AN INVESTIGATION OF SINGLE CHANNEL, GLOBAL POSITIONING SYSTEM RECEIVERS FOR FORESTRY APPLICATIONS

by

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Abstract

The forest industry in British Columbia is converting much of its spatial data to digital format for input into Geographic Information Systems. The updating of these large databases still involves digitizing of analog data. This thesis examines the suitability of a single channel hand held Global Positioning System (GPS) receiver in the forests of British Columbia. GPS provides a means of directly capturing digital spatial attributes in the field. Field trials to evaluate the effects of forest canopy on the reception of satellite signals were conducted at the Malcolm Knapp Research Forest in Maple Ridge.

Issues that need to be considered when implementing GPS in capturing spatial information are: 1) the frame of reference from which positions are calculated, (datums) 2) methods used to calculate the accuracy of position, 3) the accuracy of single point positions, 4) the accuracy of differential positioning, and 5) the effects of the forest canopy on the reception of signals from the satellites. The effect of choosing a different datum than that used to produce the base map can lead to positioning errors of several hundred metres. While commonly the largest source of error, it is preventable. Single point positions can be expected to be within 25-metres, in two dimensions, when Selective Availability is not enabled. When Selective Availability is

enabled the accuracy will be degraded to 100 metres. To regain the accuracy lost due to Selective Availability, differential GPS will need to be used. Differentially corrected positions can be expected to be within 10-metres in two dimensions. The effect of the canopy on attenuating the signals emitted from the satellites is of concern. At best, the user can only expect intermittent signals under a closed canopy with the equipment tested.

Evolving technologies are increasing the accuracy, speed and sensitivity of receivers, while decreasing the size, power consumption, and cost. The integration of GPS with other positioning and navigational aids shows the most promise for implementing GPS into forest management in British Columbia.

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AN INVESTIGATION OF SINGLE CHANNEL, GLOBAL POSITIONING SYSTEM RECEIVERS FOR FORESTRY APPLICATIONS

INTRODUCTION:

The forest industry in British Columbia is the most important contributor to the economic well-being of the province. It is also the most extensive industry, having a presence in virtually every community in the province. Nearly every activity in forest management can be related to a specific location on a map. These characteristics of the industry require that a large stock of updated accurate maps of the land base be maintained. Great strides in Geographic Information System (GIS) technologies have been made in recent years in providing forest managers with these maps. The bottleneck is in supplying the GIS database with accurate, relevant data and providing a means of supplying updates between inventory programs.

There is also a problem of implementing the planner's prescription on the ground. The problem of field crews tying themselves to a spot on the ground with an air photo and then onto an inaccurate map is well known to the man who is two kilometers in the bush and even to the crew parked at a road intersection. The author is familiar with fruitless searches for stands taking whole days.

The forest industry is probably the largest employer of navigators. Personnel hired as forest technicians spend a majority of their time navigating to and within the bush. Other industries, such as air travel, have dispensed with full time navigators and replaced them with the appropriate technology. The navigation for a forestry field crew starts early in the morning with the assembly of air photographs and maps. One person in the truck is usually assigned to keeping an eye on the maps, photographs and the surrounding terrain. Once they have reached their work site, there is the ceremony of unravelling the chain and calibrating the equipment. The field equipment, which is usually a nylon chain, Silva compass and Suunto clinometer, is light and rugged. Unfortunately, the hand instruments rely on a line of sight to the other crew member to obtain a reading. The line of sight in a forest stand is usually impaired by trees and brush, making for short distances between stations. These conditions result in expensive navigation and surveying. The same equipment is also used for surveying large cut-blocks after harvest. The line of sight is usually unimpaired, however, the length of chain, usually fifty meters, limits the distance between stations.

Other activities in forestry rely on the position of vehicles and crews for safe and efficient working conditions. The positioning of fire fighters and logging trucks is usually done by verbal means over the radio. This is usually adequate until the operation becomes large. Too much chatter on the radio degrades the safety of traffic on logging roads and impairs the ability of a fire boss to manage resources allocated to the fire, effectively.

The positioning of crews and vehicles, the location of roads and cutblocks and the production of accurate maps requires both skill and experience in a field forester. With more complex road networks and polygons being added each year, the task of locating oneself will become more demanding. The line of sight will degrade in the brushy second growth forests. For foresters to be effective in the field, better tools will be required to lessen the navigational burden, thus allowing forestry crews to attend to other tasks while in the bush.

The global positioning system (GPS) may aid the forester in many positional and navigational tasks. This paper investigates several issues of using GPS in forestry. Chapter 1 describes how a receiver relates a position of a user on the earth's surface. It also investigates how the receiver used in the study handles the datums used to fix a coordinate system. Chapter 2 explains the terms used and some issues involved in expressing positional accuracy. Chapter 3 investigates the accuracy of the receiver in single point positioning. Chapter 4 investigates the magnitude of differential error due to noise introduced by the receivers themselves. It also investigates the advantage of using synchronized versus unsynchronized differential positioning. Chapter 5 investigates the accuracy of differential positioning. Chapter 6 investigates the success of the GPS signal in penetrating a forest canopy. Chapter 7 summarizes the conclusions found in the studies performed, provides recommendations for the use of GPS, and suggest topics for further study.

Appendix A describes and tests a computer program that calculates distances based on geodetic coordinates. Appendix B describes and tests a computer program that was used to predict satellite availability. Appendix C describes a computer program that was written to analyze the data in this study. Appendix D provides a glossary of terms used throughout the thesis.

CHAPTER 1 - DATUMS

Introduction:

Coordinate reference systems:

A GPS receiver calculates a position in three dimensional space. The position is described in a three dimensional Cartesian (X-Y-Z) coordinate system, which has its origin at the centre of the earth. The error in the determination of a range to a satellite is 6-metres error in this reference frame (Feess, et al 1987). The coordinates describing a position in this system are not useful for positioning oneself on the earth's surface.

In order for the positioning data to be useful, the receiver must transform the Cartesian coordinates into coordinates based on a model of the earth. The best model of the earth's surface is the geoid. The geoid is essentially mean sea level. The mean sea-level is based on where the water level would be if small channels were cut through the land masses on the planet and friction and tides were ignored. Since it is gravity that would determine the water surface level, and gravity is not constant throughout the world, the geoid is very irregular. Maps are not manufactured on projections of the geoid, because of the irregularity of the surface. There is no convenient mathematical function to describe the geoid (Ewing 1970).

The model used for positioning on the horizontal is an ellipsoid. There are many ellipsoid models of the earth, with each continent usually having a different ellipsoid model to describe it. The Clarke ellipsoid of 1866 is the base for most on the maps of North America. This is the model used by the North American Datum of 1927 (NAD27). The Clarke ellipsoid, when assigned a specific origin (such as Meades Ranch in Kansas, for NAD27), defines a datum. The origin of the ellipsoid for NAD27-CONUS, does not intersect the centre of the earth. The NAD27-Alaska uses the same Clarke ellipsoid, that has the same semi-major and semi-minor axis, but uses a different origin.

Positions determined on the surface of the earth are reduced, through a plumb line, to the reference ellipsoid. The latitude and longitude are the 2-D coordinates of the position. The world according to surveyors is not three dimensional but two dimensional, plus one dimension (Lachappele 1991). The elevation is described as the height above the geoid. Since the geoid is based on the irregular gravity field of the earth, the gravity field is sampled and a model of the geoid is developed. This has resulted in the development of many models of the geoid. When in mountainous areas, the geoid may undulate dramatically. On the ocean the geoid is easy to model because the undulations have a long, smooth wavelength.

Datums in GPS:

The native datum for GPS is the World Geodetic System (WGS84), which uses the Geodetic Reference System (GRS80) ellipsoid. This is essentially the ellipsoid model used for NAD83. The origin is the centre of the earth. This is convenient for satellite positioning, since the satellites orbit around the centre of mass of the earth. GPS was used to determine the new coordinates for many of the control points used in determining the NAD83 network.

The task for a receiver, is to calculate a position in a three dimensional coordinate system, translate it to a latitude and longitude on a reference ellipsoid, and convert it to a set of map coordinates based on a projection. Forestry maps are based on the Universal Transverse Mercator (UTM) projection with elevation given as height above mean sea-level. The calculation for the elevation, in a receiver, is given as the height above the reference ellipsoid. The height above sea-level must be calculated from the height above ellipsoid. The final position must also be interpreted as one that must relate to coordinates assigned to a control point based on a least squares adjustment. This is described in the next section.

The Magellan receiver used in this study, can display positions in reference to a variety of datums. There are eight datums built into the receiver as well as the capability of storing five user defined datums. The transformation between differing ellipsoidal models is mathematically rigorous. For example, to change from a coordinate in WGS84 to NAD83 the flattening factor is reduced by 0.3726×10^{-4}. The transformation can take place with the one new parameter.

The Problem:

A datum can be described by an ellipsoid with an origin. To implement the datum on the ground, a coordinate reference system must be built on a network of control points. The users cannot describe their position in reference to the axes of the ellipsoid, but to a set of coordinates based on the datum that is used to describe positions of monuments on the ground.

The parameters describing the ellipsoid and origin of NAD27 are precise. The coordinates describing the control points for NAD27 however, were based on triangulation and spirit leveling starting in Kansas. The distortions from the triangulation process accumulate as one increases the distance from the origin. The triangulation was completed and adjusted using least squares in the continental United States. When Canada continued with the triangulation it used points that were already adjusted in the American network. Thus the control points used to adjust the network in Canada were already the product of an adjustment (Lachappele 1991). This contributed to even greater distortions in British Columbia. Separate adjustments such as the Alaska datum were made as an interim solution to reduce some distortions in the northwest section of North America. Therefore NAD27-ALASKA was used for the data collection in this project.

The transformation of coordinates for a set of control points between differing datums is not an easy process. The NAD27 datum can be described accurately with only five parameters (Magellan 1990). The coordinates used to describe a survey monument however, are the result of a least squares adjustment. Individual control points also suffer the problems of blunders or local distortions. The transformation software supplied by B.C. Ministry of Crown Lands applies a seven parameter transformation. Another program then computes a polynomial distortion model to remove most of the remaining distortion. (Farley and Junkins 1990). It is recommended that the inverse transformation, from NAD83 to NAD27, not be attempted.

The Magellan receiver will display coordinates and elevations based on the datums. The transformation within the unit however, is probably a simple transformation between the ellipsoid models used in each datum. The elevation, when expressed in metres above mean sea-level, is also based on a model. The elevation as displayed, is based on geoid separations from the ellipsoid based on a crude model. This can be in error of up to 5-metres (Magellan

1990). Magellan recommends that the operator use the ellipsoid height and apply the local geoid separation to the height above ellipsoid.

The objective of this section is to show how the selection of differing datums can affect the coordinates of a position .

Method:

The receiver was set up on a single location to record 200 fixes. The position was located at 2849 Cambridge Street in Vancouver B.C. The data collection took place on March 12, 1991 from 22:57-23:33 UTC. The average positional dilution of precision (PDOP) for the session was 3.3. PDOP is a measure of the strength of the geometry of the satellite constellation. The UTM zone was 10. The averaging feature of the receiver was used to calculate an average position from the 200 fixes. The data buffer was then uploaded to a personal computer for conversion.

Coordinate set 1 was produced by first passing the raw buffer file to the program RE4MAT87 supplied by the manufacturer. The datum selected was NAD27-Alaska and height above the geoid. The converted file was then passed onto the program GPSDXF, written by the author, to calculate averaged positions.

Coordinate set 2 was copied from the display of the receiver. It is the average of the 200 fixes. The receiver only displays elevation above mean sea-level.

Coordinate set 3 was calculated with GPSDXF from the data file based on NAD27-Alaska based with height above the ellipsoid for the elevation.

Coordinate set 4 was copied from the display of the receiver in NAD27.

Coordinate set 5 was calculated in the same manner as coordinate set 3, but using WGS84 as the datum.

Coordinate set 6 was calculated in the same manner as set 1 but using WGS84.

Coordinate set 7 was calculated in the same manner as set 2 but using NAD83.

Coordinate set 8 was copied from the display of the receiver using NAD83.

Results:

Table 1-1
Comparison of coordinates of one location using different datums
Magellan NAV 1000 PRO

Set		Easting	Northing	Elev.
1	NAD27-ALSKA geoid/calc	496778	5459156	66
2	NAD27-ALSKA geoid/display	496778	5459156	66
3	NAD27-ALSKA ellip/calc	496778	5459156	48
4	NAD27/geoid/display	496782	5459156	48
5	WGS84-ellip/calc	496688	5459353	66
6	WGS84-geoid/calc	496688	5459353	66
7	NAD83-geoid/calc	496690	5459350	66
8	NAD83-geoid/display	496691	5459350	66
	Range in position(metres)	90	197	18

All measurements are in metres.

The elevation of the point, as surveyed from a NAD27 monument was 43.33m

Discussion:

A comparison between the first two sets of coordinates, suggests that the calculation and display within the receiver agree with the results from GPSDXF as performed on a personal computer.

The position, as determined in NAD27 in set 4 versus that determined by NAD27-Alaska, shows a shift in coordinates describing the position. The shift from 2 to 4 is 4-metres in the Easting but no shift in the Northing.

The comparison between set 1 and set 6 show a large shift between the geocentric WGS84 and the conventional NAD27. This amounts to a negative 90-m shift in the Easting and positive shift of 197-m in the Northing.

The comparison of set 1 and 7 illustrates a large discrepancy in coordinates. The shift is -88-m in the Easting and 194-m in the Northing. An example of how a user might experience this shift is by comparing the coordinates of a point in Vancouver on a NAD27 Ministry of Forests, forest inventory map, and a Ministry of Crown Lands TRIM map based on NAD83. This shift varies as one moves around the province.

It appears that the geoidal height is insensitive to the datum selected on the receiver. If ellipsoid height is selected in RE4MAT87, the height above the ellipsoid is 18-metres greater than the geoidal height. Therefore the model in the Magellan receiver estimates the ellipsoid-geoid separation in Vancouver to be 18m based on NAD27. The method the Magellan receiver uses to calculate the height above sea-level based on the ellipsoid, is consistent among the datums chosen.

The ellipsoid-geoid separation according to Hein, et al (1989) can be expressed as:

$$N = h - H$$

where: N is the separation in metres

h is the elevation from the ellipsoid

H is the orthometric height (above sea-level)

The separation, based on the Rapp 78 geoid model at 49.375°N and 236.625° (123.375° W) would be:

$$N = 3.40\text{m NAD27}$$
$$N = -15.73\text{m NAD83}$$

The ellipsoid-geoid model within the receiver is in error by 21.4m as compared to the figures in NAD27. The receiver model is in error by only 2.27m when NAD83 is used.

If the height above ellipsoid was used with the local ellipsoid-geoid separation, the result would be:

$$h - N = H$$
$$48 - 3.4 = 44.6\text{m}$$

which compares favorably with the surveyed elevation of 43.33m.

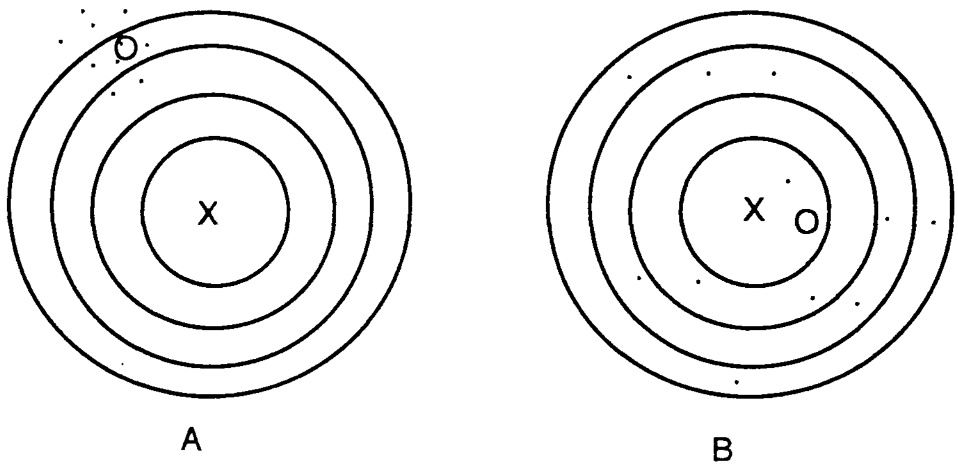
Conclusion:

The datum in which the coordinates are displayed has a significant effect on the position indicated on the earth's surface. To achieve the accuracy inherent in a GPS fix, the datums and method of expressing the elevation, between the map and receiver display must be identical. To achieve accurate orthometric heights, the elevations as displayed by the receiver, and calculated by the program RE4MAT87, should be compared only with elevations on maps based on NAD83. It would be preferable to do all height calculations based on the ellipsoid and supply a local ellipsoid-geoid separation.

CHAPTER 2 ACCURACY - INTRODUCTION

Introduction:

To address the question of the accuracy in GPS, some study of statistics and geodesy is required. Geodesy is "that branch of applied mathematics which determines, by observation and measurement, the size and shape of the earth, the coordinates of points, the length and direction of lines on the earth's surface...." (Ewing and Mitchell 1970).



X - true mean
O sample mean

Figure 2-1
Precision and Accuracy
Figure 2-1A a precise sample mean to estimate the true mean with a large bias.
Figure 2-1B an imprecise sample mean that estimates the true mean more accurately

The traditional method of explaining accuracy in statistics, is to explain the precision of the observations, and the bias of the sample mean from the true mean. Figure 2-1 illustrates these concepts.

Although knowing the magnitude and direction of the bias in the calculated position is important, it is beyond the scope of this study. The reasons are indicated in Chapter 1. That is, GPS calculates positions based on the WGS84-NAD83 ellipsoid. Coordinates for a control point need to be based on NAD83. Unfortunately, because of unacceptable distortions in trials for B.C., the least squares adjustment for NAD83 coordinates have not been released for British Columbia. Therefore, the coordinates that would be given for a control monument would be in NAD27 or a preliminary adjustment of NAD83. Approximations of the datum shift could be made, but these would be invalid when the official coordinates are made public. It was felt that estimating the precision over a period, by different receivers, using different satellites would provide a satisfactory description of the system's accuracy.

In relative, or differential positioning, the absolute accuracy is not usually a factor. The coordinate of the control monument is given by the user. It may be based on any datum. The corrected position of the remote receiver is based on the coordinates given to the base station. The accuracy of differential positioning pertains to the vector between the two stations.

RMS error: In all cases, the true user position is assumed to be the average of the position fixes. The error vector is calculated for each position from the true user position. The RMS is the square root of the average of the squares of the lengths of the error vectors.

$$2D\_RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i^2 + y_i^2)} \qquad (2\text{-}2)$$

where x is the Easting component of the error vector.
y is the Northing component of the error vector.

Another definition by Lachappele (1991) is that 2D RMS is square root of the sums of the variances in the Easting and Northing.

PDOP and UERE

The use of a receiver for field navigation, or recording the position of a feature, usually requires the estimated accuracy of the coordinates given by the receiver. The confidence a user can put into the position fix is indicated by the PDOP. The PDOP is a scalar that is used to multiply the "user equivalent range error" (UERE) to arrive at the root mean square (rms) error of the position.

The UERE is the sum of the errors that a receiver encounters when calculating a pseudo-range. The pseudo-range is the distance calculated between the receiver and a satellite. The range of the user from the satellite, places the user on a sphere encompassing the satellite, (with radius equal to the pseudo-range). The receiver needs to obtain pseudo-ranges from four satellites to calculate a position fix. The range is prefaced with "pseudo" because the range calculated is not the actual range from the user to the satellite. The range must be corrected by time (the time difference between the GPS time and the clock inside the receiver) which is a function of the extra satellite (e.g. 4 satellites for 3 D). If the extra satellite is not used, the time bias can cause errors of hundreds of kilometres (Wells, *et al* 1986).

The PDOP is essentially an index of the strength of the geometry of the satellites. Since the orbits of the satellites are stable, the PDOP can be calculated before venturing into the field. The most desirable geometry would be three satellites equally spaced 10° above the horizon, and one satellite directly overhead (Unfortunately this geometry is the worst for signal penetration of the atmosphere, landscape and vegetation). The PDOP of a position is usually saved as an attribute of the position fix in a GPS receiver.

According to Leick(1990) the equation for error in position is given as:

$$s = DOP \times s_o \tag{2-1}$$

where s_o is the standard deviation of the observed pseudo ranges, s is the standard deviation of the component in question (e.g. 2 D position). The standard deviations of the pseudo-ranges are determined by the system errors, atmospheric delays and receiver noise. The dilution of precision (DOP) can be calculated from the position of the satellites in relation to the user. The DOP can be calculated for vertical DOP, geometric DOP, time DOP and position DOP. The s_o is difficult to determine when with the receiver used in this study. In the Magellan receiver only the resultant position is given: the pseudo-range data cannot be analyzed.

Selective availability (SA) is the method in which the U.S. military will deny accurate positioning to unauthorized users (see Appendix D).Parkinson and Fitzgibbon (1987), estimate the UERE to be 6.7-metres without SA turned on. This increases to 20.8-metres with SA enabled. The ranging errors typically vary by a factor of two to three. Errors contributing to the UERE can vary widely, but usually have a compensating effect. Wells, et al (1986) estimates that the ionospheric delay bias is 150-metres at the horizon and decreases to 50-metres when the satellite is at the zenith. The Troposphere introduces a bias of 20-metres at 10^0 above the horizon, while decreasing to 2-metres at the zenith.

