditional deflection-line analysis involves field surveys which may be very difficult to perform in the terrain associated with skylines. As an alternative, deflection-lines may be derived from Digital Elevation Models (DEMs). Concern regarding the elevational accuracy of the topographic forest planning maps used to create the DEMs has limited their use for deflection-line analysis. Better understanding of the magnitude and nature of elevational errors and their effect upon deflection-line analysis are needed before DEM-derived deflection-lines may be used with confidence.

This study was performed in cooperation with Canadian Forest Products Limited (Canfor) in Woss, British Columbia (B.C.). Deflection-line analyses were performed for DEM-derived deflection-lines to test for error in yarding distance estimates. Errors in yarding distance estimates for DEM-derived deflection-lines were caused by interactions between some or all of the following: the terrain shape (concavity/convexity), large elevational errors and their location on the deflection-line, and the deflection-line length. While a majority of yarding distance estimates from DEM-derived deflection-lines were not in error (70%), the erroneous estimates may result in costly planning errors.

Restricting the use of DEM-derived deflection-lines to the efficient pre-planning of field surveys could help avoid these mistakes.

A blunder was detected in one of the study cutblock maps. Distortions were discovered in the maps for two other study cutblocks where photogrammetrically derived and ground surveyed maps had been joined through rubber sheeting. While random error was detected in the analyses, systematic error appeared to contribute more to both the general level of elevational error and to the presence of large elevational errors. Different types of systematic error were detected, with at least some types evident in all of the deflection-line comparisons. Smoothing error was observed where terrain variation had been reduced or eliminated, and positional errors were the most common and influential systematic errors detected. The positional error of map features, and positional error introduced using traditional surveying methods, may also affect operational field surveying of deflection-lines, logging roads, and harvest boundaries. The presence of positional error and its subsequent effects upon harvest planning is either not known or is ignored altogether.

Detecting the presence of systematic error in topographic forest planning maps is the first step towards using DEMs confidently for deflection-line analysis. Further studies involving the effects of positional error on DEM elevational error will allow the DEMs to be predicted and subsequently accounted for. Advances in map creation, computers, and Geographic Information Systems will allow for the acquisition and manipulation of more accurate digital elevation data now and in the future.

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> I shall be telling this with a sigh
> Somewhere ages and ages hence:
> Two roads diverged in a wood, and I -
> I took the one less travelled by,
> And that has made all the difference.
>
> Robert Frost - *The Road Not Taken*

> Of what avail are forty freedoms without a blank spot on the map?
>
> Aldo Leopold - *A Sand County Almanac*

1 Introduction

Changing social, economic and terrain conditions have led to increased utilization of long-reaching skyline cable yarding systems within the British Columbia coastal forest industry. These systems present new challenges for operational harvest planners. Deflection-line analysis, used to check for clearance between suspended logs and the ground, is the foundation of the planning process and especially critical for skyline planning (Conway 1982). Deflection-line surveys become more difficult when dealing with the long yarding distances and rough terrain associated with skyline systems. Both the effectiveness and the productivity of the planning process may suffer. Also, adequate clearance is generally more critical for skyline systems than conventional systems such as highlead and grapple yarders.

The prospect of using Digital Elevation Models (DEMs), pseudo-three dimensional representations of the terrain, for deflection-line analysis had been suggested as early as 1974 (Burke 1974). Young and Lemkow (1976) developed a Digital Terrain Simulator (a DEM) that could be used for many aspects of forest operations planning, including deflection-line analysis. Limitations with speed and storage capabilities of the desktop computers used by remote forest operations had prevented the use of such models at that time. Too often these limitations resulted in a compromise of either the accuracy of the data and/or the integrity of the models used to manipulate the data.

These conditions persisted until the rapid improvements in the abilities of personal computers in the late 1980s. Coincident with these improvements came the increasing sophistication of Geographic Information Systems (GIS), computerized mapping and analysis systems. Integrated DEMs and GIS would allow deflection-line analysis to incorporate relevant information from the GIS database. This combination could help meet the increasing challenge for better planning for forest operations.

While personal computer limitations have been reduced, concern regarding the elevational accuracy of the source data, primarily large scale topographic forest planning maps, continues. Quantification of elevational accuracy is necessary before a DEM may be used confidently for deflection-line analysis. If the accuracy is within acceptable levels, then DEMs may be used. If the level of DEM accuracy is unacceptable then a basis is needed on which to set standards for the creation of suitable elevational data. If a technique can be developed to rectify or at least quantify and classify this elevational error, more planning would be possible using DEMs.

This study was initiated by Canadian Forest Products Limited (Canfor) in Woss, British Columbia (B.C.). Canfor wished to assess the feasibility of using DEMs, developed from their 1:5000 scale topographic planning maps, as tools for deflection-line analysis. Field surveyed deflection-lines were compared with deflection-lines derived from the same locations on DEMs. Deflection-line analyses were performed for each pair to see if the yarding distance estimate for the DEM-derived deflection-line was influenced by elevational error. The elevational error between paired points on the field surveyed and

DEM-derived deflection-line were quantified and analyzed. The nature and potential causes of the elevational error were investigated, analyzed, and discussed. Recommendations have been made regarding the best approach to using existing topographic maps, as well as the acquisition of new elevation data, for deflection-line analysis.

2 Objectives

This study investigated the elevational accuracy of deflection-lines derived from Digital Elevational Models (DEMs). The DEMs were developed from large scale topographic forest planning maps. Specific objectives were:

1) to assess the accuracy of yarding distances estimated from DEM-derived deflection-lines;

2) to quantify the level of elevational error of DEM-derived deflection-lines;

3) to investigate the nature and potential causes of the elevational error of the DEM-derived deflection-lines;

4) to develop recommendations for analyzing elevational error in DEM-derived deflection-lines, which are applicable to other maps, DEMs, and geographic locations;

5) to develop recommendations for the best use of DEM-derived deflection-lines, including recommendations for minimizing or predicting the systematic error which affects the elevational error of the DEM-derived deflection-lines; and

6) to develop recommendations for acquiring and using new elevational data for DEM-derived deflection-line analysis.

3 Background and Literature Review

3.1 Operational Harvest Planning

3.1.1 Terminology

A cutblock is the smallest individual unit in operational harvest planning. A cutblock is accessed by a road or roads, which allow access for yarding equipment, logging trucks, and logging crews. A landing is a widening in the road, where the road is more or less level and the skyline yarding machine has the best access to the logs in the cutblock. Yarding is the process of transporting logs from where they are felled within the cutblock, to the landing, where they are loaded onto logging trucks. The path the logs follow while being yarded is called a yarding road. The area yarded from one individual landing is called a setting, and several yarding roads will usually be needed to reach all of the logs within that setting. One cutblock may contain several settings, as multiple landings are often needed for yarding the entire cutblock (Figure 1).

3.1.2 Skyline Yarding Systems

Operational harvest planning has become more demanding for coastal forest operations in British Columbia. Two major interrelated forces have driven this change. The first is the shift of harvesting into steeper, more rugged terrain. The second stems from environmental concerns regarding the high densities of roads and ground disturbance

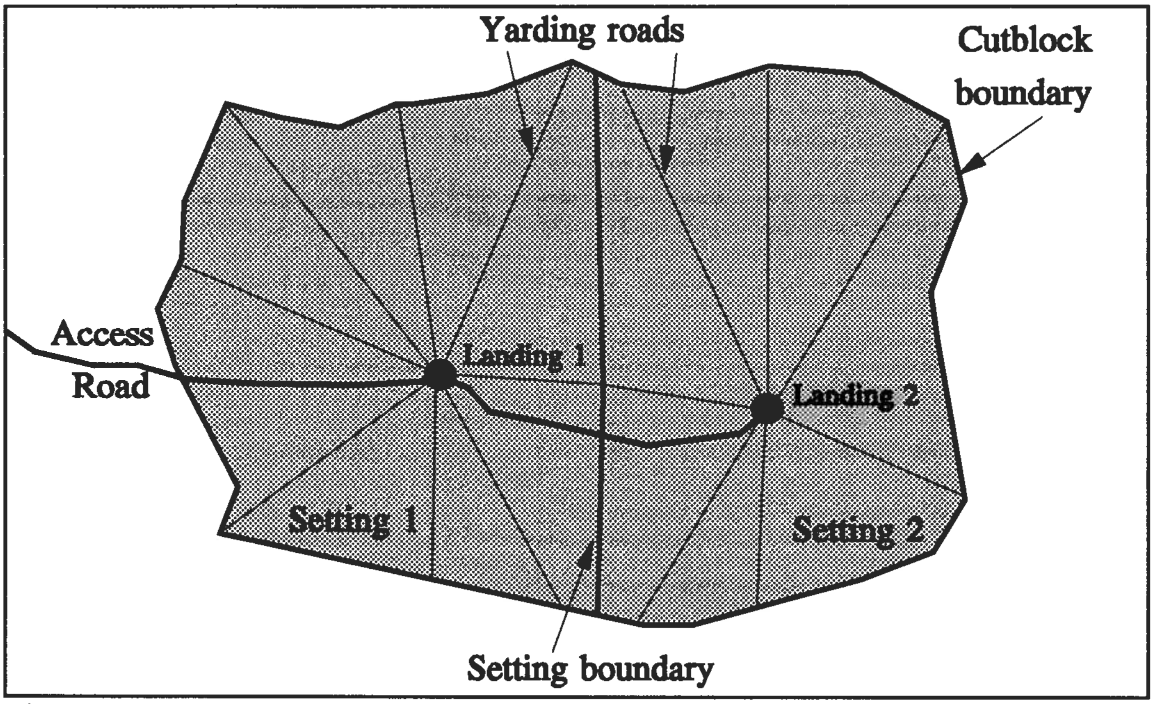


Figure 1 Cutblock design showing settings, landings and yarding roads.

associated with conventional cable yarding systems (Sauder *et al.* 1987). New, more restrictive plans require the use of alternative harvesting systems that reduce these and other detrimental impacts of conventional yarding. For these reasons, a number of British Columbia forest companies have acquired long-reaching, skyline cable yarding systems. Skyline systems can help alleviate these problems while maintaining an acceptable level of productivity (Sears 1991, McNeel *et al.* 1991, Chittick 1991).

A skyline is a wire rope suspended between two or more points (Conway 1982). The skyline yarding system uses a carriage which moves along a skyline. This provides full clearance for logs when they are yarded to the landing (Figure 2). A skyline system can avoid dragging logs on the ground during yarding which other conventional cable

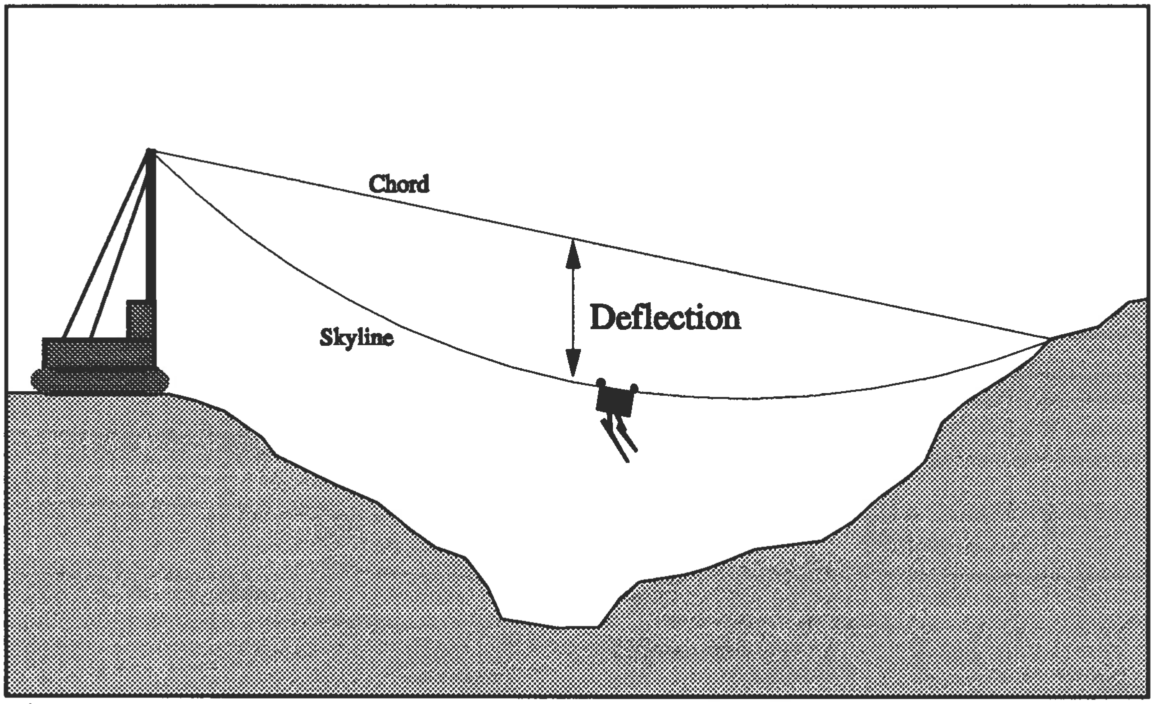


Figure 2 Deflection of carriage below chord.

systems (highlead and grapple yarder) cannot. Fully suspended logs minimize soil and site disturbance and concurrently reduce damage to logs and equipment. These disturbances have been linked to soil erosion and landslides in sensitive areas (Sauder *et al.* 1987). The skyline system also offers considerable flexibility for meeting other harvesting objectives of protecting environmentally sensitive areas. For example, many cutblocks contain creeks with critical riparian wildlife habitat. With the full suspension capability of the skyline system, suspended logs may be lifted over standing timber left to protect this habitat.

The long reach capabilities of the skyline system reduce the need for roads, particularly in sensitive mid-slope areas with unstable soils (Sauder *et al.* 1987, Hemphill 1991).

Road failures and subsequent landslides from mid-slope roads have been a major source of controversy between the forest industry and the environmental movement.

Public concern regarding the aesthetic aspects of forest harvesting has prompted the Ministry of Forests to increase the emphasis on Visual Quality Objectives (VQO), a measure of the alteration of the landscape due to human activity (Winkle 1992, Preus 1992). Mid-slope roads are particularly undesirable since they create a stark contrast to the natural surroundings. Slides caused by the construction of these roads exacerbate the problem.

3.1.3 Deflection and Deflection-line Analysis

The one condition that is an absolute necessity for skyline systems in any situation is deflection (Conway 1982). Deflection is the vertical distance, or sag, between the carriage and an imaginary chord connecting the top of the skyline supports at either end of the skyline (Figure 3). The greater the deflection the heavier the payload of logs that the skyline system can support. This usually equates to higher production and lower yarding costs. As well, when dragging logs on the ground is avoided, site damage and equipment damage is minimized.

Skyline systems are most effective for yarding over long distances and in rugged terrain. For these same situations, it may be very difficult to obtain adequate deflection necessary for the desired payload of logs. The most important aspect of planning for

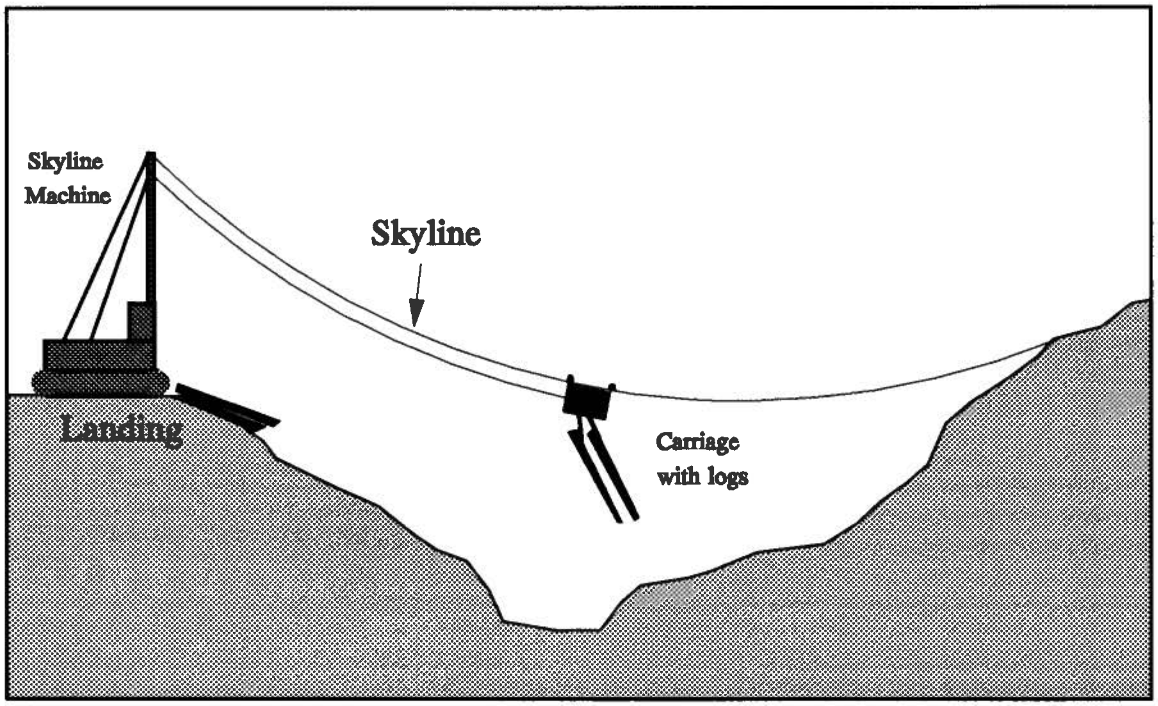


Figure 3 Skyline yarding system with carriage and payload of logs.

skyline systems is performing deflection-line analyses. Deflection-line analysis uses a profile of the ground (a deflection-line) to determine if there is sufficient clearance of payload at the required deflection (Figure 4). This process is also an integral component in determining the maximum possible yarding distance which in turn dictates the harvest boundary location. Insufficient clearance at a critical point on the deflection-line will prevent achievement of the required deflection, and yarding will not be possible beyond that point.

Deflection-lines are obtained through surveys run in the proposed location of the skyline yarding roads. Stations, key points where elevations are determined, are situated at significant changes in the slope (10% or more) along the deflection-line survey. The

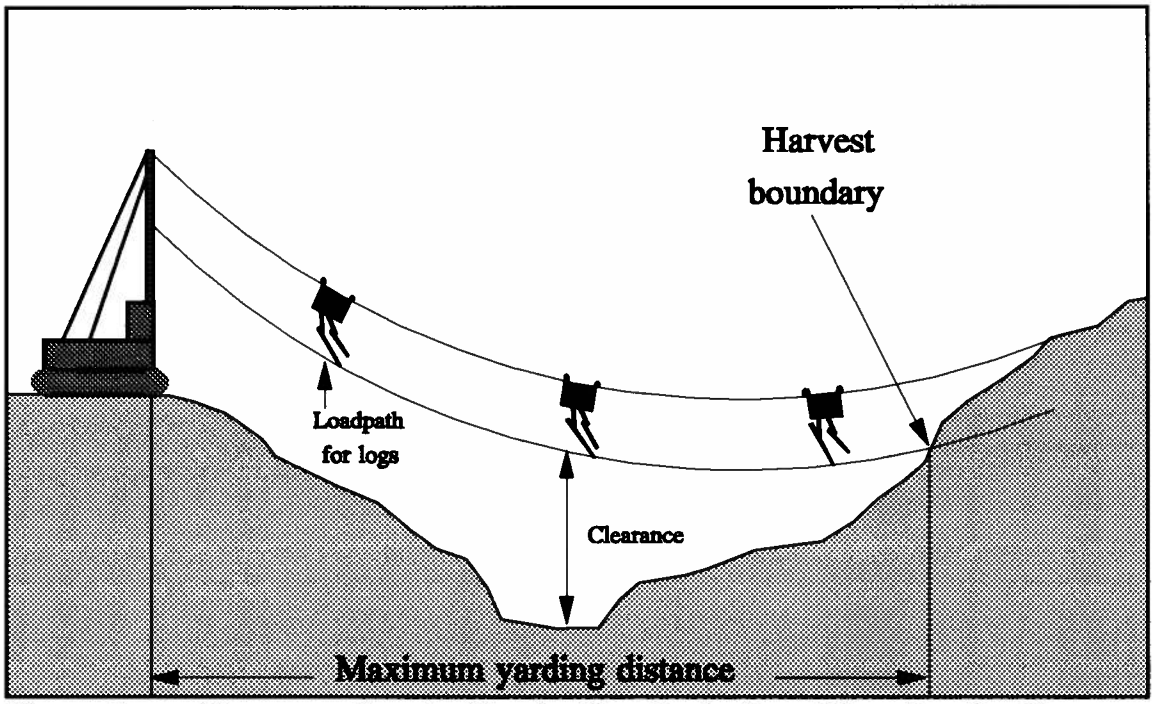


Figure 4 Clearance of payload load-path and selection of boundary location.

elevations of these stations are the most critical for clearance.

Deflection-line analysis may be performed by manual or automated methods. While the manual approach is more common, it is also very simplistic and restricted. Deflection-line analysis works best as an interactive process where several different combinations of road, landing, and boundary locations may be investigated to find the best overall solution. When using manual, field-based methods, the number of different combinations which may be analyzed is limited, especially for skyline cutblocks, and overall planning consequently suffers.

Automated methods, which require computers, may be used to perform very complex and comprehensive analyses. These automated methods may be combined with deflection-lines derived from a Digital Elevation Model (DEM). This extremely rapid approach to deflection-line analysis allows for a complexity of planning not possible using manual methods. While automated deflection-line analysis should never replace field surveys, it should be used to pre-plan those surveys, ensuring that the most critical areas are checked in the field. This is becoming essential as pressure for better forest practices increases.

3.2 Digital Elevation Models

3.2.1 Terminology

Digital Elevation Models (DEMs) are pseudo-three dimensional computer models which Burrough (1986) defined as any "digital representation of the continuous variation of relief over space." Webb (1990) described them as a "representation of a terrain surface consisting of X, Y, Z coordinates stored in digital form." The term Digital Terrain Model (DTM) is often used synonymously with DEM. Burrough (1986) distinguished the two by specifying that DEMs contain only elevational data and that the word terrain specifies additional information (slope, aspect) about the landscape. The term DEM has been used here since this study dealt solely with elevational data.

There are two distinct types of DEMs: the Triangulated Irregular Network (TIN) and the Regular Rectangular Grid (Grid). It is common practice to refer to DEMs and Grids as one and the same. From this, a comparison between DEMs and TINs is often made incorrectly when the latter is actually a specific example of the former.

3.2.2 Elevational Data Sources

Photogrammetrically-measured contour maps are the most common form of modern topographic maps (Petrie 1991). An overlapping pair of aerial photographs, called a stereoscopic pair, is used to determine the elevation of ground features. This is possible because of stereoscopic vision, which allows an observer to gain the impression of depth when viewing an object from two different viewpoints (Wolf 1980). This is the same principle by which human eyes perceive the depth of an object. The apparent displacement of the object is called parallax, and the parallax difference between the bottom of an object and the top may be used to calculate the height of that object (Avery and Berlin 1985).

Photo interpretation is the "detection, identification, description, and assessment of significance of objects and patterns imaged on a photograph" (Wolf 1980). A photo-interpreter may use parallax differences to calculate the height of trees on a stereoscopic pair of aerial photographs (Loetsch and Haller 1964). The same principles are utilized in a more complex process to determine ground elevations at different points on the photographs. When the area of concern is heavily forested it may be extremely difficult to see the ground (Loving 1980). Openings where the ground is visible are used to measure both the ground elevation and the height of the adjacent trees. These tree heights are then used to estimate ground elevations where the ground is not visible.

Aerial photography can be a relatively inexpensive method to obtain relevant data for topographic mapping over a large area. The area to be mapped is flown in a series of roughly parallel flight lines while vertical photographs are taken of the surface. Photographs are taken so that they overlap approximately 60 percent in the direction of the flight lines and 20 to 30 percent between flight lines (Avery and Berlin 1985). This provides necessary stereoscopic coverage for the entire mapping area.

A photo-interpreter may produce either analog or digital topographic maps from aerial photographs. Analog maps are made directly from the aerial photographs without digital information being stored, but maps must subsequently be converted to digital form if they are to be used for automated deflection-line analysis. This process is tedious, time consuming, expensive, and may introduce significant error into the digital map.

This undesirable conversion process may be avoided altogether using recent techniques which allow digital elevation data to be digitized directly from aerial photographs. This approach has gained strong support with the advent of Geographic Information Systems and DEMs that are supported on powerful new personal computers.

3.2.3 The Regular Rectangular Grid

The regular rectangular grid is the most common and most readily available form of DEM (Burrough 1986). It consists of a regular rectangular grid containing Cartesian coordinates in three-dimensions (Peucker *et al.* 1976). While there are many sources of data from which grids may be derived, digitized topographic contour maps are traditionally the most commonly used (Maedel and Gaudreau 1989). The British Columbia government has recently created the Terrain Resource Information Mapping (TRIM) digital terrain maps. While these maps were created digitally and with a modern coordinate referencing system, they were also created at a scale of 1:20000 and with a spot height densities appropriate for 20-metre contour intervals. The large scale (1:5000) topographic contour maps used in B.C. coastal forest planning typically have contour intervals of 5 to 10 metres. It is unlikely that the TRIM maps could meet the accuracy of these topographic planning maps.

Grid DEMs are created by mathematically overlaying a grid of points onto the digital contour map and interpolating the grid point elevations from the neighbouring contours (Maedel and Gaudreau 1989). The many different algorithms used for interpolating these points tend to 'smooth out' important terrain features such as peaks, ridgelines, gulleys, rockbluffs, and saddles. If these terrain features are not properly represented, error in yarding distance estimation may occur during deflection-line analysis. Figure 5 shows a scenario where a peak and adjacent ridge, indicated by spot elevations, were not properly represented by regular grid points. Grid elevations are interpolated from neighbouring contour and spot elevations and a weighting algorithm may be used to give more emphasis to the closest elevations. Unless a grid point falls directly on the spot elevation, the feature represented by the spot elevation will not be properly represented by the interpolated grid elevations.

