

encouragement of the networking among those trading in beech, development of a short course in indigenous forest harvesting, and expanded field days for forest owners and managers.

The sense of the meeting was that management of beech forests for timber, other products, and environmental benefits and services is in the interests of the nation as a whole and should be encour-

aged on public and private lands. In her beech forests New Zealand possesses a renewable natural wealth, whose potential has yet to be realised. The workshop has provided pointers for the way forward.

An Efficiency Evaluation of the Global Positioning System under Forest Canopies

John Firth¹ and Rod Brownlie¹

ABSTRACT

The Global Positioning System (GPS) is commonly used to provide coordinates for updating forest maps. In open situations, i.e. where the signals are not influenced by tall trees, buildings and hills, the coordinates can usually be obtained in an accurate and timely manner. When used under a forest canopy, however, the extent to which the canopy may reflect or block GPS satellite radio signals has not yet been determined.

The effectiveness of two models of GPS receiver in defining point locations and roads, was compared in the open and in or near areas of radiata pine, Douglas-fir and indigenous forest. These types of tree canopy were found to affect signal reception and hence the efficiency of both receivers.

Used in both static and roving mode, for mapping point locations and forest roads in the open, both instruments performed well. However, when used under forest canopies both receivers were less efficient, either because communication with the satellites was temporarily lost or because, in some instances, it could not be established at all over a 10 minute data collection period.

KEYWORDS

Forest mapping, GPS.

INTRODUCTION

Forest maps have traditionally been derived from ground or aerial survey data. Many New Zealand forestry companies are currently investigating the role of GPS as an alternative means for updating their maps because the technique is potentially easier to use. Manufacturers of GPS equipment often recommend the technology for this application, (e.g. Trimble, 1994). Given an unobstructed view of the sky, a suitable satellite constellation (resulting in a low PDOP² value), and differentially corrected data, the positional accuracy of the points recorded should comply with receiver performance specifications. In forestry applications, however, trees and hills will often restrict the antenna's view of the sky and this may affect the operational

efficiency of the receiver and the positional accuracy of the data recorded.

Jalinier and Courteau (1993) assessed the effect of forest cover on the quality of topometric survey data obtained using a GPS. They found that surveys in the vicinity of dense hardwoods yielded questionable results but dense softwoods presented less of a problem. Lachapelle and Henriksen (1995) carried out tests of various GPS receivers while driving along avenues of deciduous and coniferous trees. Their results indicated that, contrary to expectation, receiver characteristics and signal processing techniques had more effect on accuracy than canopy characteristics. Jasumback (1995) used a GPS in a conifer stand and found that the canopy had almost no effect on the operating efficiency of the receiver. His results indicated that the horizontal error of the coordinates could increase if the canopy was wet because of an increased likelihood of multipath reflections (Jasumback, 1996). Rempel *et al.* (1995) compared the performance of GPS under spruce, pine and mixed-wood sites and showed that there was almost no relationship between measured canopy characteristics (canopy cover, spacing, basal diameter and height) and location error. However, these authors did note that as canopy closure increased, signal interference caused a decrease in observation rate. Petersen (1990) found that tree canopies could seriously affect the accuracy of GPS data and considered that the performance of an older two-channel receiver under canopy was limited.

It might be concluded from the papers cited above that, provided a suitable multichannel GPS receiver is used and the data is processed in an appropriate way, little difficulty would be experienced in using GPS under a coniferous tree canopy. However, D'Eon (1995) tested a five-channel GPS receiver in 61 conifer and deciduous stands representing a diversity of cover types, canopy heights and crown closure. On his first visit to the study site, a GPS position was obtained in only 35 of the stands. A subsequent visit a few hours later yielded data in a further 10. Positions for the remaining 16 stands were only obtained when the leaves had fallen from the deciduous trees six months later. Firth and Brownlie (1994) used a six-channel receiver for updating a forest map in the Marlborough Sounds and found a marked deterioration in accuracy of the coordinates when the instrument was used under a mature radiata pine tree canopy. In many instances, no data could be collected at all. Lawrence *et al.* (1995) had similar difficulties using a GPS to measure the