The DOP effect may vary by a factor of ten or more. To achieve a precise position it is best to collect data during a time of low PDOP. For example using equation 2-2:

PDOP= 2, UERE = 6 m

$$\text{3D Positional error} = 2 \times 6$$
$$\text{3D Positional error} = \text{12-m 3D rms}$$

The error of a position in the example is 12 metres rms in 3 dimensions. This can be interpreted as the standard deviation in the position. Sixty-eight percent of the observations used to determine the mean position can be found within 12-metres of the average position. In other words a sphere with a radius of 12-metres would contain 68 percent of the observations. Some errors can be modeled or differenced out, however, the PDOP is a separate effect.

Terms used in describing accuracy

The statistics calculated by GPSDXF are based on an internal memo of Magellan Systems Corporation (Magellan 1990). These include:

Circular Error Probable (CEP): is the radius of the circle centred on the mean position. The circle contains one half the position fixes that are used to calculate the mean position. In other words a circle with 50% probability.

Spherical Error Probable (SEP): is the radius of the sphere centred on the mean position. The sphere contains one half the position fixes that are used to calculate the mean position.

Mean Radial Deviation: is the average length of the error vectors from the mean position.

$$MRE = \frac{1}{N} \times \sum_{i=1}^{N} \sqrt{(x_i^2 + y_i^2)} \tag{2-3}$$

where x is the Easting component of the error vector.
y is the Northing component of the error vector.

This term is probably the easiest to visualize. It answers the question of: "on average, how far are the fixes from the mean position?"

ppm: parts per million. The use varies 1) When absolute accuracy is given, ppm is the ratio of the error in position to the radius of the earth. It is used in GPS to describe the error of a single position on the reference ellipsoid. 2) **ppm:** is also used when describing the difference between positions. The number then refers to the ratio of error in measurement of the distance between points, and the distance between the points. It is used in differential GPS to describe the error between points.

The measure of accuracy to be used, is determined by the end use of the accuracy estimate. If the user was using GPS to target fire retardant drops, CEP might be a useful description. If the user is going to plot an error ellipse, the standard deviation for each component would be useful. The most common form of stating the accuracy in the literature is 2D and 3D RMS, especially in differential positioning.

"How far is the calculated position from the 'true' position?" is usually asked. Due to the uncertainty of the "true" position as discussed earlier, the means to test the bias of a mean position are beyond the scope of this study.

Assumptions:

The assumption is made that the precision of a measurement determines its accuracy. That is, the true set of coordinates is assumed to be the averaged position. The description of the variation of a set of position means will indicate the accuracy of the system. This would be the equivalent to repeatable accuracy.

The spread of fixes about the mean is assumed to be circular normally distributed. According to Lachappele(1991) the probability of a circle with a radius of RMS varies from
STD(Northing) = STD(Easting) p= 0.63
to STD(Northing) = 10 x STD(Easting) p= 0.68

where STD is the standard deviation. This is not an appreciable difference and this assumption will simplify the calculation of the description of error.

CHAPTER 3 ACCURACY - SINGLE POINT POSITIONING

Purpose:

The purpose of this section of the study was to determine the accuracy of the Magellan receiver over a period of time, with differing satellite configurations. An attempt is also made to determine the number of fixes needed to obtain a required confidence in one's position. This study was restricted to single point or autonomous positioning, and autonomous positioning with averaging.

Method:

The Magellan 1000 NAV PRO was used for data collection. The Magellan receiver was attached to an external antenna. The external antenna was attached to a pole 5-metres high, to 2849 Cambridge Street, Vancouver, B.C.. The site is shown in Figure 3-1. It was felt the antenna extended high enough to be free from multipath effects. Data were collected from October 19 to October 30, 1990. SA was not activated during this period.

All the files for the location 2849 Cambridge St. were copied into one file. This resulted in 1676 usable positions. Positions were then eliminated according to the PDOP, in decrements of one. For instance, all observations when the PDOP was greater than 5 were eliminated for the class PDOP=5.

Results:

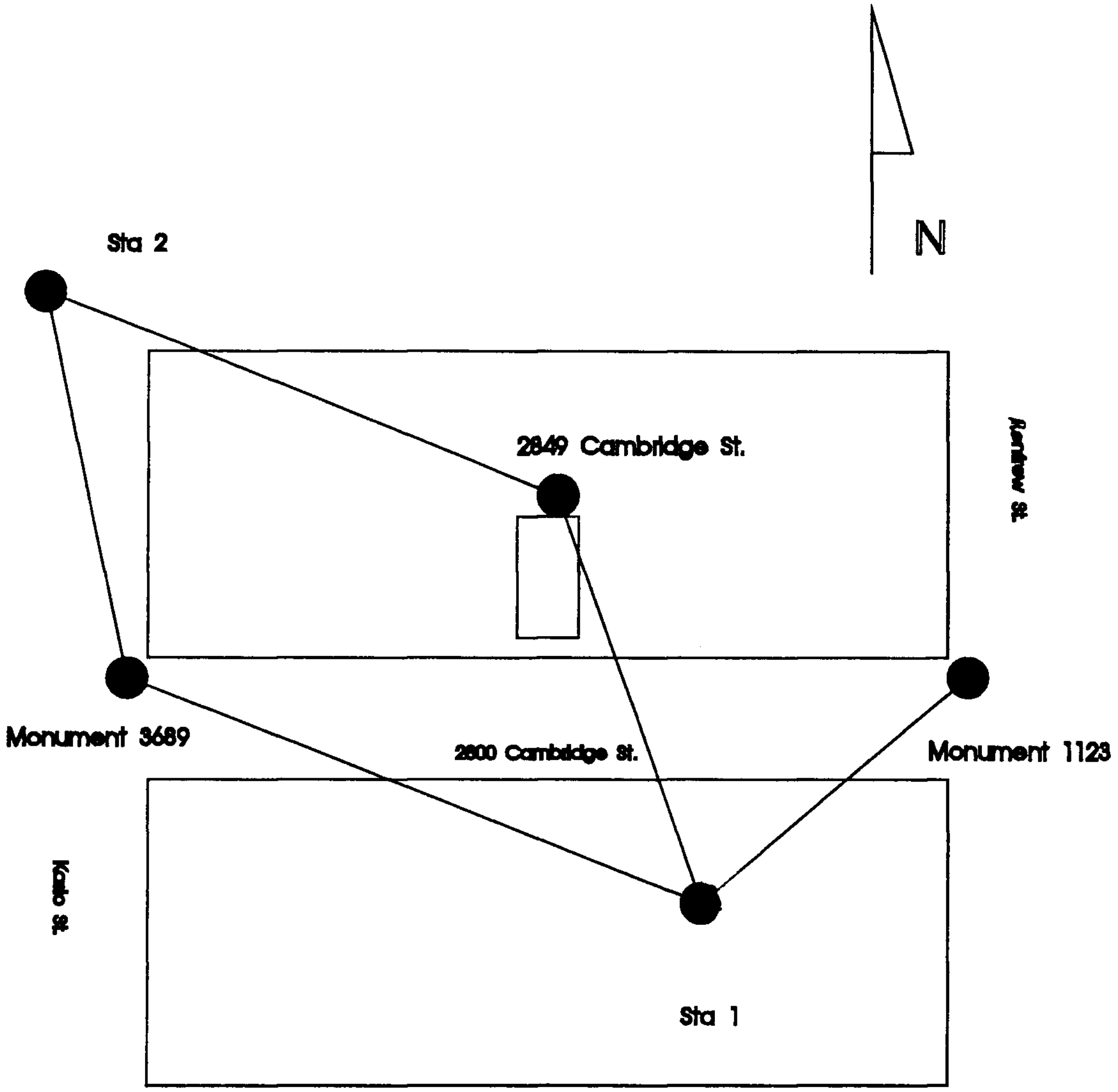
When the GPS system is fully operational, it is reasonable to expect that most observations will be taken when the PDOP is less than six (Lachappele 1991). When the constellation of satellites is complete, there will be at least 4, and usually 6 satellites above the horizon. If one refers to Figure 3-2, it can be deduced that when there are at least 4 satellites available, the PDOP will generally be less than five.

Therefore, according to Figure 3-3, if the PDOP is less than five the 2D RMS would be 24-metres, based on 1033 observations. The 3D RMS would be 49.5-metres. That is, one could expect that when the PDOP is less than 5 and using a single position fix, one could locate oneself within 24-metres on the earth's surface 68% of the time. This would be in relation to the mean position of many fixes for that particular receiver. This assumes that the positions that comprise the mean are distributed in a circular normal pattern.

An application of this statistic would be to describe repeatability. That is, if a user were to try to return to a location previously determined by the receiver, how close could one return to the position. If users relied on a single fix, and tried to return to the point 100 times, they would be within 24-metres of the averaged location 68 times.

Figure 3-1

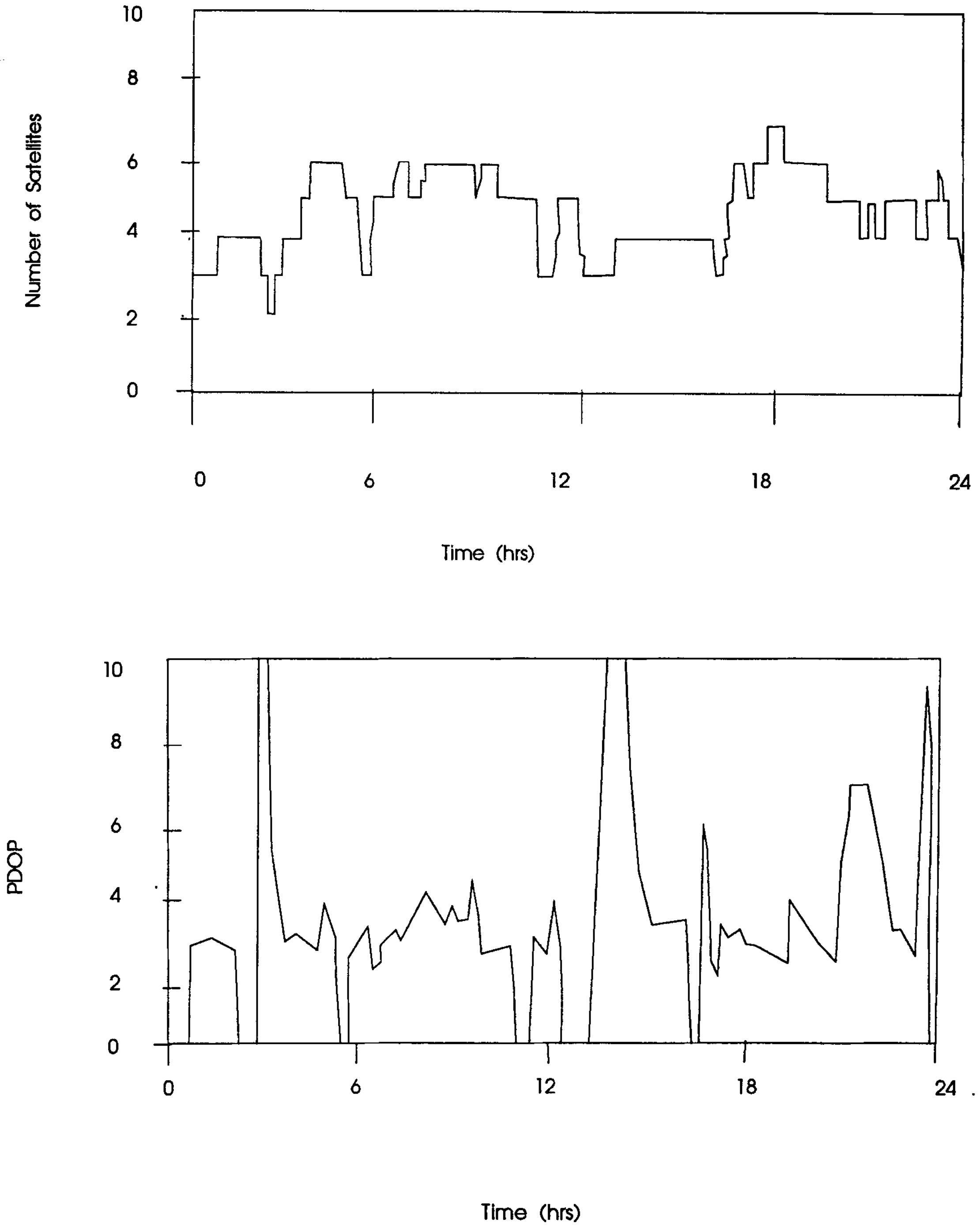
Positioning of GPS antenna at 2849 Cambridge St.



	Easting	Northing	Elevation
Monument 1123	496 878.126	5 459 139.014	35.359
Monument 3689	496 706.354	5 459 137.651	42.381
Base at 2849	496 791.413	5 459 167.411	43.33
Surveyed and drawn by Tim Shannon Sept 24, 1990			

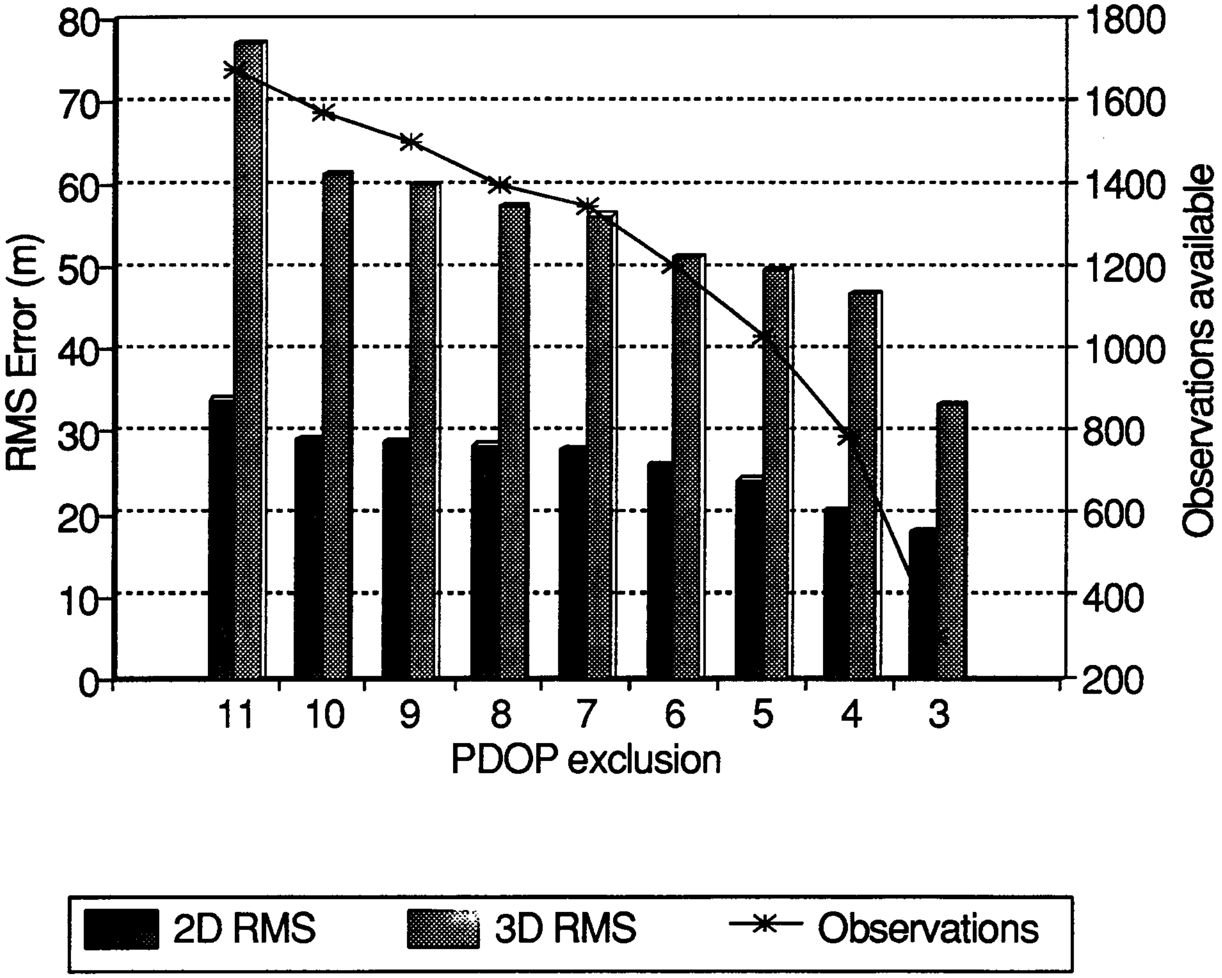
Figure 3-2

An example of PDOP vs. Time. 16 satellite constellation



(adapted from Lachappelle, 1991)

Figure 3-3
RMS error and number of observations available vs. PDOP
Autonomous single point positioning at 2849 Cambridge St.



If a user were to rely solely on a single position, the range of position solutions that can be encountered is illustrated in Table 3-1.

Table 3-1
Ranges in measurements with differing PDOP

PDOP	Obs	Range E	Range N	Range Elev.
11	1676	283	482	1521
10	1574	191	195	535
9	1503	191	191	535
8	1401	191	191	478
7	1346	191	191	478
6	1206	191	191	451
5	1003	131	149	451
4	787	113	136	449
3	297	69	78	155

All measurements are in metres.

When the PDOP exclusion limit was set at 11, the range of possible position fixes was as high as 283-metres in the Easting, 482-metres in the Northing, and 1521-metres in the elevation.

Table 3-2 shows the standard error when the assumption is made that each session is a randomly selected event, and that the user would encounter the same proportion of ranges of PDOP as encountered in this study

The standard error of the mean is the standard deviation of a set of sample means. The standard error of the mean is essentially constant in this data set. The confidence the user would have in a mean position, would therefore remain constant.

Table 3-2
Standard error(m) of the mean in position with differing PDOP

PDOP	Easting	Northing	Elevation
11	0.5	0.6	1.7
10	0.4	0.6	1.4
9	0.4	0.6	1.4
8	0.5	0.6	1.4
7	0.5	0.6	1.3
6	0.5	0.6	1.3
5	0.5	0.6	1.3
4	0.5	0.5	1.5
3	0.6	0.8	1.6

all measurements are in metres.

Averaging:

Averaging several fixes will give a user a mean position and a statistic on how variable the observations were in calculating the position. In Chapter 2, an assumption was made that the observations would follow a circular normal distribution. Figure 3-4 illustrates how this assumption holds during a period of low PDOP. Figure 3-5 illustrates how this assumption can be violated when the data collection takes place during a period of high PDOP.

The correlation coefficient between the Easting and Northing coordinates in Figure 3-5 is 0.95. This illustrates the true meaning of PDOP. PDOP is described in Chapter 2 as an index of the expected variability of the data for simplicity. It is actually the sum of the diagonal elements of the transformed covariance matrix. It is based on the position of the satellites in relation to the user.

The data plotted in Figures 3-5 and 3-6 are from the same data collection session. Figure 3-5 contains all 199 records from the session. The average PDOP is 26. Figure 3-6 contains the fixes that were recorded when the PDOP was less than 10. The average PDOP is 5. The differences in the means of positions is tabulated in Table 3-3. Although the scatter of each file looks different, and the precision of the data varies by a factor of six (2D RMS), the mean positions calculated do not differ a great deal. The mean Eastings differ by only 16-metres, the Northings by 19-metres and the elevations by 51- metres. The difference in position in 3D space is 566 metres.

Table 3-3

Error in mean positions from long term average position

Trial	Fixes	Avg. PDOP	Error in Easting (m)	Error in Northing (m)	Error in Elev. (m)	Error in 3D position (m)
1	199	26	23	4	18	29
1-edited	41	5	7	23	34	42
LT	2355					

LT is the long term averaged position.

The long-term average is assumed to be correct. The high PDOP session differs from a long term average of less than the low PDOP edited file. This suggests that is would not be prudent to delete high PDOP fixes from a file, to increase accuracy. The precision of the edited file is at least five times greater than the unedited file, but it is no more accurate.

Figure 3-5 illustrates how an autonomous position can differ in a single data session when the Average PDOP is 26. The probability is small, but two autonomous positions from the same receiver within an hour could differ by 1167-metres Easting, 398-metres Northing and 1813-metres in elevation.

