ACCURACY OF TRACKING FOREST MACHINES WITH GPS

M. W. Veal, S. E. Taylor, T. P. McDonald, D. K. McLemore, M. R. Dunn

ABSTRACT. *This paper describes the results of a study that measured the accuracy of using GPS to track movement of forest machines. Two different commercially available GPS receivers (Trimble ProXR and GeoExplorer II) were used to track wheeled skidders under three different canopy conditions at two different vehicle speeds. Dynamic GPS data were compared to position data established through precision surveying techniques. Maps from data collected by both receivers showed general travel patterns of the skidders. Mean position errors in data collected by the GeoExplorer (2.75 m) were significantly greater than those of the data collected by the ProXR (1.34 m). When tested under different canopy conditions, GPS position accuracy showed a decreasing trend us the canopy changed from open to heavy. Finally, the machine speeds tested did not significantly affect the accuracy of GPS positions.*

Keywords. *Global Positioning System (GPS), Precision forestry, Vehicle trucking, Forest engineering.*

The Global Positioning System (GPS) is being used in an ever-increasing array of applications for managing forests and our natural resources. These applications include typical forestry activities such as mapping, surveying, and forest inventory. However, accurate forest engineering design, management, and operational decisions require detailed information on machine location, speed, and performance as a function of terrain and timber stand variables. In addition, increased emphasis on minimizing environmental impacts from forest machines necessitates new methods of collecting data that will fully characterize machine operations. Intelligent, automated systems are needed that will simultaneously acquire data on basic machine parameters, productivity, and general operating conditions (e.g., position in the forest, stand density, tree size, terrain, vehicle travel patterns, and number of vehicle passes).

Information on machine performance and function have been collected by on-board data acquisition and computer systems in both research and industry applications. In addition, a location measurement system, such as the Global Positioning System (GPS), can be mounted on the forest machine and connected to the data acquisition system. With the location system input, computer hardware can collect information such as distances traveled, the machine status at each location, and the productivity of the machine at each location. The ability to track a machine's position automatically could help the forest manager or engineer in their evaluation, especially in terms of the machine velocity over time, the distances it travels between activities, and any elevation changes it encounters that may affect its performance characteristics. Other potential benefits are associated with tracking specific forest machines. For example, if the position of a herbicide sprayer is tracked over time, it may be possible to evaluate the coverage to determine skipped or overlapped areas. Furthermore, tracking the position of a forest-harvesting machine may reveal areas where repeated traffic potentially could lead to excessive soil compaction or other undesirable impacts on the local environment.

The Global Positioning System is a satellite-based positioning system developed by the United States Department of Defense. The user must have a receiver to interpret radio signals sent from a constellation of satellites orbiting the earth. The interpreted signals can be used to calculate the latitude, longitude, and elevation of the GPS receiver. A GPS receiver can be used to determine positions of stationary or moving objects in many places throughout the world, twenty-four hours a day. Considering the benefits of obtaining position data from moving forest machines and the technology available through GPS, there is a need to determine how accurately and consistently GPS can be used to track working forest machines. Accuracy results have been reported for GPS in static forestry applications. However, little data are available that report GPS accuracy in dynamic vehicle tracking applications. Therefore, the specific objectives of the research reported in this paper are to:

1. Quantify the accuracy of GPS position data collected on mobile forest machines, and
2. Examine the effects of GPS receiver types, forest canopy, and machine speed on GPS accuracy.

For example applications of vehicle tracking, this paper discusses the use of typical commercial GPS receivers to track the movement of wheeled skidders as they traversed courses laid out in a cleared area and in a thinned loblolly pine plantation.

Article was submitted for review in July 2000; approved for publication by Emerging Areas Division of ASAE in July 2001. Presented at the 2000 ASAE Annual Meeting as Paper No. 00-50 10.

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  ISSN 0001-235 1

Background

GPS in Forestry Applications

Gerlach (1991) stated that the most important recent advance in the field of remote sensing was the development of GPS. He predicted that most current surveying methods would be significantly, if not entirely replaced by more accurate GPS survey methods. Current forestry related applications of GPS include; location of sample points, verification of areas as a basis for payment, establishment of digital terrain models, and location of wood inventories in the field (Forgues, 1998). Jalinier and Courteau (1993) discussed the use of GPS as a rapid, accurate, and economical means of surveying forest road networks. A receiver was attached to a vehicle that traversed forest roads requiring a survey. The results indicated GPS could produce surveys with accuracy comparable to conventional survey techniques with a decrease in the acquisition time. While the results were encouraging, areas with thick forest cover yielded questionable results; therefore conventional survey techniques could be used in these areas to obtain greater accuracy. Bobbe (1992) also determined that aerial differential GPS (DGPS) positions agreed with surveyed positions well enough to locate them to within IO-12 m afterwards. Drake (1991) used real-time DGPS positions collected in a helicopter to map the perimeter of a forest fire. He determined that the map created from GPS data agreed well with a traditionally generated ground fire map.