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² Position Dilution Of Precision (a number related to the probable accuracy of the coordinates derived from the GPS).

coordinates of sample plots located under mature radiata pine trees. In many cases, meaningful data were unobtainable because the satellites' signals were attenuated by the tree crowns. Eggleston (New Zealand Forest Research Institute, 1992) also found it more difficult to obtain precise coordinates under the crowns of eucalypt and radiata pine trees than in the open. Flaherty and Rowe (1997) faced the same problem using a sub-metre receiver under mature radiata pine trees. In this situation, they found errors of 3-5 metres in position and height.

In view of the requirement for NZ forest managers to update their forest maps regularly, and considering the wide variety of stand conditions that exist in a typical plantation forest, there is a clear need for information relating to the forest conditions likely to cause a GPS to operate at less than optimum efficiency.

The objective of this study was to investigate the capability of two GPS receivers to record satellite signals suitable for forest mapping under, or near the canopy of radiata pine, Douglas-fir and indigenous forest.

METHOD

The receivers used for the study were a Trimble Pathfinder Basic Plus™ and a Trimble ProXL™^{3,4}. The former, a six-channel instrument commonly used in New Zealand for general survey work, provides 2-5 m accuracy. The ProXL is a higher specification eight-channel unit capable of sub-metre accuracy.

The receivers were used to record coordinates, both in the open and under or near canopies, for point sites (static mode) and along roads and tracks (roving mode).

An independent estimate of the coordinates of the test points was obtained using a Carta Instruments AP190 analytical stereoplotter and aerial photographs. Instruments of this type are routinely used for accurate map production. Statistics provided by the stereoplotter software indicated that coordinates measured using this system had an expected Root Mean Square (RMS) error of +/- 0.5 metres.

Mission planning ephemeris charts (for elevation angle mask settings of 15°, 25° and 30°) were consulted for each phase of the study to avoid time periods when the GPS satellites were in unfavourable locations.

Study area

The study was conducted in Whakarewarewa and Kaingaroa Forests where a range of topographical and forest canopy conditions was represented (see Table 1).

Performance in static mode at open sites

In order to evaluate optimal performance of the two GPS receivers, XY coordinate data were collected at 17 open site, point locations. These sites were clearly visible on 1:15,000 colour, metric aerial photographs, and were situated away from major objects (trees, buildings, hillsides) that might have obstructed the GPS satellites' signals.

For practical purposes, the ProXL antenna was always located 50 cm to the north of the Basic Plus antenna during data collection. This offset was corrected during subsequent analysis. The antennae were raised between 2 m and 4 m to clear any possible obstructions nearby.

The Basic Plus was configured to record at a rate of one data point per second. In practice, the rate was closer to one point every 1.4 seconds. The ProXL was configured to record at a rate of one data point every five seconds. Other settings for the two receivers were: PDOP mask = 6; signal to noise (SN) ratio = 6; elevation mask = 15°.

At each site, the two receivers were configured to 'record' in static mode and left functioning until 180 points had been

Table 1: Details of roads, tracks and tree stands selected for the survey

Road ID	Forest	Road length (m)	Number of times road traversed	Road type and topography	Vegetation bordering road.
A	W*	1846	4	Flat sealed highway. No adjacent hills.	Grass and low shrubs. A few tall scattered trees nearby.
B	W	618	4	Almost flat metalled road. Some adjacent low hills.	Douglas-fir (age 19 years, 900 stems/ha, height 15 m, CC** 75%).
C	W	1340	4	Gently rising metalled road. Low hills on each side.	Radiata pine (age 19 - 21 years, 230 - 300 stems/ha, height 25 - 31 m, CC65%) and Douglas-fir (aged 19 years, height 15 m, CC 65%).
D	W	2020	4	Gently rising sealed road in a steep sided valley.	Grass and low shrubs. No trees near road
E	W	213	4	Flat metalled track. No adjacent hills.	Radiata pine (aged 27 years, stems/ha 115, height 34 m, CC 70%) and Corsican pine (89 years old).
F	W	1247	5	Steeply rising metalled road. Steep hill to the South.	Upper section: low vegetation. Central section: dense stand of indigenous trees (variable height, CC 65%). Lower section: radiata pine (aged 10 years, stems/ha 600, height 12 m, CC 55%).
G	K*	434	4	Flat metalled track. No hills in vicinity.	West section: radiata pine (aged 10 years, stems/ha, 900, height 12 m, CC 55%). East section: radiata pine (aged 17 years, stems/ha 250, height 19 m, CC 40%).