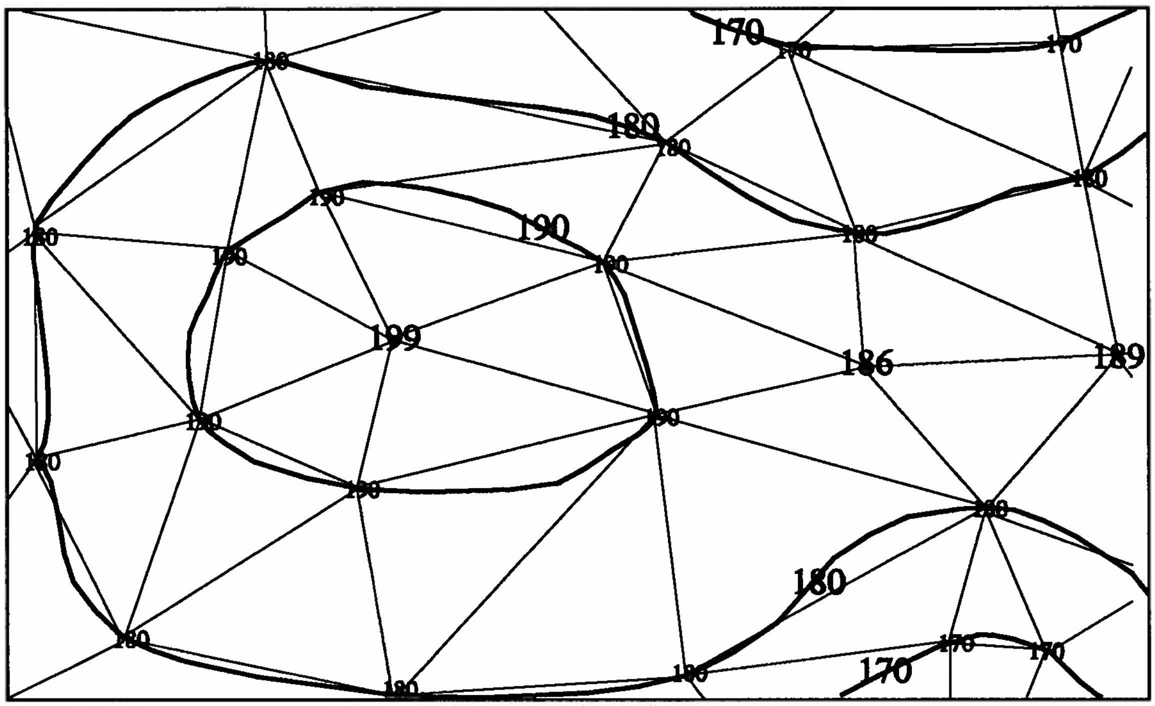


Figure 5 TIN DEM integrates important spot elevations.

The predominance of regular rectangular grid DEMs is largely due to the ease with which they can be handled by the computer (Burrough 1986). Creation, storage and manipulation of elevational data is easily accomplished when it is in the regular grid format. A variety of useful information may be derived from a grid DEM such as contours, slope and aspect, hill shading, and automatic basin delineation. Grids are also easy to conceptualize.

Problems associated with using regular grid DEMs in irregular terrain are well documented (Burrough 1986; Peucker *et al.* 1978). Foremost is their inadequacy in describing irregular features within a regular framework. For example, a grid resolution that accurately displays the roughest terrain on a map results in great data redundancy in the areas of lesser variation. This high density of data creates problems with storage and with the speed of generation, handling and manipulation of the DEM. Conversely, if resolution is decreased to reduce redundancy then accurate terrain representation is compromised. While multiple-pass models exist which can increase grid density for areas of higher variation, a regular sampling pattern is still utilized and redundancy still occurs.

3.2.4 The Triangulated Irregular Network

The Triangulated Irregular Network (TIN) model is based upon the philosophy that it is better to represent an irregular surface within an irregular data structure. In their pioneering work, Peucker *et al.* (1978) determined that it was necessary to have an elevation model where the locations of data points were dictated by the relief of the surface being modelled. This model would also have to be computatively efficient.

TINs represent surfaces through locating data points at key topological features such as peaks, pits, passes, ridges and channels (Peucker *et al.* 1976). This results in irregularly spaced points which are connected by lines to form a continuous sheet of triangles. TIN models work best in areas with sharp breaks in slope where the edges of the triangle may be aligned with those same breaks (Goodchild and Kemp 1990). Like the grid model, the TIN model may also be used to derive other useful information.

While TIN models may be created from contour data, proper selection of data points should begin at the aerial photograph interpretation stage. Rather than deriving contours from the photographs the interpreter should choose points that accurately represent all of the critical terrain features. Points are placed precisely on peaks, pits, and passes, and triangle sides aligned very closely to ridge lines, break lines, and channels. The TIN model thus allows data points to be concentrated in areas of complex relief while fewer points are collected from areas of smooth relief (Burrough 1986; Goodchild nd). This allows for both efficient and accurate modelling of areas with variable terrain. Figure 6

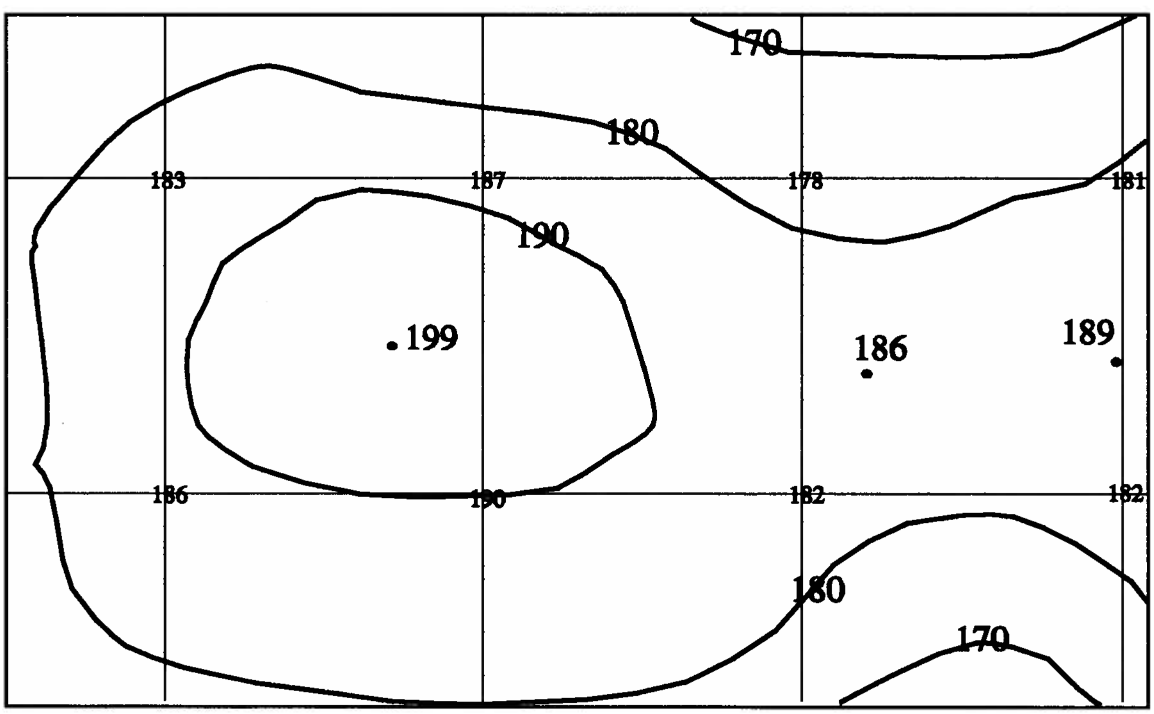


Figure 6 Regularly spaced grid points do not properly represent important features, such as peaks and passes.

shows a TIN representing the same data set from Figure 5. The critical points represented by the spot elevations are incorporated directly into the TIN without any smoothing of their elevations.

3.2.5 Using DEMs in Operational Harvest Planning

The potential of using DEMs for forest harvest planning had been suggested as early as 1974 (Burke 1974). Young and Lemkow (1976) developed a Digital Terrain Simulator (a DTM) that could be used for many aspects of forest operations planning, including deflection-line analysis. Limitations with speed and storage capacities of desktop computers of that time prevented the efficient use of such models. These limitations often resulted in a compromise of the accuracy of the data and/or the integrity of the models used to manipulate the data.

These conditions persisted until rapid improvements in the abilities of personal computers (PCs) occurred in the late 1980s. PC-based Geographical Information Systems (GIS) have allowed harvest planners to create and use their own complex DEMs. These GIS's have employed mostly grid DEMs because of their ease of handling when using computers (Burrough 1986; Maedel and Gaudreau 1989). These models are poor representations of the ground surface and they have not achieved the full potential of DEMs in forest harvest planning.

The TIN model provides a method by which surfaces may be represented with accuracies which should be acceptable to the demands of harvest planning. As described above, in order to utilize TIN's to their fullest potential, they should be created from data collected specifically for triangular representation. Creating a TIN from contour maps or grid will add additional error. Petrie (1990) stated that the accuracy of photogrammetrically derived contours is typically only one third that of spot heights measured directly from the same aerial photographs.

Obviously remapping will not be immediately practical for many forest operations. In the interim, existing analog contour maps may be used so long as proper consideration is given to their limitations with respect to accuracy. Thus, when the opportunity arises for remapping, the operator will have an increased awareness of the accuracy issues pertaining to the use of DEMs in forest operations planning.

3.3 DEM Accuracy

3.3.1 Errors: Blunders, Random, and Systematic

The United States Geological Survey (USGS) classifies DEM errors into three categories: blunders, random errors, and systematic errors (Caruso 1987). Blunders are gross errors that are usually easy to detect and therefore edit. It should be noted that blunders which go undetected could have severe effects upon DEM accuracy and the accuracy of resulting analysis.

Random error is lack of precision caused by measurement error. This could occur when the photo-interpreter makes an erroneous measurement of ground elevation for one point on the aerial photograph. This error would be a 'blip' on the map, not consistent with the surrounding errors. If these errors are truly random, then they will tend to cancel out with increased sample size. For example, a surveyor reading a compass makes a random measurement error of one degree to the west. Since this error occurred by chance the more measurements the surveyor takes, the more chance the original error will be cancelled out by a random measurement error of one degree to the east.

Systematic errors may be due to bias in measurements. For example, a photo-interpreter may consistently underestimate the height of trees on the aerial photographs when trying to estimate the ground elevation. This would lead to a consistent overestimation of ground elevations, spread evenly across the resulting map, which would be fairly easy to correct (Shearer 1991).

If more than one factor is causing bias, then there may be an interaction effect on the error. Tree height is somewhat dependent upon topography, with taller trees in valley bottoms and shorter trees on ridge tops. If the photo-interpreter assumes all the trees to be the same height, then ground elevations may be overestimated in the valley bottom and underestimated on the ridge. This would result in systematic error spread unevenly across the map which takes more skill to detect and correct.

The presence of systematic error confounds attempts to measure random error (Li 1991). This study was focused on the causes and nature of the systematic error. There were two major sources of systematic error: smoothing error and positional error. Appendix A contains a summary list of potential sources of error which may also affect this study but which were beyond its scope.

3.3.2 Smoothing Error

Smoothing error occurs when natural terrain variation has been lost or 'smoothed out' due to measurement error, interpolation patterns, or data transformations. Where the variation is not represented properly by contours, grid points, or triangle edges, then the contours, grid points, or triangle edges are positionally incorrect. Increased sampling can reduce smoothing error by increasing the representation of terrain variability. The use of intelligent interpolation routines which incorporate local terrain characteristics to predict terrain variability is an alternative to increased sampling. While smoothing error is a result of positional error, the effects of smoothing error will be considered independent since they have particular importance to this study.

The causes of smoothing error may be considered in two steps. The first step includes the processes involved in the creation of the analog source maps. K.C. Soel, Limited, created a significant portion of the 1:5000 scale topographic maps on Vancouver Island including those for Canfor's Englewood Division (Soel 1992). Soel claimed that the creation of accurate contour maps from aerial photographs is a combination of the practical field experience of the interpreters, combined with their ability to see the ground through the forest canopy. Combs (1980) stated that success in photo-interpretation "largely depends on the training and experience of the interpreter, characteristics of objects to be studied, and the quality of the photographs being used."

Using contours to represent terrain relief will contribute to smoothing error. By choosing set contour intervals, detail located between those intervals is systematically excluded. When contours are created from aerial photographs, a fixed elevation is chosen and that elevation is traced from the photographs to create the contour (LaPrade 1980). When tracing an elevation through rough terrain, it is very difficult to accurately capture all of the detail. Sharp terrain breaks could be somewhat rounded. Transfer of information from one media to another and drafting can also have an effect which will contribute to smoothing error as well.

The second step includes the conversion of contour maps to digital form and the subsequent extraction of the deflection-lines. When cartographic lines, such as contours, are represented "as sets of digitized points joined by straight line segments" (Veregin 1989), generalization error occurs. The degree of generalization error will normally increase as line complexity rises (Burrough 1986). For example, when hand digitizing contours, there is a tendency to literally cut corners on the contours as terrain variability increases. This generalization error in the contours will equate to smoothing error in DEM-derived deflection-lines.

Additional elevation points could help alleviate the effects of smoothing error. Spot elevations could either be added for hill tops, ridges, and river or creek courses, or they could be extrapolated from adjacent contours.

The TIN creation process connects elevation points into a continuous sheet of triangles. There should be no loss of accuracy in this step because all of the original information is retained. This also holds true for the deflection-line extraction procedure. Elevations for individual deflection-line points will be interpolated from their location on a triangle which should not add any new error (Figure 7).

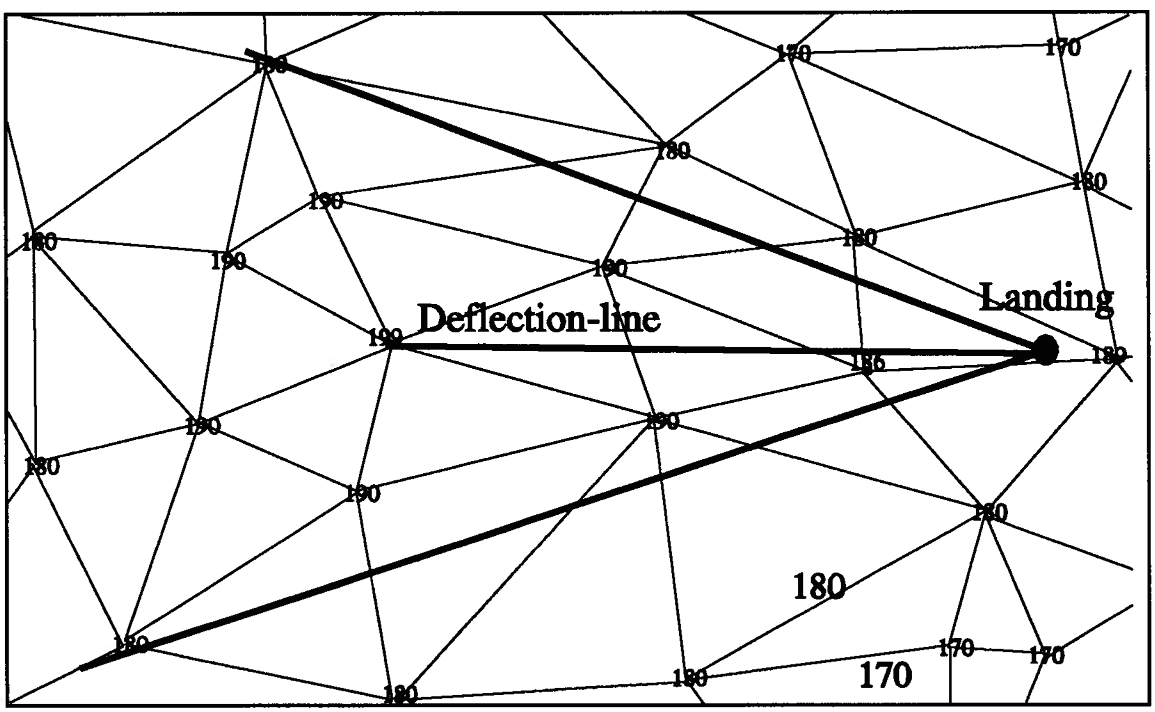


Figure 7 Deflection-lines overlayed onto a TIN DEM.

3.3.3 Positional Accuracy

For this study, positional accuracy refers to the horizontal or planimetric accuracy of any feature represented on a map, analog or digital. Veregin (1989) defined positional accuracy as "the accuracy of feature locations after transformations have been applied." If the process of measuring a feature for graphical and/or digital representation can be considered a transformation, then this definition supports the terminology used for the study.

Positional error in a feature's map location could exacerbate the elevational error of that feature (Veregin 1989). When the feature is not properly located on the DEM, the extracted elevations will most likely be in error. Positional error may be introduced in most stages of map making and DEM creation and it is heavily dependent upon the age of the data, the quality of surveying used to collect the data, and upon the relevance of the data to the intended use (Burrough 1986).

3.3.4 Age of Map Data

Tie-points are features which are easily identified both in the field and on the map. Surveys are conducted from tie-points to deflection-lines, effectively 'tying' them together. This helps locate the deflection-line when it is transferred to the maps. The accuracy of tie-points was a very important aspect of this study.

The age of the data used to represent a dynamic feature on a map influences its accuracy as a tie-point. Water bodies such as lakes and creeks are most commonly used. Over time the shore lines and banks may change. The older the map data, the more likely that this has occurred.

Photo-identification-points (PIPs) are features which are easily identifiable in the field for which the exact coordinates have been determined at the time of map making. Unfortunately, many of these features are subject to change with age. For example, lone trees in openings are often used for PIPs. These trees may die and fall over, rendering them useless as a PIP.

Logging roads are quite often used as tie-points for deflection-lines. Logging road surveys are affected by the quality of the surveying methods used and the type of equipment used as well. These are often performed a few kilometres at a time, over the span of many years. Error in bearing or in length can be compounded over the years as each new survey inherits any uncorrected error from previous surveys. This is discussed further in the next section.

Age of the data can affect the orientation of a feature when transferred to a map. Magnetic north shifts over time, and if the compass declination is not adjusted accordingly there is the potential to introduce error in orientation.

Another very significant consequence of data age comes from a change in major reference systems. The North American Datum (NAD) was adopted as the standard coordinate referencing system by Canada, the United States, and Mexico in 1913 (Pinch 1990). The origin for the NAD was a marked point known as Meades Ranch, located in Kansas. In 1927 recomputations were begun to eliminate unacceptable errors in the NAD coordinates. This became known as the North American Datum of 1927 (NAD27).

As the NAD27 network was extended and densified over the next fifty years, there was an accumulation of systematic errors (Pinch 1990). This systematic error, combined with the inherent limitations of the system led to the development of the North American Datum of 1983 (NAD83). The NAD83 uses the centre of mass of the Earth as its origin, which makes it useful for global satellite positioning. Errors in the NAD83 coordinates are much smaller, less systematic, and insignificant compared to NAD27 coordinates. Converting coordinate data from the NAD27 to the NAD83 involves transformations which add positional, and therefore, elevational error.

3.3.5 Surveying Quality

Field surveys are prone to error, the level of which depends upon the precision and condition of the equipment used. Traditional surveying methods for harvest planning utilize a nylon chain, hand-held compass, and a clinometer. The rigorous conditions of the harvest surveys can affect the equipment precision. The nylon chain can stretch after being repeatedly wetted. The compass and clinometer can lose precision when dropped or struck against hard objects. If these instruments are not checked for accuracy, they can introduce positional error to the survey data. Positional error from logging road surveys can accumulate as new surveys are performed based upon the erroneous locations of existing logging roads.

Human error in surveying may result in the displacement of the feature being surveyed. If a surveyor has a tendency to read bearings incorrectly in the same direction, then bias will be introduced. The survey will diverge from the intended bearing, which is the bearing with which the feature will be represented on the map. Elevations will be extracted from the intended location on the DEM, and will appear to be in error when compared to the field surveyed elevations. This will be more evident in more variable terrain.

Elevational data is obtained through some type of survey, usually aerial photographic surveys. The quality of the equipment used, the atmospheric conditions, and the condition of the film can all influence the positional accuracy of map features. Presence of haze when the aerial photographs were taken will make it more difficult for the photo-interpreter to see the ground, compared to aerial photographs taken when the air was clear. This could result in incorrect estimation of the ground elevation which could, in turn, result in positionally incorrect contours. While these errors are likely to occur, they will have much less influence on elevational accuracy than field surveying error.

3.3.6 Data Relevance

Another factor which can lead to positional error is the relevance of the data to the purpose for which they are applied. Roads and creeks were often drafted on maps more for representational purposes than for accuracy. The roads may be broken to fit sidehill creek crossings, with little concern for the accuracy of the road in between the crossings. Using these features as tie-points will likely add positional error, which could be significant when very high accuracy is required.

Sidehill creeks, often used as tie-points, may not be visible on aerial photographs. The location of the creek is indicated by the presence of a small valley running down the sidehill, evident in the elevations of the forest canopy. The exact location of the creek channel will be estimated by the photo-interpreter and then represented by a sharp line on the map. When road plots are transferred to the planning maps the creeks are often used to locate the roads. Any positional error in the location of the creek will be inherited by the road.

The description accompanying a PIP can often be very ambiguous. For example, a PIP may be described as being in the "Northwest corner of cleared area." The corner of this cleared area may have appeared to be a sharp line to the photogrammetrist. On the ground the boundary of the cleared area could be transitional over many metres making the exact corner very difficult to locate. To make matters worse, the cleared area may since have been extended from the corner. The PIP will then be located somewhere along the edge of the cleared area, perhaps impossible to locate. When accuracies of less than five metres are desired these types of tie-points are not very useful.

3.3.7 DEM Accuracy Standards and Tests

Thompson (1956) recognized early that a map's accuracy was not independent of the purpose for which it was to be used. Thompson (1960) also discussed many cases in which topographic maps were being used "in which an accuracy is presumed that was never intended." This is still relevant today when most of the existing topographic maps were created before the advent of small, powerful, and extremely precise GIS programs. Converting these maps to DEMs for use in more demanding operations may not be feasible. Ultimately, new elevational data should be collected specifically for DEMs at an accuracy level suitable to the new use. Since this will not always be possible, old topographic maps may be used, provided their limitations are taken into consideration. Essential knowledge of these limitations may be gained through testing maps with methods appropriate to their new intended use.

There are several accuracy standards in existence for both topographic maps and DEMs. In the United States, the definitive standard is the National Map Accuracy Standard (NMAS) which is applied to the USGS topographic map series (Veregin 1989). Tests are based upon "a comparison of at least 20 well-defined map points relative to a survey of higher accuracy." For vertical accuracy, NMAS states that not more than 10 percent of the elevations tested should be in error of more than one-half the contour interval (Thompson 1988).

In British Columbia, the Surveys and Resource Mapping Branch of the Ministry of Environment, Lands, and Parks uses accuracy standards set out under the North American Treaty Organization's (NATO) specifications for 1:5000 and 1:2500 scale topographic maps and DEMs (MoELP 1992). For 1:5000 scale "ninety percent of all discrete spot elevations and DEM points shall be accurate to within 1.25 metre". While this value is statistically derived, the error is assessed using the same pass/fail method as the NMAS.

Both the NMAS and the NATO tests are intended for compliance to an accuracy standard and provide virtually no information as to the magnitude of individual errors (Veregin 1989). There can be a significant difference in accuracy between one map with ninety percent of sampled elevations just under one-half contour interval in error and another map with ninety percent of the points free from error altogether. Similarly, a rejected sample elevation could be in error of just over one-half of the contour interval and be considered the same as one that is, for example, in error by three times the contour interval.

The American Society of Civil Engineers has developed the Engineering Map Accuracy Standard (EMAS) for large scale maps (Veregin 1989). The EMAS is designed to be application specific and checks error data against maximum acceptable limits as set by the map user. EMAS tests both the sample mean errors and the standard deviation.

An alternative statistic that has been used in the United States is called the Root Mean Square Error (RMSE) (Gustafson and Loon 1981):

$$RMSE = \pm \left(\sum e_i^2/n\right)^{-\frac{1}{2}}$$

RMSE = Root Mean Squared Error

e_i = elevational error of the ith test point

n = number of test points

The RMSE is preferred to the 90% criteria "since it is completely unambiguous and not easily subject to misuse." The RMSE is equivalent to the standard deviation when mean error is equal to zero. RMSE is often equated with standard deviation for all cases without making proper distinctions.

Another option is Koppe's formula which recognizes the relationship between vertical error and terrain slope (Gustafson and Loon 1981). A contour that is positionally incorrect by 5 metres will cause less vertical error on a 5 percent slope than on an 80 percent slope. The Koppe formula has incorporated an increasing tolerance for vertical error as terrain slope increases.

Gustafson and Loon (1981) noted that most map accuracy standards assume that blunders and systematic errors have been eliminated from map error and that the residual random error is normally distributed. In reality, systematic error will always be present to some degree, especially in areas that are difficult to map.

Thompson (1960) singled out terrain covered with tall, dense, coniferous forests as areas which caused difficulties in mapping. The problem of accuracy testing in heavily forested areas is dealt with in much the same way: it is avoided. For example, a study on DEM accuracy testing in Great Britain stated that "not every [test] point was measured because a certain number fell in a woodland area or on some other unsuitable features" (Li 1991).

Existing accuracy standards often state that points tested must be clear and well defined. For example, the NATO standards used in B.C. specify that stated elevational accuracies "relate to ground not sufficiently obscured by vegetation or other features to cause significant error" (MoELP 1992).

Finally, it is possible to have a deflection-line derived from a DEM that has an acceptable mean error but that has one or more single large errors which will significantly affect the analysis. For example, the photo-interpreter may fail to detect a ridge due to the nature of the forest cover. The ridge would not be plotted on the topographic map and subsequently not represented by the DEM. Deflection-line analysis from field surveys will identify the ridge as the yarding boundary. Analysis performed using the DEM could result in a longer yarding distance estimate due to the absence of the ridge. This could lead to significant equipment, log and site damage, as well as lower productivity.

For the purposes of deflection-line analysis, traditional statistics may not be sufficient to adequately assess the elevational accuracy of DEM-derived deflection-lines. The mean error indicates a trend in the elevational error, but it does not represent any individual feature on the deflection-line which may cause problems. Large individual errors may be masked by the mean error through the cancelation of positive and negative errors.

4 Study Site

Field surveys were performed on northern Vancouver Island, British Columbia, in cooperation with the Englewood Logging Division of Canadian Forest Products (Canfor) Ltd. The Englewood Logging Division, located in Woss, operates under Tree Farm Licence (TFL) 37 and Forest Licence (FL) A19233 in the Nimpkish Valley region (Figure 8). The dominant landforms in the region are of glacial origin with some intermixed volcanic influence (intrusions). The Nimpkish region is within the Coastal Western Hemlock biogeoclimatic zone.

Seven proposed skyline cutblocks (individual harvest units) were selected for study, three in the TFL and four in the FL (Figure 8). These cutblocks were chosen primarily due to their scheduling for harvest and secondarily for representation of the forest and terrain types within which skyline systems operate. A total of thirty-one deflection-lines were located at potential landings within the seven cutblocks (Figures 9-15). General characteristics of each cutblock are shown in Table 1. Table 2 shows the distribution of individual deflection-lines and settings within each cutblock. All cutblocks were located in old growth forest types.