Figure 3-4

Position fixes of Session C0426t-1. Low PDOP (average 3.4)

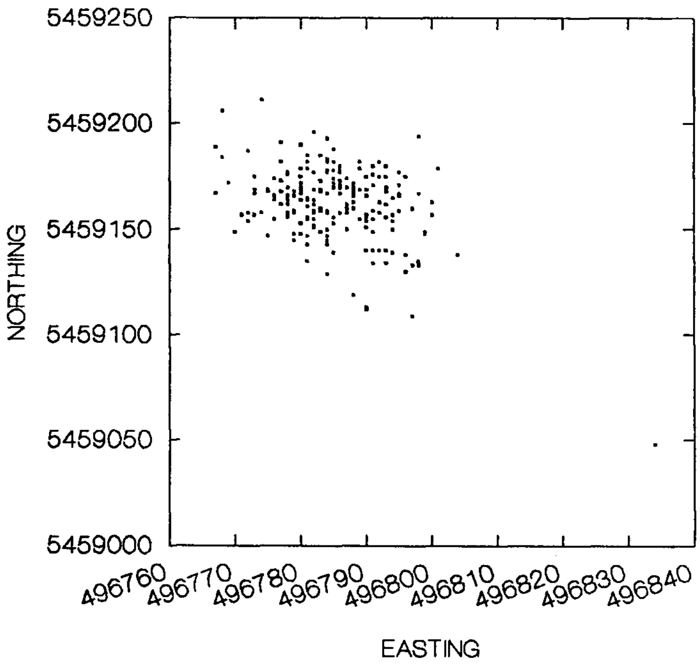


Figure 3-5

Position fixes of Session C0426t-2. High PDOP (average 26)

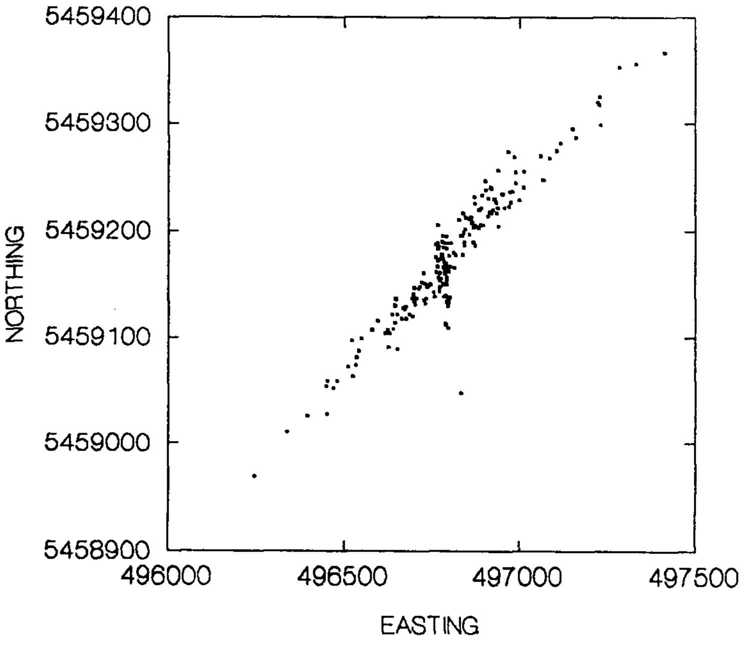


Figure 3-6

Positions of session means with PDOP <10

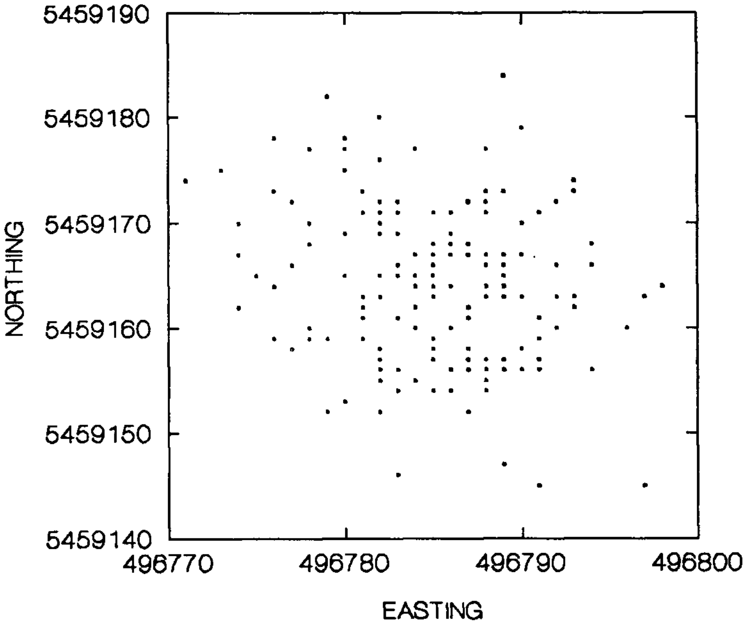


Figure 3-7

Positions of session means with PDOP <6

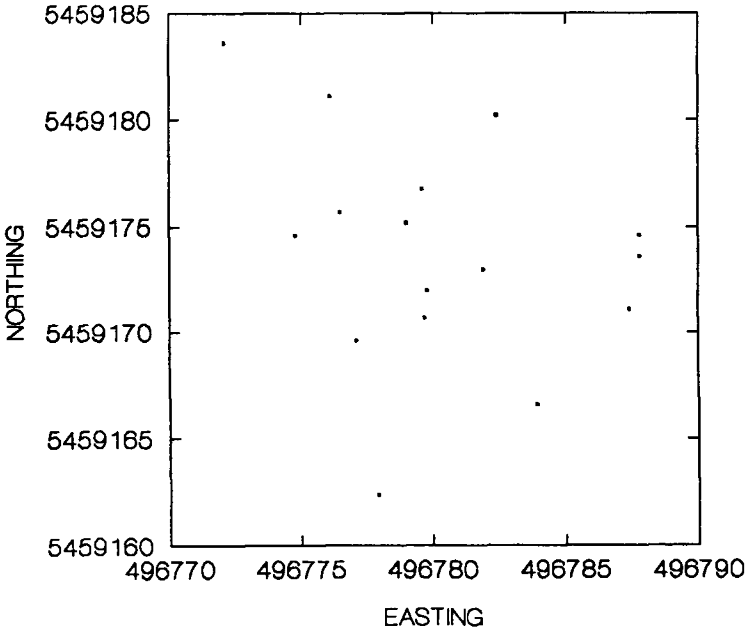


Figure 3-7 is a scatter of 16 session means taken when the PDOP was less than 6. The scatter appears randomly distributed. The properties of the means of data sessions are displayed in Table 3-4.

Table 3-4
Means of data sessions at 2849 Cambridge St.

	E	N	Elev.	StdE	StdN	StdElev
Min	496772	5459162	19.8	9.1	10	24.7
Max	496787	5459184	90	34.8	30.1	56.4
Range	16	21.2	70.2	25.7	20.1	31.7
Std	4.7	5.3	17.5	15.7	15.8	37.8
Mean	496780	5459174	53.1	6.7	6.3	8.4

The standard deviation of the means is 4.7-metres in the Easting 5.3-metres in the Northing and 17.5-metres in the elevation. The variability of the elevation means is three times that of the variability of the Easting and Northing. The application of these descriptors is in returning to a given location. If users were using the same receiver to return to a location 100 times, and averaged several fixes, they could expect to return to within approximately 5-metres of the true position 68 times.

Discussion:

The question is frequently asked of the ultimate accuracy of the system. What would be the accuracy if the user was to occupy a site continuously with a receiver? Table 3-2 shows that one would derive little benefit by increasing the number of observations with no regard to PDOP windows. If the user collected positions when the PDOP was less than 4, only 1003 fixes need be collected to derive the same confidence in position, as if 1676 fixes were collected without regard to PDOP.

Conversely, one could argue that it is not worth the trouble to edit fixes with a high PDOP. As suggested in Figure 3-3, the RMS seems to increase more dramatically at a PDOP greater than 10. Below a PDOP of 10 the curve has only a slight downward slope. Only if one could achieve a long period of PDOP below 3 would there be a large drop in the RMS.

Johannessen (1987) states that even with the full 21 satellite constellation, there is only a 70 percent probability that all satellites will be operating properly. This will produce times when the PDOP will go infinite, though only for a short time. These outages along with sunspot activity and battery life in a receiver, would make it difficult to collect a continuous stream of quality fixes to find one's "exact " position.

Averaging:

The use of an average of several fixes to derive a coordinate of a position greatly enhances the accuracy of the stated coordinates. This is especially true in periods of high PDOP. The variability in elevation means is three times the mean in the Easting and Northing direction. This is inherent in the GPS system. The reason for the poor precision in elevation is the required geometry of the satellites to obtain a fix. The elevation would have similar variability if the receiver could receive signals from a satellite at zenith, and one directly behind the receiver on the other side of the earth. Unfortunately, the signals do not penetrate the earth.

Conclusion and Recommendations:

The position fix given by a receiver is variable. With 9 hours of collection time over twelve days and PDOP less than 5, the indicated accuracy is approximately 14-metres standard deviation in the Easting, 15-metres in the Northing and 42-metres in elevation. This is within the specifications as stated in the manufacturer's brochures. The absolute accuracy as compared to the true mean is unknown.

The user can expect variations of hundreds of metres in returning to a spot if only a single position fix is used to locate a position on the ground. It would be better to use an average of at least 30 fixes to obtain a coordinate for a location.

If a user collected session means of at least 30 observations, the expectation would be to repeat the coordinates more precisely. The session means of 16 data sessions shows a standard deviation of 4.7-metres in the Easting, 5.3-metres in the Northing, and 17.5- metres in the elevation.

CHAPTER 4 - RECEIVER NOISE AND DIFFERENTIAL POSITIONING

Introduction:

A code based GPS receiver, like the one used in this study, utilizes pseudorandom noise codes to calculate a range from a GPS satellite to the receiver antenna. The receiver then intersects the ranges from a multiple of satellites to calculate a position fix.

The errors in finding a range to a satellite stem from many sources. They can be broken down into two types; 1) errors correctable by differential positioning and 2) errors not correctable by differential positioning. The errors in range, described as RMS error, with selective availability activated are:

Correctable	
Clock	3.0 m
Ephemeris	2.7 m
Ionosphere	8.2 m
Troposphere	1.8 m
Selective Availability	27.4 m
TOTAL	28.9 m

Not Correctable	
Receiver noise	9.1 m
Multipath	3.0 m
TOTAL	9.6 m

The numbers do not add up because the totals are based on rms calculations. These numbers are supplied by the manufacturer for the NAV 1000 PRO receiver, and do not apply to all receivers and data sessions (Magellan 1990).

The errors in the first group are determined to be correctable by differential positioning because they are errors that are experienced by receivers in the same region. This region can be up to 300 km wide. Multipath effects are the result of signals bouncing off surfaces and arriving at the antenna later than if they arrived directly from the satellite. Receiver noise is the largest error source when differential positioning is used.

The method of differential positioning in the receivers used in this study is based on errors in calculated positions, differenced against a known position. An error vector from the receiver left on a known position is applied to the calculated position of the remote receiver. To perform the differencing, the two receivers must be using the same satellites to calculate positions. They also must obtain the position fixes at the same instant. to ensure that the receivers are synchronized, the user must select the synchronized mode on each receiver. This restricts the receiver to calculate a fix every 20 seconds. If left in unsynchronized mode, each receiver would record a fix every 11 seconds.

The main reason time synchronization was used by the manufacturer, was to defeat SA (Magellan 1990). SA implements a quick changing algorithm to dither information coming from the satellites. This denies the user the accuracy inherent to the system. Thus, if signals between a fixed and remote receiver are to be differenced, that is they are to share the same errors, they need to be taken at precisely the same time. During data collection sessions, SA was not enabled by the U.S. military. Since the other error factors vary slowly throughout the day, strict time synchronization is not needed to achieve reasonable accuracy. However, software provided by the manufacturer can only deal with strict time synchronization.

Objective:

To determine receiver noise between the two receivers used in this study. An additional study was made to determine if there was an advantage in using unsynchronized fixes from each receiver to perform differential corrections, when SA is inactive.

Scope:

The geometric dilution of precision (GDOP) is a composite index of the strength of the satellite geometry on the position and time estimate (Leick 1990). The positional dilution of precision (PDOP) is a composite of the expected variance in the Northing, Easting and elevation. Although the variance for each component of the PDOP can be analyzed, it is doubtful that the information would be used in positioning in forestry. The goal of a data collection session is to derive a precise position in all dimensions. The lower the PDOP, the more precise the position. Therefore the PDOP, which is the index usually provided by receivers, will be used for this study.

There is no differential positioning taking place in this study. Both receivers are measuring the same position simultaneously. The differential accuracy is indicated by the difference in position calculated by the two receivers at the same spot.

Method:

The two receivers were placed on the roof of 2849 Cambridge Street. Data were collected in 3D mode, using the same four satellites for both receivers. The longest data collection time was attempted for each session (200 points). Data were collected from April 22, 1991 to May 3, 1991. SA was believed to be inactive. The antennae of the receivers were approximately 30-cm apart and were above the peak of the roof. It was assumed that both receivers would share the same, if any, multipath effect.

Sessions were carried out by setting the receivers in synchronized mode. A fix is determined every twenty seconds when the synchronize option is selected. The fixes are then matched to the nearest second.

The sessions were then repeated with the receivers set to unsynchronized mode. The receivers calculated fixes approximately every eleven seconds. The unsynchronized sessions were started simultaneously, and used the same satellites. The files were then edited to contain only fixes taken within the same minute. The fixes should be within the same minute because the receivers were at the same location and were turned on at the same time.

The data were analyzed using GPSDXF (see appendix C). Files were edited to ensure that the fixes between the two receivers were synchronized in time. Files that contained positions where the PDOP was greater than ten, were edited and analyzed again.

Results and Discussion:

The results of the analysis are displayed in Table 4-1. The first two columns contain the average differences in three dimensions between the session means of both receivers. There were eleven sessions. There was no editing for PDOP. The last two columns contain the same data that has been edited to remove fixes obtained when the PDOP was greater than ten. There are fewer session averages, because some sessions contained no fixes when the PDOP was less than ten.

Table 4-1
Comparison of accuracy between synchronized vs. unsynchronized averaged positions

	Unsynched All	Synched All	Unsynched <10	Synched <10
n	11	11	8	9
Avg PDOP	11.3	7.5	6.1	4.8
Avg Diff E	3.1	2.1	-1	1.5
Avg Diff N	1.5	3.2	-1.2	-3.2
Avg Diff Elev	6.1	1.7	-1.4	-0.1
Avg ABS E	5.6	3.9	2.2	2.8
Avg ABS N	4.5	3.5	2.8	4.1
Avg ABS Elev	11.5	8.7	6.0	7.3
Std E	11.9	4.3	2.9	3.5
Std N	5.8	4.8	3.7	4.7
Std Elev	19.4	12	7.6	9.3
2D RMS	13.2	6.5	4.7	5.9
3D RMS	23.5	13.6	8.9	11

where:
- all measurements are in metres.
n - is the number of data sessions.
Avg Diff N - is the average difference in the Northing between the two receivers.
Avg Diff E - is the average difference in the Easting between the two receivers.
Avg Diff Elev - the average difference in Elevation between the two receivers.
Avg ABS - is the average of the absolute values of differences between the two receivers.
Std - is the standard deviation.
2D RMS - is the root mean squared error in two dimensions.

The files that contained positions with high PDOPs also contained the most variation between the two receivers. The data contains the confounding factor of differing PDOPs between sessions. The last two columns in Table 4-1 show that unsynchronized fixes, may determine more precise differential positions. This is evidenced by the lower RMS values for unsynchronized sessions, although the average PDOP values are higher.

Table 4-2 contains two differential sessions with differing PDOPs in synchronized mode. The difference in the ranges of the fixes between the sessions is large. The data show that differential positioning is affected by a high PDOP. However, the error of the averaged differenced position when the PDOP is high is not nearly as extreme as the range in the autonomous positions. The table contains only one comparison between sessions.

The errors between the two receivers are probably due to the differences in the receiver clocks. The method of differential used in this study does not remove receiver clock biases. Double-differenced solutions using pseudo-ranges will reduce the receiver noise, by removing the receiver clock biases.

Table 4-2
Comparison of ranges in fixes between synchronized high PDOP vs. low PDOP sessions

Session	Obs.	Avg. PDOP	Rge E	Rge. N	Rge. Elev	Diff E	Diff N	Diff Elev
C0423t-1	198	3.45	56	112	185	0.2	3	5.8
C0426t-2	199	26.5	1167	398	1813	40	13	62.7
Ratio		7.7	20.8	3.5	9.8	200	4.3	10.8

All measurements in metres except PDOP.
Rge denotes range in the component direction.

Figure 4-1 illustrates that the differenced accuracy in the Northing, Easting and Elevation dimensions, is not strongly correlated to PDOP. The Northing is somewhat correlated to

PDOP (0.23). The correlation of the Northing to PDOP is probably a peculiarity of the data set collected. This is indicated in Figure 4-2 which is plot of all sessions. The spread in the fixes in the Easting is about 3.5 times as large as that in the Northing. This spread may change directions, depending on the satellite geometry.

The PDOP between two sessions may be of the same magnitude, but the variability in one direction may be much greater than another. The linear effects in Figure 4-2 are from individual data sessions where the PDOP was high. If all the high PDOP fixes are removed, the scatter appears more normally distributed. Only two dimensions are plotted to illustrate the spread in fixes because a three dimensional plot is hard to analyze.

There may be some advantage to analyzing the components of the predicted PDOP. For example: if one determined an average position when the Easting was highly variable, but the Northing was fairly stable, there may be some advantage to returning to the location when the predicted Easting component was to experience a low variation. The plotted data may resemble Figure 4-2, but the average position may be quit accurate. This may allow the user to collect valuable data when the PDOP was high, but the Easting component low, and use lower PDOP windows for collecting fresh data.

Figure 4-1

Error in differentially corrected position vs. PDOP

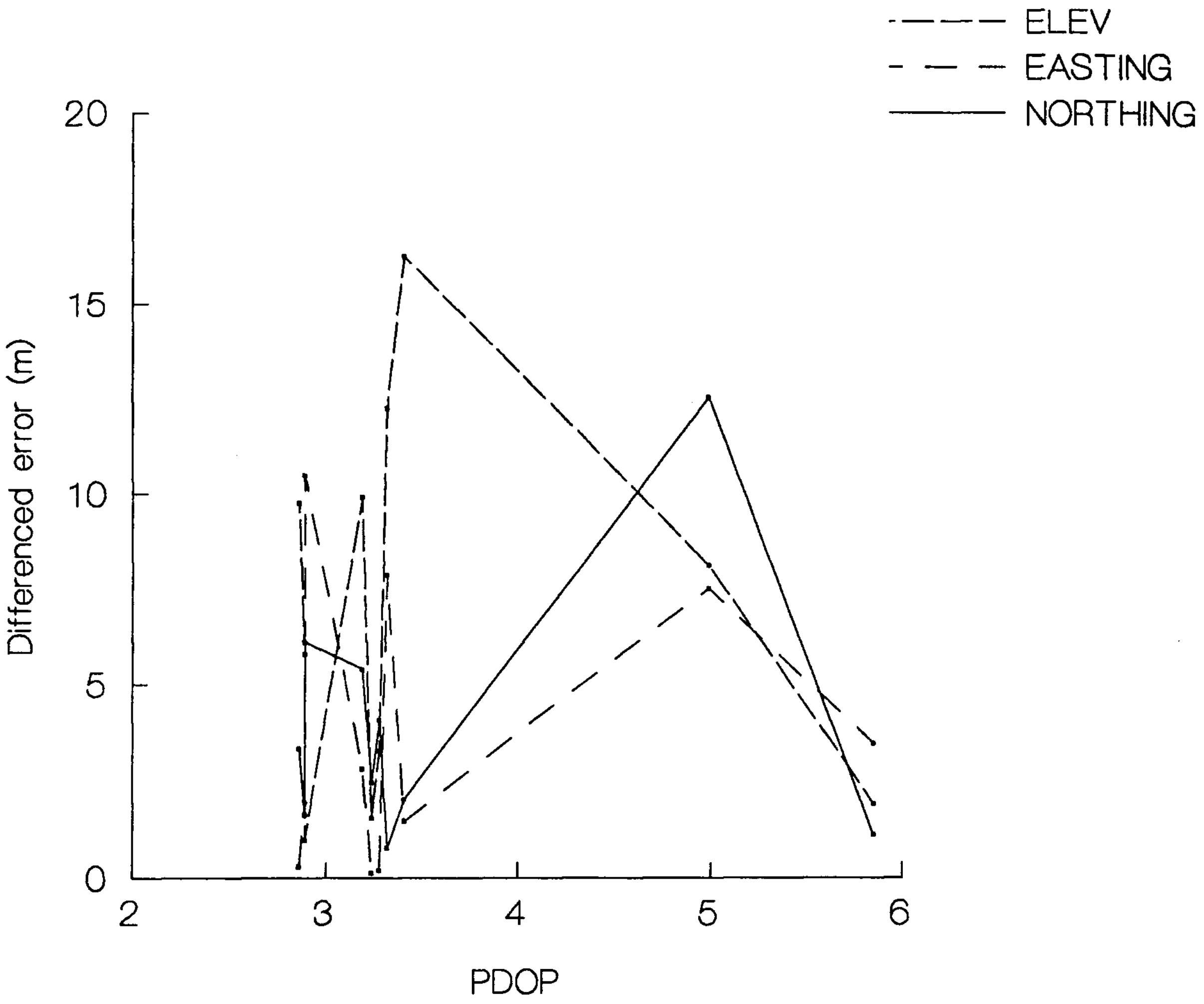
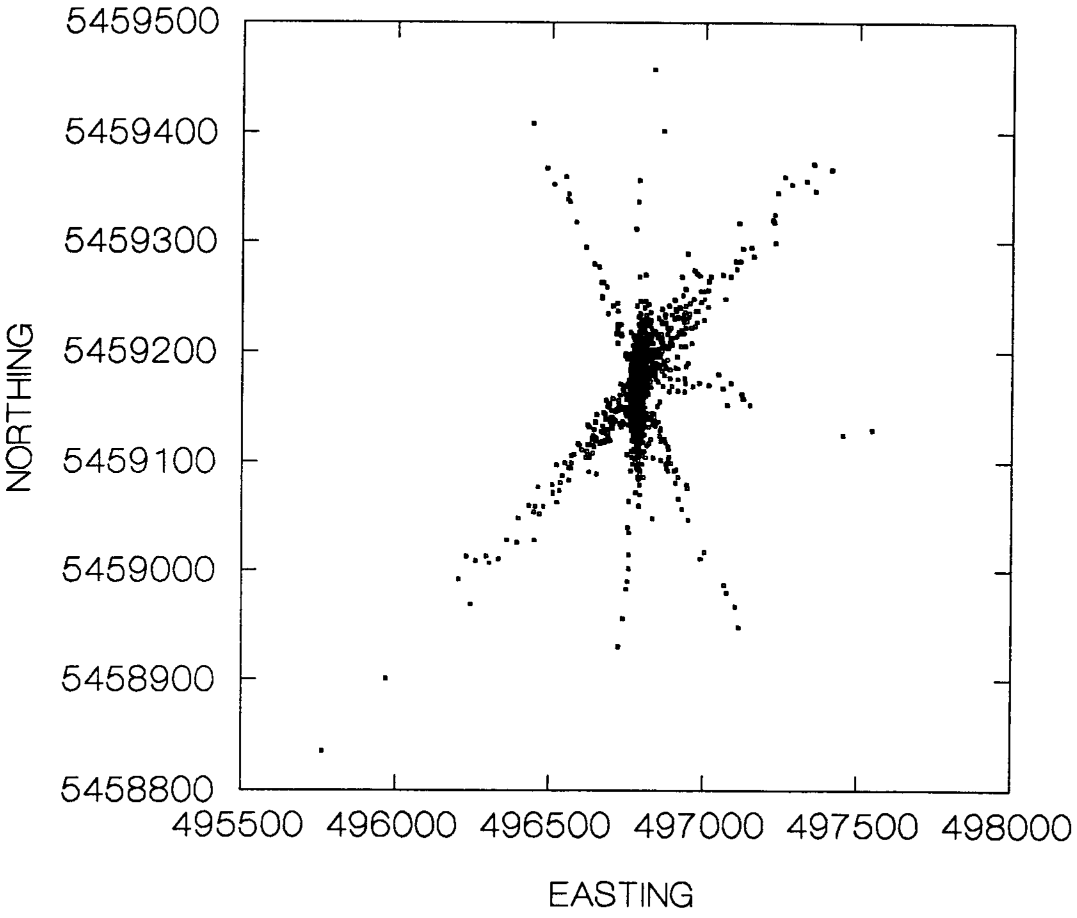