* W = Whakarewarewa Forest, K = Kaingaroa Forest.

** CC = Average crown closure over the specified road length.

recorded with the Basic Plus. This took approximately four minutes. The measurements were repeated several hours later to ensure that different satellite configurations were used.

Subsequently, the data from the two instruments were differentially corrected using a base station at Rotorua. The study sites were within 40 km of this station. The correction process removed errors due to 'selective availability'.

Under ideal reception conditions, the corrected 180 coordinates recorded by the Basic Plus over the four minute time period would be expected to have a horizontal CEP⁵ accuracy of approximately 2 m (Trimble, 1992). The horizontal RMS error of coordinates collected by the ProXL should be approximately 0.55 m⁶ (Marshall, 1996).

Coordinates of the 17 points were measured from aerial photographs using the AP190 analytical stereoplotter to provide independent estimates. Each location point was measured 10 times and the results averaged.

Performance in static mode under tree canopies

Fourteen sites were selected, each representative of a specific stand type and located about 25 m from a road. Table 2 shows their distribution in terms of the site types defined in Table 1.

³ The mention of a particular product name does not denote its official endorsement by the New Zealand Forest Research Institute.

⁴ The ProXL has recently been upgraded. The replacement model is designated the ProXR.

⁵ CEP or Circular Error Probable, is a statistical measure of horizontal precision. The CEP value is defined such that a circle of that radius will enclose 50% of the data points.

⁶ The equivalent CEP value would be approximately 40 cm.

Table 2: Location and designation of the under-canopy static mode sites

Road ID	Site designation.
B	B1, B2
C	C1, C2
E	E1, E2
F	F1, F2, F3, F4
G	G1, G2, G3, G4

The GPS settings were relaxed for this part of the study (PDOP mask = 10; elevation mask = 20°). Where signal reception may be difficult, there could be an advantage in decreasing the receiver specifications in order to increase the chances of obtaining a fix. Both GPS receivers were configured to record at 1 point per second and the SN ratio remained at 6.

The antennae were mounted on extendable poles placed 50 cm apart then raised to 4 metres.

The receivers were activated simultaneously for 10 minutes. Bias in the results due to a particular satellite configuration was reduced by surveying each of the sites on two occasions, several hours apart.

For logistical reasons, independent verification of the coordinates of the under-canopy sites was not possible for this part of the study.

Performance in roving mode in the open, and under or near forested areas

The antennae of the receivers were positioned 50 cm apart on the centre line of the roof of a vehicle, using magnetic base plates supplied by the manufacturer. The ProXL antenna had a 10 cm long spacer to minimise multipath errors associated with a flat surface

such as a car roof. A similar spacer was constructed and fitted to the Basic Plus antenna in order to maintain comparability.

The recording rate was set to one point per second and the planned driving speeds were 25 kph for the gravel roads (7 m intervals between points) and 50 kph on sealed roads (14 m intervals). Work carried out by Clark and Worley (1994), indicated that vehicle speed (within the range 16.1 to 80.5 km/h) had little effect on the accuracy of differentially corrected GPS coordinates when two or more sets of data were combined. The differences in vehicle speed between the two road types and the inevitable small variations in speed that occurred along each road, therefore, were not expected to have an adverse effect on the results of this study.

The receivers were configured to PDOP = 6; SN = 6; and elevation mask = 15°. Receiver function was checked in an open area before each road survey.

Roads listed in Table 1 were traversed in each direction on at least two occasions, several hours apart, to ensure use of different satellite constellations. After collection, data was differentially corrected using a base station at Rotorua.