Figure 8 Map of cutblock locations within Canfor operating area.

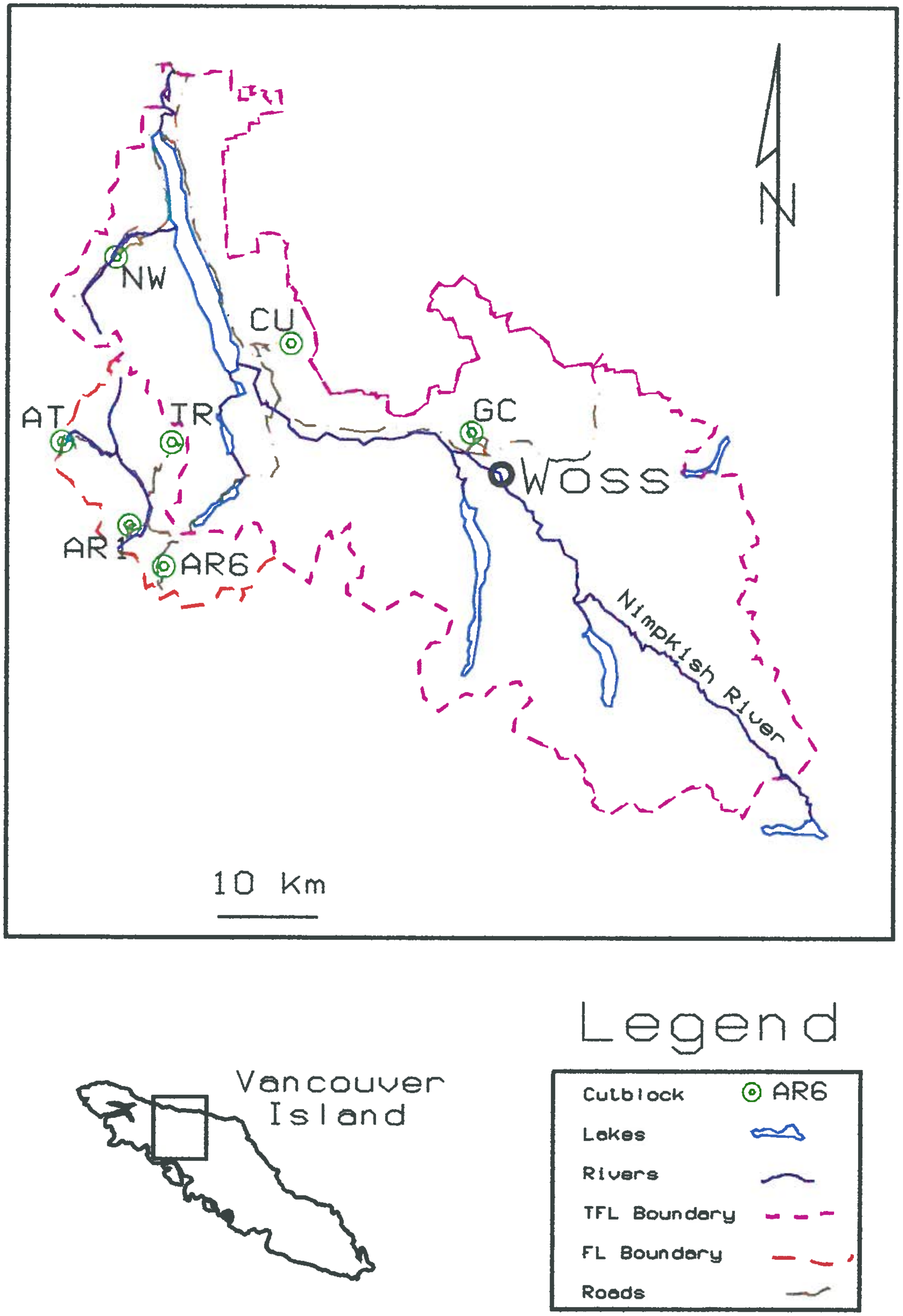


Figure 9 Map of AR1 cutblock and deflection-line locations.

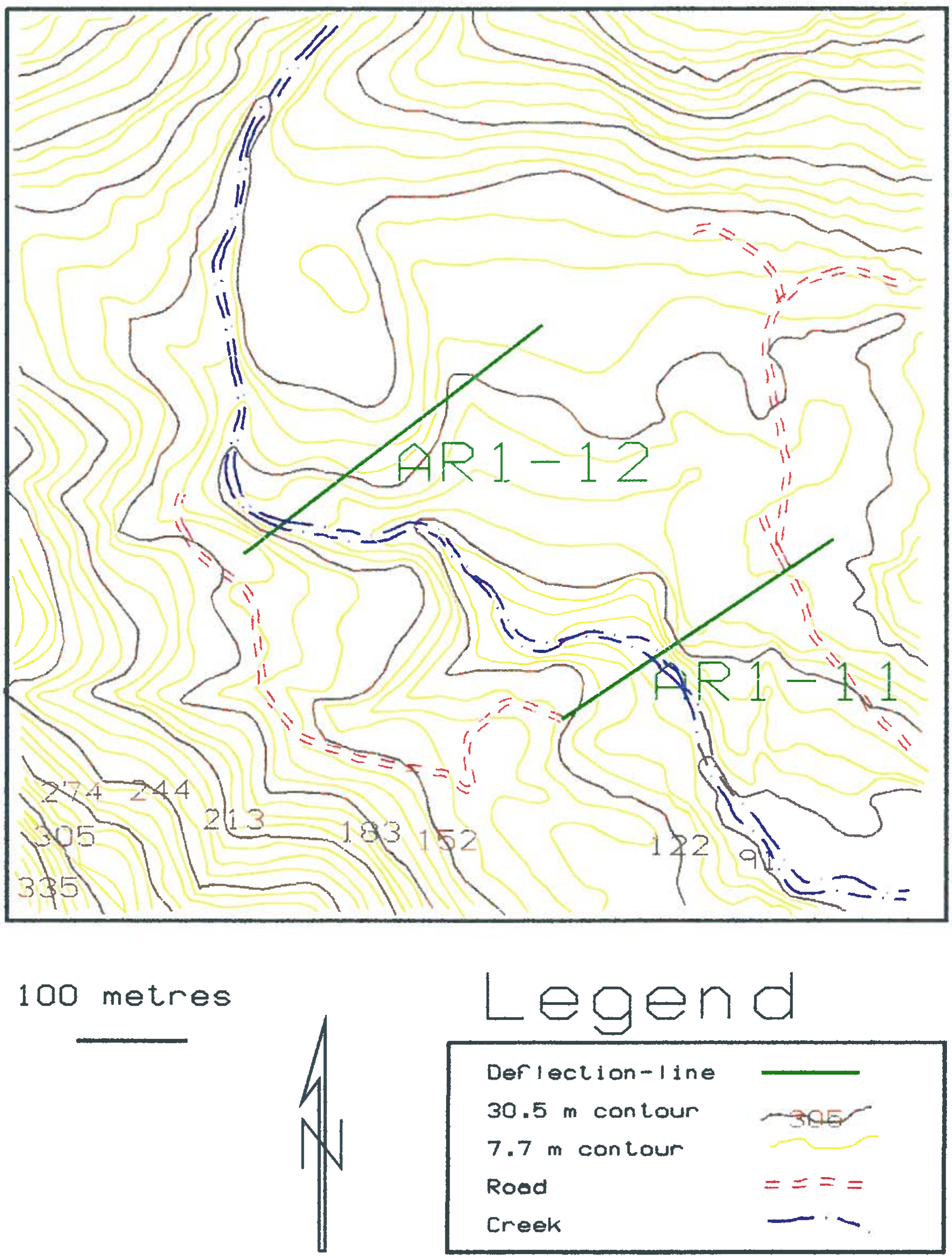


Figure 10 Map of AR6 cutblock and deflection-line locations.

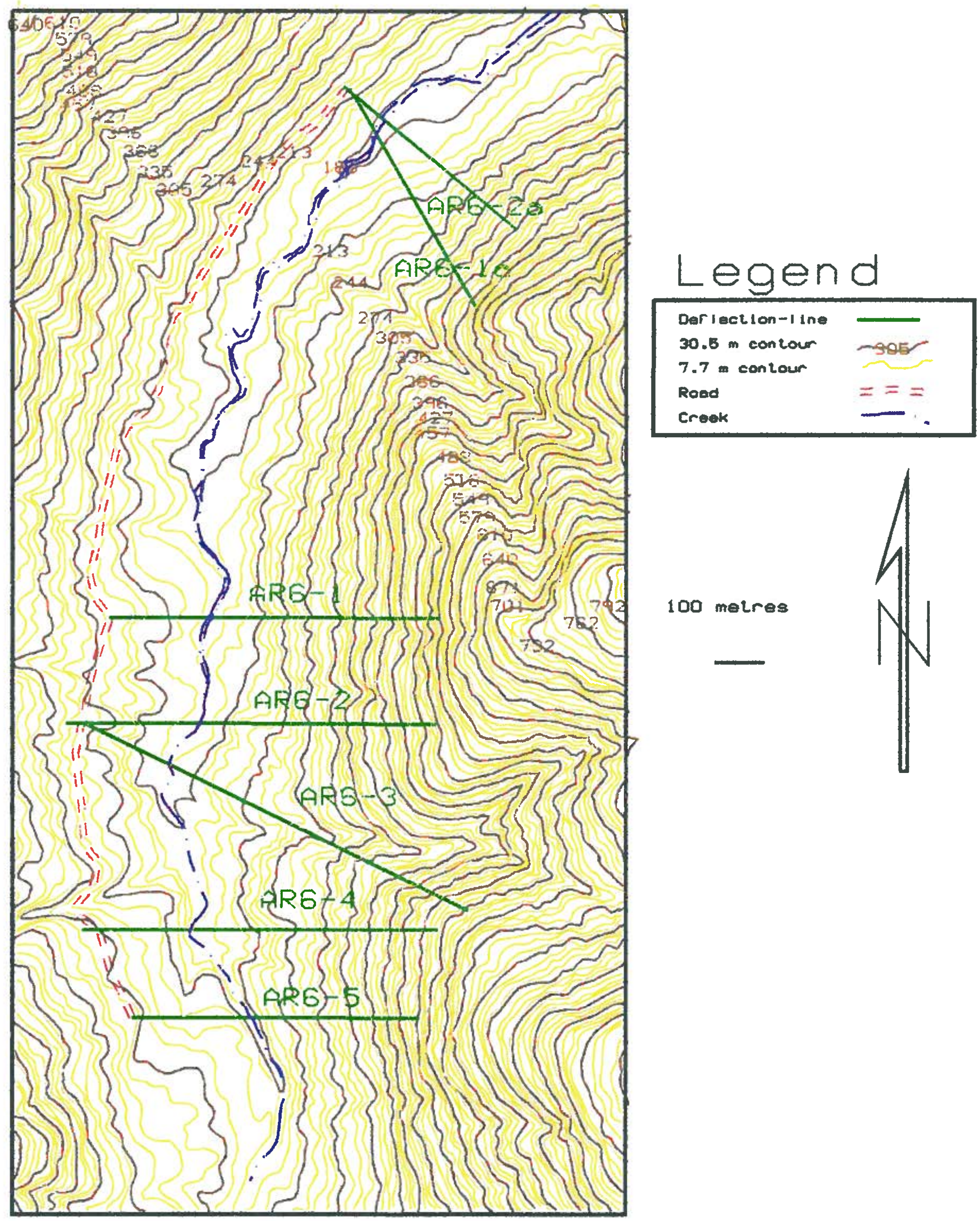


Figure 11 Map of AT cutblock and deflection-line locations.

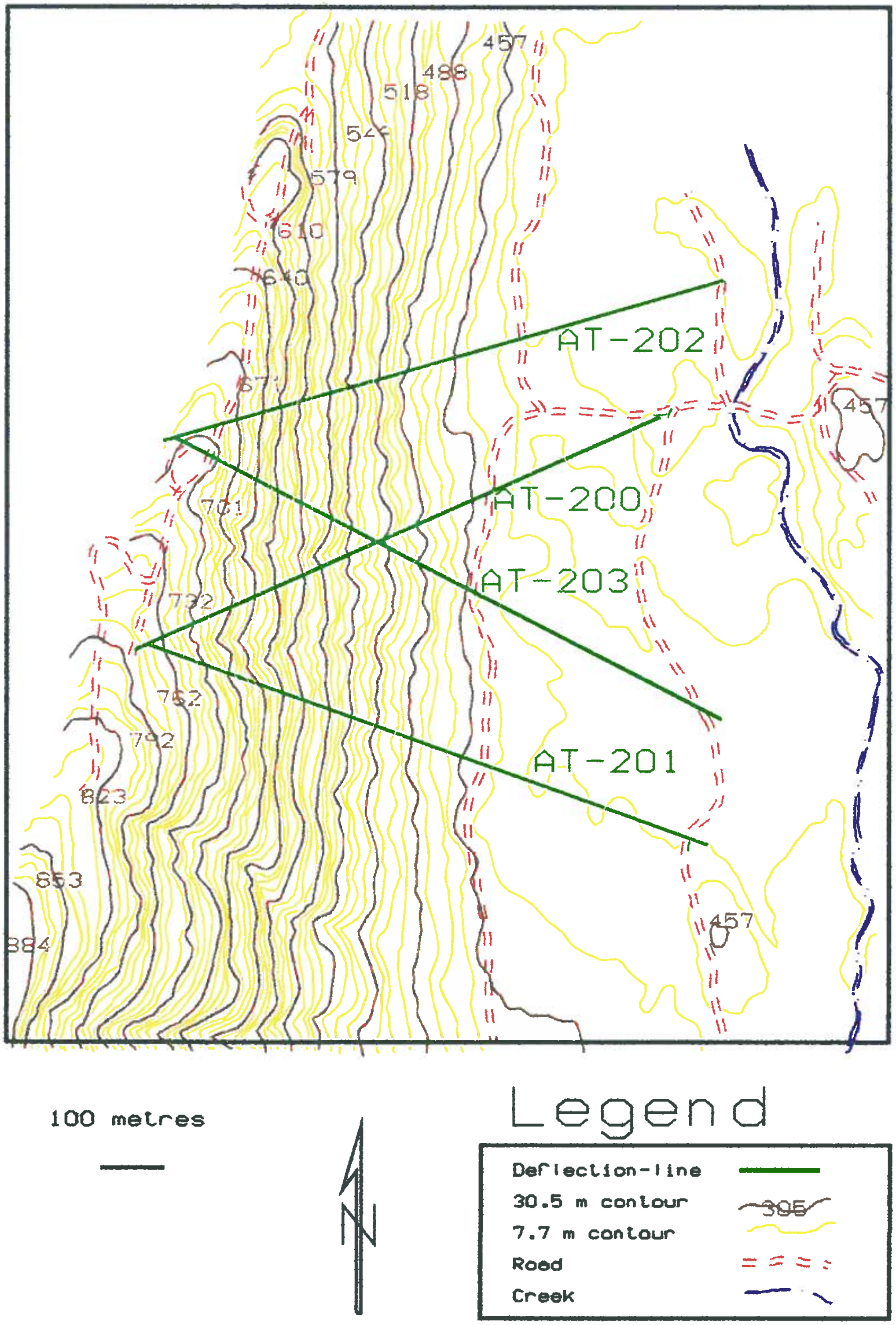


Figure 12 Map of CU cutblock and deflection-line locations.

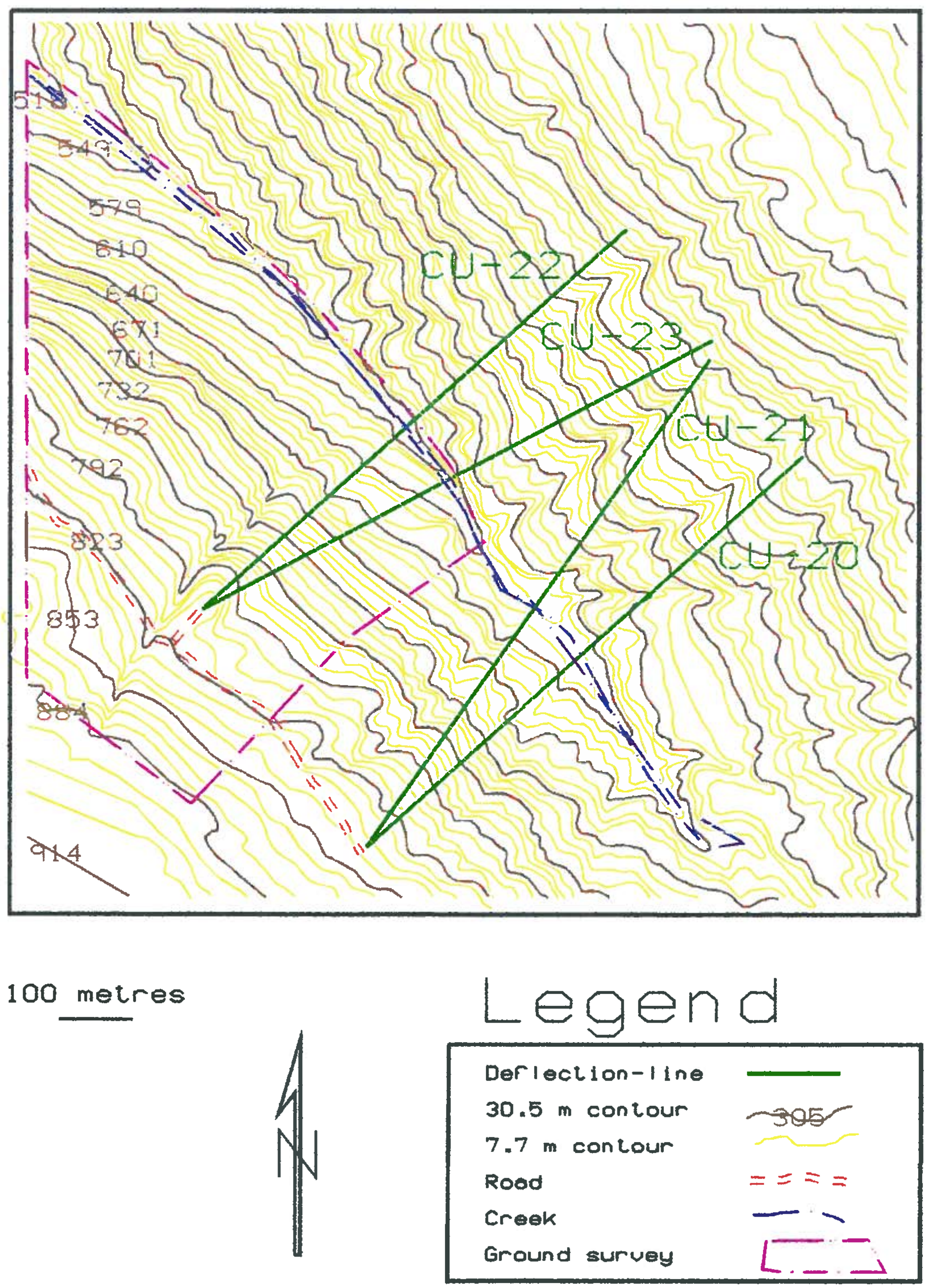


Figure 13 Map of GC cutblock and deflection-line locations.

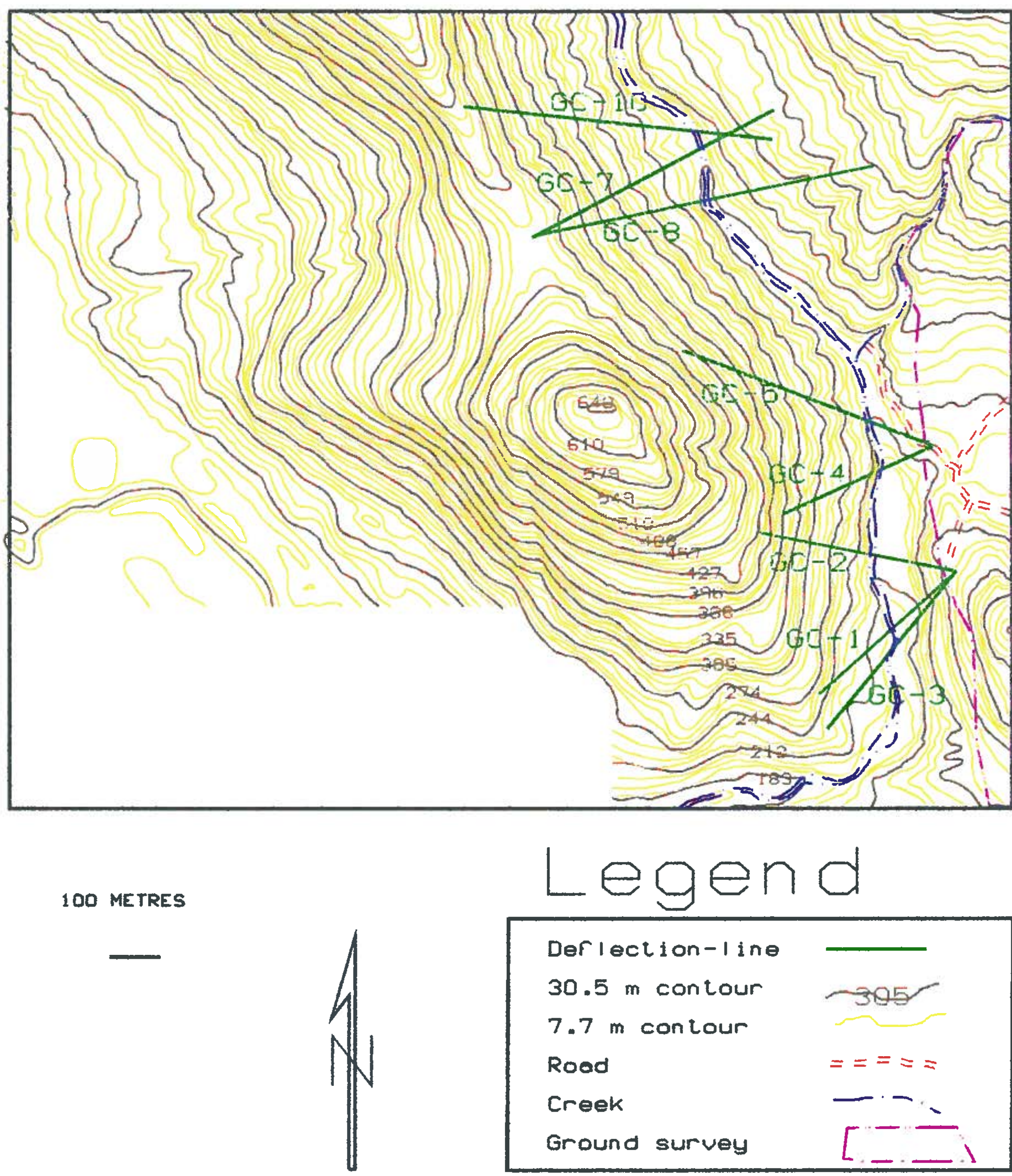


Figure 14 Map of NW cutblock and deflection-line locations.

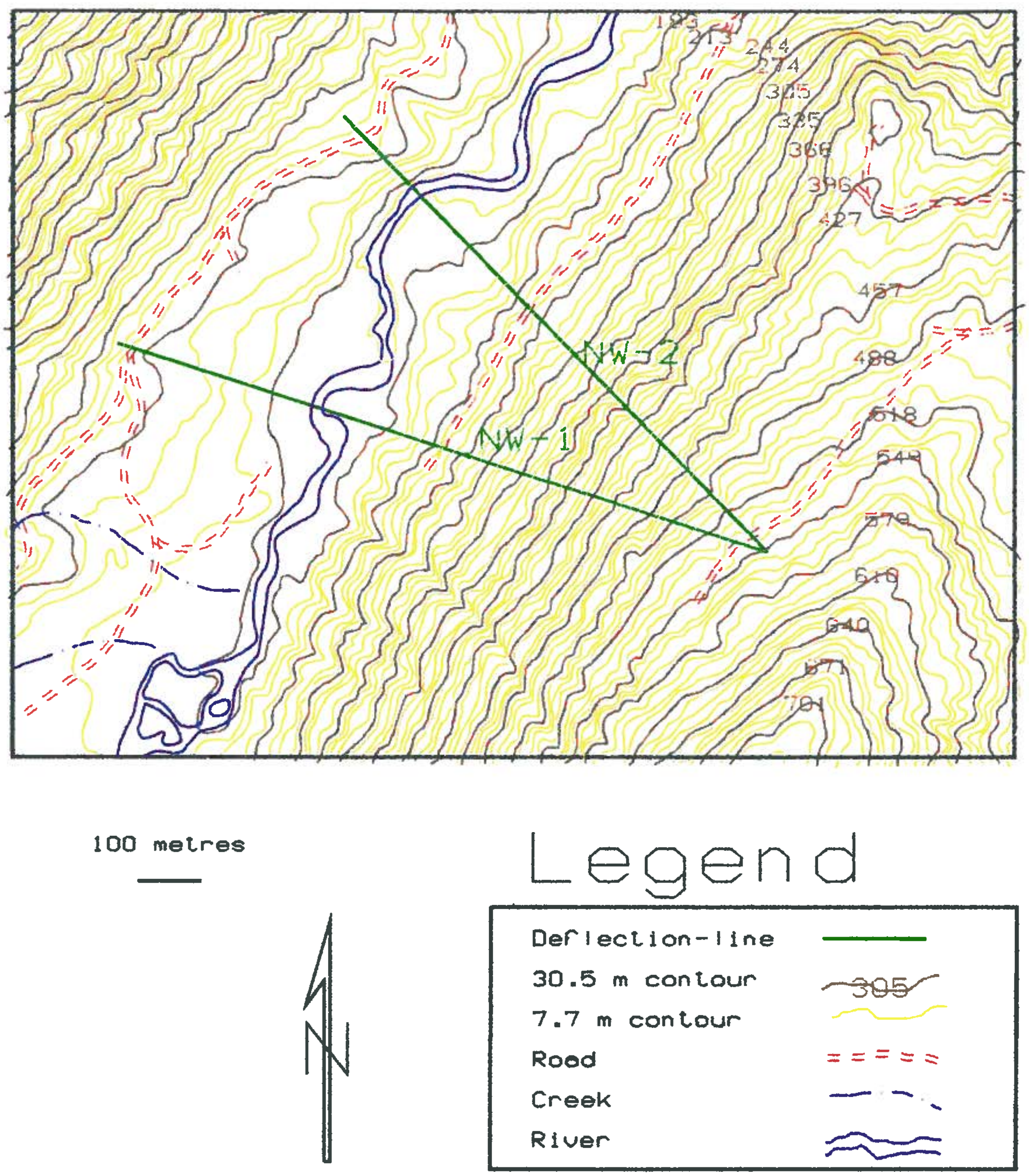


Figure 15 Map of TR cutblock and deflection-line locations.