Figure 4-2
Scatter of Northing Vs. Easting. All observations at 2849 Cambridge St.



Conclusions

The variation introduced by the receiver is uncorrelated with other receivers that may be paired for differential positioning. The magnitude of the variation in this study in unsynchronized differential positioning in three dimensions, was estimated to be 8.9-metres RMS, when the PDOP is less than 10. This increased to 11-metres when the fixes were synchronized between the two receivers. Synchronized fixes take 180% more time than unsynchronized fixes in the receiver used. Therefore, when SA is inactive, there is no advantage to synchronizing the fixes between receivers. However, the receivers must collect the data to be differenced at the same time.

Further study into the components of PDOP may reveal means of improving the efficiency of data collection.

CHAPTER 5 ACCURACY - RELATIVE POSITIONING

Introduction:

Chapter 4 indicates the expected accuracy in relative positioning. However, the accuracy of a position determined by a base receiver relative to a remote receiver, is not addressed. The effect of multipath from receivers at different sites is a factor in the error in distance between the two receivers. In Chapter 4, the receivers were at the same location and it was assumed they would experience the same multipath effects. There is still a requirement to test the accuracy of relative positioning between two points at different points at different sites.

Objective:

To test the accuracy of the Magellan NAV 1000 Pro GPS receiver in differential mode and to compare the accuracies of differential and autonomous modes.

Scope:

This test is limited to a single channel receiver using code based positioning. Code based solutions rely on correlating the pseudorandom noise code that modulates the GPS signal. By correlating the signals generated within the receiver, with those received by a satellite, the receiver may calculate the time offset and thus the range of the satellite to the antenna. Much more accurate ranges can be calculated by differing the phases of the carrier signal between two receivers. However, phase based measurements rely on continuous phase lock for the duration of the data collection session. This is virtually impossible to achieve in a forested environment.

SA was not activated during data collection. The test involves repeated sampling with respect to the same two points.

Method:

A base receiver was established at 2849 Cambridge Street in Vancouver, B.C. An external antenna was used to collect the positional data. The coordinates of the antenna were established with a theodolite and electronic distance measuring equipment. Survey monuments from the City of Vancouver were used as a control. Figure 3-1 illustrates the relationship of the positions studied. The remote location was established over monument 1123. Since all positional accuracies are expressed in relative terms, no attempt was made to convert between datums. NAD 27 was used throughout the study.

Data collection took place from October 19 to October 30, 1990. Data sessions were based on collecting at least 30 observations at the remote station. All sessions where the average PDOP was greater than 6 were excluded. Observations per session varied because the number of usable observations could not be reliably predicted.

The data were processed using GPSDXF. The data session summaries were imported into Quattro PRO where the errors in distances were calculated.

The surveyed distance between the base station and monument 1123 was taken to be true. The distance between averaged positions in a differential session were differenced to calculate the GPS distance solution. The base station position was assumed to be true. The error term reported is the vector distance from the differentially corrected GPS remote position to the true position of the monument.

Results:

Table 5-1 contains errors experienced in two and three dimensions. The PDOP averaged 3.6 for all sessions, and highest session average recorded was 6.

Table 5-1
Relative accuracy between Monument 1123 and base station

	Relative 2D (m)	Relative 3D (m)
sessions	10	10
Minimum	2.2	2.9
Maximum	14.8	17
Mean	6.0	10.1
Std	4.17	4.96

The mean difference between a differentially corrected position and the true position is 6-metres in two dimensions and 10.1-metres in three dimensions.

Figure 5-1 contains a scatter of the error in three dimensions versus PDOP. The sampling spread of PDOP is limited, however, it is apparent that the error in a differentially corrected position is not correlated to PDOP, provided the PDOP is less than 6. The correlation of PDOP to error is contained in Table 5-2.

Table 5-2
Pearson correlation coefficient: Error vs. PDOP

	2D	3D	Easting	Northing	Elev.
PDOP	0.22	-0.05	-0.07	-0.17	0.23

The Pearson correlation coefficient is 1.0 when the y variable is completely dependent on the x variable. Table 5-2 illustrates the weak correlation of error with PDOP. The strongest correlation is in the elevation to PDOP, which is the component most sensitive to satellite geometry. The coefficient of determination describes the ratio of the variation in the dependent variable, over the dependent variable. It is the square of the correlation coefficient. Five percent of the variation in the elevation could be explained by the variation in the PDOP.

Figure 5-2 contains a scatter plot of the error of the component of a position for each session. The error component is from the true position and not the overall mean. The scatter seems evenly distributed about zero. If the mean of the session means is unbiased, the expected sum of the error terms is zero. However, the sums of the error terms are -13.6 m Easting, -22.7 m Northing, and 23.8m in elevation.

Although the errors appear to be cyclical between sessions, it is probably coincidental. The magnitude of the error is unexplained by the datum problem. Relative distances

should be similar between datums, especially for short vectors (as compared to the radius of the earth).

The explanation of the bias probably lies in the sampling times. The windows of satellite availability ensured that sampling would take place with similar configurations of satellites. A bias for one session would not be compensated for by a bias in the opposite direction for a different sampling time.

The mean of the ten session averages yields a difference from the surveyed position of 1.4-metres in Easting, 2.5-metres in Northing and 2.4-metres in elevation. These component errors yielded an error in position of 2.9-metres in two dimensions and 3.7-metres in three dimensions.

The use of relative positioning versus autonomous positioning is compared in Table 5-3. Both methods used averaging of at least 30 observations.

Table 5-3
Accuracy of relative versus autonomous positioning.

Method	2D RMS (m)	3D RMS (m)
Autonomous	7.1	17.5
Relative	6.7	10.6

The 95% confidence region for a differential session of at least 30 observations has a radius of 13.4-metres. The 95% confidence region for an autonomous averaged position is 14.2-metres.

Discussion:

The use of relative positioning yields a position that is slightly less variable than using autonomous positioning with averaging. The comparison is restricted to the variability of the derived averaged positions. With SA not activated, the difference between the variability between the two methods is expected to be small. When SA is activated, the use of relative positioning will become mandatory in order to remove the effects of the increased errors added by the operators of GPS, and achieve accuracies of less than 100-metres.

Figure 5-1
Error from true position vs. PDOP in 3D space. Relative Positioning

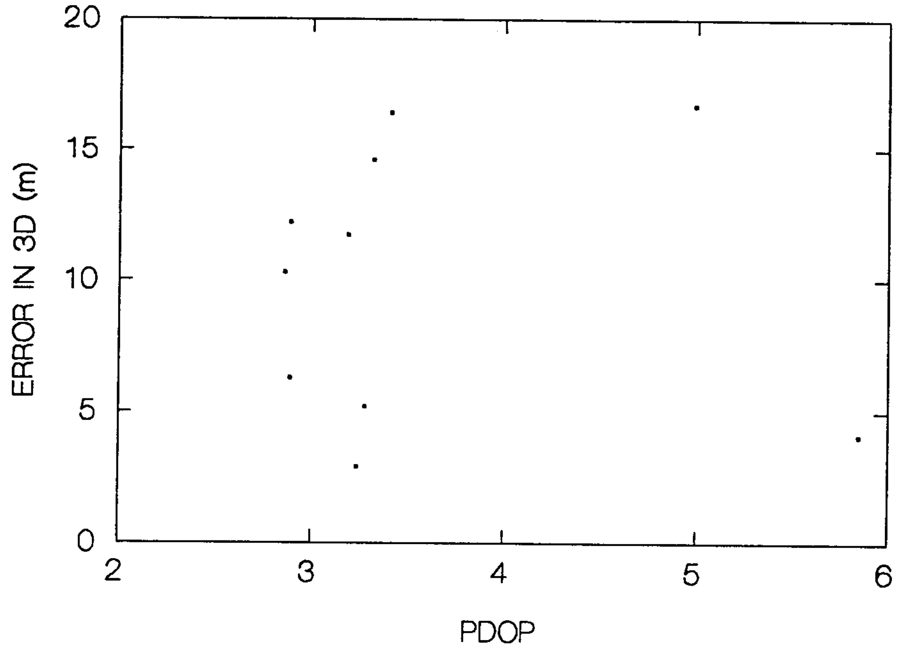
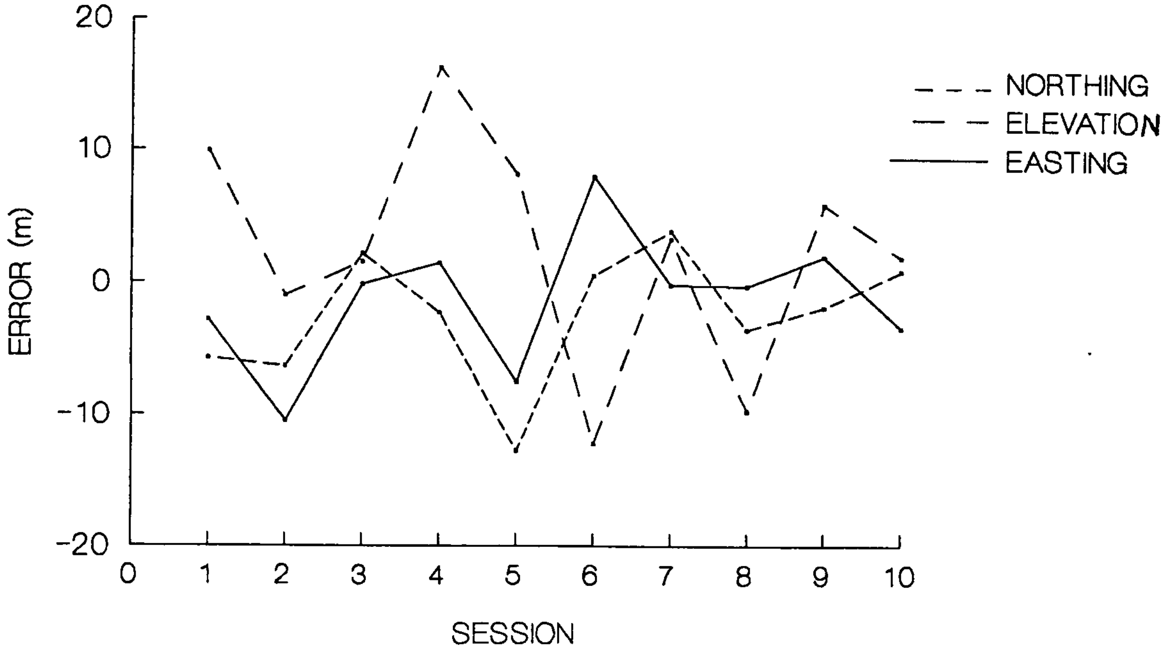


Figure 5-2
Error from true position vs. Session. Relative Positioning



Since the base station should be placed at a known point in relative positioning, the corrected remote station will have any system biases removed. The autonomous averaged position may be precise but it may contain a large bias. Without using adjusted NAD83 maps, it would be difficult to test this bias. However, the analysis of many averaged autonomous positions taken over a period of a few weeks, indicate that an averaged position does not become significantly more variable than one differentially corrected.

The use of relative positioning, depends on a reliable base station. Relative positioning demands the extra logistics of starting data collection sessions simultaneously, and communication between the remote and base stations. If care is not taken to view the same satellites simultaneously, there may be no matched fixes to perform the corrections. Fortunately, if no matches can be found between the base and the remote stations, an autonomous averaged position can be used.

Conclusions:

The use of differential positioning with the equipment tested does not merit the extra logistical effort. The enhancement of accuracy is slight. The marginal increase in accuracy does not elevate the survey to a higher order. When SA is activated, further testing should be carried out.

CHAPTER 6 UNDER CANOPY TRIALS

Introduction

The utility of GPS will be constrained by the blockage of the signals by topography and the attenuation of signals due to the forest canopy. In this chapter, the success of obtaining position fixes under a forest canopy is investigated.

The issue of whether the GPS signal penetrates a forest canopy has been addressed by Gerlach and Jasumbach (1989). Unfortunately, the forests they have studied are located in western Montana. These forests are characterized by interior Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) lodgepole pine (Pinus contorta Dougl.) and ponderosa pine (Pinus ponderosae Laws.). The amount of biomass occupying the sites is not reported, however, an estimate would be 200 to 300 m3/ha in the densest stands.

Other authors report on the problems of signal penetration of a forest canopy. However, they rarely provide any analysis of the problem. Newcomer (1990), reports that satellite visibility is a problem in forested areas. He states that the antenna cannot be taken into a forest. This would block the signal and a loss of signal lock would occur, thus preventing kinematic surveys.

In Zaire, Wilkie (1990), found that signals were readily available where openings were greater than 0.125 ha and the angle to horizon rarely exceeded 30^{o}. Although greater occupation times were required, positions were obtained when the angle to horizon exceeded 40^{o} and canopy closure reached 30 percent. Forest gaps where canopy closure exceeded 30 percent and angle to horizon averaged more than 50^{o}

generally precluded acquisition of a three or four-satellite constellation. He concludes that waiting for satellites to be more visible when they are greater than 70° above the horizon is counterproductive. The geometric dilution of precision deteriorates when the satellites cluster directly overhead. This leads to imprecise positional data.

The problem of foliage has been mentioned in the literature, but rarely has it been studied. Stratton (1987) mentions the suitability of GPS on rural roads but encountered signal blockage in an urban environment. Minkel (1989) reports the loss of phase lock due to intermittent blockage from nearby trees in his trials. This led to the elimination of the affected station from the survey. Johannessen (1987) expressed concern for signal blockage and foliage attenuation of the signal. He concludes that GPS for vehicle monitoring would require the integration of another system such as a differential odometer. Nolan and Carpenter (1988) report on the problem of shadowing of GPS signals in an urban environment. They attribute some problems of obtaining a fix to attenuation of the signal from foliage. Mooney (1985) reports on urban trials with tree lined streets of oak pine and maple. Signal attenuation, under the trees, was apparent with the signal to noise ratio dropping from 10 to 7 dB when satellite elevation was less than 40 degrees. French (1987) also finds that GPS should be integrated with another navigational system due to signal aberrations due to shadowing by buildings, bridges and foliage. Knoernschild, (1986) claims that the GPS signal is not affected by foliage but gives no indication that he has tested that claim.

The question of the suitability of using a single channel receiver on the coast of British Columbia remains unanswered.

Scope of Study

The study was limited to a single channel GPS receiver, using the pseudorandom noise codes for obtaining position fixes. The objective of the study was to decide if the receiver was suitable for positioning under a forest canopy in the coastal region of British Columbia.

The possibility exists to do an analysis of the data with regards to the satellite geometry. However, no attempt at separating the attempted data sessions based on satellite geometry was made. This was omitted due to the logistics of collecting data at specific times when there were other constraints on data collection such as short viewing windows. It is unlikely that a forester would consult more than one or two indices to decide whether to attempt to use GPS for a given project. An example of data or indices that may be considered are; the positional dilution of precision, elevation of a satellite above the horizon and interval of an effective window. No economic criteria were examined in this study.

Objectives

1) The first objective of the study was to find the suitability of using a single channel receiver under various forest canopies. The probability of obtaining a fix under a canopy was to be determined.

2) The second of objective this study was to decide what applications in forestry should be attempted with a single channel receiver.

Methods and Procedures

Introduction

Trials were conducted for kinematic and fixed positions. Five plots were established to test the signal penetration under various forest canopies and conditions. The study included trials to determine the penetration of signals under various crown closures, wet versus dry canopies, differing satellite elevations and antenna heights.

Data Collection

The data collection took place from August to November in 1990. Data were collected using the Magellan NAV 1000 PRO single channel sequencing receiver. The receiver buffer was downloaded onto an IBM compatible computer.

Site Selection

The U.B.C. Malcolm Knapp Research Forest was used for canopy effects the study. The forest is located 40 kilometres east of the University of British Columbia campus, in Maple Ridge. A description of the plots follows and is summarized in Table 6-1.

Plot 1 was in the middle of the road. It was considered the control. It did not have a clear view to the sky. The road right-of-way was narrow (10m) with trees 14m - 27m in height on each side.

Plot 2 was in a plantation of almost pure Douglas-fir. The trees were pruned to a height of about 2-metres. This area is often called the "Golf course." The canopy was closed with crown closure of 100%.

Plot 3 was in a naturally established second growth stand of Douglas-fir and Western hemlock. It is a dense stand with a low live crown ratio and full crown closure.

Plot 4 was situated on a bench above plot 3. It had been thinned in 1983. The canopy was much more open than plot 3.

Plot 5 was within the same stand as plot 4, however the plot was more open than plot 4.

Table 6-1
Description of plots used at Malcolm Knapp Research Forest

Plot	Description	Avg. DBH	Avg Ht.	Density	Volume
		cm	m	stems/ha	m3/ha
1	Road	-	-	-	-
2	Golf Course	18.6	14	650	-
3	2nd gwth. natural	33.4	26	365	278
4	2nd gwth. spaced	37.2	26	276	267
5	2nd gwth. spaced	33.1	26.8	279	214

The "Golf course" was also used to test the receiver in a kinematic mode. Traverses of the area were performed over a period of a week. Antenna height was varied from handheld (1.3-metres), to 3-metres.

Procedures

The almanac on the receiver, which contains data to determine the position of the satellites, (see appendix D) was used to find when a window occurred for positioning in three dimensions. An attempt was made ten minutes after the beginning of the window to obtain a position fix.

For the fixed plot measurements, the receiver was turned on at the plot and given 10 minutes to search for the satellites. If less than four satellites were found, the attempt was deemed to have failed. Four satellites are required to obtain a 3-dimensional fix.

For the traverse, the receiver was allowed to search until a fix was obtained. This was done in an open grassy area near the forest entrance. If the receiver lost lock on the satellites while on the traverse, the traverse was stopped until a position fix was obtained. A series of traverses was run on the same course. Two receivers were used simultaneously with the antennas at different heights.

A range pole was used to elevate an external antenna to 3-metres. The antenna affixed to the side of the receiver was used for the handheld height of approximately 1.3-metres. The mode was selected on the receiver, to record positions in 2D (3 satellites- 2 dimensional positioning) or 3D (4 satellites 3-dimensional positioning). In 2D the elevation was supplied. The elevation used, varied from 80 to 206-metres.