Following a ground survey to establish control points, the AP190 stereoplottor was used to map the centre line of each metalled road and centre line of each lane of the sealed roads, from 1:15,000 colour, metric aerial photographs.

The GIS 'TerraSoft', was used to define the position of a 2 m strip on each side of the centre lines and the GPS coordinate data, collected while the vehicle was moving, were overlaid on to this map. A calculation was made of the proportion of each road along which GPS coordinates were collected and the proportion of the road length for which the GPS coordinates fell within 2 m of the centre line.

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RESULTS

Performance in static mode at open sites

Comparison of the rate at which the GPS receivers recorded positions showed that, for all 17 open sites, operating efficiency was 100 % with the Basic Plus consistently recording data every 1.4 seconds and the ProXL every 5 seconds.

Statistical analysis (Duncan's multiple range test) showed that there was no significant difference ($p=0.05$) between the coordinates recorded during the two operating periods. The data sets were therefore combined.

The same test showed that the ProXL coordinates were significantly closer to the AP190 'reference' coordinates, than those obtained with the Basic Plus (2.1 m and 3.3 m respectively).

Performance in static mode under tree canopies

Under ideal circumstances 600 data points should have been collected at each of the 14 under-canopy sites during each 10 minute operating period. Table 3 shows the actual number of points received and the operating efficiency at each site.

Table 3: Operating efficiency of two GPS receivers in static mode during two 10 minute periods under tree canopies

Site ID	Basic Plus				ProXL			
	Period 1		Period 2		Period 1		Period 2	
	No. of points recorded	% efficiency						
B1	0	0	30	5	0	0	10	17
B2	217	36	0	0	509	85	0	0
C1	0	0	91	15	0	0	89	15
C2	33	6	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0
F1	0	0	0	0	0	0	203	34
F2	0	0	0	0	0	0	0	0
F3	234	39	159	27	435	73	304	51
F4	0	0	126	21	0	0	358	60
G1	0	0	265	44	176	29	400	67
G2	109	18	145	24	75	13	570	95
G3	0	0	153	26	0	0	83	14
G4	0	0	112	19	0	0	325	54
Mean	42.4	7.1	77.2	12.9	85.4	14.3	167.3	27.9

Table 3 indicates considerable variation between receivers, between sample periods and between sites. No data was recorded from 31 of the 56 sets of observations.

A statistical comparison (Duncan's multiple range test) of mean operating efficiencies showed a significant difference ($p=0.05$) between Basic Plus/Period 1 and ProXL/Period 2 values (7.1% and 27.9 % respectively).

Performance in roving mode in open and forested areas

Table 4 shows that, on the open road on flat terrain, (A), both receivers recorded points over at least 94% of the distance surveyed (7,384 m). Figure 1 shows a section of this road and coordinates from one of the four traverses made along it. Data from both receivers closely followed the centre line of the road section but the Basic Plus points showed slightly more variability. Only 62% fell within 2 m of the centre line, compared with 89% of the ProXL points.

For Road D, the ProXL recorded coordinates over the total road length and 99% of the points fell within 2 m of the centre line. In contrast, the ProXL recorded coordinates for only 6% of the total length of Road C and only 3% of the length had points within the 4 m total width.

Usually the ProXL collected coordinates over a greater length of road than the Basic Plus (e.g. Road F) but this was not always the case (e.g. Road E). The proportion of points falling within 2 m of the centre line was always higher with the ProXL than the Basic Plus.