Since GPS uses microwave signals, and since vegetation can influence microwave signals' effectiveness, some work has also been completed to ascertain the usefulness of GPS under forest canopy conditions. Forest vegetation and topography may block satellite signals sent to the GPS antenna causing a loss in position fixes. In the event of a signal blockage, the GPS receiver will switch to another constellation of satellites or the antenna must be relocated so unobstructed signals may be obtained. Another signal interference that occurs under forest canopies is multipath, a term describing the circumstance when a satellite signal arrives at the receiver's antenna with two or more paths (Liu and Brantigan, 1995).

Recent studies on the effects of forest canopies on GPS accuracies show the average error under a coniferous canopy was 6.4 m for a three-dimensional position (Deckert and Boldstad, 1996). These results were based on the discrepancy between values of coordinates for a point found through GPS and the coordinates of the same point determined by a theodolite survey. In addition to determining the mean error for a GPS position, the elevation coordinate or z-value was determined to have the least reliability. Brock and Karakurt (1999) demonstrated how the characteristics of a stand's canopy might affect the accuracy of GPS measurements. Plots were placed in hardwood, softwood, and mixed species stands with three distinct canopy covers in each stand. GPS measurements were made throughout the year so leaf-on and leaf-off conditions could be studied. The results indicated stands with denser canopies produced larger errors and better GPS results were obtained in hardwood stands. These results were based on precisions that were obtained from average standard deviations, therefore the actual error under the varying conditions is not known.

GPS in Vehicle Tracking Applications

GPS has been used as part of automatic vehicle location and fleet monitoring systems. A Finnish, state-owned lumber, paper, and pulp company incorporated GPS into their log transport operations in order to improve fleet management (Tolkki and Koskelo, 1993). The primary goals of this system were to bring the piles of logs into a computerized inventory management system, to optimize the pickup routes and quantities for drivers, and to move the foremen from trucks to more productive work. Each truck driver automatically received optimized pickup schedules on a mobile personal computer in their truck by means of wireless telecommunication. The driver was also able to see their position in real time on a digital map surface computed by a combined GPS navigation/dead reckoning system. The dead reckoning component was used when the GPS receiver was temporarily unable to provide position solutions. The GPS/dead reckoning system facilitated general navigation, as well as detailed navigation in selecting between various country roads and estimating distances when approaching a log pile. Tolkki and Koskelo (1993) stated the main benefit of the new system was the ability to improve the quality of the wood and decrease the inventory costs by reducing the inventory of cut wood in the forest.

Forgues (1998) reported that GPS used in the location and navigation of trucks on road networks was quite feasible due to the low precision requirement. However, they concluded that real-time applications that require more than 2 to 5 m precision, such as forest machine navigation near buffer strips, were not practical at that time. As machines traveled under a forest canopy, the rapid changes in satellite constellations and multipathing from vegetation led to considerable errors in GPS positional data (Reutebuch et al., 1999). These errors were attributed to obstructions, such as trees and components on the machine, which decrease accuracy by reducing the number of satellites a receiver can track. Spruce et al. (1993) observed the degradation of GPS signal quality under forest canopy conditions. A tractor was tracked and relative accuracies were assessed under open sky and canopy conditions. Based on the results of the open sky trails, they reported that GPS was a valuable tool for tracking machines under open sky conditions. However, under forest canopies GPS performance needed improvement as a major decrease in accuracy was observed. This decrease was attributed to multipathing associated with vegetation.

McMahon (1996) believed GPS could be used as a means of measuring machine travel. His research called for an error factor of 1.15 m when monitoring the movement of a skidder with a Trimble ProXR GPS receiver attached at the center of the cab. There was no mention of any effects that changes in canopy, location on the cab, or skidder speed would have had on this error factor. Mechanized harvest operations can be monitored with GPS to determine where the highest traffic intensities occur and the resulting impacts on soil physical properties (Carter et al., 1999). McDonald et al. (1998) monitored the traffic patterns of forest machines utilizing a Trimble ProXR on two grapple skidders and a Trimble GeoExplorer II on a feller-buncher. The positions obtained from the GPS were prone to random shifts in one or more sequential locations. The positions obtained from the GeoExpiorer tended to have larger errors occurring with greater frequency. Due to inconsistent conditions, the source of these errors could not be determined as the receivers were placed on different machines working under varying canopy conditions.