The receiver also recorded the time, and the signal quality of each satellite used for a fix. This was used to find the elevation of the satellites using the program Orbitset. A correlation was made between the elevation of the satellite, and the signal quality.

Results

Static tests

The single point trials suggest that the canopy is an effective barrier to GPS signals. Table 6-2 summarizes the success rate of obtaining fixes under a canopy. Table 6-3 compares the success of obtaining fixes under dry versus wet forest canopies. The effect of the elevation of the satellite on received signal quality is also explored.

Column 1 describes the plot number and the antenna height used to attempt to collect data. Column 2 is the total number of fixes acquired. Column 3 is the percentage of the potential number of fixes that could have been acquired during a successful data collection session. The potential number of fixes is the number of fixes that would have been acquired if fixes were obtained without interruption during a successful session. Column 4 is the number of session attempts made at the particular plot antenna height combination. Column 5 is the number of successful attempts of at least one fix during a data collection session. Column 6 is the percentage of successful session attempts.

Wet and dry canopies were compared for data collected at plot 2 with a 2-metre antenna height. The mean percent acquired represents the average of the percent of successful fixes of potential fixes. The average of the proportions contain mixed sample sizes.

Table 6-2
Under canopy single point acquisitions with varying antenna height

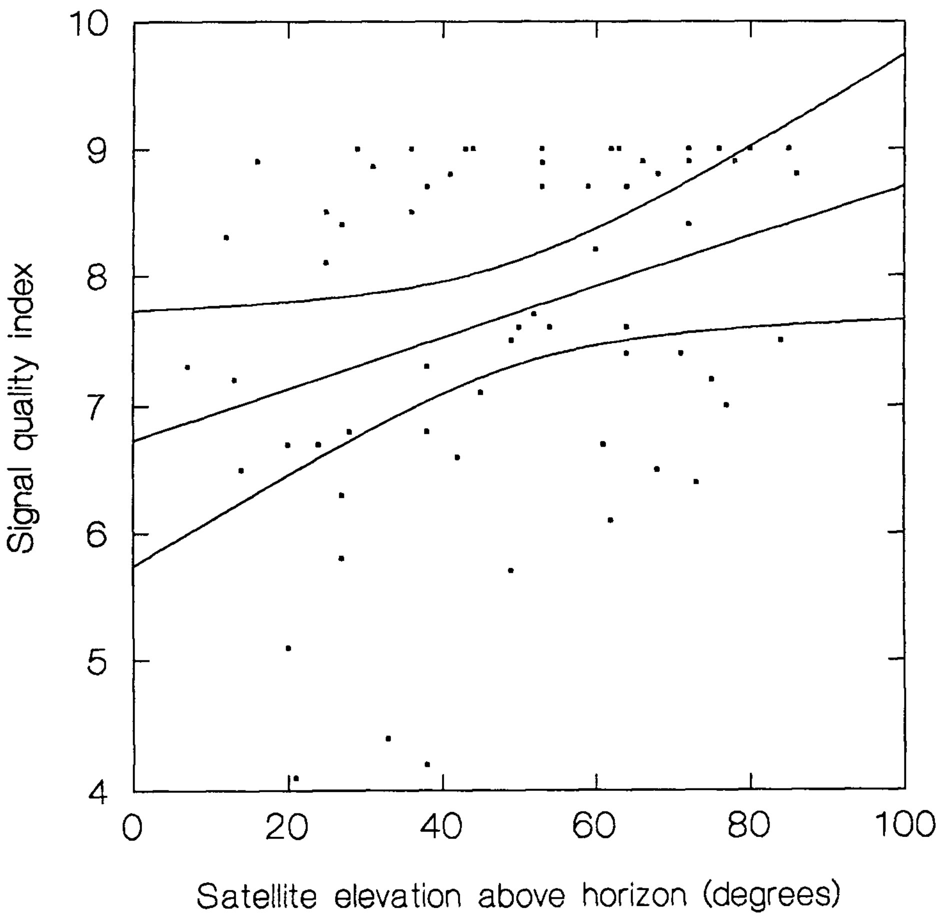
Plot - antenna ht.	# fixes	% acquired	Attempts	Success	% Success
Plot 1 - 5m	122	70	8	8	100
Plot 1 - 2m	38	95	1	1	100
Plot 2 - 5m	358	57	9	6	67
Plot 2 - 2m	172	40	9	6	67
Plot 3 - 5m	0	0	7	0	0
Plot 3 - 2m	0	0	1	0	0
Plot 4 - 5m	0	0	7	0	0
Plot 4 - 2m	18	17	2	1	50
Plot 5 - 5m	0	0	7	0	0
Plot 5 - 2m	0	0	2	0	0
1	2	3	4	5	6

Table 6-3
Percentage of successful/attempted fixes in dry versus wet canopy

	Dry	Wet
Mean percent acquired	56	62
Standard deviation	38	16
number of sessions	4	2

Wilkie(1990) reports that the higher a satellite is above the horizon, the greater the likelihood of obtaining a fix. The assumption was made that signal strength (signal quality) is correlated to the probability of being able to obtain a fix. This assumption was used to study the effect of the canopy on the ability of obtaining a position fix. Figure 6-1 illustrates the correlation between the signal quality and the satellite elevation. The signal quality displayed by the receiver as an index of 0 to 9, where 9 has the highest signal strength. A linear regression was performed on the data using Systat using distance weighted least squares and a confidence interval of 0.95. The correlation is not strong. The Pearson correlation coefficient is 0.32, suggesting a weak correlation between the signal quality and the elevation of the satellite above the horizon. The coefficient of determination is 0.10. That is 10% of the variation in the signal quality can be explained by the variation in the elevation of the satellite.

Figure 6-1
Signal quality index vs. Satellite elevation



Discussion of Results

Static tests

The single point positioning trials indicate that the GPS signal penetrates the forest canopy to a limited degree. However, the probability of a successful position fix drops dramatically as the size of the stand increases beyond 14-metres in height.

When situated at plots 3 through 5, there were many instances of satellite acquisition and data collection, with only two and three satellites. However, in twenty-six attempts, there was only one instance of a successful data session in those plots. This represents a 0.038 probability of obtaining a position fix. All attempts were made in 3D mode. If 2D mode were used there would have likely been more successful attempts.

In plot 1, (on the road) there was a probability of 1.0 of obtaining a fix. In the Golf course (plot 2) the success rate of obtaining a fix was the same whether a 2-metre or 5-metre antenna height was used. However, the antenna at 5-metres collected over twice the number of fixes as were collected with the antenna at 2-metres in height, during the same period.

There was no advantage in using a higher antenna in plots one and four. Plot one was on the road surrounded by trees. There is too small a sample size to say that it may apply to other situations. However it seems that if there is a clear view to the sky there would be no advantage to raising the antenna. In plot four, the base of the live crown was about 15 to 20-metres above the ground and there was very little undergrowth. There was no advantage in using a longer pole (5-m) because the antenna would still be far below the crowns. In table 6-2 there was a successful attempt in achieving a fix with 2-metre pole. This was probably a chance occurrence

In plot 2 however, the increased antenna height resulted in a 208% increase in the number of fixes for a given period. This may be because the antenna position is bettered by raising it. The increase in height to 5-metres puts the antenna above most of the crown, whereas at 2-metres the crown is above the antenna. However, there was no increase in the number of successful data collection sessions with increased antenna height. The lack of increase in successful attempts with the increased antenna height is probably because a 10-minute session is sufficient to obtain a position fix with a lower antenna height.

The elevation of the antenna poses a risk of damaging the unit. The antenna used in the study is susceptible to shocks. When the antenna is situated 5-metres above the ground, great care is needed to keep it from swaying and hitting the trees. An antenna was damaged and rendered inoperable during the study. The choice to elevate the antenna increases the complexity of the field operations. There is also an increased risk of component failure. A handheld unit is simple to transport, power and protect. The handheld receiver weighs 0.85-kg., but when an external antenna is used, there is exposed cabling, an additional battery and antenna, increasing the weight to 3.7-kg.

Some problems of obtaining a fix stem from the lack of satellites. During a ten minute attempt, there were usually insufficient satellites available for the receiver to attempt another satellite configuration. The success rate should increase as the number of satellites increase.

Another factor that would aid in the analysis of the results would be to monitor the satellite status bulletins. It was only on completion of the study that information sources for the constellation status were discovered. Some unsuccessful attempts at acquiring a fix may have stemmed from the satellite being turned off by the United States military, rather than where the antenna was situated.

The data suggests a slightly higher proportion of fixes to potential fixes for a wet canopy. However, the small sample sizes, with unequal sample sizes and large variances suggests that there is no significant difference signal acquisition under a wet or dry canopy.

Results

Dynamic tests:

The traverse course was in the southern end of the Malcolm Knapp forest. The overlaid data are displayed in Figure 6-2 which contains all positions determined when PDOP was less than ten. It is composed of 1365 points. Some positions were determined in 2D mode. Figure 6-3 contains only the fixes that were determined in 3D mode. It contains 175 points.

Table 6-4 contains the results of six traverses with two receivers tracking positions simultaneously. The mode of each receiver was set at either 3D or 2D. The ratio is the number of fixes of one receiver over the other on the same traverse.

Figure 6-2
Malcolm Knapp Golf course traverse. All 2D - 3D positions with PDOP < 10

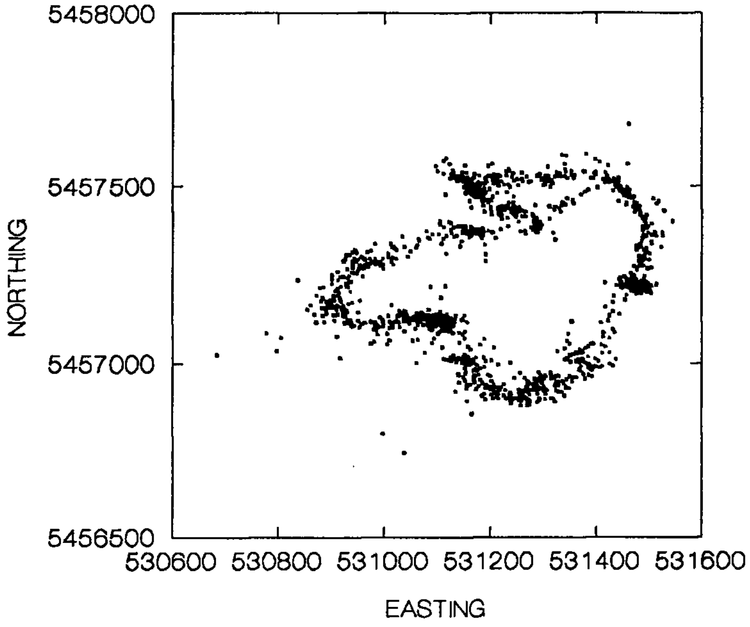


Figure 6-3
Malcolm Knapp Golf course traverse. All 3D positions with PDOP < 10 2D excluded.

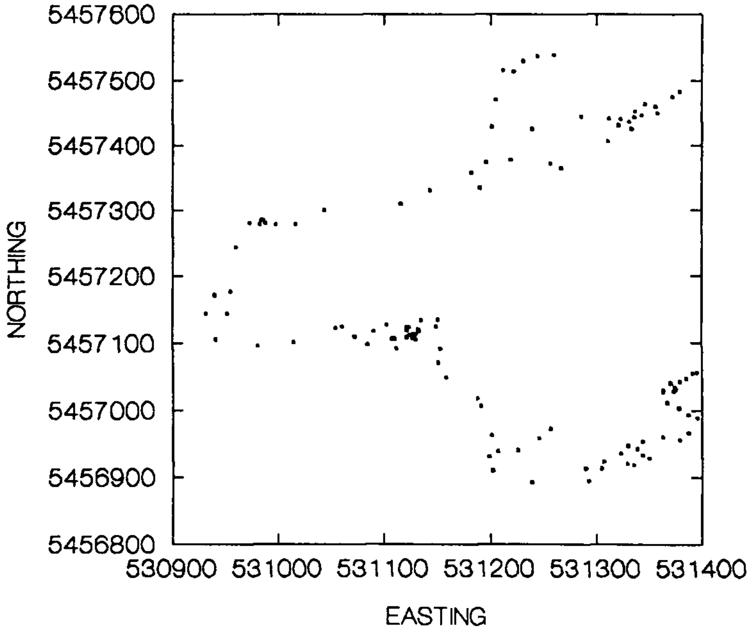


Table 6-4
Ratio of successful/attempted fixes in dry versus wet canopy
Two receivers at 1 and 3-metres elevation used simultaneously
Ratio of number of fixes

Traverse	Antenna Ht.	Mode D	# fixes	Ratio
1	3m	3	98	0.76
dry	handheld	2	129	
2	3m	2	200	1
dry	handheld	2	200	
3	3m	3	41	0.35
wet	handheld	2	118	
4	3m	2	194	1.4
wet	handheld	2	139	
5	3m	3	36	0.27
wet	handheld	2	135	
6	3m	2	160	6.67
wet	handheld	2	24	

Discussion of Results

Dynamic tests:

The dynamic test of performing a traverse indicates that operating the receiver in 2D mode enhances the reception of GPS signals. The ratio of 3D/2D fixes is 0.45. This is partially due to the faster data capture rate in 2D mode inherent in the receiver. The receiver calculates a position fix every 11 seconds in 2D if unobstructed. This increases to 15 seconds when 3D mode is chosen. This alone would account for a ratio of 3D/2D fixes of 0.73. If the effect of the slower acquisition rate in 3D mode is considered, and the effect of a higher antenna is ignored, the 3D/2D ratio would still be 0.62. This suggests that the probability that the receiver obtains a position fix when using 2D is greatly enhanced.

The antenna height also affects the success of obtaining fixes. When both receivers were put in 2D mode and used simultaneously, the ratio of fixes of 3m over handheld heights was 1.5. Since the data acquisition rates should be 11 seconds per fix in 2D for both receivers, the discrepancy can be entirely attributed to antenna height.

Conclusions

The use of a single channel receiver under a forest canopy 12 - 15-metres high, for single point positioning, is not recommended. When under a canopy less than 12-metres, it is recommended that the antenna be elevated, preferably over top of the canopy. When in stands of greater than 20-metres in height, there is no benefit in raising the antenna from 2-metres to 5-metres. Procedures and equipment need to be developed to ensure that the antenna is not damaged when a long pole is used.

The rate of data capture in dynamic mode using 2D was increased by 150 percent when a 3-metre antenna height was used versus 1.5-metre antenna height. The data indicate that there was no significant difference in obtaining fixes under a wet or dry canopy for fixed positions. The data cannot be distinguished in the dynamic tests, to learn if a wet canopy affected the acquisition rates. However, it is felt that there was no discernable difference.

The use of 2D in dynamic mode increased the number of position fixes during the same period by 222 percent over the use of 3D. This increase is due in part to an increase in data capture inherent in the receiver, but also due to the increased likelihood of obtaining a fix because fewer satellites are required using 2D.

When 2D mode is selected, the user must supply an accurate elevation to obtain an accurate position. For single point positioning an elevation may be typed into the receiver. For kinematic positioning it is not feasible to enter the elevation whenever it changes, unless the terrain is very uniform.

Recommendations

The use of a single channel receiver under immature and mature coastal forests should not to be pursued at this time. When a full constellation of satellites is present, and the inevitable improvements in technology are made, this study should be repeated.

The use of a single channel receiver in regenerated stands up to 14-metres in height deserves further study. With an elevated antenna, traverses were easy to complete. The study of the accuracy of traverses completed by GPS should be pursued.

Any further experimentation should involve a more rigorous experimental design. Most of the analysis in this study involve ad hoc methods. An ANOVA would define for the user, the factors affecting GPS signals. Further testing should be designed to distinguish variation of satellite acquisition by 1) mapping of the vegetation through a fish-eye photograph 2) elevation of satellites 3) geometry of satellites 4) health of satellites 5) biomass of canopy and 6) technology receiving the signals. In this study only one type of receiver was tested.

CHAPTER 7 - DISCUSSION AND CONCLUSIONS

Discussion

The field of geodetic positioning with GPS is moving at a rapid pace. For example, the single channel receiver used in this study was received in May of 1990. It was one of the first units of the model line produced. Since then it has gone through two upgrades, and now has been superseded by a 5-channel receiver with claims of sub-metre accuracy during differential positioning. The post-processing software has also been completely rewritten. Several areas of GPS that have changed significantly since the start of this study are:

1) DGPS - Differential GPS. The U.S. military has confirmed that SA will be implemented to prevent the use of precise GPS positioning by enemies of the United States, and its allies. This will render autonomous positioning accuracies of 100 metres 95 percent of the time. To achieve higher accuracies, inherent within the system, differential positioning will need to be employed. GPS receivers are now offered as a plug in module for desktop and hand held computers. Coupled with modems (or radio modems) real-time differential positioning is now possible at a reasonable cost. The U.S. Coast Guard is committed to upgrading its network of radio beacons to broadcast differential GPS corrections. A nationwide network of GPS compatible beacons should be in place by 1996. The service will be available up to 200 miles offshore and accuracies should be under 10-metres. There is also the possibility of sub-decimetre accuracy while using phase differential positioning within harbours. The governments of Canada and British Columbia are planning to establish an Active Control System (ACS), for differential GPS. This will allow users to perform differential positioning relative to a number of established control points. This will allow users such as navigators and surveyors to obtain high quality differential information. Several private concerns already offer differential data for post-processing.

New techniques in surveying, such as rapid-static are enabling users of GPS to obtain centimetre accuracies with a site occupation time of only minutes. The task of post-processing differential data a few years ago required a highly trained technician. Today's receivers are being shipped with menu driven software that virtually any GPS user can use effectively. The Receiver Independent Numerical EXchange (RINEX) format will allow users of receivers from different manufacturers to exchange data for differential positioning.

The use of many of these techniques will not be available to forester's at the present time. Real-time differential will depend on a radio link between the base station and the remote user. Given that most of the radio frequencies are already allocated and the difficult terrain in British Columbia, the quality of the signal in many areas renders radio data communications unreliable. However, in the near future, satellite based cellular communications will be available. Where there are enough GPS satellites visible for a position, there should also be a communications satellite available to broadcast the differential corrections. Many communication satellites have some positioning ability. This will strengthen the amount of radio navigation information on the airwaves.

The use of satellites to broadcast differential corrections, however, begs the question, "why use GPS in the first place?" If one user is to use differential corrections from a satellite that is broadcasting over a quarter of the globe, then the remote user needs to broadcast the approximate position of the remote receiver to the satellite. The satellite then may broadcast the appropriate correction parameters for that area of the globe. If there is two-way communications between the remote user and the communications satellite, a range to the satellite from the user can be derived. If the communication satellite is acting as a transponder for radio signals there is no need to carry a series of atomic clocks. A communications satellite can be built and launched for less cost than a GPS satellite. With the promise of SA, it might be more cost effective for a civil agency to launch its own constellation of satellites for navigation and communication.

The greatest potential for the use of DGPS in forestry is in post-computed corrected positions. This will eliminate the need for the extra components required for communications. However it will require greater onboard data storage on the remote receiver. DGPS ca be used effectively for establishing coordinates for tie points, road and polygon traverses and virtually any aerial application.

The rapid-static surveying technique requires a couple of minutes of uninterrupted satellite signals. Given the difficulty of obtaining even intermittent signals under a canopy, this technique is not feasible for under-canopy applications at the present time nor for the foreseeable future.

2) Software improvements. The first software shipped with the Magellan receiver was command line driven with no data management capabilities or mission planning. The most recent version has pull-down menus with satellite prediction software included.

Most manufacturers now provide data conversion software to allow the user to upload spatial data into a variety of GIS's. There is also attribute capture software that supports most receivers. This software allows the user to tag an attribute such as a culvert with a time and position. This may be accomplished with the use of function keys or bar-codes. There is also the capability to view the position of the antenna as a cursor on a computer video display. The screen background may contain a geo-referenced image of the area being traversed or a digitized map.

3) Permanent Limitations - The long life span (7-10 years) of a GPS satellite, the large cost of each satellite, and the budget reductions occurring in the U.S. military, suggest that there is little chance of rapid improvement in the GPS satellite constellation. The oscillators that drive the radio signals, the power of the signals, and the satellite constellation can be considered to be a constant for the next decade. The ability of the transmitted signals to penetrate a closed canopy will remain a problem.

There is opportunity for the Russian GLONASS satellite navigation system to be integrated with GPS. This will allow for integrity checks of the navigation message being broadcast by GPS satellites. The user will also have more satellites above the horizon to choose from. There are also proposals to establish communication satellites to broadcast signal integrity messages to users and supply crude corrections for differential positioning.

The most rapid advancement will come in the user equipment. The price/performance ratio is rapidly declining. The unit cost of the receiver modules will probably be halved again within the next two years. The biggest advancement will come with the integration of GPS modules with other navigational aids. For instance there is a small gyro costing several hundred dollars that can be used to interpolate positions between GPS fixes. A GPS receiver, combined with a digital compass, an inertial navigation unit and a radio receiver to receive differential corrections would approach a "black box". The box could tell you where you are within a metre, how fast you are moving, and in what direction.