Table 4: Results obtained from the roving mode survey of seven forest roads (maximum and minimum values shown in brackets)

Road ID	GPS receiver	No. of coordinates collected over total road	Proportion of total road length for which coordinates were collected	Proportion of total road length for which collected coordinates fell within 2 m of the centre line
A	Basic Plus	365	99 (94 - 100)	62 (45 - 92)
	ProXL	576	99 (96 - 100)	89 (84 - 93)
B	Basic Plus	299	62 (50 - 74)	38 (29 - 45)
	ProXL	293	60 (45 - 66)	48 (38 - 57)
C	Basic Plus	21	2 (0 - 7)	1 (0 - 3)
	ProXL	122	6 (4 - 9)	3 (0 - 5)
D	Basic Plus	226	55 (0 - 100)	41 (0 - 83)
	ProXL	643	100 (100-100)	99 (99 - 100)
E	Basic Plus	60	26 (6 - 47)	6 (0 - 15)
	ProXL	68	20 (0 - 36)	10 (0 - 21)
F	Basic Plus	522	76 (73 - 94)	33 (15 - 73)
	ProXL	763	83 (49 - 95)	50 (28 - 68)
G**	Basic Plus	269	84 (61 - 97)	71 (10 - 92)
	ProXL	328	93 (81-100)	93 (81-100)

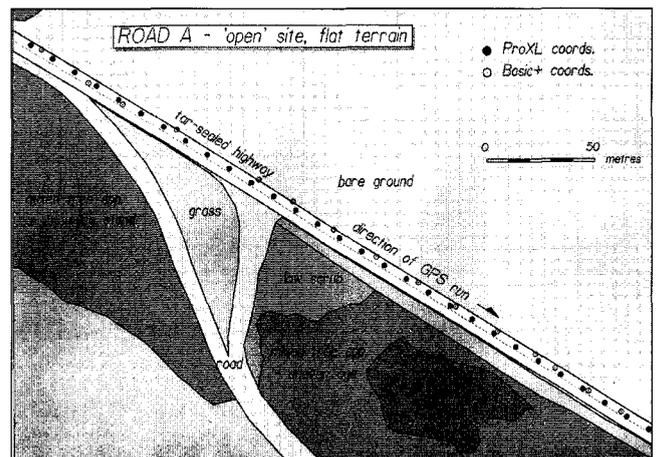
* Both receivers were set to record 1 point per second. Under ideal conditions, the Basic Plus records an average of 1 point per 1.4 seconds.

** The data shown relates to the West section of road G (see Table 1)

On roads near steep terrain and/or under a tree canopy (all roads except A), there was considerable variability in the accuracy of coordinates (Figures 2, 3 and 4). On Roads B, E and F, ProXL coordinates followed the road more closely than those of the Basic Plus. In some places both receivers were 'off track' and on some segments of road no data was collected at all.



Figure 1: Part of Road A showing coordinates collected under an 'open site' situation.



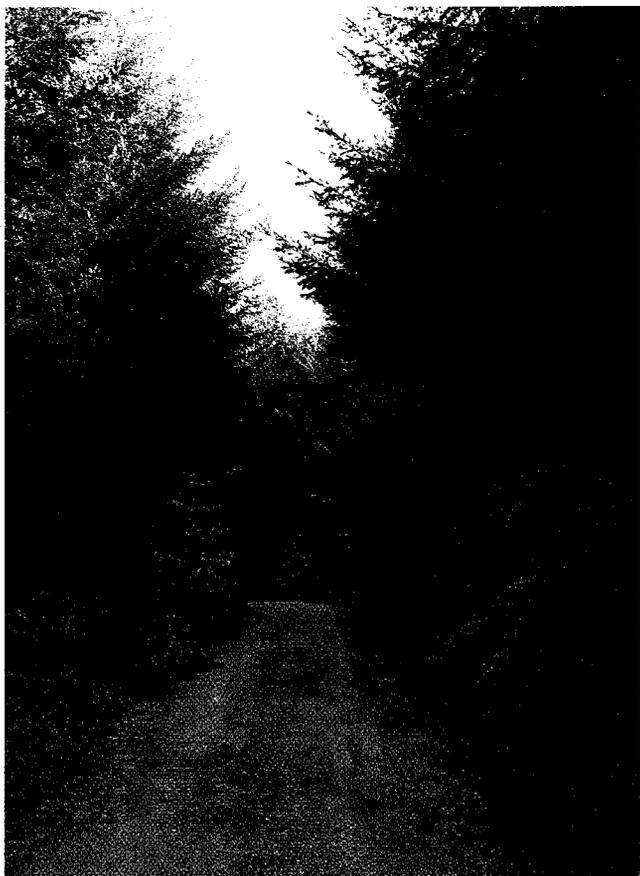


Figure 2: Part of Road B showing coordinates collected under a dense Douglas-fir canopy.