Because of the great expense and potential safety hazards associated with evaluating the productivity of harvesting systems, researchers are considering GPS as a safer, more efficient process for conducting automated time studies. Recent research by Reutebuch et al. (1999) described one such method. They placed a GPS receiver on a feller–buncher, a hydraulic shovel, and a tracked skidder. The machines were monitored throughout the course of a harvest in which various harvesting methods were applied, so cycle distances and times could be calculated. Due to apparent large errors (occasionally over 100 m) in the positional data, the vehicle travel distances could not be calculated accurately. The errors appeared to decline as canopy cover decreased, although no values for the errors were given. Also, true error values could not be determined, since there were no landmarks on the ground to use as references for the GPS-based machine paths. When conducting **time** studies, McDonald (1999) pointed out the need for accuracy as the unpredictable nature of skidder movements may lead to difficulties in determining events in a cycle. A primary area of concern is when a skidder changes from forward motion to reverse, because this may indicate a new element such as gate delimbing or adjusting a bundle.

PROCEDURES

This section describes the use of two commercially available GPS receivers to track forest machine movement. Although these techniques can be applied to a variety of machines, the machines used in this research were typical wheeled skidders. The skidders were tracked in three different canopy conditions and at two different ground speeds.

GPS EQUIPMENT

Two hand-held GPS receivers manufactured and sold by Trimble Navigation, Ltd. functioned as rover units and were used to collect all location data in the tests. The receivers were the ProXR and the GeoExplorer II. The ProXR is a 12–channel receiver that uses coarse acquisition code (C/A code), is capable of real-time differential corrections, and is considered as having submeter accuracy in static differential modes. The ProXR is also capable of collecting carrier phase GPS data. The ProXR used a TSC1 datalogger that was running Trimble's AssetSurveyor software version 4.01. The GeoExplorer II is a six-channel receiver that uses C/A code. It can collect carrier-phase GPS data and has a nominal horizontal accuracy of two to five meters. The GeoExplorer was using version 2.20 operating software. Both receivers used external antennas mounted on the top surface of the cab of the skidders. During the field tests, both receivers were used simultaneously to track the movement of skidders. Therefore, both antennas were mounted on the skidder cabs at the same time. Antennas were placed along the longitudinal centerline of the cab with the ProXR antenna placed 1.50 mm behind the geometric center of the cab. The GeoExplorer antenna was placed 150 mm in front of the geometric center of the cab.

Data collection rates were set at one position per second. Both rover units were configured with a position dilution of precision (PDOP) mask of 6.0, an elevation angle mask of 15 degrees, and a signal-to-noise ratio mask of 4: 1. Rover receivers were placed in the Auto 2D/3D mode. Auto 2D/3D mode allows the receiver to collect 3D data if signals from four or more satellites are received or collect 2D data if signals from three satellites are received. During 2D data collection the elevation used to determine a position solution was either input manually prior to data collection or the elevation from the last collected 3D position was used. In this mode, the receivers would collect three-dimensional data as long as there were sufficient satellites and the other data collection parameters were satisfied. When the number of visible satellites was insufficient to allow computation of three-dimensional solutions, a two-dimensional position was recorded. Elevation data were based on the WGS84 datum.

In addition to the rover units, a Community Base Station from Trimble Navigation was used to collect data for use in differential corrections. This base station unit is an eight–channel receiver installed in a desktop computer. The base station was on the Auburn University campus. Base station position data were collected at a rate of one position every 10 sec. The elevation angle mask was set at 10”. The PDOP mask was set at 6 and the signal-to-noise ratio mask was set at 6:1. After all field data collection sessions, data from the rover units were differentially corrected using Pathfinder Office Version 2.10 from Trimble Navigation.

TEST LOCATIONS-CANOPY CONDITIONS

Vehicle tracking sessions were conducted at the Caterpillar Forest Products Training Center near Opelika, Alabama (approximately 32” 42’ 48.14” N, 85” 17’ 25.07” W, 214 m MSL). This site has mixed stands of hardwoods and pine. Three different vehicle-tracking courses were established in stands of loblolly pine at the site. Each of the courses reflected a different forest canopy situation: open, light, or heavy. Canopy conditions are described in table 1 for each of the three areas. The open canopy condition, shown in figure 1, was established in a clearcut area and had a **tracking** course 400 m in length. The light canopy condition, shown in figure 2, was established in an area that had been heavily thinned and had a tracking **course** 200 m in length. The heavy canopy condition, shown in figure 3, was established in an area that had been lightly thinned and had a tracking course 175 m in length.