4) Applications in Forestry - The application of GPS to forest management will probably be in the areas of photogrammetry, mapping, and vehicle navigation. The cost of establishing ground control for aerial surveys can be greatly reduced if not eliminated if the aircraft uses GPS to record the position of the camera.

The use of GPS for navigation can provide immediate benefits for the positioning of crews on large fires, locating project areas, growth and yield plots, and road network navigation. Traversing large openings, together with a hip-chain can easily be accomplished with today's technology. When a forest canopy is present, the use of a telescopic range pole may be used, however the pole must extend to the upper reaches of the canopy.

The problem of the canopy may be reduced in the future by the use of receivers specifically designed for forestry applications. Present day receivers rely on obtaining near simultaneous readings from at least four satellites with an omnidirectional antenna. The author feels that if an array of high-gain antennae, each directed to a specific satellite were used, the receiver may lock onto very weak signals. If sophisticated modeling of the satellite orbits were achieved, ranges to each satellite could be taken in seconds or minutes instead of simultaneously. If the receiver were static, the receiver could capture enough data over time to calculate a position. It was felt that during the study opportunities of obtaining signals were missed due to the lack of a channel being dedicated to each satellite. Multi-channel receivers will help to correct this problem.

The use of GPS in may cases can reduce the cost of surveying positions. The savings can quickly disappear as the accuracy required increases and the time required for a solution decreases . For accuracies in the 25-metre range the user may purchase a receiver for about $2000 and quickly average a number of fixes by pushing a button. To obtain a position within 10-metres two receivers are required. This may be a receiver owned by a service agency or the user may purchase another unit. The remote receiver would need a storage capability for post-processing of the positions obtained. Alternatively, a radio link would need to be established to receive differential corrections in real-time. If the user wanted to upload the positions into a GIS, onboard data storage would still be required. If the user wanted to obtain accurate positions under a canopy, a telescopic range pole and external antenna would need to be purchased.

If the requirement was for sub-metre accuracy, real-time positioning would be unrealistic. Considerably more storage capacity would be required at both the base station and remote stations to store the extra data required. If the requirement was for sub-centimetre accuracy, the user would need to be trained in differential processing. New issues would need to be addressed such as the phase center and orientation of the antenna. The modeling of errors from ionospheric and tropospheric refraction would need to be incorporated into the solution. The purchase of post-computed ephemiredes (orbital data) would also be required. The cost of the equipment and the level of expertise would necessarily increase.

Conclusions

A single channel GPS receiver is not adequate for obtaining positions under a forested canopy. A multiple channel receiver will probably be more successful in obtaining a position fix. However the quality of the fix may be degraded from the manufacturer's specifications. The degradation is due to; 1) the scattering and attenuation of the signal by the forest canopy, and 2) the poor satellite configuration of using only satellites high above the horizon. The second cause of degradation can be controlled by only recording fixes when the configuration of satellites yields a strong geometry, however the net effect will in many cases, be the exclusion of all fixes attained. Thus the receiver cannot be used effectively under a canopy.

The utility of GPS can be realized where the antenna is not obscured by a forest canopy. Activities that occur on wide road right-of-ways and clearcuts are good candidates for the use of GPS. Young stands where the effort of carrying and extending and collapsing a telescopic pole is offset by the ease of collecting positional information are also areas where GPS may be used. However, the pole must extend to the height of the topmost branches to be of any benefit. The system may also be used to traverse clearcuts, if a hip chain and compass is also carried to determine positions during signal blockages.

The first uses of GPS should involve equipment on aircraft. The view of the antenna to the sky is usually unobstructed when the antenna is mounted atop a fixed wing, or on the tail-boom of a rotary-winged aircraft. Since the cost of renting aircraft is high, small gains in the effectiveness of the use of aircraft are worth pursuing. The author feels that the use of GPS for air navigation and collection of data would be cost effective. This can be achieved by enhanced navigation to areas of study and automatic time and space tagging of observations from the aircraft. For example, a mountain-pine beetle flight may be planned by entering coordinates of the study area into the helicopter's navigation system. This will allow the pilot to fly directly to the area in question without having to interpret maps. Any new infestations encountered may have their positions recorded by the simple pressing of a button. This would be far superior to navigating by air photographs and hand mapping the infestations.

The accuracy of code based receivers will ultimately be 100-metres RMS in autonomous mode. In differential positioning, a user can expect accuracies of 6-10-metres RMS in 3 dimensions. That is, given an average of 100 fixes on a given location 63 of them will fall within 8 metres of the mean position. Ninety-eight percent of the fixes will fall within 16-metres of the mean position. However, improving methods of data collection and processing promise to bring higher accuracy for differential positions with shorter site occupation times.

GPS allows the direct collection of time tagged spatial information in a digital format. This information is valuable for the operation of vehicle monitoring systems. Positional data coupled with vehicle performance data will allow supervisors to easily determine operator performance, efficiency and safety on a road network.

Further testing should involve multi-channel receivers. Comparisons should be made in an operational setting with competing technologies. For instance the updating of disturbed areas with GPS including qualitative information gathered by the field personnel, should be compared with Landsat, SPOT, aerial photographs, and tight-chained traverses.

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APPENDIX A - VINCENTY INVERSE

Introduction:

As suggested in Chapter 1, traditional methods of surveying calculate coordinates in two dimensions on a reference plane. The third dimension, elevation, is calculated from a different reference datum by different procedures. Geodetic coordinates, (Latitude and Longitude) are based on a three dimensional world, but only describe the coordinates of a position on the reference ellipsoid. The orthometric height (height above mean sea-level), is an attribute assigned to a position. The task of a GPS receiver is to derive coordinates on the ellipsoid. The elevation is given as the height above ellipsoid.

Objective

The objective of this section of the study is to examine the effect of convergence of the meridians on the distance between two points on the earth's surface.

Convergence:

On a spherical earth, the distance between degrees of latitude is essentially constant. The degrees of longitude (meridians) converge at the poles. At the equator, all meridians are parallel. At the poles all the meridians converge to a single point. (Ewing and Mitchell 1970).

Assuming a spherical earth, the convergence angle for a UTM projection is given by:

$$C = ABS[\lambda \sin(\phi)]$$

where:

C - is the angle of convergence.

λ - is the difference in longitude from the central meridian.

ϕ - is the degree of latitude

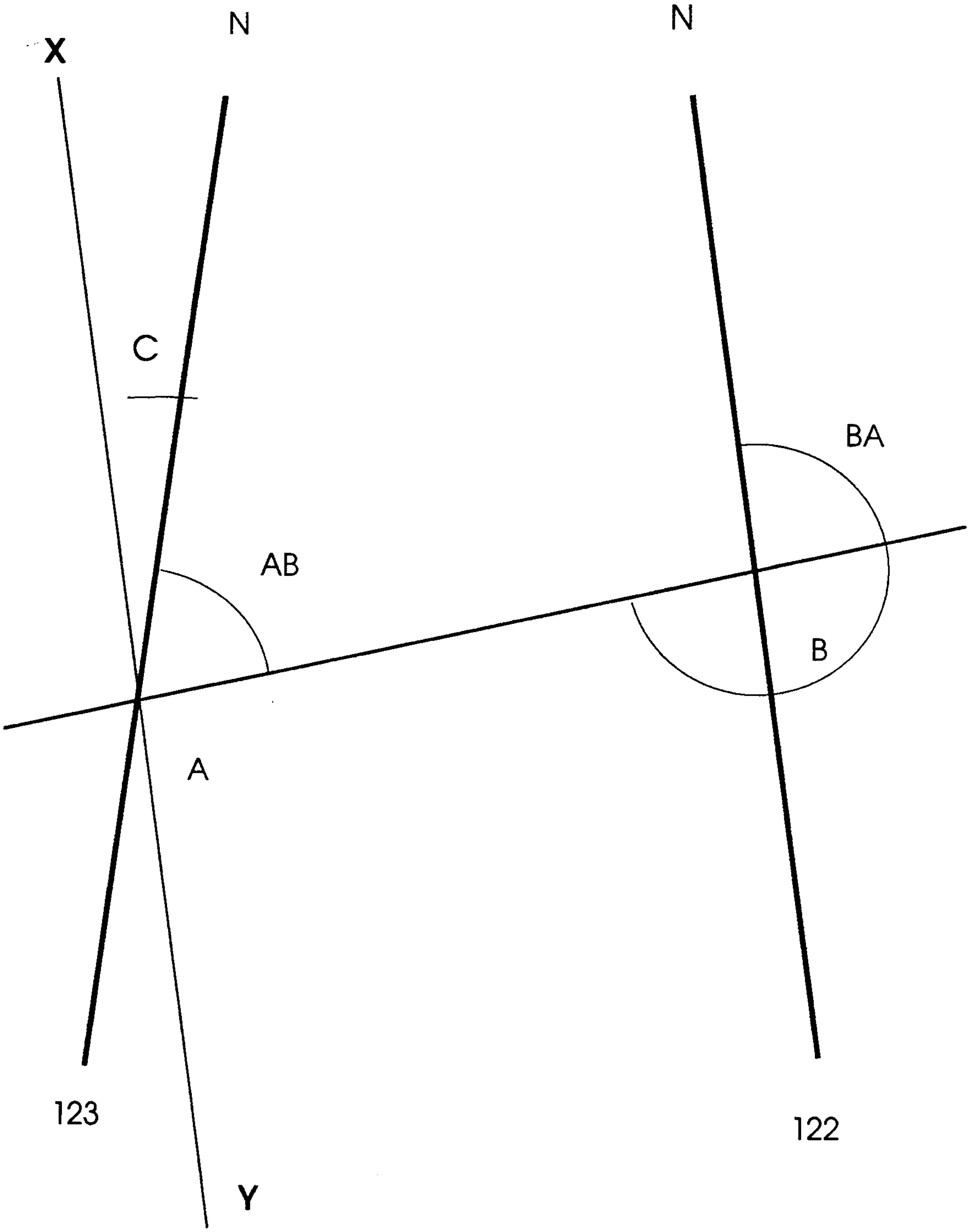
(Wong 1989)

Forest surveying with a two man crew usually depends on a foresight and backsight from each crew member. The foresight from the tailman should differ by 180^0 from the compassman or leading member of the crew. This is true for the crude compasses used and the short distances between crew members. The significance of convergence for geodetic positioning, is the forward and back azimuths do not differ by 180^o. They differ from 180^0 by the amount of convergence. The significance of convergence on UTM coordinates is that the UTM grid is regular while the meridians are curvilinear. The features printed on a map are distorted by the Transverse Mercator projection. Thus the UTM grid lines running North-South are in error with respect to the lines designating longitude by the amount of convergence.

Figure A-1 illustrates convergence. The meridians of longitude are shown with the convergence exaggerated towards the North Pole. An azimuth bearing with reference to true north from point A to point B, on meridian 123, is AB. An azimuth from point B, on meridian 122 to point A is BA. However angle BA is not 180^0 greater than angle AB. The thin line XY is parallel to the meridian 122. The angle C is the amount the two azimuths differ and is defined as the angle of convergence.

Figure A-1

Convergence of the meridians



Geodesics:

The shortest distance between any two points on a sphere, describe a great circle. The sighting of a theodolite in Figure A-1, from point A to B and B to A would be identical. The plumb or normal from the levelled theodolites would intersect at the centre of the earth. The foresight bearing between the two points would be identical with the backsight.

The shortest distance on an ellipsoid describes an arc, or a geodesic. The surface normals of two points on the ellipsoid are skewed to one another; the normals do not intersect. Therefore the sighting of a theodolite from point A to point B does not record the same azimuth as the sighting from point B to point A. The difference in azimuths between the two points is slight however. The difference for two points separated by 50 km amounts to 0.02" in an example in Torge(1980). The amount of convergence that affects azimuth calculations, depends on the separation in longitude as well as the scalar distance. Two points lying on the same meridian, would not suffer any convergence in the azimuth.

Purpose:

The motivation for writing the program Geodist was to calculate distance when given the longitude and latitude of two points. This could be used when capturing raw geodetic positions from the receiver. This saves transforming the geodetic positions to a mapping plane. The function may be used to perform differential corrections over short distances. It is also more convenient to use latitude and longitude when calculating distances between positions that span two or more UTM mapsheets or UTM zones.

Method:

The program Geodist was written in Turbo Pascal version 5.5. Topaz units were used for the menus and input screens. The calculations were based on C code as supplied by Pointon (1991), which were based on a paper by Vincenty(1975).

The GRS80 ellipsoid model is used. This GRS80 ellipsoid uses 6378 km for the semi-major axis, and 6357 km for the semi-minor axis. This is essentially the model used in WGS84, which is the native ellipsoid reference system for GPS. (Lachapelle 1991)

The geodetic distances were calculated using Geodist. These were compared with distances calculated from examples in Torge (1980). UTM transformations from geodetic coordinates were calculated from the program GSrugpc. This program is supplied by the Geodetic survey of Canada (Farley and Junkins 1990).

Results:

The results of the model as compared to the example in Torge(1980) are displayed in Table A-1. The first column is the difference in latitude or longitude of the position from 50^0 N and 123^0 W. The second and third columns are the distances in metres calculated by Torge and Geodist respectively. The last column is the difference between the Torge and Geodist calculations.

Table A-1
Example by Torge compared to Geodist
Differences in distances calculated from geodetic positions

Delta	Torge(m)	Geodist(m)	Difference(m)
Lat 1 degree	111229	111229	0
Lat 1 minute	1853.8	1853.8	0
Lat 1 second	30.30	30.97	0.07
Long 1 degree	71696	71596	100
Long 1 minute	1194.9	1193.3	1.6
Long 1 second	19.92	19.21	0.71

Taken at 50° latitude. 123° longitude

The model Geodist, agrees within 1 cm of the ellipsoidal arc distance parallel to longitude of the example in Torge. However the distance calculated along an arc of latitude do not readily agree. For one degree of longitude this is only 0.1% error. At the one minute interval, the magnitude of the discrepancy decreases. At the one second interval of longitude, the error amounts to 3.6% of the distance.

Further calculation with Geodist, estimates that with an interval of three degrees of latitude, representing a distance of approximately 214 kilometres on the ground, the forward and backward azimuths differ from 180° by 3°. The implications for calculating distances on the mapping plane are illustrated in Table A-2. The results of Geodist , are compared to distances between UTM coordinates. The UTM coordinates are calculated by the program GSrugpc (Farley and Junkins 1990). Points two to six are calculated as the distance from point one.

Table A-2
Comparison of distances from GSrugpc and Geodist

Point	Latitude	Longitude	Distance (m)	Geodist (m)	Difference (m)
1	49:00:00	123:00:00			
2	49:01:00	123:00:00	1852.8	1853.5	0.7
3	49:00:01	123:00:00	30.9	31	0.1
4	49:00:00	123:01:00	1219.2	1217.8	1.4
5	49:00:00	123:00:01	20.3	21	0.7
6	49:01:00	123:01:00	2217.72	2217.63	0.9

All distances are in metres. The difference between calculating distances from UTM coordinates versus directly from geodetic coordinates is generally less than 1 metre. Only when the distance calculated along an arc of latitude of one minute (1.2 km) does the discrepancy grow to 1.4-metres.

Discussion:

The discrepancies in calculating the geodesic between the textbook example found in Torge, and the calculated distances in Geodist, are cause for concern. Since the results strongly agree in the distance along a meridian (N-S), it is felt that the effect of convergence may have been left out of the Vincenty algorithm. Until the reason for the discrepancy is found and corrected, the function in Geodist should only be used for approximations.

When the distances calculated with Geodist, are compared to those calculated by the program GSrugpc, the discrepancy is lessened. For 1 minute of latitude, the discrepancy is only 0.04%. For one second of longitude however, the discrepancy is 3.5 %. When a combination of change in the latitude and longitude of one minute is made, the

When the distances calculated with Geodist, are compared to those calculated by the program GSrugpc, the discrepancy is lessened. For 1 minute of latitude, the discrepancy is only 0.04%. For one second of longitude however, the discrepancy is 3.5 %. When a combination of change in the latitude and longitude of one minute is made, the discrepancy is only 0.004%. Again it appears that convergence may play a role in the discrepancy. The UTM grid also suffers from convergence of the meridians. That is the UTM graticule is at right angles, while the meridians of longitude are curved towards the poles.

Conclusion:

The Vincenty inverse function can be used to approximate distances and azimuths on the earth's surface using geodetic coordinates. When incorporated into the program Geodist, these agree to an acceptable degree on distances of approximately 20 kilometres. However, for short distances, especially along an arc of latitude, the discrepancy is unacceptable as compared to distance calculated on a UTM grid. However, if one keeps in mind the map scale that GPS data should be used at, the program Geodist is useful for calculating distances.

Bibliography

Ewing, C.E. and M.M. Mitchell. 1970. Introduction to geodesy. American Elsevier Publishing Co. Inc. New York.

Farley, S.A., Junkins D.R. 1990. The national transformation. Program descriptions and user instructions for software package. In Preliminary proceedings. Moving to NAD '83. Richmond, B.C. Canadian Institute of Surveying and Mapping. 40pp.

Pointon, K. 1991. Personal correspondence. Ministry of Crown Lands. Geodetic Control Unit . Victoria B.C.

Torge, W. 1980. Geodesy, an introduction. de Gruyter. Berlin, New York.

Vincenty, T. 1975. Direct and inverse solutions of geodesics on the ellipsoid with application of nested equations. Survey Review XXII, 176: 88-93.

Wong, F. 1989. Course notes for F435. Forest Inventory Systems. University of British Columbia.

APPENDIX B - ORBITSET

Introduction

A program written in Turbo Pascal to predict visibility of satellites of the Global Positioning System (GPS).

Objective:

The purpose of the project was to write a program to predict the orbits and visibility of NAVSTAR (GPS) satellites for a person on the earth's surface. The motivations to embark on this project were:

1) The author was unaware of any IBM PC compatible software that was non-proprietary, and used the NASA supplied orbital parameters.
2) To analyze signal reception under forest canopies, it was believed that polar plots of satellite tracks would be required. This information would be needed to analyze overlays of satellite tracks and the fish-eye lens photographs of the canopy. This would enable a study of what was interfering with the satellite signals.
3) Tables of satellite elevations were required to analyze satellite elevation and signal availability.
4) A prediction program was needed to allow the planning of differential positioning sessions.
5) The flexibility of providing future reports can only be handled by having access to source code. It was felt that it would be advantageous to have a program written in a high level language for easy maintenance.
6) The program could provide the core for a satellite prediction program that incorporated a digital terrain model. The satellite availability would be determined

after analyzing the specific area the user was interested in, using local physical barriers (e.g. mountains).

7) It also may provide a core for a system for pointing a high-gain antenna array in a forest environment. The typical GPS antenna is currently omnidirectional.

Method:

The program was written in Turbo Pascal version 5.5. TOPAZ (1990) units were used to handle the data files and create the menus. The graphing function was written as a unit by modifying a program from Turbo Pascal Programmer's Toolkit(1989). The algorithm for the calculation for the elevation angles was found in Pratt and Bostian(1986). Methods for handling Julian dates were found in Duffet-Smith P.(1981). These are included in the annotated bibliography.

The data for the orbital parameters were found in the NASA prediction bulletins. These can be acquired by writing to the address in Appendix B-III.

Results:

While writing the program, the numerical example in Pratt and Bostian (1986), was continuously checked. The results of the Pratt example are contained in Appendix B-I. The results for ORBITSET compare favorably as indicated in Table B-1.

Table B-1
Comparison of ORBITSET to Pratt Numerical example

Program	Elevation (degrees)	Azimuth (degrees)
Pratt & Bostian	32.28	229.39
ORBITSET	32.4	229.24

This example was for a geosynchronous satellite. The results change very little on a daily cycle.

The GPS results were tested against the Trimble SATVIZ™ program and the Magellan NAV 1000 PRO™ receiver. The Trimble almanac was collected by a survey receiver on July 7, 1990. The inability of updating the SATVIZ program without owning a Trimble receiver was one of the motivations for writing ORBITSET. The almanac for the Magellan was collected on November 25, 1990.

Since ORBITSET cannot work backwards in time, a test to compare satellite PRN 17 was made on August 10, 1990 with NASA data from a bulletin issued on August 3, 1990. The results are:

August 10 1990 00:00 UTC

Program	Elevation (degrees)	Azimuth (degrees)
SATVIZ	25	244
ORBITSET	25.5	244.05
Magellan	25	244

August 10 1990 02:00 UTC

Program	Elevation (degrees)	Azimuth (degrees)
SATVIZ	74	296
ORBITSET	74.6	296
Magellan	75	297

Since the Magellan receiver had a much later almanac it may have suffered a problem in working backwards in time. Therefore another comparison for December 3, 1990 was made.

December 3, 1990 16:00 UTC

Program	Elevation (degrees)	Azimuth (degrees)
SATVIZ	31	242
ORBITSET	33.6	240.76
Magellan	34	243

December 3, 1990 18:00 UTC

Program	Elevation (degrees)	Azimuth (degrees)
SATVIZ	80	317
ORBITSET	81.78	326
Magellan	80	320

Discussion:

More testing is required to fully evaluate the program. Since the data input for each program is different, some variation is to be expected. A few degrees in elevation may be a cause for concern in some applications. However, one degree of elevation may represent only about 2 minutes of time for a satellite passing high overhead.