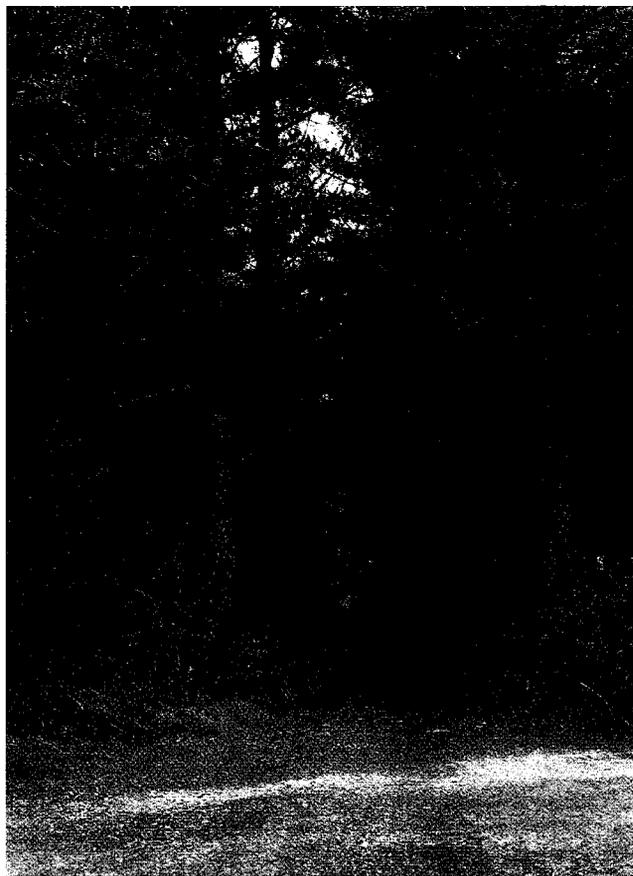


Figure 3: Part of Road E showing coordinates collected under mature radiata pine trees.

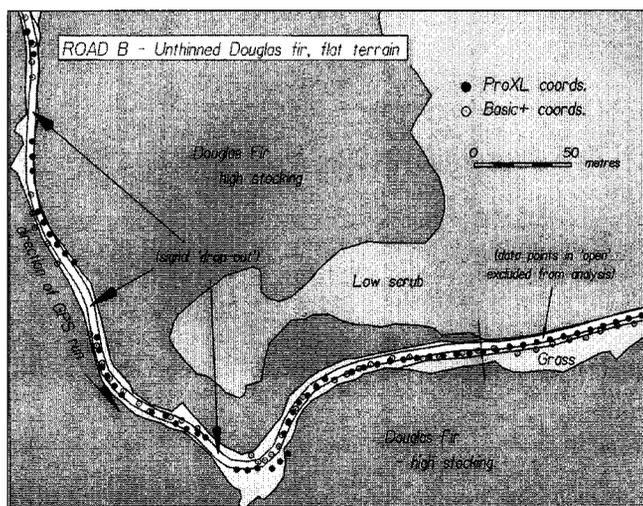
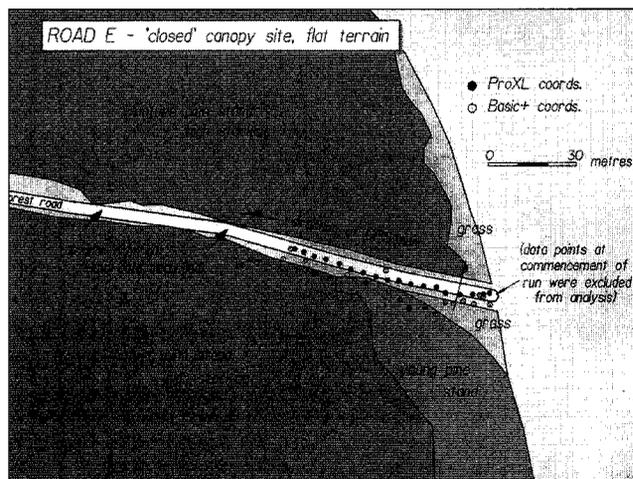


Figure 3 shows that on Road E, ProXL coordinates followed the road line closely for the first 60 m, but beyond this where mature radiata pine was present, no data points were recorded at all. The Basic Plus recorded for a further 20 m, but the points did not closely follow the road line.