For each tracking course, a general path was established for the skidder to follow. On each of these paths, general areas were established where the position of the skidder would be marked as it passed by that position. The position of the outside edge of the left rear skidder tire was marked by a pin flag as the skidder passed near the sampling point. The number of these sampling points is listed in table 2 for each canopy condition. Differences in sampling points for the different canopy conditions are due to differences in accessibility to the points. Table 2 lists the number of test runs conducted in each canopy condition and the total number of GPS positions marked by the pin flags.

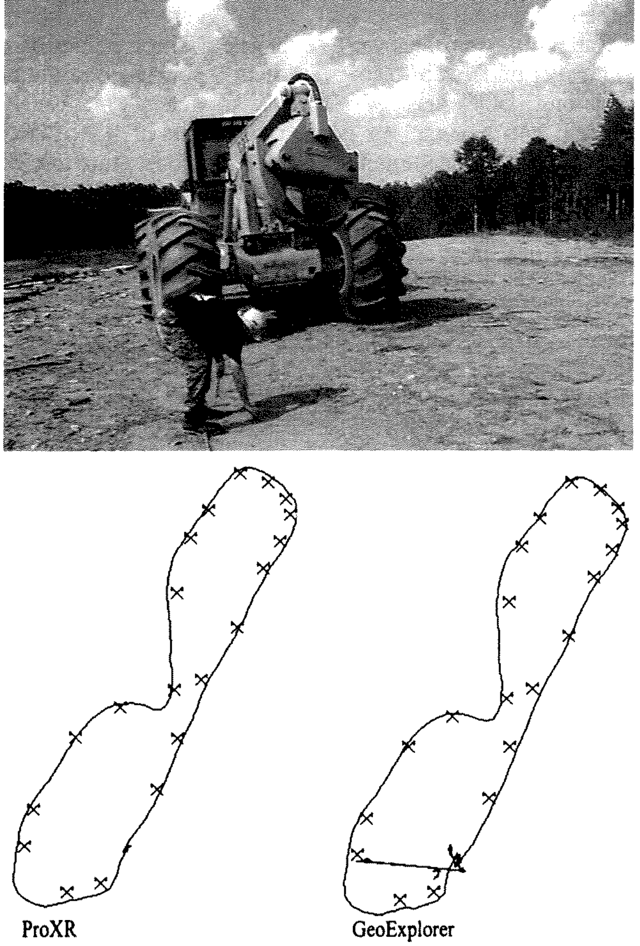

Figure 1. Photograph of open canopy test conditions with example plots of GPS-based skidder paths in that test condition. Data collected at the low travel speed were used for these maps.

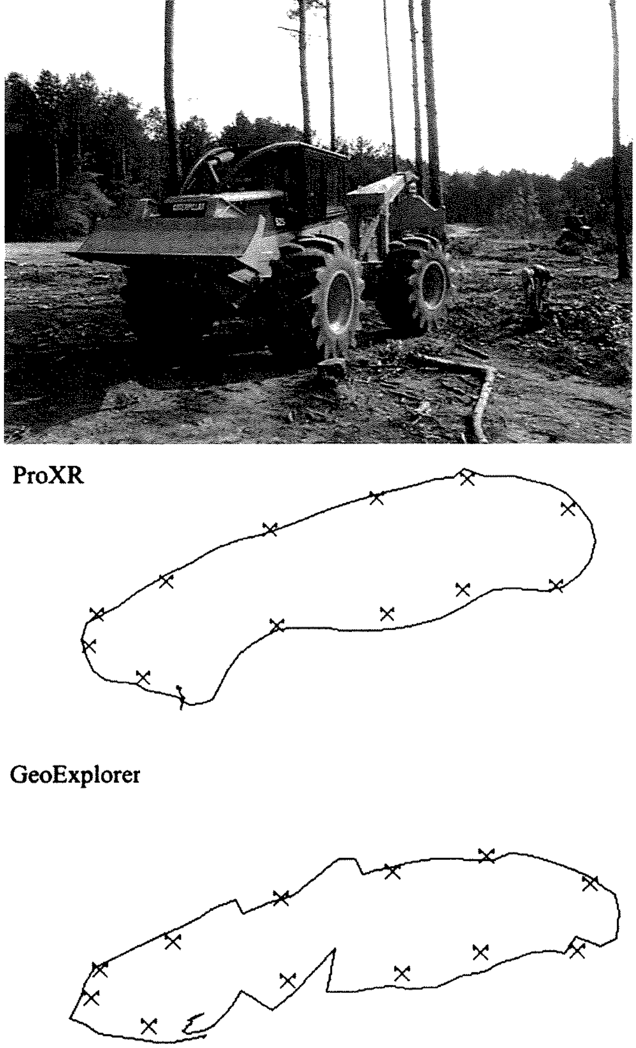

Figure 2. Photograph and map of light canopy test conditions with example plots of GPS–based skidder paths in that test condition. Data collected at the low travel speed were used for these maps.