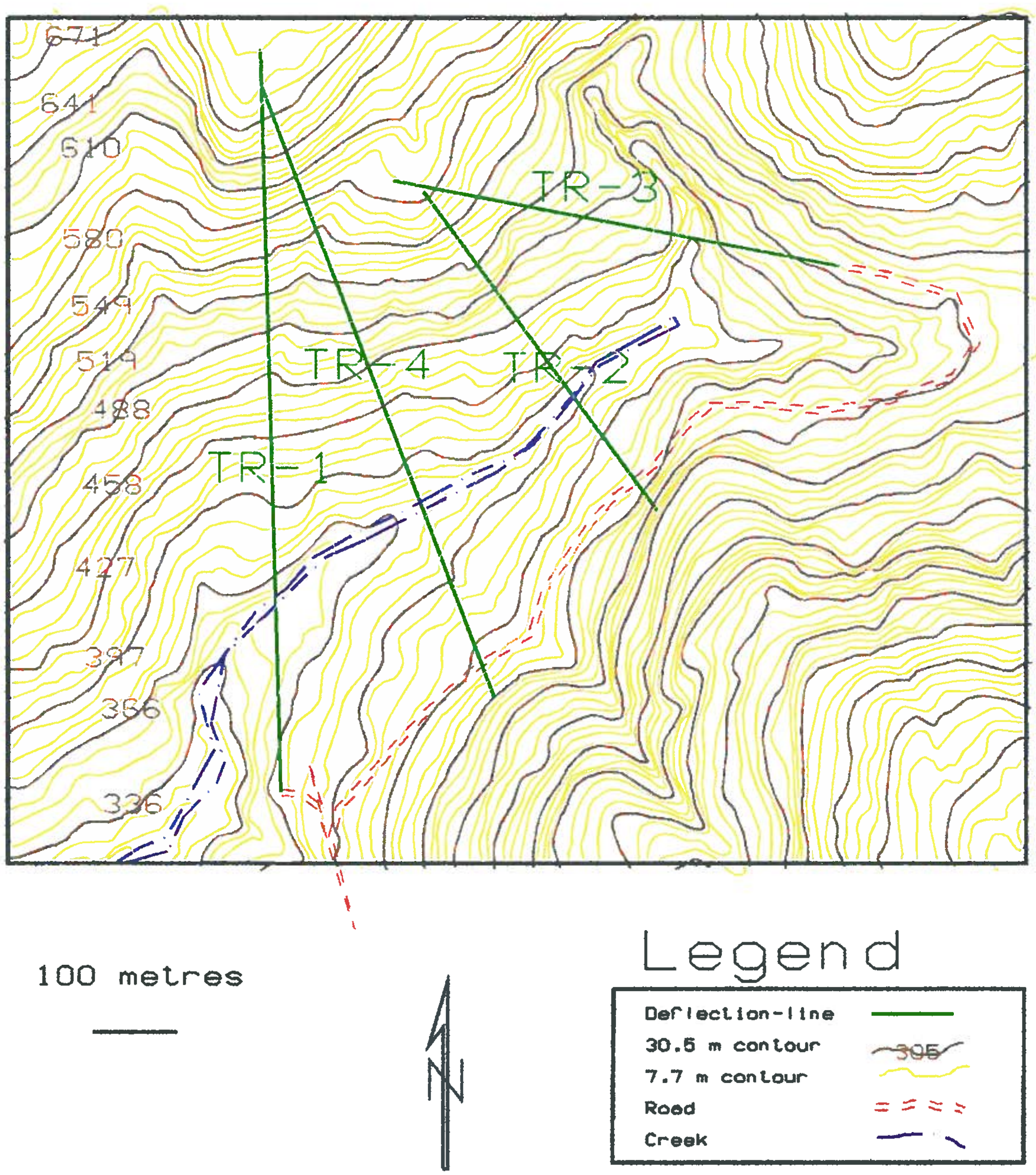


Table 1 Summary of cutblock characteristics.

Cutblock	Slope [1] (%)	Elevations (m)	Brokenness [2]	Forest Type [3]
AR1	30 (0-146)	90 - 200	M H - creek canyon	CWHb1, CWHb2 Hw, Cw,Ba
AR6	50 (2-120)	180 - 500	M H - upper slopes	CWHb1,2 Hw, Ba, (Cy ,Ss)
AT	46 (0-104)	400 - 800	S - lower flat area L - slope and ridge	CWHb1,2 Hw, Ba, Cw, Cy
CU	47 (11-72)	600 - 850	M	CWHb2, MHa Cw, Hw, Ba, (Cw)
GC	46 (0-131)	200 - 550	M	CWHa1 Df, Hw, (Cw)
NW	44 (0-96)	150 - 550	M - upper slope L - valley bottom	CWHb1 Hw, Ba, (Cw)
TR	55 (2-150)	350 - 700	H	CWHb2 Hw, Ba, Cw, Cy

1) average slopes found from deflection-line surveys (range in brackets)

2) S - Smooth - terrain is basically flat, no impediment to traverse.
L - Low - gently undulating, rock outcrops, no impediment to traverse.
M - Moderate - significant rock bluffs, creek canyons, difficult to traverse.
H - High - cliffs, sheer sided creek canyons, difficult to impossible to traverse.

3) Biogeoclimatic Units (Nuszdorfer et al. 1985)
MHa - Mountain Hemlock, Maritime Forested
CWHa - Coastal Western Hemlock, Maritime, dry
CWHb1 - Coastal Western Hemlock, Windward Submontane Maritime, wet
CWHb2 - Coastal Western Hemlock, Windward Montane Maritime, wet

Dominant Tree Species (Watts 1983)
Ba - *Abies amabilis* (Dougl.) Forbes (amabilis fir, Pacific silver fir, balsam)
Cw - *Thuja plicata* Donn (western red cedar)
Cy - *Chamaecyparis nootkatensis* (D. Don) Spach (yellow cedar, cypress)
Fd - *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (Douglas-fir)
Hw - *Tsuga heterophylla* (Raf.) Sarg. (western hemlock - may be mountain hemlock in upper elevations - not specified)
Ss - *Picea sitchensis* (Bong.) Carr. (sitka spruce - adjacent to main creek, AR691)

Table 2 Distribution of deflection-lines and settings within cutblocks.

Cutblock [1]	Setting	Deflection -lines
AR1	AR1-S1	AR1-11
	AR1-S2	AR1-12
AR6	AR6-S1	AR6-1
	AR6-S2	AR6-2, AR6-3
	AR6-S3	AR6-4
	AR6-S4	AR6-5
	AR6-S5	AR6-1a, AR6-2a
AT	AT-S1	AT-200, AT-201
	AT-S2	AT-202, AT-203
CU	CU-S1	CU-20, CU-21
	CU-S2	CU-22, CU-23
GC	GC-L1	GC-1, GC-2, GC-3
	GC-S2	GC-4, GC-5
	GC-S3	GC-7, GC-8
	GC-S4	GC-10
NW	NW-S1	NW-1, NW-2
TR	TR-S1	TR-1, TR-4
	TR-S2	TR-2, TR-3

1 Cutblock names have been shortened for clarity and for consistency with setting and deflection-line names. The full names are listed below:

AR1	=	AR160
AR6	=	AR691
AT	=	AT295B
CU	=	CU7
GC	=	GC6
NW	=	NW74
TR	=	TR38

5 Methods

5.1 Cutblock and Deflection-line Selection

Thirty-one deflection-lines were located in the seven proposed skyline cutblocks by the Englewood engineering staff. The first step involved visual inspection of the topographic maps to identify potential landings for the skyline machine. Landings were located on established, traversed or proposed road locations depending on the area and the state of its development. Deflection-lines started from these landings and were surveyed on constant bearings. The bearings were chosen in areas which, through the visual inspection, were potential problem areas for clearance. All landings located on surveyed roadway were surveyed to the nearest established roadway.

5.2 Field Surveys

Field surveys were conducted using Canfor's standard method of tight-chaining with a 50-metre nylon chain, hand-held compass and clinometer. Survey stations were located at changes in terrain slope of ten percent or more, and at significant features such as creeks and traversed and established roads. Foresights and backsights were taken with the compass to identify and eliminate bearing errors due to human error or magnetic anomalies. The nylon chain had tags set at increments 1.0 metres, with tags at 0.1 metre for the first metre. Length measurements were taken in such a way as to ensure that they were accurate to within the 0.1 metre markings. The compass had a minimum increment of 2 degrees. The clinometer had increments of 1 percent for slopes of 0 to 70 percent and 2 for slopes of 70 to 150 percent.

Tie-point surveys were conducted to locate the deflection-lines. Initial tie-points were established or surveyed roads and junctions, creeks and junctions, as well as PIPs which were located from the original air photo mapping. Potential tie-points were first selected on maps and then attempts were made to locate them in the field. It became evident that, for the most part, the map representation of these tie-points contained a high degree of positional error and most of them were found to be unreliable. Furthermore, some tie-points were extremely hard to find in the steep and heavily forested terrain of the study cutblocks.

In an attempt to improve tie-point accuracy, a Trimble 4000SE Land Surveyor (Trimble Navigation Ltd. 1992) Global Positioning System (GPS) in conjunction with a Criterion (Laser Technologies Inc. 1992) hand held laser surveyor were tested in the GC cutblock. The GPS was used to locate four well distributed tie-points and then the laser was used to traverse the deflection-lines and tie them to the tie-points.

All of the cutblock maps were in NAD27 coordinates and any recent additions to the data, from sources such as GPS, were in NAD83. To bypass the problems associated with transferring between these two datums, GPS survey data were integrated by fitting them to the map features, independent of the reference system. This avoided the necessary complex transformations.

Deflection-line and tie-point survey notes were compiled using ROADENG (Softree Technical Systems 1992) forest engineering software. The deflection-line and tie-point locations were plotted from ROADENG using a HP DraftMaster 1-drum plotter (Hewlett-Packard Company 1987). The plots were used to transfer deflection-line locations to the maps.

5.3 Digital Elevation Models

Canfor provided mylar map copies for each of the seven cutblocks. These maps were of 1:5000 scale with a 7.62-metre (25-foot) contour interval. The original mylar base maps were compiled in 1973 at a scale of 1:4800 (1 inch = 400 feet) and later photo-reduced to 1:5000 scale. The base maps were primarily photogrammetrically-measured. Although small portions of the GC and CU cutblock maps were field surveyed, the analysis focused on the photogrammetric portion of the maps.

Contours and relevant features were hand digitized into TerraSoft version 10.03 (Digital Resource Systems Ltd. 1992) map files using an Altek Model AC30 (Gentian Electronics Ltd. 1987) digitizing tablet. Contours were stream digitized, with points recorded every 0.3 millimetres (1.5 metres ground scale) along the contours. Since smoothing error had already existed in the maps, additional effort was made to keep the cross hairs of the digitizer puck in the centre of the contour at all times. While this was often difficult, especially in the most variable terrain, the addition of more smoothing error was likely kept to a minimum. Contour points were thinned using a weeding corridor of 1.0 metres to reduce data redundancy (Digital Resource Systems Ltd. 1992). Deflection-line locations were digitized from the mylar maps into the corresponding map files.

Triangulated Irregular Networks (TINs) were created for each map. The TIN model was chosen over the grid model due to its superior representation of terrain features. Specialized software extracted deflection-line data by draping the location of the deflection-lines onto the DEM. The software allowed the horizontal spacing of the elevation points to be set at one metre to conform with the precision of the field surveys. An ASCII file was produced in the form of cumulative horizontal and vertical values referenced to the origin of the deflection-line.

5.4 Estimating Yarding Distance

Deflection-line analysis was performed on the deflection-line pairs to estimate the yarding distance. These distances were compared to see if the DEM-derived deflection-line caused any erroneous estimations. The Terrain module of ROADENG (Softree Technical Systems 1992) was used for the deflection-line analysis. Cable configurations, machine specifications, type of analysis, calculation parameters, and other options were selected to conform to Canfor's procedures.

Analyses for deflection-line pairs were performed keeping most, but not all, options constant. Within given ranges, different payload weights and equivalent mid-span deflections were allowed for analysis of each deflection-line pair. The DEM-derived deflection-line was analyzed independent of the analysis of the field surveyed deflection-line and vice versa. This was done to mimic an operational deflection-line analysis in which a forest engineer would be using one type of deflection-line, or the other, but not both.

For example, a midslope bench, evident on a field surveyed deflection-line, may prove to be an impassable boundary for yarding when performing deflection-line analysis. Since reducing payload or mid-span deflection cannot overcome this obstacle, these options would not be pursued. If the bench were less evident on the corresponding DEM-derived deflection-line, reducing payload and mid-span deflection may provide clearance over the bench, causing an erroneous yarding distance estimate. In an operational use of DEM-derived deflection-lines, the forest engineer would not have the field surveyed deflection-line with which to compare, and would therefore make the erroneous estimation.

5.4.1 Statistical Analysis

Deflection-line analyses were performed using the DEM-derived and field surveyed deflection-line pairs to estimate yarding distances. These distances were then compared to see if the DEM-derived deflection-lines give significantly different results. The hypothesis for this experiment was:

H_1o: There is no significant difference between yarding distance estimated using paired DEM-derived and field surveyed deflection-lines.

H_1a: There is a significant difference between yarding distance estimated using paired DEM-derived and field surveyed deflection-lines.

Failure to reject the null hypothesis indicates that the elevational error of DEM-derived deflection-lines does not affect yarding distance estimates. Rejection of the null hypothesis shows that the elevational error of DEM-derived deflection-lines does affect yarding distance estimates.

The errors in yarding distance estimates were tested using Systat 5.2 (Systat 1992). The errors were checked for normalcy using the Lilliefors Test, a modification of the Kolmogorov-Smirnov test used for non-standardized data (Systat 1992). A significance level of $\propto$=0.1 was used. This large alpha value (0.1) was used to reduce the chance of a Type 2 error, accepting the null hypothesis when it is false (Walpole 1982). In practical terms, the test was designed to reduce the chance of indicating that the yarding distance estimates from the DEM-derived deflection-lines were the same as those from the field surveyed deflection-lines, when they were not. Since the error displayed a non-normal distribution, a sign-test was used to test the mean.

5.5 DEM Elevational Error

Elevations were sampled using deflection-lines, which are ground profiles. Gossard (1976) lists profiles as an objective means for analyzing elevational errors, while Kellie and Bryan (1981) found no statistical differences between elevational error estimates based upon profile data and on randomly located point data. Kellie and Bryan located the profiles randomly, unlike the methodology in this study, in an attempt to estimate the general elevational accuracy of the DEM. The systematic selection of deflection-line locations was considered to be within the bounds of the study, since the study focussed on accuracy issues related to DEM-derived deflection-lines.

The ASCII files were loaded into a spreadsheet for manipulation and comparison with field surveyed deflection-line data. Macros were created to eliminate extraneous data and to interpolate and extract points that aligned with the survey stations. This allowed the field surveyed and DEM-derived deflection-line elevations to be compared at common horizontal points. These deflection-line pairs were plotted together as a visual check for blunders in the elevations of the DEM-derived deflection-line. When deflection-lines indicating blunders were detected, the DEMs and topographic maps were checked to determine the source of the blunder. If the blunder could not be corrected, analyses were performed with and without the affected deflection-lines and the results compared.

The field surveyed and DEM-derived deflection-line elevations were given the same elevation, or calibrated, at one station. This station was chosen as the one where the photo-interpreter could obtain the best measurement of the ground elevation. This would be the station on the DEM-derived deflection-line with the most accurate elevation. This was usually a creek crossing, if it was sufficiently visible on the aerial photographs. If there was no major creek, or if the creek was hard to see on the aerial photographs, a ridge-top or an open rock-bluff was used.

Deflection-line pairs were then compared at individual stations to obtain elevational differences. The field surveyed elevations were the controls, and any differences between them and the DEM elevations were considered to be errors. The error was positive when the DEM elevation was higher than the field surveyed elevation. Conversely, the error was negative when the DEM elevation was lower than the field surveyed elevation.

It had been assumed that the elevations of the field surveyed deflection-lines were measured without error. Although this was not possible, most accuracy tests specify that DEM elevations should be tested against a survey of higher accuracy. Since the field surveyed elevations should be, on average, more accurate than those of the DEM-derived deflection-lines, this criteria of accuracy testing had been met. However, when considering the results, the possible confounding effects of field surveying error should be considered.

5.5.1 Statistical Analysis

Elevational errors were grouped by individual deflection-line, setting, cutblock, and by entire study area. Characteristics common to these groupings might have influenced the nature and/or magnitude of the elevational errors. For example, some of the cutblocks had distinctly different forest types when compared to other cutblocks. These different forest types may have had differing effects upon the photo-interpreters ability to accurately measure ground elevations. These differences may have led to varying levels of error, or different patterns of systematic error, depending upon the forest type.

Error was grouped by settings to test the quality of the tie-points used to locate the landings within each setting. The landing within each setting served as a common tie-point for all the deflection-lines contained within that setting. Some settings contained only one deflection-line, a result of the limited resources available for manually surveying skyline deflection-lines. Error grouped by deflection-lines was used to assess the elevational accuracy of the deflection-lines themselves and the comparison plots were used to detect and illustrate the different error patterns which may exist in DEMs and DEM-derived deflection-lines.

The hypothesis for this section of the study was:

H_2o: There is no significant difference between the elevation of paired points on the DEM-derived and field surveyed deflection-lines.

H_2a: There is a significant difference between the elevation of paired points on the DEM-derived and field surveyed deflection-lines.

The statistical testing determined if the mean error was significantly different from zero. This was intended to show if the elevations of the DEM-derived deflection-lines adequately represented the elevations of the field surveyed deflection-lines. While forest planners may be willing to accept mean errors which are not equal to zero, it was not possible to pick one mean error level acceptable for every deflection-line. Therefore, error testing was restricted to detecting mean errors which were significantly different from zero, allowing forest planners to judge how much error may acceptable.

Existing accuracy standards had various inadequacies which made them unacceptable for testing the elevational accuracy of DEM-derived deflection-lines. Statistically based standards assume that the error is normally distributed; an assumption not made in this study. Other standards stated that ground points tested for elevational error must be clear and well defined, a situation not often found in the heavily forested areas planned for harvesting. Finally, some standards required only ninety percent of the errors to meet an acceptable level. The largest errors, which were the most critical for estimating yarding distance, were therefore ignored. This was not acceptable for assessing the elevational accuracy of DEM-derived deflection-lines.

Data from the spreadsheet comparisons was imported into Systat 5.2 (Systat 1992) in order to perform the statistical analyses. Histograms were created for visual inspection of the distribution of the errors. The data were then checked for normality using the Lilliefors Test, a modification of the Kolmogorov-Smirnov test used for non-standardized data (Systat 1992). A significance level of α=0.1 was used for all tests (results at α=0.05 are included). The large alpha value (0.1) was used to reduce the chance of a Type 2 error, accepting the null hypothesis when it is false (Walpole 1982). In practical terms, the test was designed to reduce the chance of indicating that the DEM-derived elevations were the same as the field-surveyed elevations when they were not.

For samples with normal distributions, a paired t-test was used. For samples with non-normal distributions, a sign-test was used. The sign test is less efficient than the t-test in that it does not utilize as much information (Walpole 1982). In this study, if the number of negative errors was approximately equal to the number of positive errors, the sign test indicated that the mean error was not significantly different from zero. Results of this test could have been misleading since it did not consider the size of each individual error. A deflection-line could have had an equal number of positive and negative elevational errors, but the positive errors were greater in absolute magnitude than the negative errors. This would have been indicative of some type of systematic error which could have had a very significant effect upon the yarding distance estimates. Also, the severity and type of error in the yarding distance estimates may have varied, depending upon whether individual elevational errors were positive or negative. Neither the sign test nor the paired t-test provided this information. To avoid these scenarios, results of hypothesis tests were evaluated in conjunction with histograms, comparison plots, and basic descriptive statistics (mean error, mean absolute error, maximum negative and positive errors, the range of the error, and the standard deviation). As well, on the ground experience gained from field surveying each individual deflection-line added valuable insight to the evaluation.

Mean and mean absolute errors were used as a guide to the relative levels of systematic and random error in the elevations of the DEM-derived deflection-lines. If both the mean error was low (less than two metres) and mean absolute error was low (less than four metres) then there was a low level of both types of error. If the mean error was low and the mean absolute error was high then the error was mostly random. If the mean error was high but very similar to the mean absolute error (within two metres) then the error was mostly systematic. If the mean error was high and the mean absolute error more than two metres higher then there was both random and systematic error present. The size of the mean and mean absolute errors used to detect the presence of the different error patterns were determined by comparing deflection-lines which displayed obvious error patterns with deflection-lines which displayed no obvious error patterns.

6 Results

Visual inspection of both deflection-line comparison plots for the AR1 cutblock, AR1-11 and AR1-12, showed an apparent blunder. Both deflection-line pairs diverged steadily indicating a possible error in the contour interval of the source map. Since the cause of this blunder could not be determined conclusively (and corrected), analyses were conducted with and without the cutblock for comparison.

Portions of both the GC and the CU cutblock maps had been created from field surveys while the rest were photogrammetrically derived. The GC deflection-lines were all located within the photogrammetric portions of the maps so they were not affected. For CU approximately one half of deflection-lines CU-22 and CU-23 were located within the field surveyed map. It was possible that significant positional error could have occurred at the boundary between the two different mapping techniques. This error could not have been accounted for and therefore would have had an unknown influence upon the elevational error. Due to this uncertainty, analyses were also conducted with and without these two deflection-lines.

6.1 Estimating Yarding Distance

Error in yarding distance estimates was deemed positive when the estimate from the DEM-derived deflection-line was longer (an overestimation) and negative when the estimate was shorter (an underestimation). Twenty-two of thirty-one (71%) deflection-lines produced the same yarding distance estimates. For all thirty-one deflection-lines the mean error in yarding distance estimates was -4.1 m and the range of error was -54.1 m to 127.7 m. Two errors were positive and seven were negative. The mean error was not significantly different from zero using a sign test ($\alpha = 0.1$). The inherent inefficiency of the sign test should be taken into account when considering these results.

Of the four deflection-lines which were eliminated, only AR1-12 displayed an error in yarding distance estimate and this error was the largest from all thirty-one deflection-lines, at 127.7 m. When CU-22, CU-23, AR1-11, and AR1-12 were eliminated, the mean error in yarding distance estimates was significantly different from zero at $\alpha = 0.1$ but not significantly different from zero at $\alpha = 0.05$ ($p=0.07$). Once again the sign test was used, and the results analyzed accordingly. The mean error was -9.4 m, and ranged from -54.1 m to 7.8 m. Nineteen of twenty-seven deflection-line pairs (70%) produced the same yarding distance estimates. More detailed information is presented in Appendix B.

Longer deflection-lines had more tendency towards erroneous yarding distance estimates than did shorter deflection-lines. The four longest deflection-lines had erroneous yarding distance estimates, and six of the nine deflection-lines with different estimations were from the eight longest deflection-lines. Considering the error in yarding distance estimates as a percentage of the deflection-line length, the average error percentage was 2.4% for all deflection-lines and 8.2 % for the nine incorrect yarding distance estimates.

6.2 DEM Elevational Error

Descriptive and inferential statistics were calculated for the elevational differences at individual stations for all pairs of the thirty-one deflection-lines. The mean error for all data (n=675) was 1.4 m, which was significantly different from zero for α=0.1. The mean absolute error was 5.8 m. The error ranged from -22.9 m to 26.8 m and the standard deviation was 7.5 m. Elimination of AR1-11 and AR1-12 made virtually no difference to the mean error, range, or standard deviation. The same was true when CU-22 and CU-23 were eliminated. Additional results for AR1 and CU, by cutblock, setting, and deflection-line are tabulated in Appendix C.

All of the following results are for the twenty-seven deflection-lines remaining after the elimination of CU-22, CU-23, AR1-11, and AR1-12. The mean error for all data (n=594) was 1.6 m, which was significantly different from zero for α=0.1. The mean absolute error was 5.3 m, the error range was 49.2 m (-22.4 m to 26.8 m), and the standard deviation was 6.9 m. Data were also analyzed by cutblock, setting, and by individual deflection-line to identify patterns and attempt to isolate the error sources. Detailed results, including the statistical tests used for individual analysis, are tabulated in Appendix C.

The mean error by cutblock ranged from -1.0 to 5.8 m. Three cutblocks had positive mean errors and three had negative mean errors. The mean absolute error ranged from

4.4 to 7.0 m. The smallest range of error was 29.2 m and the largest was 42.7 m. The standard deviations ranged from 5.7 m to 8.8 m.

The mean error was significantly different from zero for AT, GC, NW, and TR (α=0.1). AT had the highest overall error with the largest mean error, mean absolute error, positive error, range, and standard deviation. CU had the lowest overall error with the smallest mean error, mean absolute error, range and standard deviation.

The mean error by setting ranged from -2.2 to 8.4 m and thirteen of the eighteen settings had positive mean errors (72%). The mean absolute error ranged from 3.5 to 12.0 m. The smallest range of error was 15.4 m and the largest was 42.7 m. The standard deviation ranged between 4.5 m and 14.2 m.

The mean error was significantly different from zero for five of eleven settings. One of these was GC-S1, which had the lowest overall error, and which had the smallest mean absolute error, range, and standard deviation. Another setting with a mean error significantly different from zero was AT-S2 which had the highest mean error, mean absolute error, maximum positive error, range, and standard deviation.

For the error analyzed by deflection-line, the mean ranged from -4.1 to 7.4 m. Eleven of twenty seven (41%) deflection-lines had mean errors that were significantly different from zero (α=0.1). Nineteen deflection-lines (70 %) had positive mean errors. The mean absolute error ranged from 2.7 to 9.5 m. The smallest range was 9.2 and the largest was 42.3. The smallest standard deviation was 2.8 and the largest was 10.4.

GC-2 had the overall lowest error with the smallest mean absolute error, range, and standard deviation. TR-4 had the overall highest level of error with the largest mean absolute error, range, and standard deviation.

7 Discussion

7.1 Estimating Yarding Distance

Statistical analysis had shown that the error in yarding distances, estimated from DEM-derived deflection-lines, was not significantly different from zero ($\propto = 0.1$) when the thirty-one deflection-lines were tested and was significantly different from zero ($\propto = 0.1$) when CU-22, CU-23, AR1-11, and AR1-12 were eliminated. Conclusions were not made based upon these results since a sign test was used for the analysis. It was more valuable to investigate the deflection-lines which produced erroneous yarding distance estimates and to discuss the cause of those errors.