ORBITSET uses the six classical Keplarian parameters. These are:

Inclination - the inclination of the satellite orbit to the equator.

Eccentricity - the measure of how out of round the ellipse is.

Mean Anomaly - the angle created by the position of the satellite at epoch (point in time) and the argument of perigee if the orbit was circular.

Argument of perigee - the angle created by the point where the orbit is closest to the earth and the point of the ascending node.

Right ascension of the ascending node - angle on the equatorial plane from the point of Aries (fixed in space) and the ascending node.

Mean Motion - the number of orbits per day.

The navigation message collected by the receivers contains 16 parameters. This is needed to model the satellite's orbit more precisely. These extra parameters consider the effects of a non-spherical earth and third body gravitational effects. It is updated every 90 minutes (Wells, et al 1986).

To test the sensitivity of the parameters to time several graphs were produced for the Pratt example. Since the Pratt example uses a geosynchronous satellite in a very stable orbit, it would be expected to remain the same over millennia. The satellite orbit was predicted, for the time the orbital parameters were calculated: December 27, 1978. It was then run every year until 1988 on December 27. Figures B-1 and B-2 illustrate how the prediction starts to deteriorate.

Figure B-1

Satellite elevation above the horizon vs. Time. December 1978

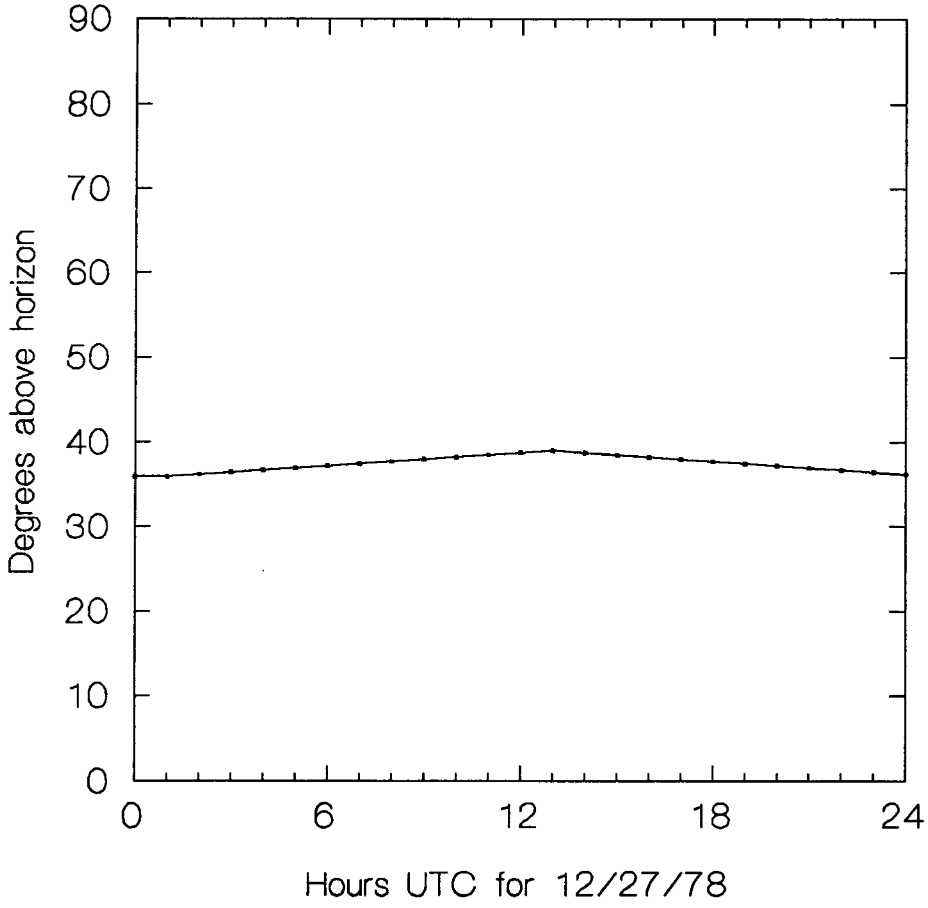
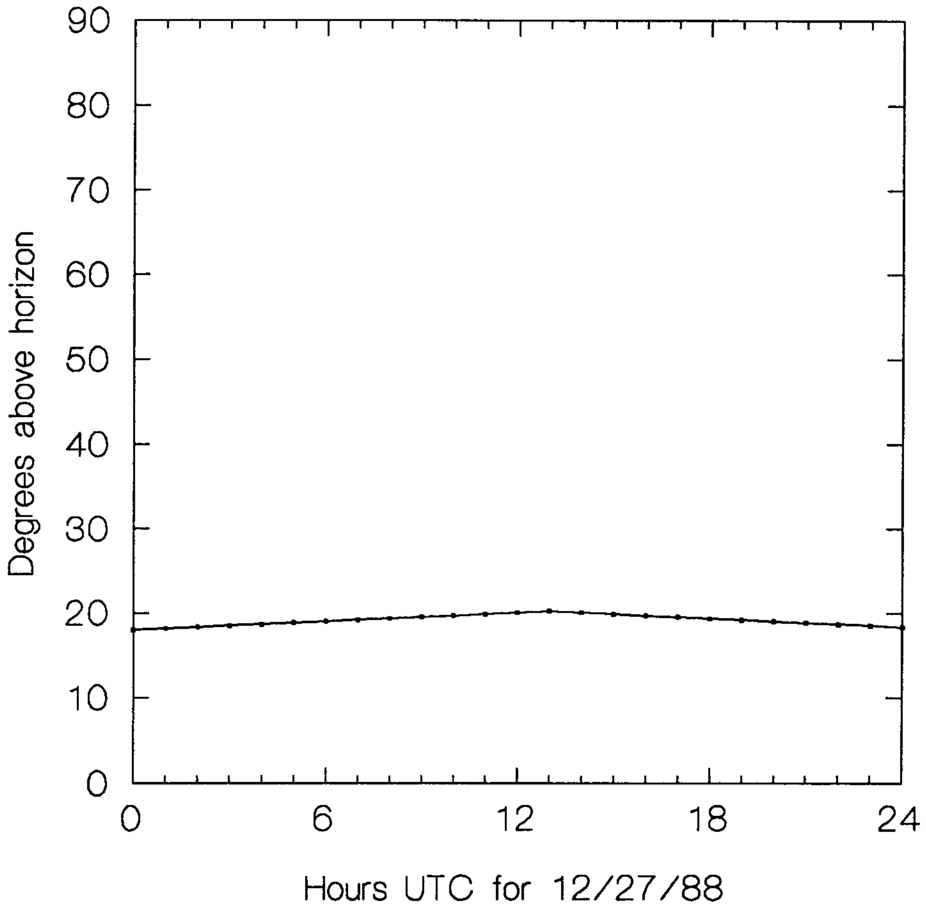


Figure B-2

Satellite elevation above the horizon vs. Time. December 1988



Future Developments:

The program is at the stage where it can be used as a planning tool by a GPS user. The author would like to see developed:

1) Output files in ASCII and .DBF format to be read by other modules and programs.

2) A polar plot of each satellite to be used for analyzing data collection sites. Plots should be available at various scales.

Other variables that are calculated in the program are:

> longsub latsub - these are the ground tracks of the satellites. They may be used to plot the satellite's path along a map of the earth.
> azimuth - the azimuth angle of the satellite in relation to the user's position. Plots may be made to help the user find the position of the satellite in relation to the user.

3) Amalgamation of model with a GIS digital terrain model. This would enable the user to produce a site specific satellite window.

4) The positional dilution of precision (PDOP) should be added to the model. This would indicate the accuracy that could be expected from a GPS session.

The project suggested in 3 could then be upgraded to incorporate vegetation. A GIS could be used to provide maps of GPS availability based on land forms and vegetation type.

A further version could incorporate the PDOP and elevation masks. Even with a full constellation of satellites available, this could prove to be a valuable planning and research tool.

The source code should be cleaned up by removing redundant code and finding quicker algorithms. The bugs related to spurious elevations should be corrected. The spurious elevations are felt to be from the omission of a means of determining rise and set times for the satellite. A crude mask is provided in the program that excludes satellites that are on the other side of the earth. The interface can also be made smoother.

Upon completion of the project it was found that various computer bulletin boards are in existence for the GPS community. A good project would be to scan the various bulletin boards for available source code and executable programs.

Conclusion:

The program is useful for a GPS user to plan daily activity. Although some spurious elevations creep into the results, these are confined to elevations less than 15 degrees. It is felt that satellite elevations this low should be ignored as the satellite is too close to the horizon to be used successfully for positioning. The elevation mask however, can be changed by the user.

It is felt that predictions will be accurate enough for planning purposes with orbital parameters up to a year old. The parameters should however, be updated when a new satellite has been launched, or when satellite orbits have been altered.

The structured feature of Turbo Pascal should allow modification of the program to support other functions and produce more varied reports.

Bibliography

Duffet-Smith, P. 1981. Practical astronomy with your calculator. Cambridge University Press. London. Second edition. 188pp.

A good guide with numerical examples for calculating Julian dates. Also useful for rotation matrices for converting between coordinate-ordinate systems.

Lachapelle, G. 1991. Global positioning system. GPS workshop at GIS91, Vancouver, B.C. 180 pp.

Contains many excerpts from Wells, et al (1986). Each page is designed to be used as an overhead transparency. Also includes some notes taken during workshop.

Morgan, W.L. and G.D. Gordon. 1989. Communications satellite handbook. John Wiley and Sons. Toronto. 900pp.

The bible of satellite communications. Compendium of formulae and constants. Some FORTRAN code included but not used.

National Aeronautics and Space Administration (NASA). 1990. NASA Prediction Bulletins. Greenbelt, MD. 9pp.

Free bulletins containing the Keplarian satellite parameters. Now available on electronic bulletin boards.

Pratt, T. and C.W. Bostian. 1986. Satellite communications. John Wiley and Sons. Toronto. 472pp.

Was essential for developing the program. Provides a numerical example on pg 31. An error was found in a rotational matrix in equation 2.47. The precision of their calculations also may be questioned.

TOPAZ. 1990. User's guide and reference manual. Software Science Inc. Brisbane, California. 399pp.

Useful Turbo Pascal units for handling data in .dbf format. Also used for building menus. Source code not included.

Turbo Pascal. 1989. Reference guide, version 5.5. Borland International. Scotts Valley, California. 468pp.

Version 5.5. Version 6.0 and Turbo Pascal for Windows are now available.

Rugg, T. and P. Feldman. 1989. Turbo Pascal programmer's toolkit. Que Corporation. Carmel Indiana. 539pp.

Used for graphing the results. Code is commented and suggested modifications are found in the book. Source code included.

Wells, D.E. N. Beck, D. Delikaraoglou, A. Kleusberg, E.J. Krakiwsky, G. Lachappelle, R.B. Langley, M. Nakiboglu, K.P. Schwarz, J.M. Tranquilla and P. Vanicek. 1986. Guide to GPS Positioning. Canadian GPS Associates. Fredericton, NB. 544pp.

Comprehensive guide. However too concise to be useful for a specific topic.

APPENDIX B- I PRATT SOLUTION

Reference:

Pratt T., and C.W. Bostian, 1986. Satellite communications. John Wily & Sons. Toronto.

Numerical example on page 30.

Epoch:

UT December 27, 1978
Julian Date: 2443869.5

Initial parameters:

semimajor axis	42164.765 km.	
eccentricity	0.001181	ratio
inclination	0.802	degrees
mean anomaly	116.636	degrees
arg of perigee	138.167	degrees
RA of Ascending node	84.178	degrees

User's location:

Latitude	37:13:44	degrees N
Longitude	80:26:17	degrees W

Results:

Subsat lat	-0.7736	degrees	calculated by Pratt
Subsat lat	-0.775	degrees	published in almanac
Subsat long	116.2342	degrees	calculated by Pratt
Subsat long	116.0230	degrees	published in almanac

Elevation	32.28 degrees
Azimuth	229.39 degrees

Appendix B-II Orbitset Users guide

Getting started:

The disk contains the files:
ORBITSET.EXE
ORBITSET.OVR
ORBITSET.DBF
ORBIT.DBF
DEADSATS.DBF

The first two files contain the executable code. To start the program type ORBITSET <enter>.

ORBITSET.DBF is a file in dBase format that contains configuration information.

ORBIT.DBF is a file in dBase format that contains the orbit data for each satellite. Included are the Keplarian parameters.

DEADSATS.DBF contains data regarding the identification of each satellite. It provides a cross reference of identifiers from different organizations. It is used by the Import facility to weed out unusable satellites. It is also used by Import to assign the satellite pseudorandom noise number (PRN).

Menus

The menus can be stepped through by pressing the space bar, using the arrow keys to highlight the selection. The <enter> key is then pressed. Alternatively, the hot key may be used. The hot key corresponds to the first letter of the menu selection. For example, to choose Setup in the main menu, the user would press S.

Changing configuration

At the main menu type S or highlight SETUP and press <enter>. The date of the setup can be changed by typing E or highlighting Edit and pressing <enter>. The program defaults to overtype mode. The setup can be named. The longitude is negative for positions West of Greenwich. To exit the module, cursor past the last field until the cursor lands on the menu. Alternatively one may press Page Down to enter the menu. To exit type Quit. All latitudes are North.

The program also allows the user to select the window of time for the prediction. This is useful in reducing the clutter on the graph. UTC is a 24 hour clock based on the Greenwich Meridian. It is commonly known as Greenwich Mean Time. Pacific Standard Time is eight hours behind UTC.

The mask angle can be changed by the user. The program requires that the start and stop times differ by at least two hours.

Editing Bulletins

The control keys are the same as those for editing the configuration. A satellite may be disabled by pressing Disable when the satellite is on the screen. The disable key is a toggle. Pressing D when the satellite is disabled enables it. By disabling a satellite it will not appear on the prediction.

Disabled satellites can be deleted from the database by using the Clean function. A prompt will ask if the user wishes to continue with the deletion.

The orbital parameters can be entered by hand from the NASA prediction bulletin. To enter the edit mode, cursor over to Edit or press E.

Importing parameters

An alternative to entering the numbers by hand is to import them from a file. The parameters may be imported from a two-line Kepler parameter file. The data may be downloaded from one of the bulletin boards listed in Appendix C. The Import facility is found in the Bulletin menu. The files supplied by this program are NASA90.dat and NASA831.dat.

The import facility allows the user to maintain a dead satellite file. This file stores identifiers and the status of each satellite. If the satellite is tagged as "DEAD" it is skipped by the import program. Marginal satellites are read into the database.

The number of records in the bulletin is not appended by the import facility. The user must add records to the ORBIT.DBF file. This can be done by using the Add function in the Bulletin menu. The easiest way is to use Add, and press Page Down on the keyboard to add a satellite. The import function overwrites the existing Orbit.dbf file.

The NASA parameters can be used for up to a year with no apparent degradation in orbit prediction. The user may find however, that the satellite constellation is continuously changing. The bulletin needs maintenance as new satellites are launched and older ones fail. The user will need to delete some satellites that are inoperable and enter parameters from new satellites as they become available. Presently, there is no way to correlate the satellite catalog number as assigned by NASA, with the satellite PRN number. There is a listing of the present identifiers in Appendix C.

GO

This initiates the prediction. Press G or highlight GO and <enter>. This result is graphical output, with satellite elevation versus time. The graph may be printed on a dot-matrix printer.

Table

This function prints out a table of satellite elevations versus time. It does no error checking with regards to the printer. It uses one page of output for every satellite that is enabled. The header gives the start time in UTC, and date of the configuration. The pseudorandom noise code (PRN) is given in the first column. The time, given in UTC, in decimal hours is the second column. The elevation, in degrees above the user's horizon, is given in the third column. The time increment is the same as that used to produce the graph. That is, there are ninety-six divisions, whatever the time frame. The result is a finer resolution of time for a shorter prediction time. The time frame is chosen in the Setup configuration.

Using ORBITSET

Once the program is run, the user will notice that the screen will be cluttered with satellite tracks. The user should determine their local time from UTC. This is UTC - 8 for Pacific Standard Time. For example 23:00 UTC is 23-8= 15:00 local or 3:00 PM PST. The satellites that are below the horizon during the user's planned use of GPS may be disabled. This is done by toggling the Disable key in the Bulletin module.

The user will also find the graph much easier to read if the times are chosen to coincide with the times of the planned field collection.

Appendix B-III

To receive free NASA orbital parameters write to:

NASA Prediction Bulletin subscriptions
Control Center Support Section
Code 513.2
Project Operations Branch
NASA Goddard Space Flight Center
Greenbelt, MD 20771

The user should request the NAVSTAR GPS subset of prediction bulletins.

NASA prediction bulletins are also available from the computer bulletin boards:

Celestial Remote CP/M

9600 baud
File to download: BULLETIN.TXT

Datalink

9600 baud

Mainly for remotely sensed images from the U.S. space program.

The Eyeballer

baud
data bits 1 stop bit no parity

Dedicated to the surveying community.
Information on Eyeballer may be obtained by writing:
David L. Hough
Associated Consulting Inc.
North Decateur Boulevard
Las Vegas, Nevada
(702)647-9265

If on bitnet you may use the CANSPACE server.
To subscribe to CANSPACE send the message:

`SUB CANSPACE` *yourfirstname yourlastname*

to LISTSERV@UNB.CA

Cross reference for GPS satellites

NASA Catalogue Number	Satellite PRN	GPS Description
4	GPS-0001	*
7	GPS-0002	*
6	GPS-0003	marginal
8	GPS-0004	*
5	GPS-0005	*
9	GPS-0006	*
11	GPS-0008	exceeds specs
13	GPS-0009	exceeds specs
12	GPS-0010	exceeds specs
3	GPS-0011	exceeds specs
14	GPS-BII-01	
2	GPS-BII-02	
16	GPS-BII-03	
19	GPS-BII-04	
17	GPS-BII-05	
18	GPS-BII-06	
20	GPS-BII-07	
21	GPS-BII-08	
15	GPS-BII-09	
23	GPS-BII-10	
24	GPS-BII-11	

* inactive satellites at time of printing (ie. dead)
BII satellites are those that are capable of selective availability (SA).

Sources: Lachapelle (1991). NASA Prediction Bulletin(1991) Magellan 1000 NAV PRO receiver almanac.

APPENDIX C - GPSDXF

Description:

GPSDXF is a program to convert data files from the Magellan NAV 100 PRO (TM) GPS receiver into .DXF format. The data input is restricted to data files created with the Magellan Systems Corporation, RE4MAT, utility using the Universal Transverse Mercator (UTM) option. For instructions on the use of the program, refer to Appendix C-I.

Introduction:

Data can be downloaded from the buffer of the Magellan Nav 1000 Pro GPS receiver. The receiver may also be connected to an IBM™ compatible personal computer for a data logging session. The raw GPS data can be reformatted with the software RE4MAT, supplied by Magellan Systems. The data is converted and written to an ASCII file. CS87 is another program supplied by the manufacturer. It is used to perform statistical analysis of the raw data from the receiver. The software does not have a satisfactory capability of viewing or plotting the results. It also only provides average positions in latitude and longitude, with elevation given as height above the ellipsoid.

It was these limitations that motivated the author to write the program GPSDXF and the companion program TALLY. The software is intended to convert the data as output by the RE4MAT program. The output is a "bare bones" .DXF format file. That is, no attempt was made to produce labels for points, or construct lines or polygons.. The resultant output file should be easily imported into various Computer Aided Drafting (CAD) programs or Geographic Information Systems (GIS). These programs should provide ample scaling, viewing, editing and plotting functions.

The program GPSDXF, also writes the summary of each calculation statistics to the file TALLY.DBF. This file can then be read into other programs such as spreadsheets for further statistical analysis. The program TALLY, allows the user to view and edit the file TALLY.DBF.

Purpose:

The program GPSDXF is used to convert UTM files produced by the program RE4MAT into a .DXF format. The user may also choose to produce a .DBF file. A statistical analysis of session averages may be viewed and printed. A summary of session averages is written to the file TALLY.DBF. The program may be used to plot the positions to the screen at various scales. A screen image of the plot can be sent to be printed on an Epson FX compatible 9-pin printer.

Method:

The program was written in Turbo Pascal (1989) version 5.5. TOPAZ version 3.0 (1990) units were used to handle the data files and create menus. The graphing function was written as a unit by modifying a program from Turbo Pascal Programmer's Toolkit (1989).

The program was developed and tested on an AST Bravo 486/25 IBM compatible computer. The program makes use of colour in text mode and was tested on a VGA screen. To test the results of each program the file C0403-3.GPS was used. The file was analyzed with CS87 as supplied by the manufacturer. The raw file was then converted using RE4MAT with the NAD27-Alaska datum and height above geoid. A second file was created using NAD27-Alaska and height above ellipsoid. The resulting files were then analyzed using GPSDXF. A third file was created using RE4MAT. The original file was converted with WGS84 as the datum, and height above ellipsoid, for the elevation.

The statistical calculations were based on formulae from an internal memorandum from Magellan Systems.