MACHINES

The machines used for tracking were Caterpillar wheeled skidders. For test runs conducted in open and light canopy conditions, a Caterpillar Model 525 skidder was used. For test runs in heavy canopy conditions, a Caterpillar Model 515 skidder was used since it was more maneuverable. The Caterpillar 525 skidder is 3.3 m wide, has a wheelbase of 3.5 m, and a cab roof height of 3.2 m. The Caterpillar 5 15 skidder is 2.9 m wide, has a wheelbase of 3.3 m, and a cab roof height of 3.0 m.

Test runs were conducted at two machine speeds: low and high. Low speed runs were made with the skidder in second gear, low range. This resulted in an average ground speed of 5.4 kph. High-speed test runs were made with the skidder in second gear, high range. This resulted in an average ground speed of 9.1 kph. High-speed runs were conducted in the open and light canopy conditions only. Low-speed test runs were made in all three canopy conditions.

Before each test run, the machine was positioned in the skidder path and the GPS receivers were configured to record data. Then, the skidder was allowed to proceed around the test course. As the skidder traversed the course, pin flags were placed at the position of the outside edge of the left rear skidder tire.

Table 1. Descriotion of canopv conditions.

Canopy type	Open	Light	Heavy
Crown density (% cover)	0	57	85
Light intensity (lumens)	857	555	263
Mean DBH (cm)	NA	32.7	33.7
Mean tree height(m)	NA	19.9	17.1
Trees per hectare	NA	125	210
Maximum elevation change (m)	4.52	3.12	7.23
Maximum slope (%)	5	3	12
Number of sampling points	20	13	9

Table 2. Summarv of GPS data sample sizes.

Soeed	Data collection	Open	Light	Heavy
High	Sampling points	20	13	N/A
	Number of runs	5	5	N/A
	GPS positions sampled	100	85	N/A
Low	Sampling points	20	13	9
	Number of runs	5	5	9
	GPS oositions samoled	100	85	81

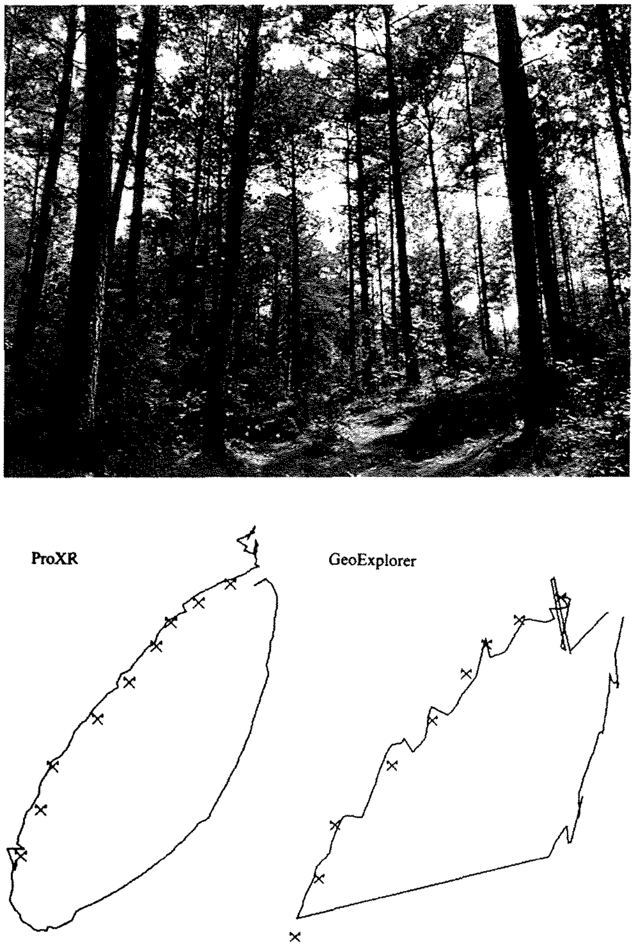

Figure 3. Photograph and map of heavy canopy test conditions with example plots of GPS-based skidder paths in that test condition. Data were collected at the low travel speed

Selective Availability

The initial open, light, and heavy canopy tests were conducted in summer 1999. These tests were conducted with the United States Department of Defense's selective availability (SA) feature active. Additional tests under the open canopy condition were conducted in June 2000 to evaluate how the deactivation of selective availability affected the accuracy of GPS positions. GPS configuration settings and atmospheric conditions similar to the tests conducted in summer 1999 were used in the June 2000 tests. Both the Trimble Pro XR and GeoExplorer II were used to track a Caterpillar Model 525 wheeled-skidder around the open canopy course at speeds of 5.4 kph and 9.1 kph.