7.1.1 Deflection-line Length and Concavity

Of the thirty-one deflection-lines analyzed, nine (29%) displayed error in yarding distance estimates, and most of these nine were of the longest deflection-lines. This shows that error in yarding distance estimates was more likely to occur as deflection-line length increases. There were several possible reasons for this, one being that the longer the deflection-line the more chance that elevational error sufficient to influence yarding distance estimates would occur. A more likely cause was an interaction between deflection-line length, the elevational error, and the concavity of the deflection-line.

For the skyline system considered in this study, adequate skyline deflection was obtainable only on primarily concave terrain surfaces. Problems with concavity generally occur at the beginning and/or end of the deflection-line where it rolls over onto a ridge or similar feature. These were generally poor areas for clearance due to the proximity to either the landing or the boundary. Relatively small errors in elevation on the DEM-derived deflection-line can cause problems with obtaining adequate deflection and subsequently cause problems with yarding distance estimates.

Evidence of this can be seen in the deflection analysis plots for the five longest deflection-lines with incorrect yarding distance estimates; NW-1, AT-203, NW-2, AT-202, and AT-200. Adequate clearance was not obtainable for the entire length of these five deflection-lines. For example, deflection-line NW-2 had problems with deflection in the convex terrain around 300 metres (Figure 16). When this occurred and adequate deflection could not be obtained for the entire deflection-line, a small elevational error on the DEM-derived deflection-line caused an incorrect yarding distance estimate.

By comparison, CU-21 provided adequate clearance for the entire length of both the field surveyed and DEM-derived deflection-lines. It was therefore easier to obtain the same yarding distance estimates for the deflection-line pair. This had to do with the position of the deflection-line relative to the terrain (Figure 17). CU-21 was symmetrically located with respect to the valley so that it could best take advantage of the terrain concavity. NW-2 on the other hand started at the bottom of a valley, continuing up the side of a ridge and into an area of convex terrain.

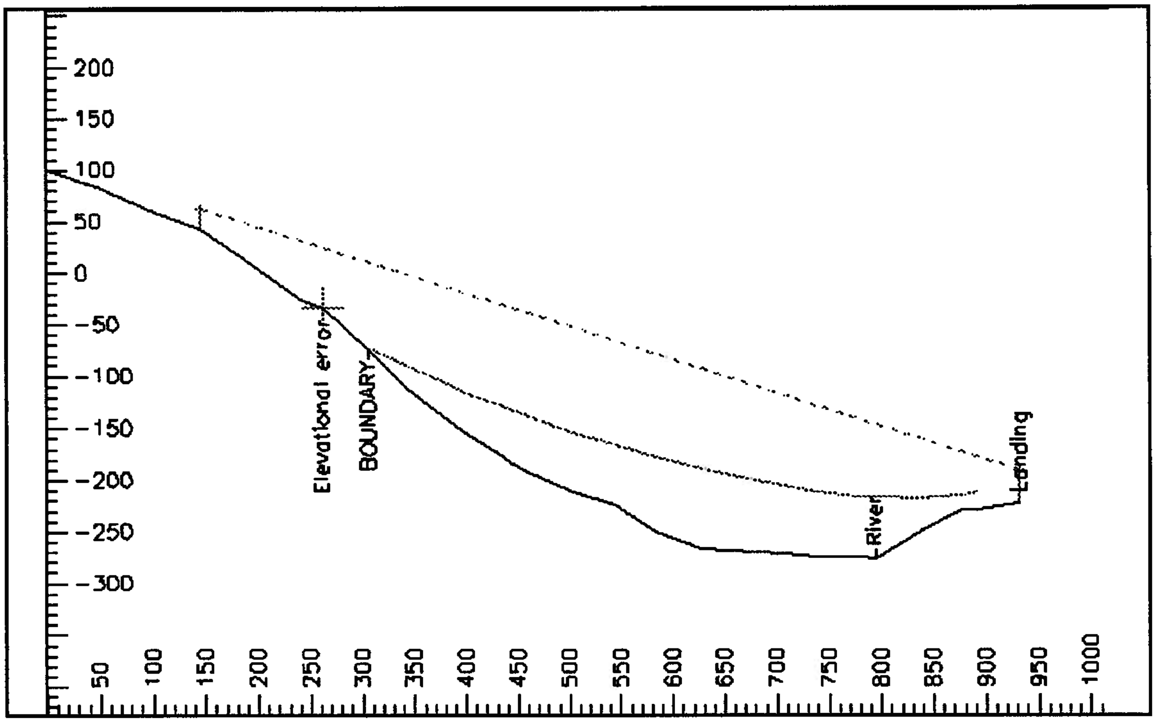


Figure 16 A positive elevational error in concave terrain resulted in the incorrect placement of the boundary for the NW-2 DEM-derived deflection-line.

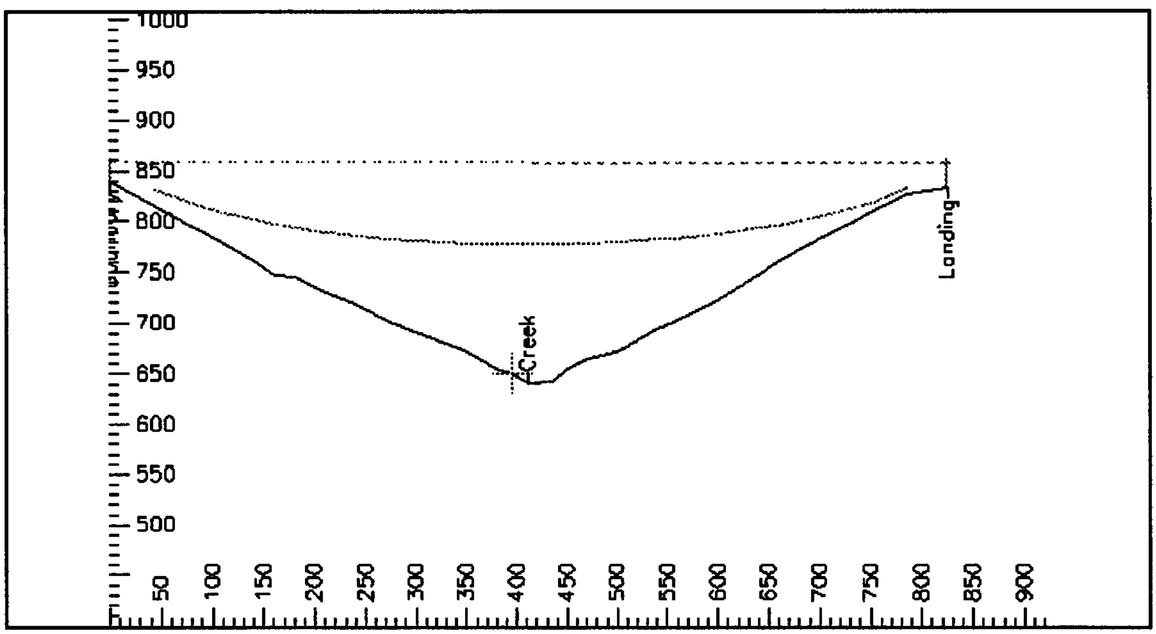


Figure 17 The concave shape of both deflection-lines for CU-21 provided adequate clearance for the entire length of the deflection-lines.

Of the four deflection-lines which were eliminated, only AR1-12 displayed an erroneous yarding distance estimate, an overestimate of 127.7 metres. This was the longest error for all the deflection-lines and AR1-12 was the shortest deflection-line with an incorrect yarding distance estimate. AR1-12 was primarily convex, and the elevational errors were of a size which may have not influenced yarding distance estimated on concave terrain. The other deflection-line eliminated from cutblock AR1, AR1-11, had elevational errors of similar magnitude, but it was on concave terrain and did not experience error in yarding distance estimates. The two deflection-lines eliminated form CU, CU-22 and CU-23, were much longer than AR1-12 but did not experience error in yarding distance estimates. These two deflection-lines were similar to CU-21 (Figure 17) in that they were symmetrically located in concave terrain. These results emphasize the important relationship between elevational errors, and their location with regard to the terrain, and their effect upon yarding distance estimates.

7.1.2 Large Elevational Errors

While the mean error gives a good indication of the general trend in the elevational error of a DEM-derived deflection-line, large individual errors are much more relevant when analyzing potential problems with yarding distance estimates. A large error may indicate a significant local feature such as a ridge that was not represented properly on the DEM. This appears to have been the problem for the three remaining deflection-lines which had incorrect yarding distance estimates. In Figure 18 it can be seen that a missing rock bluff on the DEM-derived deflection-line had affected the yarding distance estimate, resulting in a difference of -35.4 metres.

A small mean error and standard deviation could hide the presence of a few large individual errors. Only one large error is needed to cause an erroneous yarding distance estimate. If a large negative error occurs at the end of a deflection-line, an underestimation may result such as occurred for GC-5. Conversely, a large positive error at the end of the deflection-line could lead to an overestimation.

A large negative error towards the centre of the deflection-line could cause an overestimation of yarding distance (Figure 19). Conversely, a large positive error

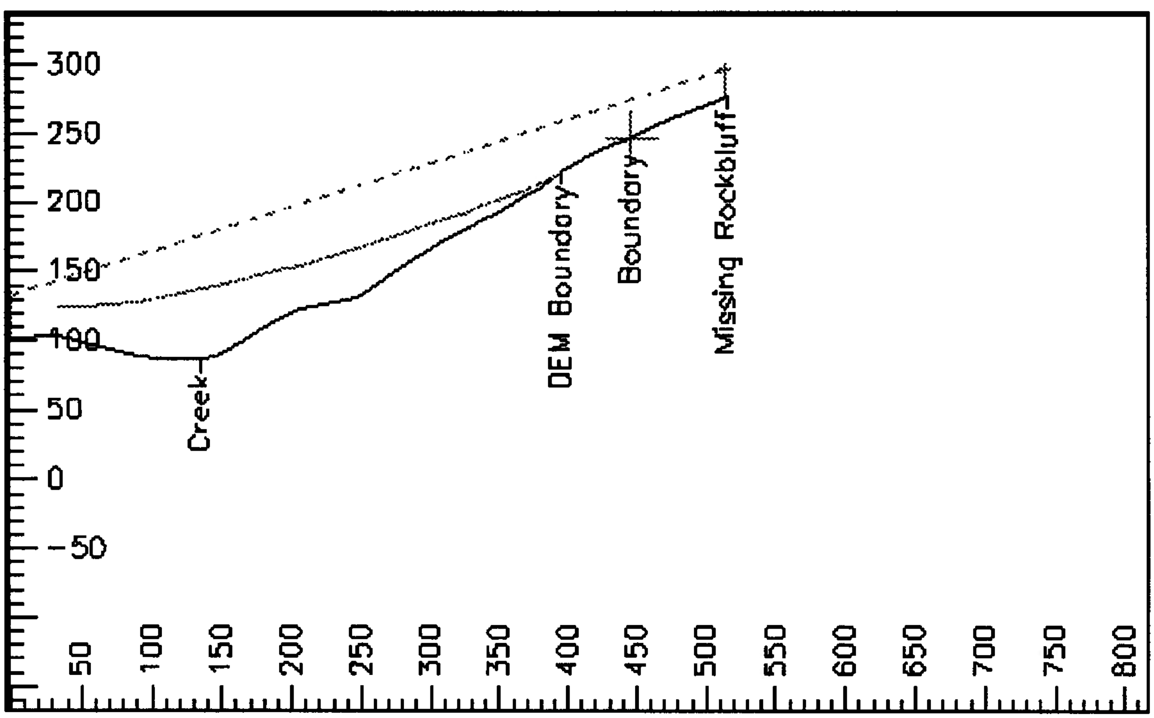


Figure 18 A large elevational error at the end of the GC-5 DEM-derived deflection-line resulted in an incorrect boundary location.

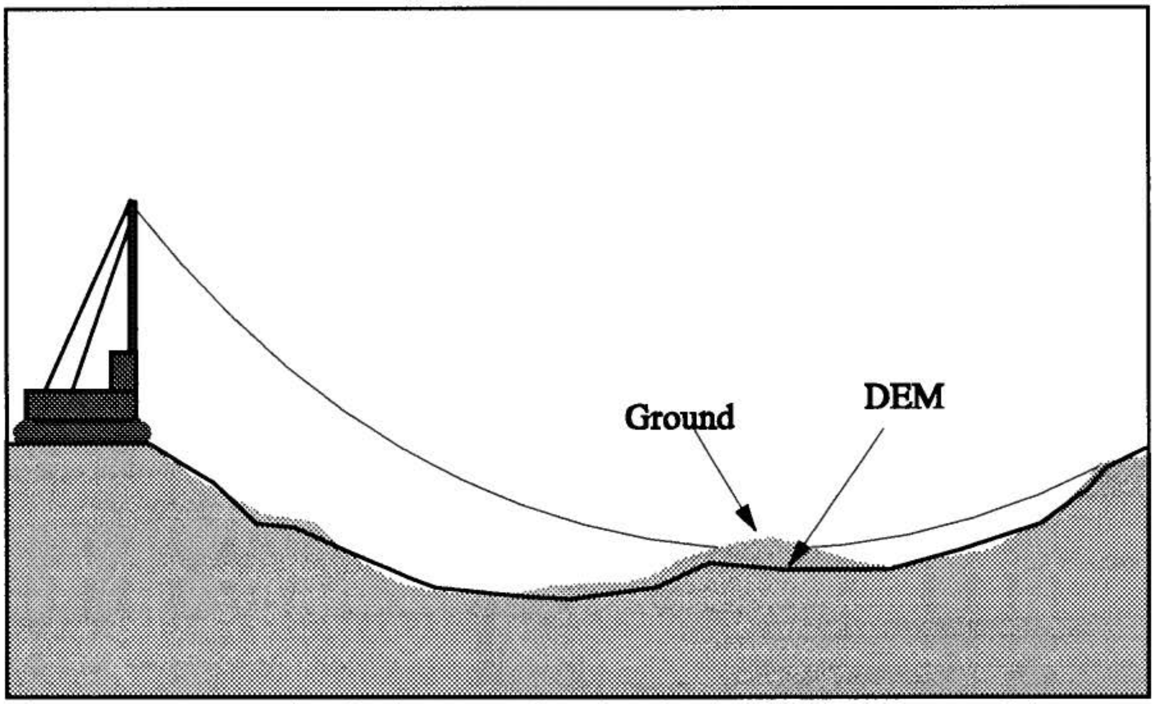


Figure 19 Example of a large negative elevational error in the centre of the deflection-line, causing an overestimate of yarding distance.

towards the centre of the deflection-line could cause an underestimation of maximum yarding distance. These errors were much less likely to occur simply because there was usually more clearance at the centre of a deflection-line than at the end.

While the above scenarios were possible, they do not appear to have had a large influence on the study. The large elevational errors were usually indicative of a localized feature which caused other adjacent large errors. In the case of GC-5, it appears that the deflection-line ended on the edge of one feature that was not represented by the DEM. If the deflection-line had incorporated more of this feature, more elevations would have been affected . This would be reflected in either the mean or the standard deviation or both.

Seven of the nine errors in yarding distance were underestimates (Table B1). Underestimating the maximum yarding distance will always result in boundary locations placed too close to the landing (unless corrected by field surveys). This equates to reduced access to timber, which may be compensated for by increased road density when it is not necessary. When additional roads are not possible, the timber will be left unharvested when in fact it is accessible.

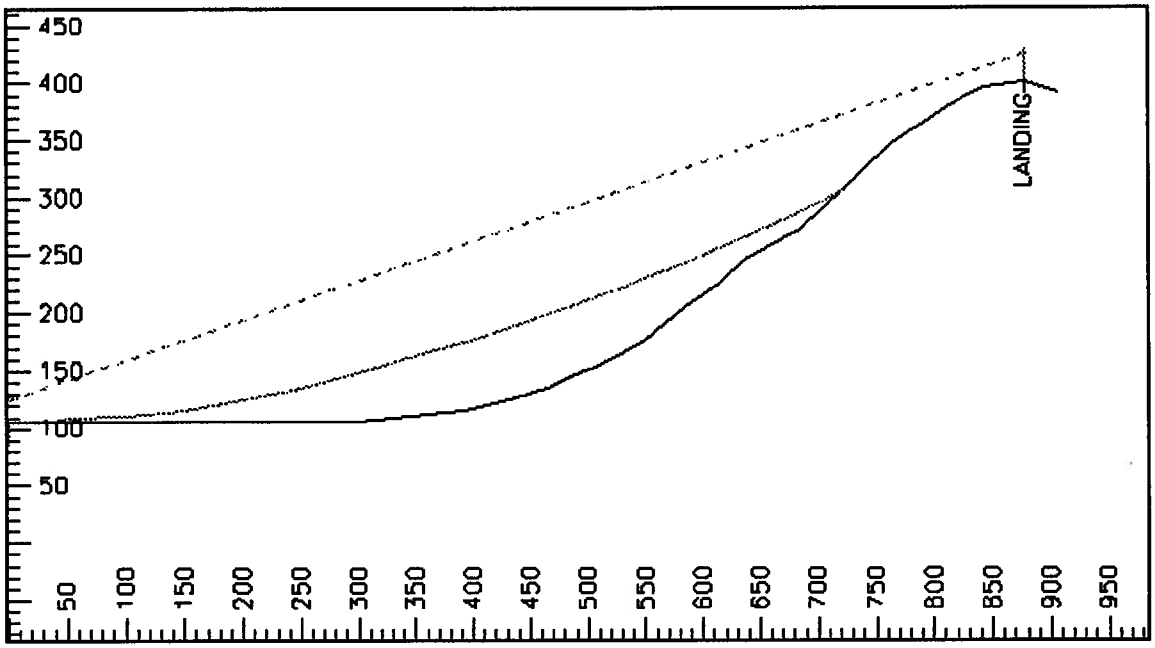
The effects of underestimation of maximum yarding distance will also depend somewhat upon the individual deflection-line. Reduced payload clearance may result if the proper location for the boundary should have been a raised feature such as the top of a rock bluff. An example of this, once again, is Figure 18. The rock-bluff afforded better clearance than the location chosen using the erroneous DEM-derived deflection-line.

AR6-5 displayed the other overestimated yarding distance, which was caused by a large positive error at the end of the deflection-line. This will always result in lower clearance or lower payloads. Inadequate clearance may lead to the carriage being dragged on the ground which can cause significant and expensive damage. Logs may be damaged leading to reduced value and lower volume recovery. Damage may also occur to the site when the carriage and or logs are dragged across the surface exposing or displacing the soil. Turn times will likely increase as will the per cubic metre cost of yarding.

When the boundary occurs at a prominent feature then error in yarding distance estimates from DEM-derived deflection-lines may be negated when the boundary is finally located in the field. For example, the yarding distance estimate for the AT-202 DEM-derived deflection-line was found to be 33 metres shorter than that for the field surveyed deflection-line. Careful visual inspection of the deflection-line analysis plots (Figure 20) indicated that the landing was placed in the same location on the ridge for both analyses.

The difference between the yarding distances appears to be due to a positional error in the start location for the DEM-derived deflection-line (left side of plot). The significant yarding boundary placement occurred at the landing since the ridge was part of Canfor's Forest Licence boundary. As well, the other yarding boundary occurred at the bottom of the ridge, since the flat on the left portion of the deflection-line had already been harvested. Since the ridge was such a prominent feature, the field surveys placed the landing and boundary in the correct location.

While the error in maximum yarding distance estimates considered as a percentage of deflection-line length was low, the economic impact of these errors could be substantial. Building more roads than are necessary, especially in steep and sensitive terrain, is extremely costly, both financially and environmentally. With increasing emphasis on



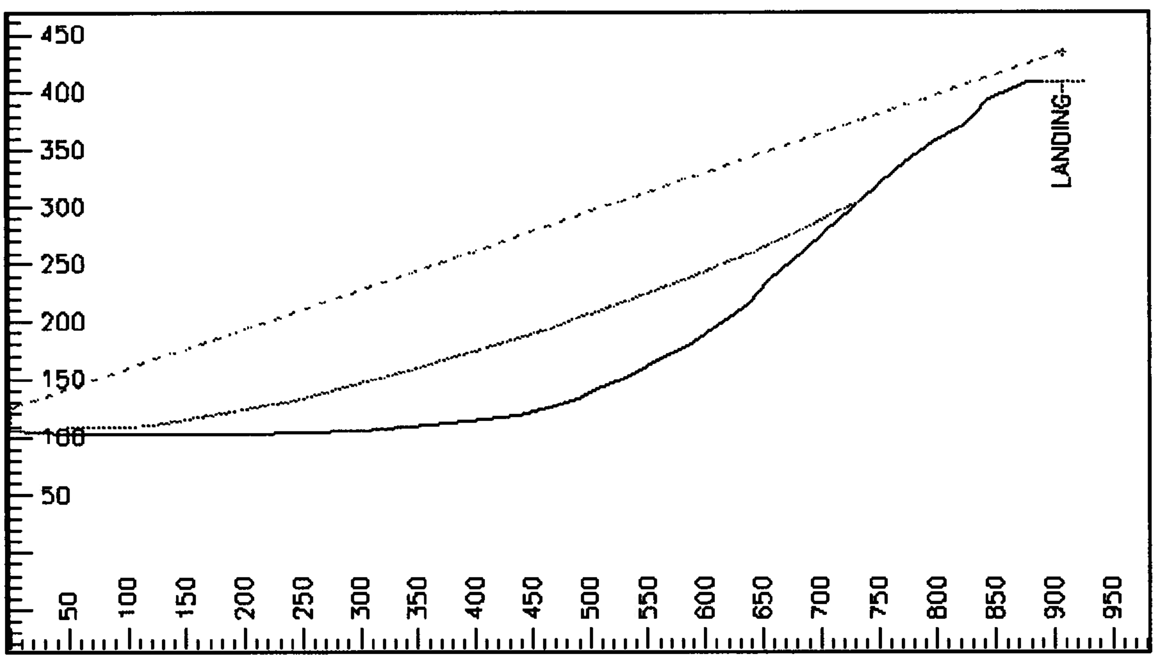


Figure 20 The deflection-line analysis plots for AT-202 show that the landing was located properly on both plots despite the 33 metre underestimation of yarding distance from the DEM-derived deflection-line (upper plot).

better forest practices, and the consequent penalties, environmentally damaging practices will also become heavy financial burdens. If road densities are not increased then timber will be left standing when it could have been harvested. Damage to site, logs, and equipment as well as the consequent reductions in yarding productivity could be extremely costly. These substantial impacts of either underestimated or overestimated yarding distances may be tempered if DEM-derived deflection-lines are used to pre-plan field surveys only. The most critical deflection-lines can be targeted for field surveying with crews given the freedom to adjust plans where the field surveys dictate.

7.2 Elevational Error and Error Patterns

Comparison plots used to illustrate the presence of one type of error may also display other types of error. It is likely that most types of error discussed in this section, with the exception of blunders and rubber sheeting, may be found in all of the deflection-line comparisons. For some comparisons, different types of error have interacted making it difficult to identify any particular error as the most influential. For the comparison plots used as examples in this section, the error type being discussed was not the only error type present, just the most prominent.

The mean error of all deflection-line data was positive. The majority of data groups (cutblock, setting, and deflection-line) also had positive mean errors. This suggests a trend towards overestimation of ground elevation by the DEMs which indicates the presence of systematic error. Processes used to create the DEMs and extract the deflection-lines likely cause small, random errors. Systematic error of the size determined was likely present in the analog maps having been introduced during the photo-interpretation process. The error was likely exacerbated by positional error present in the source maps and introduced during various stages of the study. It is the various potential sources of this systematic error on which the following discussion will concentrate.

7.2.1 Blunders

Visual analysis of deflection-line comparison plots turned up an apparent global error, or blunder, in the AR1 cutblock map. Figure 21 and Figure 22 show divergence between the DEM and field surveyed deflection-lines.

The elevational error for cutblock AR1 was not significantly different from zero. The same was true for AR1-11. For AR1-12 the elevational error was significantly different from zero. This was also the same deflection-line that gave the greatest error in yarding distance estimate. This error, 127.7 m, was larger than the range of error from the other eight erroneous estimates.

There were two 1:5000 scale mylar maps available for cutblock AR1. Only one had a grid reference system and it was chosen for that reason. After the problems were detected, the two mylar maps were compared and it was found that there were some significant differences in contour locations between the two maps. The two maps were

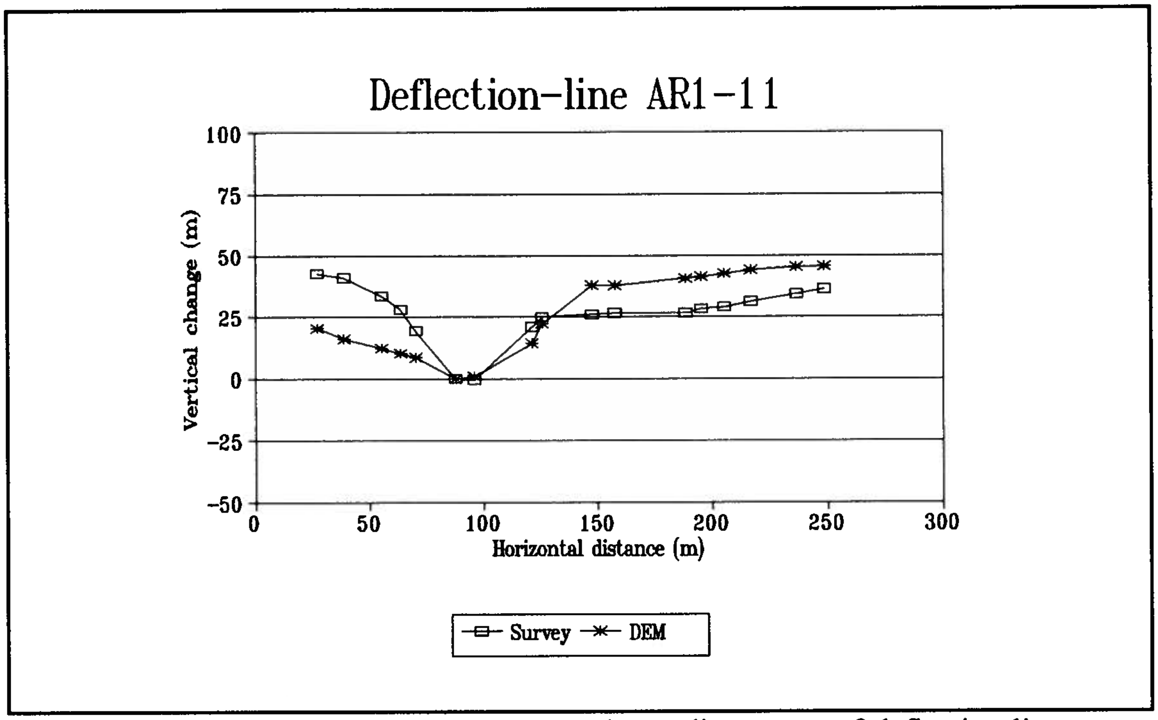


Figure 21 Comparison plot for AR1-11 shows divergence of deflection-lines, apparently due to a map blunder.