Figure 2 (Road B) shows that, with both instruments, at least three signal 'drop outs' of about 40 m occurred within a road length of 618 m, and that these were all associated with the presence of dense tree stands. Horizontal accuracy of some coordinates was low.

Similar problems were caused by the indigenous forest. These are illustrated in Figure 4.



DISCUSSION

Performance in static mode at open sites

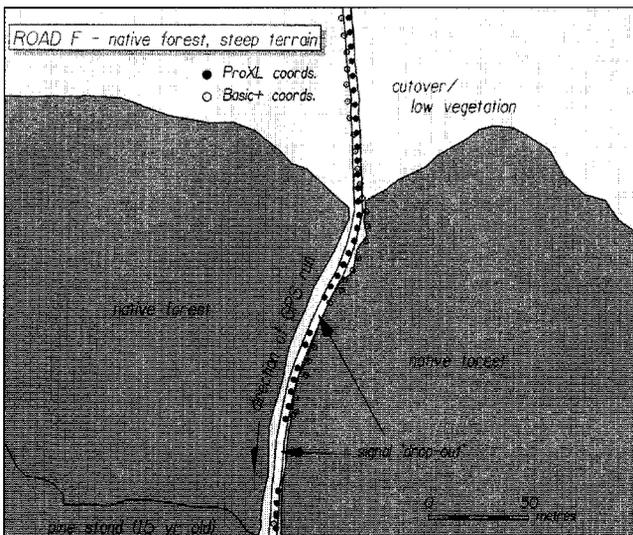
An operating efficiency of 100% over four minutes was demonstrated for the Basic Plus and ProXL receivers used in static mode at open sites. After differential correction, the coordinates obtained were within 3.3 m and 2.1 m of those derived independently with an analytical stereoplotter. While these figures contain a possible sub-metre error in the GPS Latitude/Longitude to NZ Map Grid translation, as well as the previously mentioned sub-metre stereoplotter error, both receivers are considered to have performed close to specification.

Performance in static mode under tree canopies

Even though the instrument settings were relaxed at the under-



Figure 4: Part of Road F showing coordinates collected under an indigenous forest canopy.



canopy sites, a marked reduction in the operating efficiency of both the Basic Plus and ProXL was observed. The Basic Plus recorded data for only 12 of the 28 recording periods while the ProXL collected points for only 13 periods.

Without knowledge of the true coordinates of the 14 under-canopy sites, it was not possible to determine whether the GPS-derived values were within the manufacturer's specification or whether errors had been introduced due to the presence of the trees or hills.

Variability in the performance of both GPS receivers made it difficult to correlate results with the tree canopy type. The data suggest that efficiency decreased with increasing tree age.

GPS coordinates can usually be obtained under trees.

However, the operator may have to wait for an extended period of time before the satellites become aligned with gaps in the canopy which allow signals to reach the antenna. Although it was not possible to predict the length of the delay period, performance of the ProXL was better than that of the Basic Plus in this respect. Reference to ephemeris charts on a site specific basis, and relaxation of the PDOP and SN settings, may help to optimise the performance of GPS under these conditions. However this approach will compromise accuracy. The overriding influence of canopy density and its proximity on the attenuation and reflection of radio signals is significant and currently unpredictable.

Performance in roving mode in open areas

When either the ProXL or Basic Plus receiver was used in roving mode in the 'open' situation (Road A), coordinates were collected for over 94% of the road line. The ProXL-derived coordinates followed the road line, traced using the analytical stereoplotter, more closely than the Basic Plus coordinates.