Survey Techniques

At the completion of the skidder test runs, traditional surveying techniques were used to establish the location of each point identified by the pin flags. First, two reference points were established in an area with a clear view of the sky. At these reference points, the ProXR GPS receiver was used to determine the coordinates by collecting code and carrier–phase GPS data for 3 hours (9600 GPS positions were collected at each of the points). The sixty-eight percent precisions of the resulting reference position coordinates were + 15 cm horizontal and + 24 cm vertical. Once these reference positions were established, a Topcon Model GTS-710 optical total station and a signal prism were used to determine the location of each of the mobile skidder tire positions marked by the pin flags, based on the reference position coordinates. The optical total station has an accuracy of ± (2 mm + 2 ppm x distance). Based on the longest distance shot with the optical total station, all measurement were within an accuracy of ± 2.174 mm. The two reference positions were used to establish a north reference for the total station surveying activities.

Accuracy Calculation Procedures

The procedure used to determine the error between the GPS-based skidder path and each of the surveyed (pin–flagged) points on each test run is depicted graphically in figure 4. The procedure was:

1. The coordinates (latitude, longitude, and elevation) for the position of the pin flag were determined.
2. The 3D positions of the closest two sequential GPS points were selected. (The GPS receivers were configured to subtract the height of the antenna during data collection.)
3. The three points (i.e., the pin flag and the two GPS positions) were assumed to define a plane in space upon which the skidder was operating.
4. The perpendicular distance, D, on the plane defined in step 3, between the line segment connecting the two GPS positions and the pin flag was determined.
5. Finally, assuming that the skidder was sitting on the plane defined by the three points, and that the pin flag was placed at the outer edge of the tire, the error term, E, was

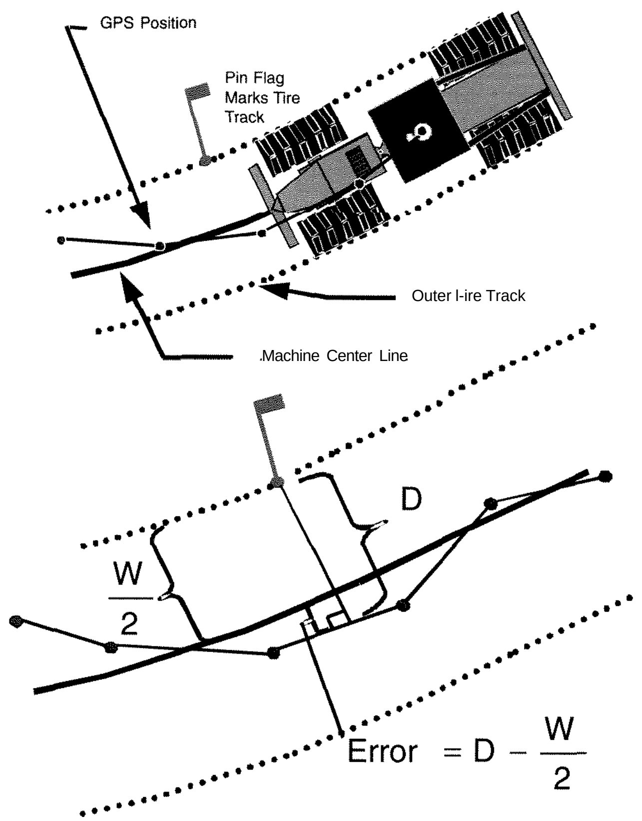

Figure 4. Graphical representation of procedure used to determine GPS position error.

determined by subtracting one half the width of the machine, W/2, from D.

$$E = D - \frac{W}{2} \quad (1)$$

The resulting errors are discussed in the next sections.

RESULTS AND DISCUSSION

GPS VEHICLE TRACKS

Example plots of low-speed skidder paths recorded by the GPS receivers are shown in figures I through 3 for the ProXR and GeoExplorer receivers. These plots show the path of the centerline of the skidder as a line and the location of the pin flags, which is where the edge of the left rear tire was. The plots show that in the open and light canopy conditions, the ProXR successfully mapped the skidder path. When the ProXR mapped the skidder path in the heavy canopy, a few small discontinuities developed in the line that mapped the skidder path. These discontinuities are much more frequent and of greater magnitude in the data recorded by the GeoExplorer receiver. It appears that these discontinuities are the result of changes in the satellite constellation and multipathing errors, which would result from the GPS signals being deflected by the trees. The difference in the apparent accuracy of the plots from the different receivers is probably due to more advanced firmware and hardware in the ProXR receiver.