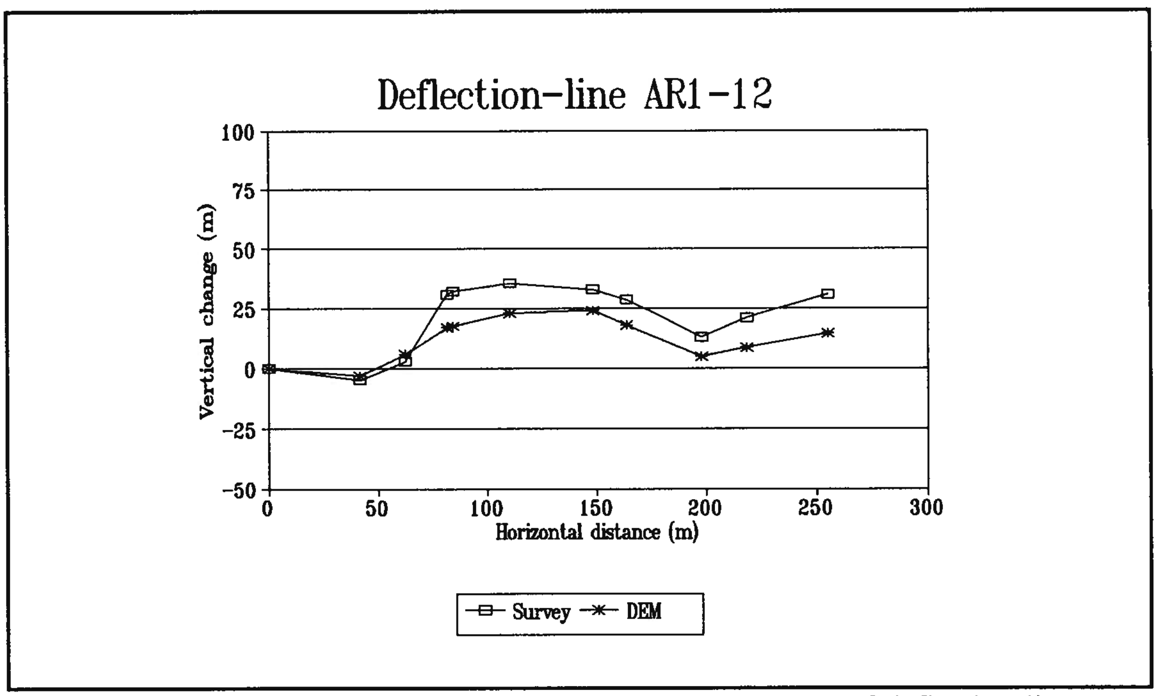


Figure 22 Comparison plots for AR1-12 shows divergence of deflection-lines, apparently due to a map blunder.

compared with the field surveyed deflection-lines. It was found that the unused map was more representative of the field surveyed deflection-lines than the map that was used. The reason for the differences between the two maps was not determined.

The error in yarding distance estimate for AR1-12 was caused by a poorly represented ridge on the DEM-derived deflection-line. More field surveys are needed to see if the error, evident in this major feature, was globally distributed throughout the map. It should be noted, however, that without testing the DEM-derived deflection-line this blunder may not have been detected. This demonstrates the extreme value of field checking the accuracy of topographic planning maps.

7.2.2 Distortions Caused by Rubber Sheeting

It was expected that the GPS and laser survey of GC would reduce the general level of elevational error found in this cutblock. Surprisingly, the level of error increased for the cutblock as a whole, for three of the four settings, and for four of the eight deflection-lines. This unexpected result may have been due to the presence of two types of mapping in the cutblock (Figure 13). The right portion of the map was field surveyed and the left portion created from aerial photographs.

The only setting which experienced a decrease in error, GC-S3, was comprised entirely of two of the deflection-lines which had also had reduced error. These deflection-lines were located entirely in the photogrammetrically-measured portions of the maps. The main tie-points used were all in this portion of the map as well.

Two of the three settings which showed increased error, GC-S1 and GC-S2, were located by the laser survey after it crossed the boundary between the two different mapping types. The other setting with increased error, GC-S4, was also entirely in the photogrammetric portion of the map but was very close to the mapping type boundary.

Rubber sheeting is the process of rectifying one map to a more accurate map depicting the same geographic location. Common tie-points are identified on both maps, and a mathematical correction is applied to the entire map, based upon the corrections that were used to align the tie-points (Burrough 1986). It was suspected that when the two map formats in GC were merged, there was significant difference between the two and a certain amount of very crude rubber sheeting was performed.

The GPS-laser survey located all deflection-lines as one complete survey and crossed the map type boundary several times. The results indicated that something was wrong. Since three of the four deflection-lines that have increased error were located by a traverse that crossed the map type boundary it was believed that the distortion at the boundary caused the increase in error. The GPS-laser survey was very tightly controlled and was of a precision that would not allow this degree of error. The accuracy of the GPS-laser survey, and the confidence in it, was what allowed this distortion to be detected. When the deflection-lines were originally placed on the map they were located individually, using creek crossings as tie-points. Distortions due to the mapping type boundary were not relevant since the deflection-lines were not tied together by a survey which crossed the map type boundary.

The CU cutblock also contained portions of the map which were field surveyed. When the problems with GC were discovered the results from CU were re-analyzed. Deflection-lines CU-20 and CU-21 were located entirely within the photogrammetrically derived portion of the map (Figure 12). The comparison plots for CU-20 shows an example of how well matched these deflection-line pairs were (Figure 23).

Deflection-lines CU-22 and CU-23 started from a landing that was located in the field surveyed portion of the map. The boundary between the mapping types was just to the north side of the main creek. The comparison plots for CU-23 showed a large discrepancy in elevational error between the left side of the creek, which was field mapped, and the right side, which was photogrammetrically mapped (Figure 24). This was likely caused by an error in reconciling the two different mapping types. This discrepancy may have been due to positional error instead, since shifting the DEM-derived deflection-line to the right would have made for a better match. However, this was probably not the case since the two profiles were tied together at the creek crossing which was a very good tie-point. Even if the DEM-derived deflection-line was shifted, it still would not match well on both sides of the creek for the same alignment.

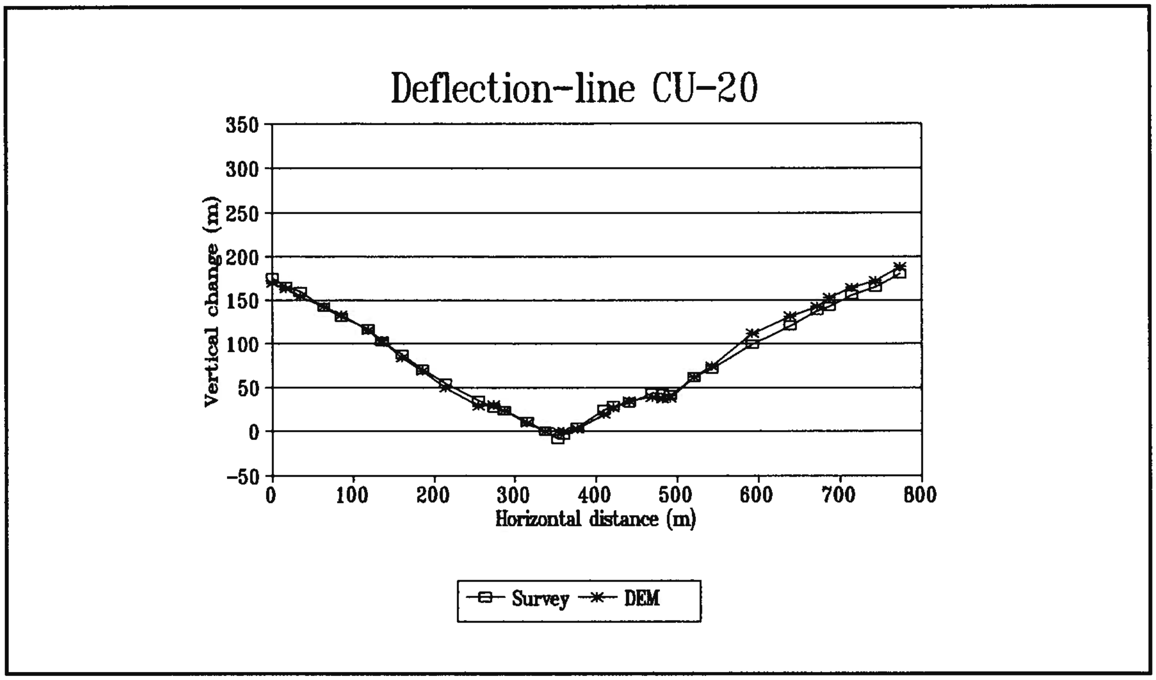


Figure 23 The well matched deflection-line pair for CU-20 is an example of the deflection-lines contained entirely within the photogrammetrically derived portion of the map.

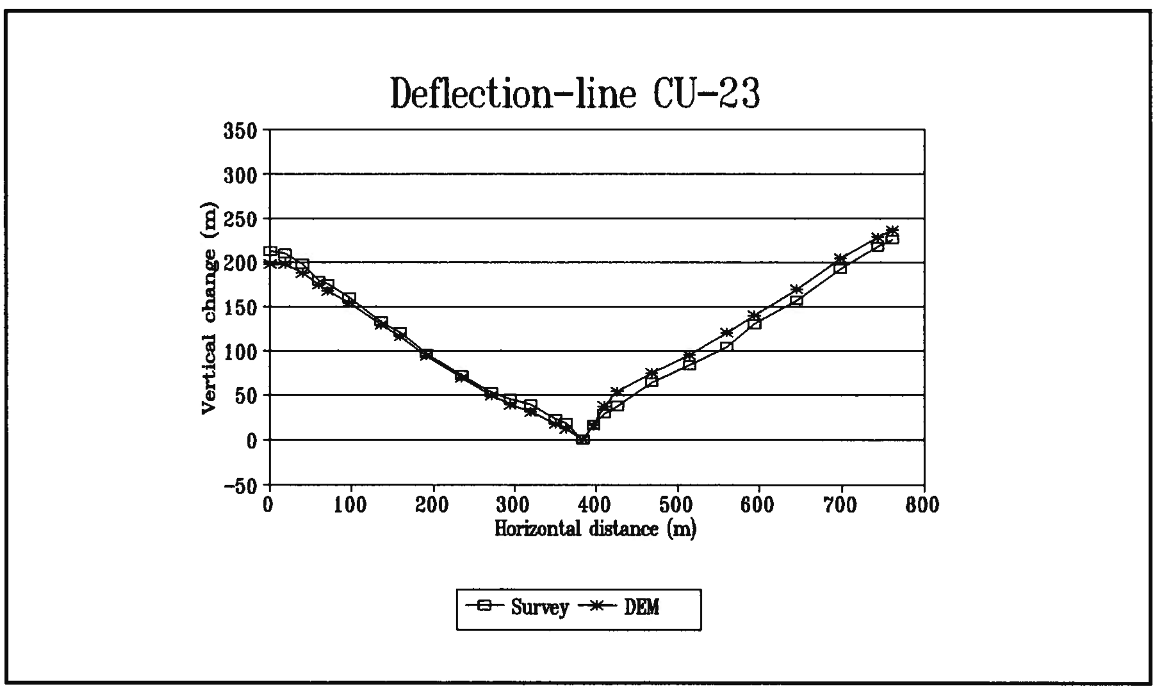


Figure 24 Comparison plot for CU-23 shows a large discrepancy in elevational error between the photogrametrically derived portion of the map (left side of plot) and the ground surveyed portion (right side).

The mean elevational error was not significantly different from zero for either CU-22 or CU-23 ($\propto$=0.1). These results were obtained using a sign test which is not an efficient test. Figure 23 shows quite obvious errors in the elevations of the DEM-derived deflection-line. These errors were fairly evenly distributed between positive and negative errors. The same was the case for CU-22. Since the sign test only checks positive differences against negative differences, and not the magnitude of those differences, the test had probably failed to detect important errors in both CU-22 and CU-23.

Even if these two DEM-derived deflection-lines did have mean errors which were significantly different from zero, they did not cause any errors when estimating yarding distance. This was due to the very favourable terrain location of these deflection-lines. As was mentioned for CU-21 previously, the deflection-lines were symmetrically located in the valley to take best advantage of the terrain concavity. If the deflection-lines were not symmetrically located, or the rubber sheeting error occurred in less favourable terrain, then errors in yarding distance estimates may have occurred. Once again, this demonstrates the importance of field testing topographic planning maps.

7.2.3 Random Error

Many of the DEM-derived deflection-lines displayed patterns indicative of random error. GC-5 was a good example where the elevational error appears to be mostly random in nature. Looking at the comparison plot (Figure 25) it can be seen that the

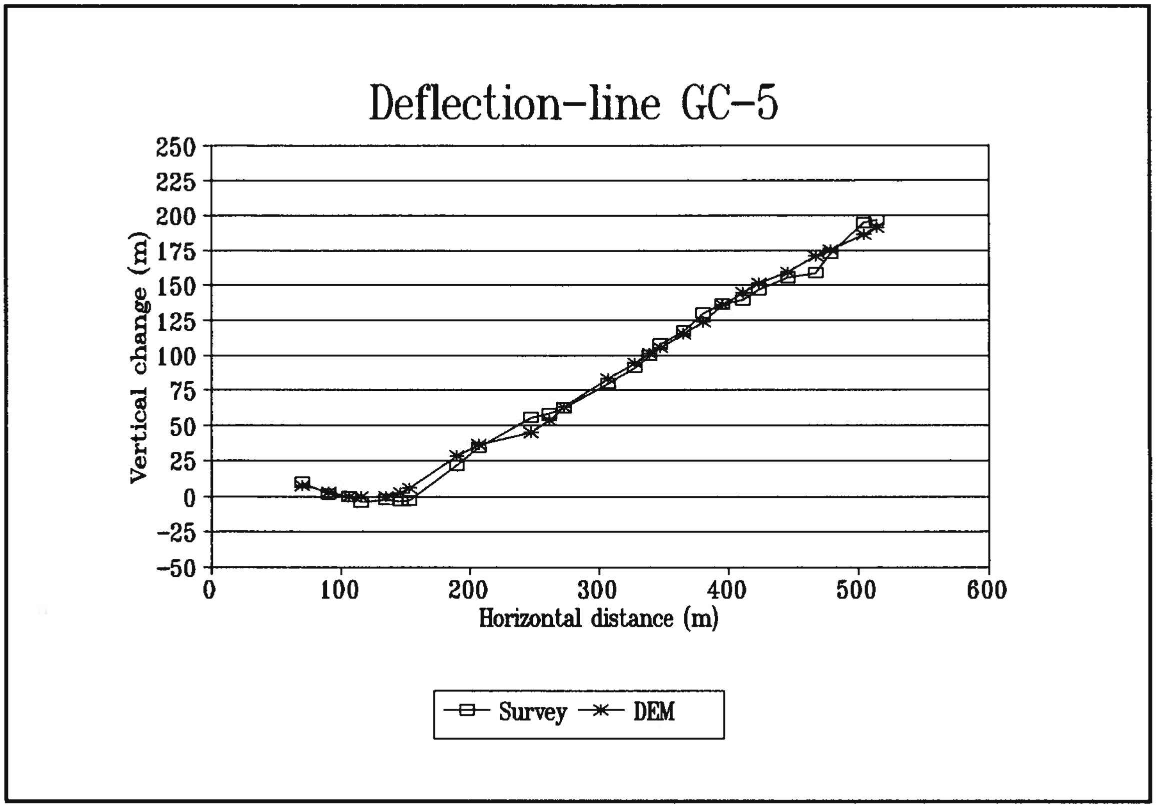


Figure 25 Deflection-line comparison plot for GC-5 indicates minor, random variation in elevations.

two deflection-lines have the same basic shape with only minor, random variations. The histogram of the error (Figure 26) describes a normal curve. Statistical tests showed the elevational error to be normally distributed and the mean error was not significantly different from zero (α=0.1).

Other deflection-lines had normally distributed error and mean errors which were significantly different from zero. The histogram for AT-200 is a narrow, normal distribution that is skewed slightly to the right (Figure 27), indicating the presence of systematic error. The comparison plot shows that the deflection-lines were well

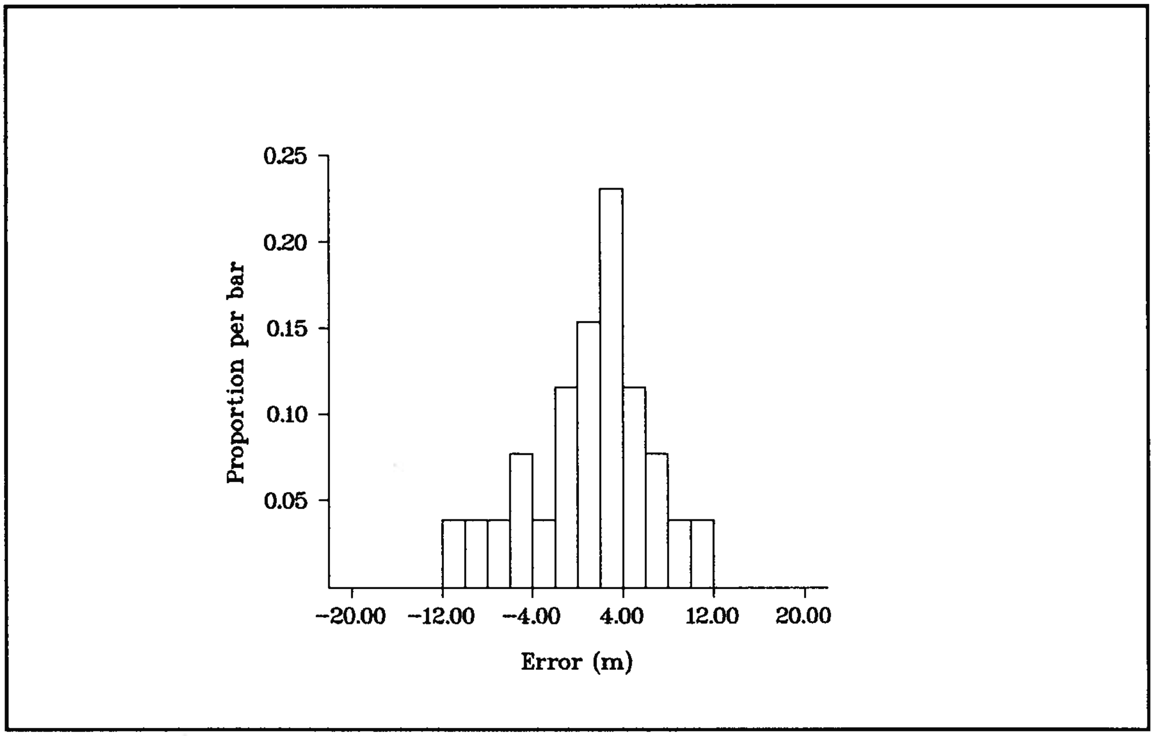


Figure 26 Elevational error histogram for GC-5 describes a normal curve.

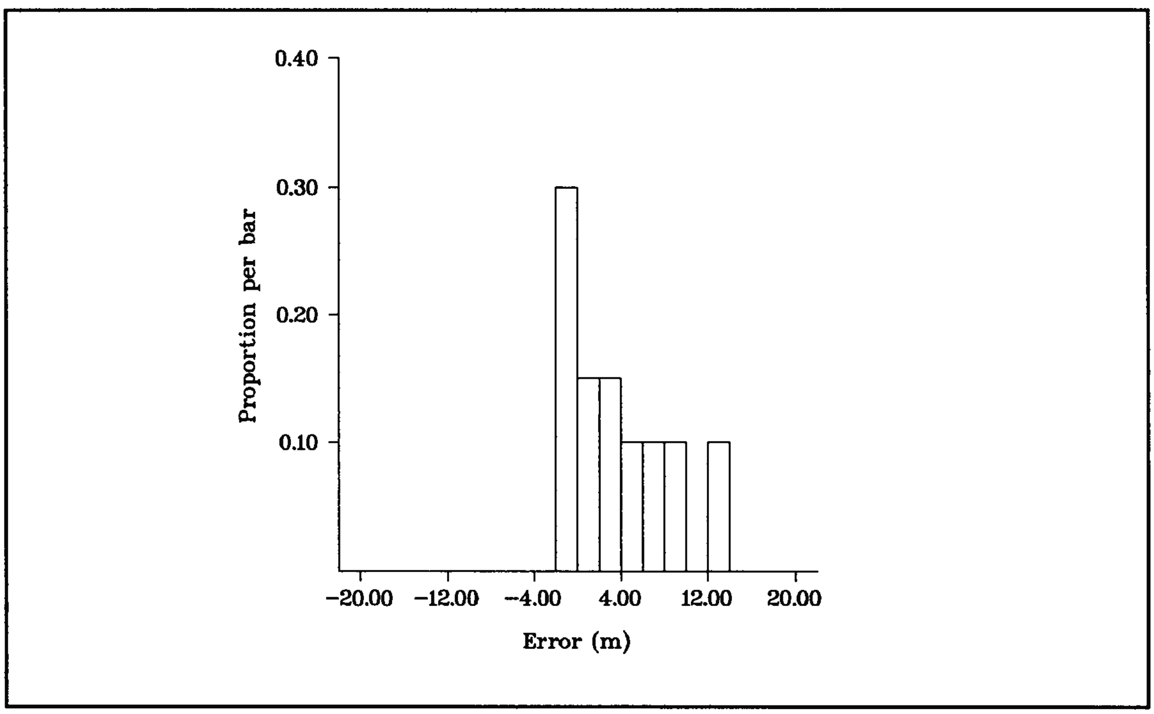


Figure 27 Elevational error histogram for AT-200 is right skewed, indicating the presence of systematic error.

matched although the DEM-derived deflection-line had a tendency to be higher (Figure 28). For some reason, the photo-interpreter overestimated the ground elevation for this area. This may have been caused by site characteristics which produced taller trees than the photo-interpreter believed. Systematic error of this sort was evident in most of the deflection-line comparisons to some extent. Potential sources of this systematic error are dealt with in the following section.

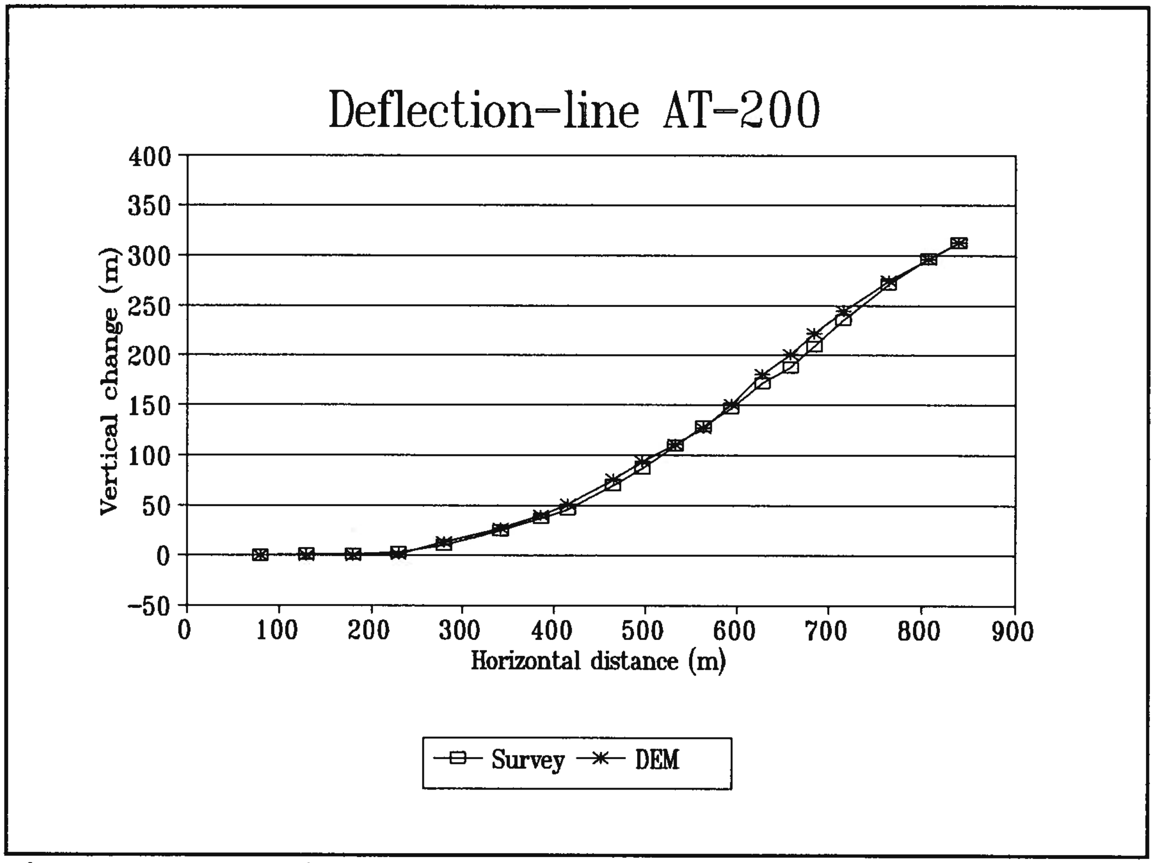


Figure 28 Comparison plot for AT-200 shows a well matched deflection-line pair, with the DEM-derived deflection-line tending to be higher in elevation.

7.2.4 Systematic Error

There was strong evidence that systematic error had influenced the overall elevational error of the DEM-derived deflection-lines. The proportion of elevation error due to systematic error probably exceeds the proportion due to random error. Reduction of systematic error in DEM-derived deflection-lines would probably result in yarding distance estimates which are the same as those from the field surveyed deflection-line.

The systematic error identified in this study was primarily the result of positional error and smoothing error. These errors were introduced through processes used to create the original source material, processes which were controlled by this study. As well, both positional and smoothing error were likely introduced during the study, although to a lesser extent.

7.2.5 Smoothing Error

Smoothing error occurs when natural variation in the terrain, evident in the field surveyed deflection-lines, has been 'smoothed out' in the DEM-derived deflection-lines. Figure 29 is a good example of smoothing error. The left portion of the comparison plot shows how both the minor concave and convex portions of the field surveyed deflection-line have been lost in the DEM-derived deflection-line. This portion of the GC cutblock had been influenced by past fire activity which had created differing stand composition.