Results:

The results of each program are displayed in Figures C-1 and C-2. Although the original data file contained 161 fixes the program CS87 only used 159. The program RE4MAT successfully read all 161 fixes and wrote them to the file C0403-3.UTM. GPSDXF read all 161 fixes contained in the file C0403-3.UTM.

The averaged position given by CS87 cannot be readily compared with that calculated by GPSDXF. CS87 only prints results in latitude and longitude using WGS84, while GPSDXF only calculates positions in UTM. The datum usually chosen for coordinates in UTM was NAD-27-Alaska.

The average elevations between the two programs cannot be readily compared, when the height above geoid is selected in the RE4MAT program. The average elevations in Figures C-1 and C-2 differ by more than 17-metres. CS87 only uses the height above ellipsoid. The height above ellipsoid is the method native to GPS. However it is not useful to map users. Height above the geoid, (height above mean sea-level) is the most useful.

Figure C-1

Analysis of GPS session C0403-3 by CS87 software. ALSKA datum used. Height above ellipsoid only.

```
FILE NAME: C0403-3.GPS
OUTLIER LIMIT  (M) : 1000
NO. OF SAMPLES EXCEEDING OUTLIER LIMIT:  0
NO. OF GOOD SAMPLES USED: 159
KNOWN POSITION NOT AVAILABLE FOR CALCULATION OF FIX ERRORS
AVE LATITUDE (DEG, MIN, SEC)
49      17     12.35018512943952     NORTH
AVE LONGITUDE (DEG, MIN, SEC)
123      3    43.17744807507211      WEST
AVE ALT. ABOVE/BELOW (+/-) WGS-84 ELLIPSOID METERS: 17.31037594462341
STANDARD DEV. OF SCATTER X-COMPONENT, METRES : 5.287900157026478
STANDARD DEV. OF SCATTER Y-COMPONENT, METRES :   28.35823822303291
STANDARD DEV. OF SCATTER ALT-COMPONENT, METRES : 24.73886936827894
2-DIMENSIONAL RMS DEVIATION, METRES: 28.84703733808665
3-DIMENSIONAL RMS DEVIATION, METRES: 38.0021475814512
2-DIMENSIONAL MEAN RADIAL DEVIATION, METRES:  22.40414954647002
2-DIMENSIONAL MEAN RADIAL DEVIATION, METRES:  32.15537970794367
CEP RELATIVE TO AVERAGE POSITION METRES :   17.615591897899
SEP RELATIVE TO AVERAGE POSITION METRES :   28.65457541177065
```

Figure C-2

Analysis of GPS session C0403-3 by GPSDXF software. ALSKA datum used. Elevation given as height above geoid.

```
                          GPS Data Analysis
File:    C:\GPS\DATA\C0403-3.UTM      Collection date: 04/04/91
Number of records: 161  Datum: ALSKA   From: 3:50:55 - 4:20:56 UTC
Zone  Average Northing (m)   Average Easting (m)   Average Elevation(m)
10          5459139             496794                   34.61
Standard Deviation (m)                       RMS (m)
      Easting             5.26               2- Dimensional:   28.73
      Northing           28.33               3- Dimensional:   37.85
      Elevation          24.75

Mean Radial Deviation(m)               Mean PDOP:        5.38  Lowest SNR
      2- Dimensional:    22.34         Mean SNR          9.0          9
      3- Dimensional:    32.10         Highest PDOP      5.73

Circular Error Probable(m)                   Spherical Error Probable(m)
      18.11                                  28.4
```

Figure C-3A

Analysis of GPS session C0403-3 by GPSDXF software. ALSKA datum used. Elevation given as height above ellipsoid.

```
                           GPS Data Analysis
File:    C:\GPS\DATA\C0403-3G.UTM    Collection date: 04/04/91
Number of records: 161  Datum: ALSKA   From: 3:50:55 - 4:20:56 UTC
Zone  Average Northing (m)   Average Easting (m)   Average Elevation(m)
10          5459139               496794                17.06
Standard Deviation (m)                    RMS (m)
      Easting           5.26              2- Dimensional:   28.73
      Northing         28.33              3- Dimensional:   37.85
      Elevation        24.71

Mean Radial Deviation(m)            Mean PDOP:         5.38  Lowest SNR
      2- Dimensional:  22.34        Mean SNR           9.0         9
      3- Dimensional:  32.06        Highest PDOP       5.73

Circular Error Probable(m)                Spherical Error Probable(m)
      18.11                               28.32
```

Figure C-3B

Same file as in C-3A but with WGS84 ellipsoid.

```
                           GPS Data Analysis

File:    C:\GPS\DATA\C0403-3W.UTM    Collection date: 04/04/91
Number of records: 161  Datum: ALSKA   From: 3:50:55 - 4:20:56 UTC
Zone  Average Northing (m)   Average Easting (m)   Average Elevation(m)
10          5459336               4967704               17.06
Standard Deviation (m)                    RMS (m)
      Easting           5.28              2- Dimensional:   28.64
      Northing         28.24              3- Dimensional:   37.78
      Elevation        24.71

Mean Radial Deviation(m)            Mean PDOP:         5.38  Lowest SNR
      2- Dimensional:  22.28        Mean SNR           9.0         9
      3- Dimensional:  32.00        Highest PDOP       5.73

Circular Error Probable(m)                Spherical Error Probable(m)
      17.64                               28.06
```

The results in Figure C-3 are based on height above the ellipsoid but still using NAD27-Alaska as the datum. The elevations compare favorably. When the results of CS87, are compared with those from GPSDXF, when WGS84 and height above ellipsoid are used, the most favorable comparison should be made. However it appears to be no better than using the NAD27-Alaska datum. The statistics calculated by each program are summarized in Table C-1.

Table C-1
Comparison of results from GPSDXF and CS87 in analyzing GPS data

	CS87	GPSDXF			
	ellip	geoid	ellip	WGS84	difference
Elev	17.31	34.61	17.06	17.06	17.3
STD E	5.29	5.26	5.26	5.28	-0.03
STD N	28.36	28.33	28.33	28.24	-0.03
STD Elev	24.74	24.75	24.71	24.71	+0.01
RMS	28.85	28.73	28.73	28.64	-0.12
RMS	38.00	37.87	37.85	37.78	-0.13
M Rad	22.40	22.34	22.34	22.28	-0.06
M Rad	32.15	32.10	32.06	32.00	-0.05
CEP	17.62	18.11	18.11	17.64	+0.49
SEP	28.65	28.40	28.32	28.06	-0.25

All measurements are in metres.
Average Difference in % 0.52%
Difference is between GPSDXF/geoid and CS87
STD - standard deviation
RMS - root mean square
M Rad - mean radial error
CEP - circular error probable
SEP - spherical error probable

Discussion:

The program CS87 performs the statistical calculations on raw data from the receiver. GPSDXF performs all calculations on the product of the program RE4MAT. The raw data is transformed and coordinates are usually based on a datum different from that used in CS87. The user is usually concerned with the positioning error on a mapping plane. Thus the statistics performed by GPSDXF are more relevant, because they deal with coordinates on a mapping plane (UTM). The differences in the expression of error or precision, between the two programs is negligible. The largest discrepancies occur when differing models are used (i.e. reference point for elevation), rather than transformed data analyzed by different programs.

The program RE4MAT contains a geoid separation model. The position on the earth's surface is calculated on an ellipsoid based on WGS84 within a GPS receiver. If the user requests the display of positions in any other system (e.g. UTM, height above geoid), the receiver must perform a transformation. To calculate the height above the geoid, the program or receiver must model the separation between the geoid and ellipsoid. Since the receiver works for positions anywhere in the world, the separation model must necessarily be crude. The user would achieve more accurate elevations by calculating the height above ellipsoid, and applying a local geoid separation to the elevation.

Future Developments:

The program currently only provides UTM coordinates in a .DXF format. It may be desirable to convert other formats such as longitude and latitude as can be supplied by RE4MAT.

The program currently converts only data files as supplied by the RE4MAT program. The next step is to capture the data in the raw form as supplied by the receiver itself. All transformations should be performed by a program where the source code is available to the user. Currently, Magellan Systems Corp. does not provide the algorithms for the transformations.

Another development would be to write an integrated package for the analysis of the GPS data. This would include:

- reading raw data from the receiver.
- performing statistical functions on the positions obtained.
- performing differential corrections on positions.
- plotting points to the screen.
- plotting to paper.
- editing points, either manually or by a statistical test.

Conclusions:

The program GPSDXF is a useful program to convert GPS data into other formats. It contains more features and productivity benefits than the software supplied by Magellan Systems. The .DXF format allows plotting by various CAD and GPS packages. The GPSUTM.DBF file is in a format that can be read by various database and spreadsheet packages.

The discrepancies in the reporting of the errors are negligible between the two programs. The difference is only 0.52 percent overall.

Bibliography

TOPAZ. 1990. User's guide and reference manual. Software Science Inc. Brisbane, California.

Turbo Pascal. 1989. Reference guide, version 5.5. Borland International. Scotts Valley, California.

Rugg T. and P. Feldman. 1989. Turbo Pascal programmer's toolkit. Que Corporation. Carmel Indiana.

Appendix C-I User's Guide

Getting started:

The program diskette contains six files:

GPSDXF.EXE

GPSDXF.OVR

GPSDXFCF.DBF

GPSUTM.DBF

TALLY.EXE

TALLY.DBF

The first two files contain the executable code. The file GPSDXFCF.DBF contains configuration information to run the program. The file contains such information as the default path and filename extensions.

The file GPSUTM.DBF contains all the data found in the file provided by the program RE4MAT. The graphing module reads the positions to plot from this file. For a complete listing of the fields, refer to Appendix C-II.

The file TALLY.DBF is appended with statistical summary information every time the statistics module is used. The program TALLY allows the user to view and edit the records in the file TALLY.DBF.

To use the program load all the files into a single directory. To start the program type GPSDXF.

Menus

The menus can be stepped through by pressing the space bar, using the arrow keys to highlight the selection. Then the Enter key is pressed. Alternatively, the hot key may be used. The hot key corresponds to the first letter of the menu selection. For example, to choose **C**onfigure in the main menu, the user would press **C**.

Changing the configuration:

At the main menu type **E** or press <enter> when Edit is highlighted.

Editing:

To edit the fields the keys are similar to Wordstar or dBase. An example of the more useful function and keys:

Function	Key
Beginning of line	Home
End of line	End
Delete line	Ctrl-Y
Delete character under cursor	Delete

Next field	Enter
Skip fields	Page Down
Escape	Ctrl-Q
Escape	ESC

Fields:

Path: This is the valid DOS path to the desired input file. Examples include:

```
\gps\data
\
```

The program does a validation check on the path entered.

Input file: This is the file produced by the program RE4MAT as supplied by Magellan. The options selected in the program RE4MAT must be selected to produce a file in the Universal Transverse Mercator (UTM) format. The program does no error checking in the reading of the file. The file may be selected from a directory listing by pressing the F2 key. If the user chooses to supply the name of the file by typing it in, the extension must also be supplied.

Extension: It is suggested that when using the program RE4MAT, the extension .UTM be used for the output files. The extension may be changed however, as required, in the program GPSDXF to match the output file from RE4MAT. The program displays only those files that contain the extension supplied by the user, when F2 is used.

Output file: This is the file to be created by the program. The default is given as the input file but with a .dxf and/or .dbf extension. The user may supply another name. It must be a valid DOS name without the extension. The program supplies the extension. The program checks if the file with a .dxf extension already exists, and if so, will respond with an inquiry to overwrite the existing file. It will not check if a file of the same name, with a .dbf extension, exists.

GO!: Performs the conversion to the file formats as selected in the configure menu.

Statistics: Calculates relevant statistics on a set of fixes on the same position. Also provides the maximum and average PDOP and signal quality. To print the report press **P**rint.

View: Allows the user to view the input file. The file viewed is GPSUTM.DBF. This file is overwritten on every conversion. Allows the user to view the file on a record by record or table format.

Plot: Enters the SEEPLOT menu system for plotting the positions to screen and to paper.

Quit: Allows the user to exit the program and return to DOS. All files used by the program are saved and closed upon exit.

Using GPSDXF:

Once the configuration is completed the user should cursor, or escape, to the main menu. Help may be obtained by selecting HELP from the main menu or pressing F1. To perform the conversion, **G**O should be selected. To exit to DOS, **E**XIT should be chosen.

The program will read a maximum of two hundred positions. This corresponds to the maximum number of fixes in the buffer of the Magellan receiver. The file TALLY is only limited by the space on the disk.

The program will only provide statistics or plot the currently converted data file. To view another file, the user must edit the **C**onfigure menu and convert the desired file.

Using SEEPLOT:

The SEEPLOT module allows the user to plot the positions of the current file onto the screen. The default conditions are shown on the screen. The user selects **G**O to perform a plot with the default parameters of autoscale and pop or display all the points at once.

The **A**utoscale selection, ensures that all the fixes in the file will be displayed. The program calculates the dimension that has the most spread and uses the largest dimension to calculate the scale to be used. It centres the plot on the largest dimension. The plot may not be centred in both dimensions. When the plot is shown, the spread in the largest dimension is displayed on the bottom of the screen. This will enable the user to select a suitable scale for future display.

The **P**oint option allows the user to step through the positions one at a time. This may be useful, for example, to indicate which direction a vehicle was moving. It may also be useful, to examine how a position may drift with time, when on a stationary platform. Alternatively, the user may choose to display all the points at once. The default is to display the points all at once.

Appendix C-II Database structures

Database structure for GPSUTM.DBF

```
GPSUTM_Record = Record

Deleted    : Boolean;
_STATION   : LongInt;      { width =   6}
_HOUR      : LongInt;      { width =   2}
_MIN       : LongInt;      { width =   2}
_SEC       : LongInt;      { width =   3}
_UTMZONE   : LongInt;      { width =   2}
_EASTING   : LongInt;      { width =   7}
_NORTHING  : LongInt;      { width =   8}
_ELEVATION : LongInt;      { width =   7}
_MODE      : LongInt;      { width =   1}
_SAT1      : String[  2];
_SAT2      : String[  2];
_SAT3      : String[  2];
_SAT4      : String[  2];
_SIG1      : String[  2];
_SIG2      : String[  2];
_SIG3      : String[  2];
_SIG4      : String[  2];
_PDOP      : Real;         {width= 6,decimals =4}
_MONTH     : String[  2];
_DAY       : String[  2];
_YEAR      : String[  2];
_DATE      : String[10];   { Date field }
_DATUM     : String[  8];
end;
```

NOTE:

The file GPSUTM.DBF contains information that is not included in the .DXF file. GPSUTM is overwritten on every conversion. It is found in the same DOS directory as the program GPSDXF.exe. A copy of the file GPSUTM, using the input file name with the .dbf extension is written to the same directory that the input data file resides.

Database structure for TALLY.DBF

```
type
TALLY_Record = Record
Deleted         : Boolean;
_FILE           : String[ 12];
_RECORDS        : LongInt;      { width =  7}
_MEASTING       : Real;         { width = 12, decimals = 3}
_MNORTHING      : Real;         { width = 12, decimals = 3}
_MEANELEV       : Real;         { width =  7, decimals = 3}
_STDX           : Real;         { width = 12, decimals = 7}
_STDY           : Real;         { width = 12, decimals = 7}
_STDZ           : Real;         { width = 12, decimals = 7}
_RMS2           : Real;         { width = 12, decimals = 7}
_RMS3           : Real;         { width = 12, decimals = 7}
_CEP            : Real;         { width = 12, decimals = 7}
_SEP            : Real;         { width = 12, decimals = 7}
_HIGHPDOP       : Real;         { width = 12, decimals = 7}
_LOWESTSNR      : Real;         { width =  8, decimals = 4}
_AVGSNR         : Real;         { width =  8, decimals = 4}
_AVGPDOP        : Real;         { width = 12, decimals = 7}
end;
```

APPENDIX D GLOSSARY OF TERMS

Almanac - The information received from the satellites that contains the orbital parameters of the satellites. The data contained in the almanac can be used to predict the positions of the satellites. This allows the receiver to determine which satellites to use for positioning.

Azimuth - Measure of arc, in degrees, in a clockwise direction from true north.

Carrier - A radio wave having at least one characteristic (e.g. frequency, amplitude, phase) which may be varied from a known reference value by modulation. In GPS the carrier frequency is 10.23 MHz..

Datum - The frame of reference for a coordinate system. Latitude and longitude are coordinates on an ellipsoid model of the earth. The parameters that describe the ellipse (semi-major and semi-minor axes) and the point of origin of the ellipse define a datum e.g. Meades Ranch, Kansas for NAD27, centre of the gravity of the earth for NAD83.

DOP - dilution of precision. A general term, used to describe expected positioning variances based on the strength of the geometry of the triangulation. see PDOP.

Ellipsoid - an ellipse rotated on its minor axis through a revolution. The ellipsoidal model that is used for Earth is often called a spheroid.

Ephemeris - the path or trajectory of the satellite around the earth. The path is described by an equation requiring 14 parameters. The ephemeris parameters broadcast by a satellite is called the broadcast ephemeris.

Error ellipse- The terms used to describe the accuracy of a position vary according to field of study. A frequently used term in surveying is the ellipse of standard deviation. It can be extended to three dimensions as a rotational ellipsoid. For example, given a degree of confidence required, an ellipse can be magnified to encompass a probability of 0.9 (Leick

1990). This method of description of error is useful when the position fixes do not suggest a circular normal distribution. The error ellipse is the most rigorous method of describing the error, but is not the most convenient. (Lachappele 1991).

Geodesic - an arc on the surface of an ellipsoid. The shortest distance calculated on the ellipsoidal surface of the earth between two geodetic coordinates (latitude and longitude)

Geoid - bounding equipotential surface of the earth. Every facet of the surface is normal to gravity. Essentially mean sea-level.

Geoidal height - the elevation above the geoid or mean sea-level. This is the elevation used by foresters. Ellipsoidal height is the height above the ellipsoid. Ellipsoidal height is the elevation calculated by GPS.

GDOP - geometric dilution of precision. The sum of the expected variances in time, Easting, Northing and elevation. see PDOP.

Ionospheric refraction - a signal traveling through the ionosphere (which is non homogeneous and dispersive medium) experiences a propagation time different from that which would occur in a vacuum. Phase advance depends on electron content and affects carrier signals. Group delay depends on dispersion in the ionosphere as well, and affects signal modulation (codes).

Kinematic positioning - refers to applications in which a trajectory of an object is determined.

Multipath error - is an error resulting from interference between radio waves which have travelled between the transmitter and the receiver by two paths of different electrical lengths.

Outage - the occurrence in time and space of a GPS Dilution of Precision (DOP) value exceeding a specified value.

PDOP - Positional Dilution of Precision. A scalar that is used to multiply the UERE to derive the expected RMS error of a position. Usually thought of as an index of the strength of the geometry of the satellite constellation used to determine a position. A PDOP of 3 would be very good, 6 acceptable, 10 undesirable. The PDOP is the sum of the expected variances in the

Northing Easting and Elevation, based on the position of the user, in relation to the position of the satellites.

PPM - parts per million. One ppm in the point positioning mode is the rms of one millionth of the length of the geocentric position vector. (1 ppm- 6.4m.). In the relative positioning mode it is usually assumed to be the error/length of the baseline.

Precision and Accuracy- As indicated in the introduction, these terms for this study are assumed to be the same.

Pseudorandom noise code - (PRN). Any group of binary sequences that exhibit noise like properties, the most important of which is the sequence has a maximum auto correlation at zero lag. The PRN code number is usually used to distinguish satellites e.g. PRN 3 is satellite 3.

Pseudo-range - the time difference to correlate a replica of the GPS code generated by the receiver with the received GPS code, scaled into the distance by the speed of light. This time shift is the difference between the time of signal reception (measured in the receiver time frame) and the time of emission (measured in the satellite time frame). The range then must be corrected by removing the timing error between the two clocks.

Relative Accuracy: The accuracy of a position of a receiver with respect to another receiver at a known location.

Relative positioning - the determination of relative (as opposed to absolute) positions between two or more receivers which are tracking the same signals. Also called differential positioning.

Repeatable Accuracy- The accuracy that a user can use to return to a position previously determined by GPS.

RMS - root mean square. The standard error of estimate. Essentially the standard deviation of observations that were regressed to estimate a point position.

Satellite configuration - the state of the satellite constellation at a specific time, relative to a specific user.

Satellite constellation - the arrangement in space of the complete set of satellites of a system like GPS.

SA - selective availability implements a quick changing algorithm to dither information coming from the satellites. This will be in the form of clock or orbital errors. This will deny unauthorized users of the system to accuracies of greater than 100-metres in position in real-time. The effect of SA can be lessened if not eliminated by differential positioning.

Static positioning - positioning applications in which the positions of the points are determined, without regard to the they may or not have. This allows the use of various averaging techniques that improve accuracy by factors of over 1000.

UERE - User Equivalent Range Error. The contribution from an error source in measurement units (metres) to the calculation of the range of the user's antenna to a satellite. This value is multiplied by PDOP to determine the expected RMS error of a position

WGS84 - World Geodetic System. The coordinate system used by GPS. Essentially identical to the reference ellipsoid used in NAD83. However the observations used in the adjustment used to describe the stations may be different.