Information on PDOP was recorded during the test runs to determine if satellite geometry varied during the various test runs. Table 3 contains summary statistics for PDOP collected during the tests. Although there were slight differences in mean PDOP, these differences were probably not large enough to cause significant differences in GPS accuracy during various tests.

ACCURACY RESULTS

Receiver Effects

Table 4 contains summary statistics for threedimensional GPS position errors for the ProXR and the GeoExplorer receivers. Figure 5 also contains a graphical representation of these data. Overall, the mean position error of all test runs for the ProXR was 1.63 m with a coefficient of variation of 144.8%. The mean position error of all test runs for the GeoExplorer was 4.26 m with a coefficient of variation of 85.4%. This increased accuracy in the ProXR was expected due to the more advanced hardware and firmware used in the ProXR receiver. Since these receivers are generally expected to provide position accuracy to within ±2–5 m, these mean errors are within the range that would be expected from these types of receivers. Note that the maximum position errors were 14.63 m and 21.59 m for the ProXR and the GeoExplorer receivers, respectively. Although the mean position errors were within the normally reported accuracy of the receivers, the magnitudes of these maximum errors indicate that there are times when the GPS position will be significantly different from the true position of the machine. An analysis of variance was conducted on the GPS data using the general linear models procedure. The results are shown in table 5. This analysis showed that the GPS positions calculated by the ProXR resulted in position errors that were significantly less than the position errors from the GeoExplorer (alpha levels less than 0.001).

Canopy Effects

Summary statistics for GPS position error in the different canopy conditions are shown in table 6. Figure 5 also contains a graphical representation of these data. The data indicate that there is a downward trend in accuracy as canopy conditions change from open to light to heavy canopy. Mean GPS position errors for the ProXR were 1.26 m, 1.77 m, and 3.76 m for the open, light, and heavy canopy conditions, respectively. Similarly, the mean GPS position errors for the GeoExplorer were 4.11 m, 4.16 m, and 5.14 m for the open, light, and heavy canopy conditions, respectively.

It is important to note that for much of the data collected by the GeoExplorer and the data collected by the ProXR in the heavy canopy, the GPS-based map of the vehicle travel path could have been in error by distances equal to or greater than the width of the skidder. Therefore, for many machine tracking needs, these data may not be of sufficient accuracy. Analyses of variance showed that differences in GPS position accuracies for the different canopy conditions would have

Table 3. Mean PDOP results for data collection sessions of the Pro XR and GeoExplorer receivers.

Receiver	Speed	Canopy		
		Open	Light	Heavy
ProXR	Low	3.14	2.56	2.52
	High	2.52	2.43	N/A
GeoExplorer	Low	N/A	N/A	3.66
	High	3.03	N/A	N/A

Table 4. Three-dimensional GPS position error (meters).

ProXR	Mean	1.63
	Coefficient of variation	144.8%
	Minimum	0.00
	Maximum	14.63
	n	831
GeoExplorer	Mean	4.26
	Coefficient of variation	85.4%
	Minimum	0.02
	Maximum	21.59
	n	424
All	Mean	2.52
	Coefficient of variation	123.7%
	Minimum	0.00
	Maximum	21.59

Table 5. Analysis of variance results for GPS position errors with treatment factors of receiver type, forest canopy density, and machine travel speed.

Source	DF	Mean square	F value	PR>F
Receiver	1	531.535	70.01	0.000 1
Canopy	2	33.914	4.47	0.0346
Speed	1	I.444	0.19	0.662X
Receiver x canopy	2	2.401	0.32	0.5739
Receiver x speed	1	57.3910	7.28	0.2510
Canopy x speed	2	41 .8956	5.52	0.0189
Receiver x canopy x speed	2	110.011	14.49	0.0001
Error	2500	7.86868 I		

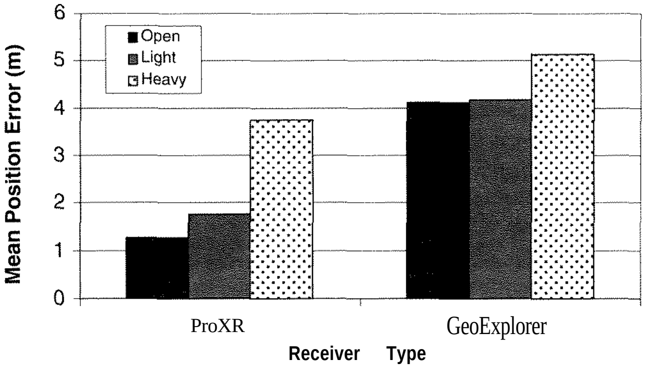

Figure 5. Mean GPS position errors for different receiver types and canopy conditions

Table 6. Three-dimensional GPS position error (meters) due to canopy effects.