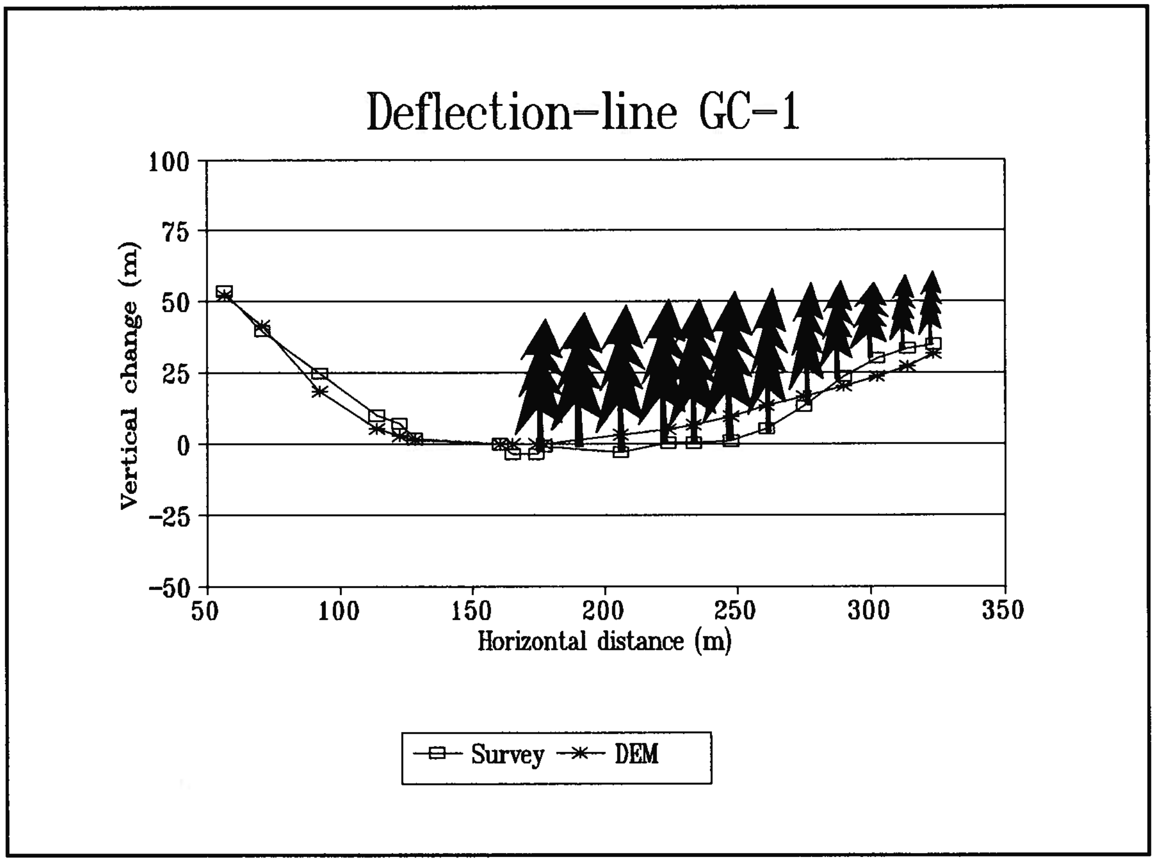


Figure 29 Differing tree heights, due in part to variable sight conditions, have resulted in an even forest canopy which masked the terrain variation from the photogrammetrist.

Much of the variability in the ground surface between about 175 metres and the end of the deflection-line had been eliminated by the DEM. The concave portion of the field surveyed deflection-line was a superior growing site compared to the convex portion. Old growth Douglas-fir trees, which survived the fire, predominated in this area.

The convex portion of the field surveyed deflection-line was rocky and dry. The fire caused more damage here resulting in a younger forest of shorter western hemlock trees. It was quite likely that the top of the forest as a whole was very consistent. The photogrammetrist may have seen a consistent, rising slope and then plotted the contours accordingly.

The comparison plot for TR-4 (Figure 30) shows smoothing occurring consistently along the entire DEM-derived deflection-line. The TR-38 cutblock had fairly consistent forest cover with no recent evidence of fire. It was a wetter site with much evidence of replacement by windfall. Wind may have had a greater influence in this area, shearing off the tops of trees and creating a consistent canopy surface. Once again the

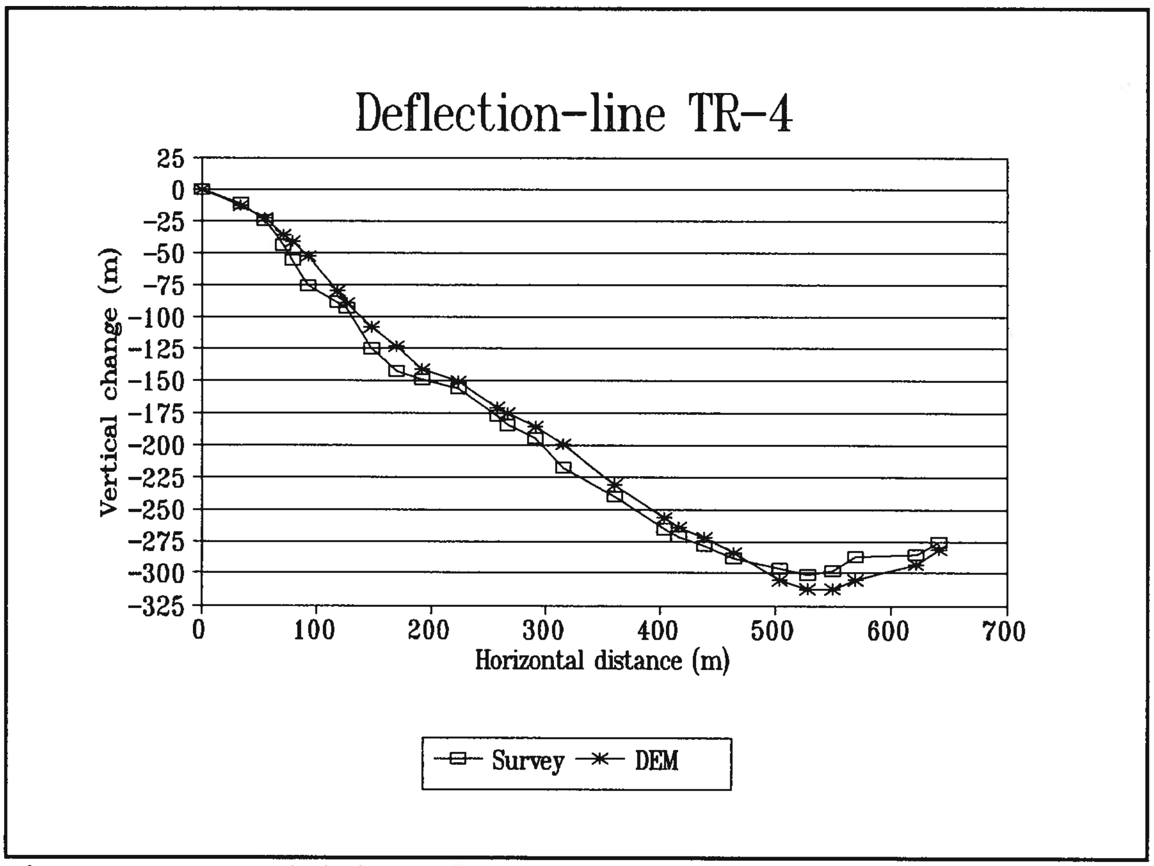


Figure 30 Past wind history created an even forest canopy which prevented the photogrammetrist from detecting terrain variation.

photogrammetrist may have believed that the ground surface was less variable than it actually was.

While it appears that shifting the DEM-derived deflection-line to the left might eliminate most of the differences, the variation shown in the field surveyed deflection-line would still not have been represented in the DEM-derived deflection-line. The two deflection-lines were tied together at the left side which was on an open ridge. For this reason it was believed that the two lines were fairly well matched. The discrepancy evident at the creek crossing, the only portion of the comparison plot where the field surveyed elevations were higher, was probably due to some site characteristics which had affected the estimation of the ground elevations. This is dealt with in more detail in the next section.

7.2.6 Effect of Site

The nature of the cutblocks, that they were planned for forest harvesting, ensures they were heavily forested. It appears that the photo-interpreters who created the maps generally underestimated tree heights, thereby overestimating the ground elevation. This may have been confounded by the topographic location of the cutblocks. Cutblocks were primarily located in valley bottoms and on lower slopes. Soil and moisture conditions on these sites tend to produce taller trees. For the GC cutblock, the trees in the valley and lower slope areas were 50 to 60 metres tall. Progressing upslope along each deflection-line, the tree heights gradually decreased. For the deflection-lines which ended on the ridge top, GC-7, GC-8, and GC-10, trees were approximately 30 to 35 metres tall.

While this trend was evident for other cutblocks, it was most pronounced in GC. GC was the only cutblock which was predominantly forested with Douglas-fir and western hemlock. The other cutblocks were dominated by western hemlock, amabilis fir, and western red cedar. The presence of Douglas-fir in GC may indicate better growing conditions than in the other cutblocks. Within GC, there was more of a pronounced difference in growth between the better valley bottom sites and the poorer ridge top sites.

For the AT cutblock the deflection-lines indicated a different pattern of tree heights. There was no major valley in this cutblock. The deflection-lines started on a plateau, extended along this plateau and then up the adjacent ridge top. The tree heights were low, 30 to 35 metres on the plateau and on the ridge top while they were around 40 to 45 metres on the lower and mid-slopes. The trees were shorter on the plateau because it was a very moist site with limited tree growth. Vegetation was probably sparse and the ground elevation therefore easy to estimate. These conditions would combine to give the error pattern for AT-200 which was discussed previously (p. 80).

For deflection-lines which did extend to ridge tops the ground elevation was well estimated. The trees tended to thin out in these locations allowing for less obstructed views of the ground. Adding to this, on the aerial photographs, these locations were closer to the camera lens and therefore at a larger scale than the valley bottoms. More detail was evident and the ground easier to detect at the larger scale.

All deflection-lines were located on lower slopes and usually in valley bottoms. Only eleven of the twenty-seven deflection-lines extended to ridge tops. Therefore, the majority of deflection-lines did not benefit from the better ground elevation estimation that occurred on the ridge tops. Even for the eleven deflection-lines that extended to the ridge tops, most of the elevation points were not located on the ridge top. For all deflection-lines either most, or all, elevation points were erroneously estimated due to inaccurate tree height estimations.

7.2.7 Positional Error

Positional error was evident in the deflection-line comparison plots and throughout the error analysis. The main cause of the positional error appeared to come from poor tie-points. When deflection-line were transferred to the maps they may not have been properly located. If this occurred, then subsequent elevations extracted from the DEM would most likely be in error. This positional error was likely exacerbated by the traditional surveying methods used in the study. This influence could have been minimized by using high accuracy GPS and laser surveying equipment for all field surveying.

The effect of positional error upon elevational error may be significant. The comparison plots for AT-202 and AT-203 (Figure 31 and Figure 32) displayed the most obvious cases of positional error. Both plots appeared to be fairly well matched in shape but not in elevation. Both deflection-lines had some of the highest error levels of all the deflection-line comparisons. Amongst the cutblocks, AT had the highest level of elevational error, and amongst the settings, AT-S2 had the highest level of elevational error. The large errors in AT were likely due to a lack of effective tie-point features in the cutblock or in the adjacent area. The deflection-lines were tied to the intersection of a creek with an adjacent lake. This tie-point was approximately 250 m from the closest deflection-line and 1200 m from the furthest deflection-line. Considering the low accuracy of the surveying methods used in the study, which mimicked operational methods, these distances were too far for reliable tie-points.

In fact, it appeared that tie-points features were only useful when they directly intersected the deflection-line, such as a creek, or were very close to it (50 m). In comparison to AT, the deflection-lines of NW did not exhibit much positional error. This was most likely due to the presence of a large river which both deflection-lines crossed. The river was about 50 metres wide and very obvious on the aerial photographs. This would have enabled the photo-interpreter to make precise measurements of the river banks, channels, sandbars, and other easily identifiable features.

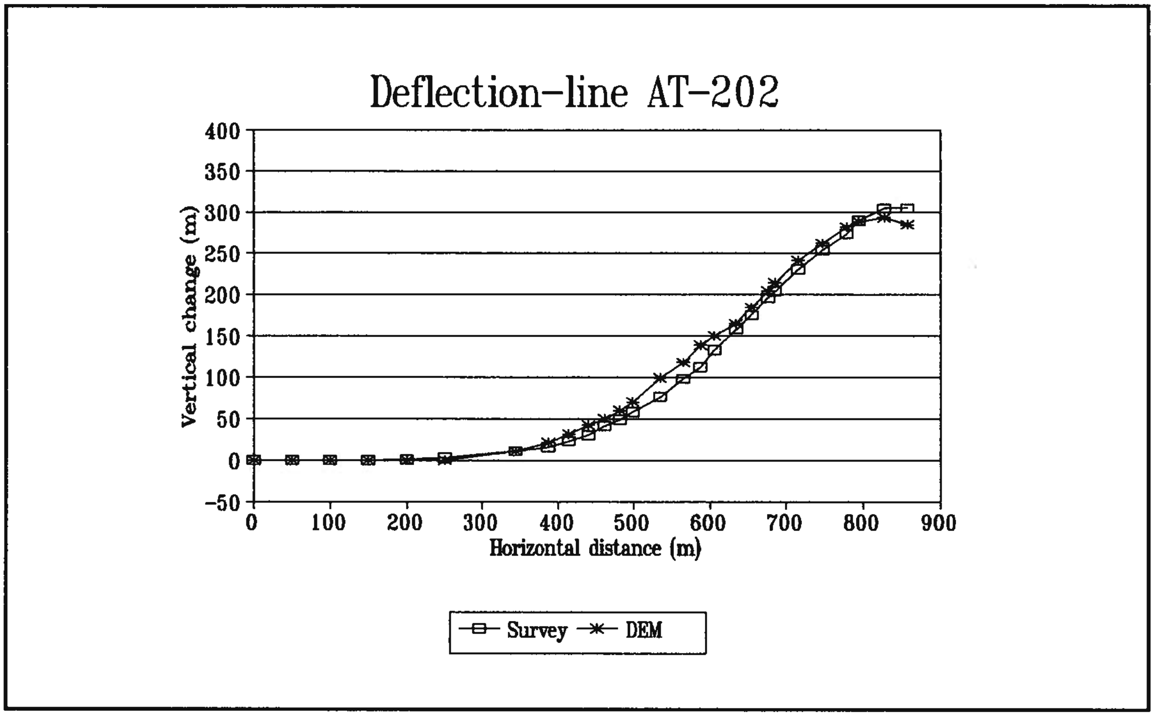


Figure 31 Comparison plot for AT-202 indicates presence of positional error.

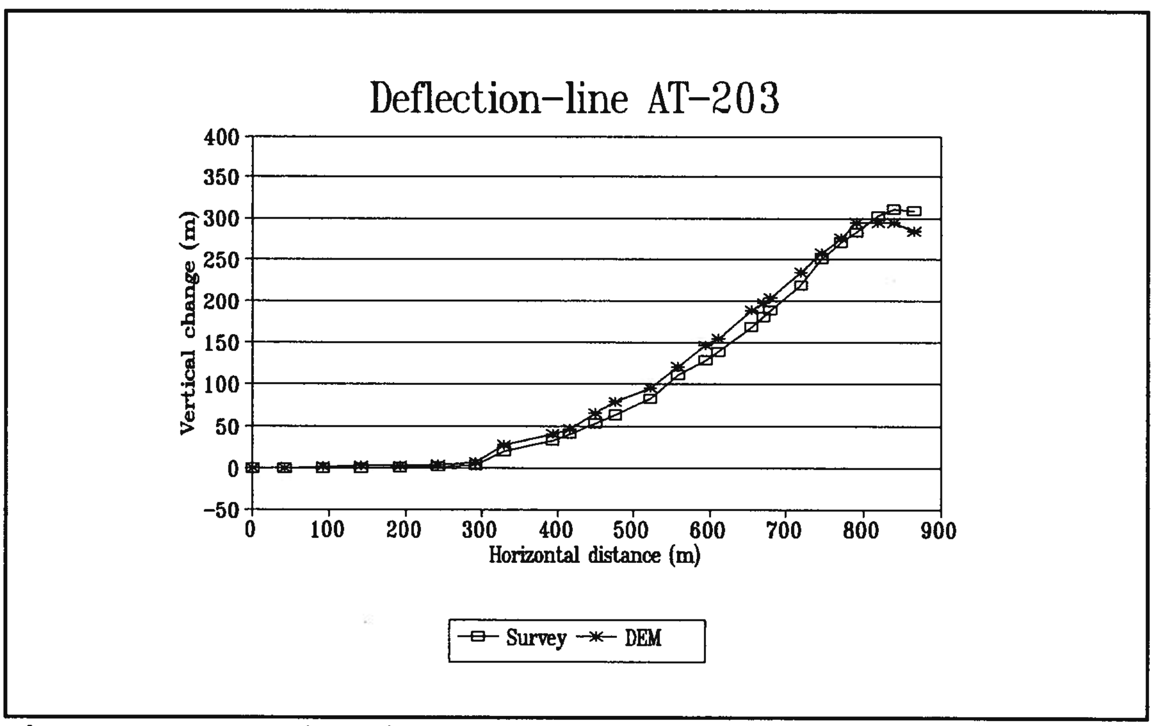


Figure 32 Comparison plot for AT-203, which shares a common landing with AT-202 (Figure 31), also indicates presence of positional error.

CU had the lowest level of error and did not appear to suffer from positional error. The creek in CU was much narrower than the creek in GC yet CU had even lower error than GC. The main creek in CU was sufficiently open to be seen effectively on aerial photographs. This creek was also in a sheer rock canyon which prevented the creek from shifting over time. In other cutblocks such as GC, it appeared that the creek had shifted significantly and this caused difficulties with the placement of some deflection-lines.

7.2.8 Age of Map Data

The age of map data was a extremely important when considering the reliability of tie-points. The maps used in this study contained PIPs and it was only possible to find one of these during the study. Other PIPs marked on the maps had disappeared in the field through age related processes. One particular PIP in cutblock AR6, a large tree on a point in the main creek, was easily identifiable on the aerial photographs. When checked in the field it was found that the creek had since shifted course and the entire point of land, tree and all, had washed away.

The one PIP that was found in AR6, along the main creek, was approximately 25 metres from AR6-1. The comparison plot for AR6-1 shows that the deflection-line was located well when transferred to the map (Figure 33). AR6-1 also had some of the lowest levels of elevational error displayed by all of the deflection-lines.

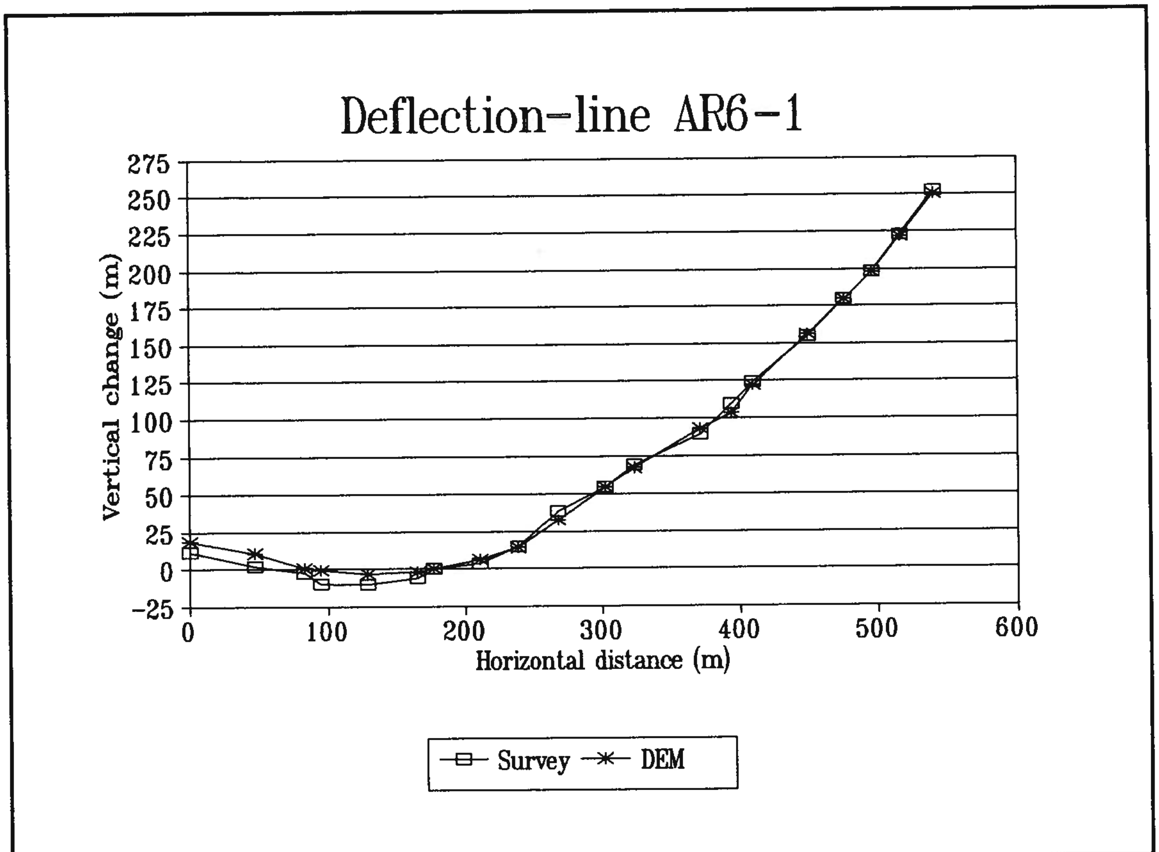


Figure 33 A PIP near deflection-line AR6-1 helped to reduce the effects of positional error when the deflection-line location was transferred to the map.

AR6-3 was approximately 300 metres away from AR6-1 and the comparison plot suggests that it was not located properly when transferred to the map (Figure 34). This positional error was caused by a lack of proximity to a reliable tie-point. The main creek, which AR6-3 crossed, was not a good tie-point due to its low visibility on the aerial photographs.

While the issue of age has come last in this discussion, it is by no means the least important. In fact, many of the issues of this study were age related to some degree.

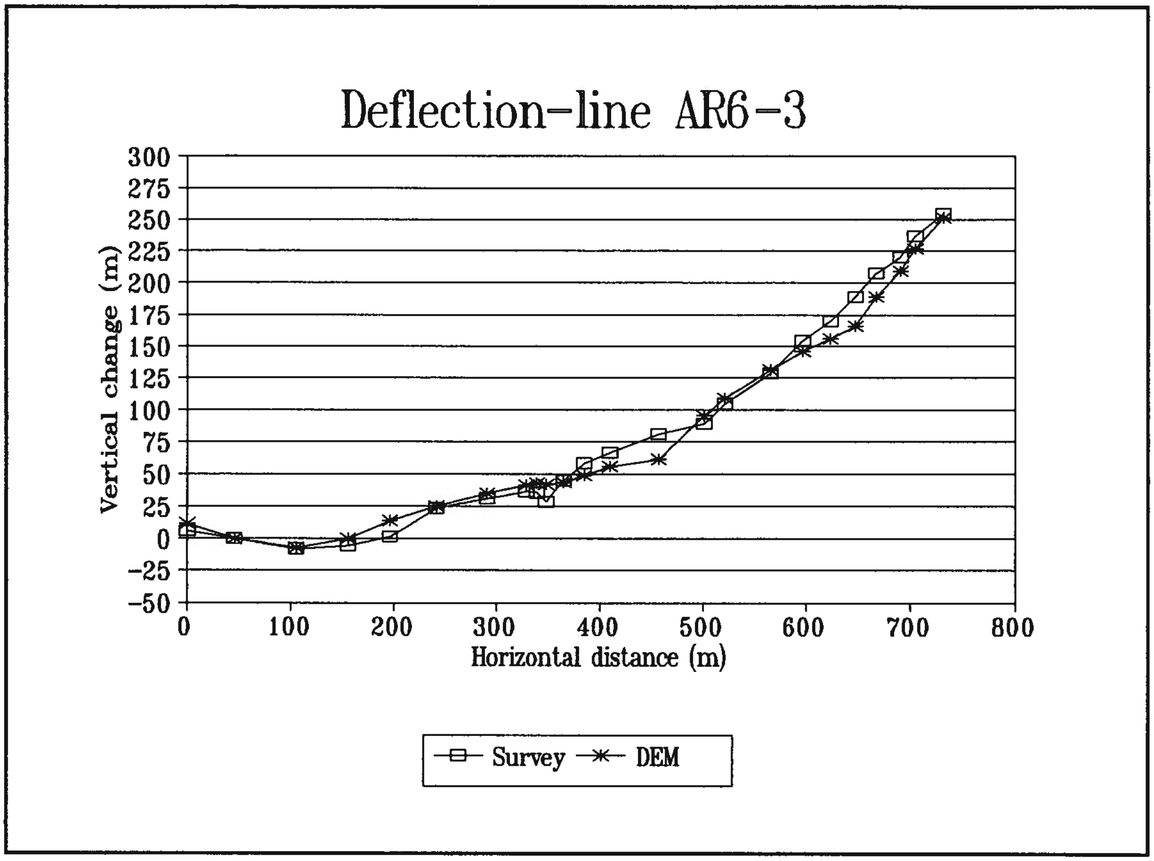


Figure 34 Deflection-line AR6-3 was not located close to a PIP and therefore experienced positional error when transferred to the map.

The issue of PIPs and the shifting of creeks over time were both mentioned. The shift from NAD27 to NAD83 coordinates, while avoided in this study, did preclude certain options for data transfer especially with the GPS and laser survey.

The age of map data is also relevant when considering the effects of technological obsolescence. Surveying methods and equipment used twenty years ago may have been adequate for analog maps and the analysis that was possible at that time. Those methods are certainly not adequate for the level of analysis now possible with the advent of micro-computers and Geographic Information Systems.

For example, Canfor acquired new digital orthopohoto maps for their entire operating area in 1993. Their entire network of established road was correctly located at that time, eliminating past surveying and transfer errors. The maps were also in NAD83 coordinates facilitating the addition of new data from such sources as GPS. Any further additions of road locations surveyed with a nylon chain and hand-held compass will compromise these new levels of accuracy.

While it is possible to use existing topographic planning maps for deflection-line analysis they must be used with an understanding of their limitations. These limitations cannot be realized without proper field checking. It may be necessary to field check dynamic features, such as creeks, on a periodic basis. Eventually it will be necessary for maps to be updated to detect all changes at one time and to keep pace with current technologies. This should be done with careful planning not just for present but for future needs, whether those needs are known or just anticipated.

8 Conclusions

The majority of yarding distances estimated using DEM-derived deflection-lines were not in error. The magnitude of the errors was relatively low, when considered as a percentage of deflection-line length. However, many potential economic and environmental impacts associated with these errors make it prohibitive to completely replace field surveyed deflection-line analysis with DEM-derived deflection-line analysis.