Both receivers were suitable for surveying 'open' forest roads but, as expected, the higher specification ProXL provided more accurate results.

Performance in roving mode under or near forested areas

With both receivers, signal loss was a common occurrence when trees and/or hills were located close to the road. Coordinates recorded with the ProXL were, after differential correction, more likely to fall within 2 m of the road centre line than the Basic Plus values.

It was not possible to determine relationships between canopy characteristics and GPS performance. Results suggest an undefined inverse relationship between tree age and the operating efficiency of the receivers.

Use of GPS is unlikely to provide accurate data for mapping a winding road in the immediate vicinity of trees or hills. Under certain circumstances (e.g. on straight roads), it might be possible to interpolate data to provide missing points.

CONCLUSIONS

GPS can play a useful role in obtaining coordinates for forest map updating. However, it is important for users to be aware of the limitations inherent in the application of this technology near or under forest canopies.

For the open situations used in this study, the Basic Plus and ProXL GPS receivers performed efficiently and provided accurate results in both static and roving modes.

For static measurements in sites influenced by a radiata pine, Douglas-fir or indigenous forest canopy, the receivers did not perform well, with efficiencies ranging from 0% to 39% for the Basic Plus, and 0% to 95% for the ProXL. In the authors' opinion, this variability can be mainly attributed to attenuation and reflection of the GPS radio signals by tree biomass. Some improvement might be achieved by relaxing the receiver settings, raising the antenna (if practical), or increasing the site occupancy time.

When the GPS receivers were used under or near tree canopies in roving mode, point accuracy was usually lower than that in open situations and signal 'drop out' was a common occurrence. As it may be impractical to interpolate missing data points when mapping roads and tracks in forests, traditional ground survey or photogrammetry may be a more suitable approach for these situations.

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ARTICLES

Assessing the risk of wind damage to plantation forests in New Zealand

John Moore and Alan Somerville¹

Abstract

Current techniques for assessing the risk of wind damage to plantation forests attempt to rank different sites and/or silvicultural treatments, but cannot successfully assign a probability value to the occurrence of damage. Probability values derived from historical records of wind damage events are only applicable to stands with the same structure and location as those from which the historical records were obtained. Since 1994 research at the New Zealand Forest Research Institute and the British Forestry Commission Northern Research Station has focused on the development of a fundamentally-based system designed to predict both site wind speed at which a stand is likely to fail and the probability of occurrence of wind speeds in excess of this threshold value. This approach will allow evaluation of the effects of geographic location and changes in species selection, silviculture and rotation age on the risk of wind damage.

Introduction

A number of classification systems have been devised to assess the risk of wind damage to forests. Many of these rank the relative risk of different sites and/or silvicultural treatments, but do not assign a probability to the likelihood of damage. One such system is the British Windthrow Hazard Classification (Booth

1977, Miller 1985, Quine and White 1993) which combines an assessment of geographical locations in which damage is likely to occur with an estimate of when in the life of the crop it may take place.

Quantitative assessments of risk require magnitude and frequency data on the occurrence of wind damage. The probability of wind damage can be derived from a time series of wind damage records. In New Zealand records date back to the 1940s. Many of the main events are documented in published accounts (Wendelken 1955; Prior 1959; Wendelken 1966; Chandler 1968; Irvine 1970; Wilson 1976; Somerville 1989) and unpublished records, inventories and aerial photographs. During the 50-year period to 1990, New Zealand's plantation estate has suffered over 50,000 ha of catastrophic wind damage, defined as continuous damage covering more than one hectare (Somerville 1995). Damage in many of the worst wind storm events has been aggravated by orographic lee waves and wind channelling associated with mountainous topography. These effects are most prevalent in the Canterbury Plains, due to the Southern Alps, and in the central North Island, due to the eastern chain of mountains (Littlejohn 1984). A large proportion of the damage was directly associated with management activities, particularly recent clearfelling, late thinning and the creation of new non-windfirm stand boundaries. Documentation of damage to young plantations, and attritional losses in stands from smaller storm events is rare. However, stand condition and wind damage in plantation

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