Field surveying will negate some of the impacts of error in yarding distance estimates. Prominent features which physically define a boundary will likely be chosen by field crews, regardless of the estimated yarding distances. Boundaries defined by such features may be identified during pre-planning with DEM-derived deflection-lines and designated for special attention by field crews.

Errors in yarding distance estimates for DEM-derived deflection-lines were caused by interactions between a few or all of the following: the deflection-line length, the terrain shape (concavity/convexity), elevational errors and their location on the deflection-line. When assessing the suitability of DEM-derived deflection-lines for estimating yarding distance, these interactions were more critical than the mean elevational error. The mean elevational error indicated a trend in the data and did not indicate any individual feature which was not properly represented.

The longest DEM-derived deflection-lines had more tendency to display error in yarding distance estimates than did the shortest DEM-derived deflection-lines. These errors occurred when the shape of the deflection-line changed from concave to convex. Elevational errors, particularly large ones, had a greater influence on yarding distance estimates in convex terrain, where clearance was often reduced. Shorter deflection-lines usually did not reach convex portions of the terrain. Symmetrically located deflection-lines on concave terrain displayed no error in yarding distance estimates.

The majority of errors in yarding distance were underestimates. Underestimates may reduce access to timber, necessitating an increase in road densities. Building more roads than necessary, especially in steep and sensitive terrain, is extremely costly, both financially and environmentally. With increasing emphasis on better forest practices and potential penalties, environmentally damaging practices could also become heavy financial burdens.

Overestimation of yarding distance may lead to inadequate clearance which may in turn cause site, equipment and log damage. Damage may be minimized by methods such as reducing either yarding speeds or payloads. Productivity will subsequently suffer when yarding techniques are adjusted to minimize the damage. If planning crews are allowed flexibility during field surveying, both underestimates and overestimates may be corrected in the field.

Existing elevational accuracy standards did not adequately address the importance of large elevational errors and were therefore not suitable for testing DEM-derived deflection-lines. These accuracy standards also assumed that the elevational error was normally distributed, an assumption not made in this study.

Several data groups did not have normal distributions, apparently affected by systematic error, which had confounded the elevational error and skewed the distributions. While random error was detected in the analyses, systematic error appeared to contribute more to both the general level of elevational error and to the presence of large errors. Inefficient statistical tests were therefore required making it difficult to draw conclusions with reasonable confidence from the results of hypotheses tests. Instead, deflection-lines were assessed by considering the results of hypotheses tests in conjunction with descriptive statistics, plots of DEM-derived and field surveyed deflection-line comparisons, histograms, and insight gained during the field survey of each deflection-line.

A blunder was detected in one of the study cutblock maps. This map was being used for operational planning and had likely never been checked for elevational accuracy. As well, distortion was found in the maps for two other study cutblocks where photogrammetrically derived and ground surveyed maps had been joined through rubber sheeting. High accuracy GPS and laser surveying detected the distortion, which had also not been detected due to a previous lack of accuracy testing.

For most comparisons the mean elevational error was positive, suggesting a trend towards overestimation of the DEM elevations. This may have been due, in part, to the location of deflection-lines relative to the overall terrain. Most deflection-lines were located in valley bottoms and lower to mid slopes, where taller than expected trees may have lead the photo-interpreter to overestimate ground elevations. Since overestimating the ground elevation may not be a problem when dealing with the more open forest conditions of the upper slopes and ridge tops, the level of elevational error detected in this study may not be applicable to all areas of a DEM.

The presence of systematic error was the biggest impediment to using DEM-derived deflection-lines confidently for estimating yarding distance. Different types of systematic error were detected, with at least some types evident in all of the deflection-line comparisons. Smoothing error was observed where terrain variation had been reduced through various steps in the creation of the original maps or through the data transformations and manipulations which occurred during this study. Smoothing error may have been caused primarily by the photo-interpreter's inability to detect variation in ground elevations when the ground was not visible through the forest canopy. Past fire and wind disturbances may have combined with site characteristics to create smooth and level canopies. The photo-interpreter would have had no way of detecting the actual variation of the ground and would have plotted the contours accordingly.

Positional errors were the most common and influential systematic errors detected. Inadequate tie-points prevented features from being properly located when transferred to maps. Positional error was strongly influenced by the age of the map data. Particularly, dynamic features used as tie-points varied over time including creeks which had shifted their course. The relevance of a tie-point feature for the purpose of accurately locating deflection-lines was important when considering positional error. Many commonly used tie-point features, such as logging roads, were not plotted on maps with precision equivalent to that required for deflection-line analysis.

Positional error introduced through traditional surveying methods exacerbated both the level of elevational error and the errors from yarding distance estimates. Positional error increased the magnitude of elevational error when deflection-lines were transferred to the wrong map location and the elevations were subsequently extracted from the wrong location on the DEM. This produced deflection-lines which were misaligned with the field surveyed deflection-lines but which had the same general shape. Several of the erroneous yarding distance estimates placed the yarding boundary in the proper location, negating the effects of this error.

The positional error of map features, and that introduced using traditional survey methods, may also affect operational field surveying of deflection-lines, logging roads, and harvest boundaries. The presence of positional error and its subsequent effects upon harvest planning is either not known or ignored altogether.

9 Recommendations

The substantial impacts of erroneous yarding distances estimated from DEM-derived deflection-lines may be tempered if DEM-derived deflection-lines are used only to efficiently pre-plan and guide field surveys. Automated deflection-line analysis using DEM-derived deflection-lines may be used to perform rapid iterative planning of landing, road, and boundary combinations which is not possible using traditional field surveyed deflection-lines. Forest engineers could then choose the most promising combinations for confirmation through field surveys.

If the forest engineer decides to field check only critical DEM-derived deflection-lines then standards to guide the field checks are necessary. Differing terrain, stand, and site conditions may cause different levels of elevational error. These elevational errors will also have varying impacts on the estimation of yarding distance depending upon their location on the DEM-derived deflection-line.

The best recommendation for using DEMs for deflection-line analysis is to obtain new elevational data specific for that use. New aerial photographs should be obtained for the mapping area at a scale appropriate for the intended use. The photo-interpreter should have relevant field experience in order to better understand and interpret the forest and terrain images. Photo-interpretation should select elevation points, ridge lines, valleys, and other features compatible with a TIN model. Data from the photo-interpretation should be created digitally. Hard copy is of secondary importance and may be produced later.

Since creating new maps is an expensive process that some organizations cannot afford, other approaches may prove satisfactory for the interim. Canfor has considered converting their existing 1:5000 scale maps to digital form and then reconciling these maps to their new 1:20 000 scale digital base maps using sophisticated rubber sheeting techniques. These base maps consist of recently aquired digital orthophotographs and new B.C. government Terrain Resource Information Mapping (TRIM) digital maps.

Large scale forest planning maps should be accuracy tested prior to their use for DEM-derived deflection-line analysis. Testing should consider both the positional and elevational accuracy of features, with particular attention given to detecting the presence of blunders, distortions, and systematic errors. The nature of these errors and how they affect deflection-line analysis should be investigated. The continuous sampling provided by deflection-line surveys facilitates the detection of patterns which indicate blunders, distortions, and systematic errors. High precision GPS and laser surveys may be particularly useful for detecting the presence of blunders and distortions.

If deflection-lines are surveyed using high precision equipment, then the introduction of additional error will be minimized. Traditional tight-chain, hand-held compass, and clinometer surveys are not adequate for future or even present demands for accuracy. GPS has been suggested for performing entire deflection-line surveys but at present this is not a feasible option. The type of GPS receiver which could provide the precision necessary for deflection-line analysis is not designed for rapid, mobile surveys. Heavy forest cover and steep terrain may block satellite signals, necessitating time consuming reacquisition of the signals. The high precision GPS should instead be used to create a few high accuracy tie-points, and then a laser surveyor used to perform the deflection-line and tie-point surveys. This survey data is collected digitally and may be imported into a GIS for locating the DEM-derived deflection-lines. With new maps created using the NAD'83 coordinate reference system, GPS surveyed tie-points may be referenced directly to GIS map coordinates.

It may be possible to predict the effect of different systematic errors on the elevational error of the DEM-derived deflection-lines. If systematic errors could be predicted then they could be incorporated into an automated deflection-line analysis program. Performing the deflection-line analysis within the GIS graphics environment would allow forest cover and site information to be extracted from the GIS database and terrain information extracted from the DEM. The deflection-line analysis program could then indicate when payload clearance is less than the level of elevational error predicted by the regression model.

Further research should be performed to determine the relative effects of different positional errors on the elevational error of the DEM-derived deflection-lines. The relationship between these errors and the terrain conditions should also be investigated.

The different positional errors may then be ranked and priorized for elimination, minimization, or prediction.

The automated detection of blunders and large elevational errors may be facilitated through the use of a local filter with the DEM. This filter would traverse the DEM, checking for small groups of elevations that are significantly different from their neighbours. The filter could be passed over the DEM several times using varying tolerance levels to detect different magnitudes of elevational error. This process becomes more practical as computing power and speed improve.

'Intelligent' deflection-line analysis programs could be developed which would reduce the influence of smoothing error on the elevational error of DEM-derived deflection-lines. For example, a deflection-line derived from a TIN DEM is composed of a series of straight segments which represent the individual triangular facets. For each triangular facet intersected by a deflection-line segment, the program could investigate the neighbouring triangular facets to see if they form a concave, convex, or flat surface. The deflection-line segment which intersects this facet could then be adjusted accordingly to give a more realistic representation of the local terrain.

An automated and iterative routine could be developed to locate the least number of deflection-lines needed to analyze a proposed cutblock. Utilizing a regression model developed from forest, terrain, and site variables, this routine could scan the GIS map of the cutblock area and determine which portions are prone to elevational errors. The routine could also determine the type of errors likely to occur and the predicted magnitude of these errors.

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Appendix A Sources of Error Affecting DEM Accuracy

Sources of Error Affecting DEM Accuracy

"How the error is distributed across the area of any one DEM is currently unknown, and factors that may affect the distribution of error are largely unresearched." (Fisher 1991).

DEM accuracy is a function of the accuracies of the equipment, the operators and methods used to acquire, process and manipulate the source data. While it is possible to measure the error associated with each step the errors may not be additive (Bolstad and Smith 1992). It is preferential, and more practical, to measure the accuracy of the resultant DEM. The following is a partial list of factors which may affect the accuracy of a DEM:

The Nature of the Earth's Surface (Thompson and Gruner 1980):

1) the relief of the terrain,
    a) shadows,
    b) parallax - trying to fit a 3D surface onto a 2D map,
2) atmospheric refraction,
3) curvature of the Earth,
4) forest cover (Soel 1993, Young 1978).

Light conditions will also effect the photo-interpreter's ability to see the ground. Shadows cast by local terrain features may obscure portions of the aerial photographs (Loving 1980). The terrain will also limit the light reaching the valley bottoms even when not in shadow. Shadows cast by individual trees can hide the ground in small openings. Time of day, time of year, weather, latitude, and slope aspect may all have significant effects upon the photo-interpreter's ability to see the ground. These conditions will be more influential in valley bottoms further affecting the estimation of ground elevation.

Obtaining and Processing the Basic Data (Thompson and Gruner 1980).

Aerial photography:

1) exact position and altitude of photo,
2) optical axis of lens should be known when photograph taken,
3) azimuth orientation of camera,
4) forward movement of aircraft during exposure period,
5) lens distortion and optic quality,
6) metrical characteristics of camera,
7) orientation of emulsion-bearing surface,
8) uniformity and resolution of emulsion,
9) dimensional stability of film base,

10) atmospheric conditions.

Aircraft can drift laterally, run into headwinds, be pushed by tailwinds, gain and lose altitude, vibrate, etc.

Compatibility and scale (Petrie 1992):

1) the scale and resolution of the aerial photography,
2) the flying height at which the photographs were taken,
3) the base:height ratio (geometry) of the overlapping photographs.

Processing the Data (Thompson and Gruner 1980):

1) developing the negative films or plates,
2) making positive prints from the negatives,
3) operating the photogrammetric plotting instruments,
    a) the equipment,
    b) the operator - experience

Obvious Sources of Error (Burrough 1986):

1) age of data,
    a) data collected discontinuously over time,
    b) natural changes (watercourses shift),
    c) different data standards / purposes,
    d) data medium (paper warping, shrinkage).
1) areal coverage,
2) map scale,
3) data relevance,
4) data format,
5) accessibility,
6) costs.

Random Error and Measurement Error (Burrough 1986):

1) positional accuracy,
    a) age of map (watercourses shift),
    b) cartographic representation (1 mm map line width = 5 m on the ground),
2) accuracy of content (qualitative vs. quantitative),
3) the sources of variation in data,
    a) measurement errors,
    b) field data,
    c) laboratory errors,
    d) spatial variation and map quality.

Errors Associated with Digitizing (Warner and Carson 1991; Burrough 1986).

The digitizing tablet:

1) warm-up period (electrostatic),
2) anomalies associated with wires in tablet,
3) cursor orientation,
4) resolution (digitizing is sampling!).

The digitized material and software:

1) temperature and humidity,
2) handling, storage, and folding,
3) registration process,
4) age.

The digitizer operator,

1) training and skill,
2) experience,
3) visual acuity,
4) personal daily condition (ie. fatigued).

Processing Digital Data (Burrough 1986):

1) numerical errors in the computer,
    a) the limitations of computer representations of numbers,
2) faults arising through topological analyses,
    a) misuse of logic,
    b) problems associated with map overlay,
3) classification and generalization problems,
    a) methodology,
    b) class interval definition,
    c) interpolation.

DEM Creation (Burrough 1986):

1) type of DEM (TIN or Grid),
2) method of conversion - mathematical,
3) method of conversion - TIN from spot elevation, grid from contours,
4) precision of computer.

Check Point Surveying Quality

Holmes (1989) gives the following list of common causes of error in tight-chaining:

(i) the care and attention given to the project by the people doing the chaining...
(ii) the topography and ground conditions.
(iii) the instruments used to maintain the correct direction and to read the slope angle.
(iv) accuracy of the chain used. Check the nylon or steel chain occasionally against a known precise tape.

Rotation error or error in compass bearing could have been due to a number of factors. Holmes gives the following list for common causes of error in compass work:

(i) Magnetic articles near the compass that attract the compass needle.
(ii) Careless set up -- compass not directly over the T.P. [tie-point], or the sighted T.P. not vertical.
(iii) Forgetting to let the needle down on the pivot.
(iv) Reading the wrong end of the needle.
(v) Sighting across the needle rather than along it when reading the bearing, thus introducing parallax.
(vi) Reading south for north or vice versa when bearings are near due east or west, or reading east for west when or vice versa when bearings are near due north or south.
(vii) Reading the wrong side of the 10th degree -- i.e., 51° instead of 49°.

Some causes will result in random error which will tend to cancel out. Errors, such as those due to the needle being attracted to a magnetic article, will most likely result in bias. This bias will introduce positional inaccuracies when the feature is transferred to the map. Many of the above causes could be reduced or eliminated through proper training, experience, and attention to detail.

Field traverses are normally carried out with a range of accuracy which varies between 1/100 to 1/1000 (Holmes 1989). Considering the topography and ground conditions of a skyline deflection-line assuming 1/100 would be the cautious approach.

Appendix B Yarding distance estimates

Table B Yarding distance (m) estimated for thirty-one deflection-line pairs.

Deflection-line	Length of Deflection-line	Yarding Distance (Survey)	Yarding Distance (DEM)	Error
AR1-11	260.5	125.4	125.4	0.0
AR1-12	310.2	182.5	310.2	127.7
AR6-1	625.3	614.9	614.9	0.0
AR6-2	712.7	712.7	712.7	0.0
AR6-3	821.0	736.7	685.6	-51.1
AR6-4	682.8	662.5	662.5	0.0
AR6-5	543.1	535.3	543.1	7.8
AR6-1a	472.2	472.2	472.2	0.0
AR6-2a	428.9	428.9	428.9	0.0
AT-200	888.8	684.0	657.4	-26.6
AT-201	904.0	701.5	701.5	0.0
AT-202	907.2	877.2	844.2	-33.0
AT-203	942.5	916.6	896.1	-20.5
CU-20	806.9	806.9	806.9	0.0
CU-21	817.7	817.7	817.7	0.0
CU-22	779.1	779.1	779.1	0.0
CU-23	793.9	793.9	793.9	0.0
GC-1	323.8	323.8	323.8	0.0
GC-2	352.8	352.8	352.8	0.0
GC-3	406.9	406.9	406.9	0.0
GC-4	328.3	328.3	328.3	0.0
GC-5	514.6	514.6	479.2	-35.4
GC-7	548.7	548.7	548.7	0.0
GC-8	687.9	687.9	687.9	0.0
GC-10	623.0	623.0	623.0	0.0
NW-1	1057.4	828.3	787.1	-41.2
NW-2	931.7	724.4	670.3	-54.1
TR-1	841.5	841.5	841.5	0.0
TR-2	427.1	427.1	427.1	0.0
TR-3	501.9	501.9	501.9	0.0
TR-4	735.1	735.1	735.1	0.0

Appendix C Summaries of DEM Elevational Error

Table C1 Summary of DEM elevational error (m) by cutblock.

Cutblock	n	Mean	Mean (Abs)	Max(-)	Max(+)	Range	sd	Test
AR1	28	-3.6	10.9	-24.9	13.8	38.7	12.4	t-test
AR6	136	-0.1	4.9	-22.4	16.0	38.4	6.5	sign
AT	95	** 5.8	7.0	-15.9	26.8	42.7	7.5	sign
CU - all	113	-0.4	6.3	-17.1	23.8	40.9	8.2	sign
CU-20/21	60	-1.0	4.4	-17.1	12.1	29.2	5.7	t-test
GC	166	** 1.2	4.9	-16.0	15.1	31.1	6.1	t-test
NW	51	** 0.8	4.9	-18.4	11.4	29.8	6.5	sign
TR	86	** 2.5	5.8	-19.2	23.1	42.3	7.2	t-test

* significant for α=0.10   ** significant for α=0.05

n = sample size = number of elevation points   sd = standard deviation

Table C2 Summary of DEM elevational error (m) by setting.

Setting	n	Mean	Mean (Abs)	Max(-)	Max(+)	Range	sd	Test
AR1-S1	17	-0.5	12.0	-24.9	13.8	38.7	14.2	sign
AR1-S2	11	** 8.4	9.3	-16.3	3.2	19.5	6.9	t-test
AR6-S1	20	1.4	3.5	-6.1	9.3	15.4	4.5	t-test
AR6-S2	46	* -2.2	6.1	-22.4	13.8	36.2	7.8	t-test
AR6-S3	21	** 4.2	4.8	-5.2	16.0	21.2	4.6	t-test
AR6-S4	17	0.8	4.5	-12.1	8.6	20.7	5.5	t-test
AR6-S5	32	-1.3	4.2	-15.7	8.7	24.5	5.6	sign
AT-S1	44	** 3.9	4.8	-4.0	21.3	25.3	5.8	sign
AT-S2	51	** 7.4	8.9	-15.9	26.8	42.7	8.4	t-test
CU-S1	60	-1.0	4.5	-17.1	12.1	29.2	5.7	t-test
CU-S2	53	2.0	8.3	-15.0	23.8	38.8	10.1	sign
GC-S1	60	** 1.5	4.1	-12.9	8.8	21.6	4.8	t-test
GC-S2	38	0.6	4.3	-10.9	12.0	22.9	5.4	t-test
GC-S3	42	-1.1	5.6	-16.0	14.6	30.5	7.2	t-test
GC-S4	26	** 5.2	6.4	-6.9	15.2	22.1	6.1	t-test
NW-S1	51	** 0.8	4.9	-18.4	11.4	29.8	6.5	sign
TR-S1	56	** 3.3	6.7	-19.2	23.1	42.3	8.0	t-test
TR-S2	30	1.0	4.1	-12.8	10.2	22.9	5.2	t-test

* significant for α=0.10   ** significant for α=0.05

n = sample size = number of elevation points   sd = standard deviation

Table C3 Summary of DEM elevational error (m) by deflection-line comparison.

Deflection-line	n	Mean	Mean (Abs)	Max(-)	Max(+)	Range	sd	Test
AR1-11	17	-0.5	12.0	-24.9	13.8	38.7	14.2	sign
AR1-12	11	** 8.4	9.3	-16.3	3.2	19.5	6.9	t-test
AR6-1	20	1.4	3.5	-6.1	9.3	15.4	4.5	t-test
AR6-2	22	* -1.9	3.8	-7.9	6.6	14.5	4.2	t-test
AR6-3	24	-2.5	8.3	-22.4	13.8	36.2	10.2	t-test
AR6-4	21	** 4.2	4.8	-5.2	16.0	21.2	4.6	t-test
AR6-5	17	0.8	4.5	-12.1	8.6	20.7	5.5	t-test
AR6-1a	17	-0.5	3.3	-8.9	8.7	17.6	4.6	t-test
AR6-2a	15	-2.2	5.3	-15.7	7.9	23.6	6.7	t-test
AT-200	20	** 3.8	4.3	-2.0	13.7	15.7	4.7	t-test
AT-201	24	* 4.0	5.2	-4.0	21.3	25.3	6.7	sign
AT-202	26	** 7.4	8.6	-11.0	26.8	37.8	8.5	t-test
AT-203	25	** 7.4	9.3	-15.9	20.1	36.0	8.6	t-test
CU-20	33	0.9	4.2	-6.0	12.1	18.1	5.2	t-test
CU-21	27	** -3.3	4.6	-17.1	5.9	23.0	5.6	t-test
CU-22	26	3.5	8.6	-14.9	23.8	38.7	10.8	sign
CU-23	27	0.5	8.1	-15.0	15.9	30.9	9.3	sign
GC-1	19	0.7	4.2	-6.4	8.2	14.6	4.9	t-test
GC-2	21	1.9	2.7	-3.0	6.2	9.2	2.8	t-test
GC-3	20	1.7	5.5	-12.8	8.8	21.6	6.3	sign
GC-4	12	-0.4	4.3	-9.0	9.3	18.3	5.7	t-test
GC-5	26	1.0	4.3	-10.9	12.0	22.9	5.3	t-test
GC-7	20	2.3	4.2	-3.6	14.6	18.2	5.3	sign
GC-8	22	** -4.1	6.8	-16.0	9.7	25.7	7.4	t-test
GC-10	26	** 5.2	6.4	-6.9	15.2	22.1	6.1	t-test
NW-1	28	1.3	3.9	-11.9	11.4	23.3	5.1	t-test
NW-2	23	0.2	6.0	-18.4	11.3	29.7	7.9	t-test
TR-1	29	** 2.3	4.1	-5.8	10.5	16.3	4.8	t-test
TR-2	13	1.1	4.3	-9.8	10.2	20.0	5.7	t-test
TR-3	17	0.9	3.9	-12.8	7.4	20.2	5.0	t-test
TR-4	27	** 4.4	9.5	-19.2	23.1	42.3	10.4	sign

* significant for α=0.10   ** significant for α=0.05

n = sample size = number of elevation points   sd = standard deviation

Appendix D Glossary of Terms

Analog maps - Map information stored on hard copy map such as mylar or paper. As opposed to digital maps.

Cutblock - the individual unit area of operational harvest planning. A cutblock may be further subdivided into individual settings (Conway 1982).

Deflection - the vertical distance, or sag, between a chord connecting the top of the skyline supports at either end of the skyline.

Deflection-line - profiles acquired when straight line surveys are run on the ground directly beneath the proposed location for the skyline cable.

Deflection-line Analysis - the process used to determine the feasibility of yarding in a particular location by checking for adequate clearance between suspended logs and the ground. This, in turn, is used to locate the harvest boundary.

Deflection-line pairs - the matched pair of deflection-lines used in this study. One deflection-line was field surveyed in a proposed harvest area. A DEM was created for the harvest area and then the second deflection-line was derived, using the DEM, in the same spatial location as the field surveyed deflection-line.

Digital Elevation Models (DEM) - pseudo three-dimensional computer models. Any "digital representation of the continuous variation of relief over space" (Burrough 1986). A "representation of a terrain surface consisting of X, Y, Z coordinates stored in digital form" (Webb 1990).

Digital maps - Map information stored in digital format on a computer. GIS maps are digital maps.

Digital Terrain Models (DTM) - a digital elevation model which also contains terrain information such as slope or aspect.

Geographic Information System (GIS) - a GIS is a "set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes" (Burrough 1989). This set of tools may be incorporated into a system of computer software, hardware, and peripherals.

Landing - a widening of the road which provides room for the yarding machine, logs, log loader and log trucks. It is a transition location for logs after they are yarded and before they are loaded onto trucks.

Operational Harvest Planning - the planning for individual cutblock level harvest operations.

Parallax - "The apparent displacement of the position of a body, with respect to a reference point or system, caused by a shift in the point of observation" (Wolf 1980).

Photogrammetry - "The art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images [photographs] and patterns of electromagnetic radiant energy and other phenomena" (Wolf 1980).

Photogrammetrically-measured contour maps

Photo interpretation - "The detection, identification, description, and assessment of significance of objects and patterns imaged on a photograph" (Wolf 1980).

Positional accuracy - "the accuracy of feature locations after transformations have been applied" (Veregin 1989).

Positional error - error resulting from a feature with low positional accuracy.

Regular Rectangular Grid (Grid) - the most common and most readily available form of DEM (Burrough 1986). They consist of a regular rectangular grid containing cartesian coordinates in three-dimensions (Peucker *et al.* 1976).

Rubber Sheeting - the process of rectifying one map to a more accurate map depicting the same geographic location. Common tie-points are identified on both maps, and a mathematical correction is applied to the entire map, based upon the corrections that were used to align the tie-points (Burrough 1986).

Setting - smallest individual unit in operational harvesting process (Conway 1982). The setting is the area logged from one landing.

Skyline Yarding System - a type of cable yarding system which utilizes a skyline cable to provide improved lift when yarding logs.

Smoothing error - when natural terrain variation has been lost or 'smoothed out' due to measurement error, interpolation patterns or data transformations.

Triangulated Irregular Network (TIN) - a type of DEM which represents surfaces through locating data points at key topological features such as peaks, pits, passes, ridges and channels (Peucker *et al.* 1976). This results in irregularly spaced points connected by lines to form a continuous sheet of triangles.

Triangulated Irregular Network - A type of digital terrain model where the terrain is represented by irregularly spaced elevation points connected together to form a continuous sheet of triangular facets.

USGS - United States Geological Survey

Yarding - the act of transporting logs from where they were felled to the landing where they will be loaded onto trucks.

Yarding machine - the machine used to move the cables which transport logs to the landing. The yarding machine utilizes a tower or crane like structure to lift the cables off of the ground.

Yarding road - the path the logs follow while being yarded from within the setting to the landing. The yarding road is the area under where the skyline cables are set and the area adjacent that can be reached from the skyline carriage.