		Canopy			All conditions
		Open	Light	Heavy	
Pro XR	Mean	1.26	1.77	3.76	1.63
	C.V.	58.0%	260.1%	80.5%	144.8%
	Minimum	0.00	0.01	0.03	0.00
	Maximum	9.98	5.17	14.63	14.63
	n	620	130	81	831
Geo Explorer	Mean	4.11	4.16	5.14	4.26
	C.V.	54.6%	119.3%	91.3%	85.4%
	Minimum	0.03	0.05	0.02	0.02
	Maximum	11.81	13.16	21.59	21.59
	n	240	130	54	424
All	Mean	2.03	2.96	4.31	2.52
	C.V.	90.3%	166.1%	88.8%	123.7%
	Minimum	0.00	0.01	0.02	0.00
	Maximum	11.81	13.16	21.59	21.59
	n	X60	260	135	1255

been significant at a level of alpha of 0.04. These results indicate that when tracking machines in heavier canopy conditions, the more sophisticated receivers yield more accurate data.

Further inquiry into the effects of forest canopy on GPS positional accuracy revealed an apparent relationship between increased canopy density and higher occurrences of satellite constellation changes. A change in satellite constellation means the receiver either began receiving signals from a new satellite or lost the signal from a satellite. The position data from the GPS receiver were studied to determine which satellites the receiver used to determine the position solution at a selected point. These satellites made up the satellite constellation for that selected point. By comparing the satellites forming a satellite constellation at two successive points, changes in satellite constellations were quantified. The average number of satellite constellation changes per test run for the Pro XR were 16, 28, and 104 for open, light, and heavy canopy conditions, respectively. For the GeoExplorer, the average number of satellite constellation changes was 14, 24, and 30 for open, light, and heavy canopy conditions, respectively.

The numerous satellite constellation changes correspond to the greater GPS position errors under the denser canopies. The inability to establish a strong lock on a consistent satellite constellation would probably lead to poor GPS position accuracy. The gain or loss of a satellite signal affects the geometry of the tracked satellite constellation and poor satellite geometries lead to high PDOP values and less accurate positioning solutions. While the PDOP data collected during this experiment does not fully support this claim, it appears that the inability of the receiver to lock onto a single satellite constellation and establish a high signal to noise ratio affects the accuracy of GPS positions. The satellites affecting the structure of the constellation the most were those located near the fifteen-degree elevation mask. The satellites along the elevation mask were continuously falling in and out of reception thereby causing the receiver to lose signal lock. It might be possible through appropriate mission planning to set an elevation mask such that no satellites fall on or near the mask during the data collection period to minimize the occurrence of loss of signal lock.

The Pro XR experienced a greater number of satellite constellation changes because of its ability to receive and track a greater number of satellites than the GeoExplorer. The Pro XR fluctuated between a five-satellite and a six-satellite constellation; meanwhile the GeoExplorer would steadily track a four-satellite constellation. Although the fluctuations between various satellite constellations appeared to affect the positional accuracy of the Pro XR, the larger constellations that it used still provided better position solution than the smaller satellite constellations tracked by the GeoExplorer.

Multipath error occurs when a satellite signal is reflected off of a nearby object before it reaches the GPS antenna. The travel time of a reflected signal is greater than the travel time of a signal that travels directly from the satellite to the GPS antenna. The additional time created by the reflected signal causes the receiver to calculate a longer distance from the satellite and produce an incorrect position solution. As the canopy cover increases, there are more opportunities for a multipath error to occur as there is an increase in objects that may reflect a satellite signal. This assumption is widely accepted, however there is not a readily available method to quantify the occurrence of multipath under varying canopy conditions. The ways in which the ProXR and GeoExplorer detect and compensate for multipath are significantly different. The ProXR has multipath rejection technology, known as Everest, incorporated in its firmware. The GeoExplorer does not have this technology. Therefore, the ProXR is capable of working under a canopy with improved accuracy because of its superior firmware.

Machine Speed Effects

Errors in GPS positions as a function of machine speed are summarized in table 7 and figure 6. These data show that there are no clear trends in accuracy as the machine speed changed from 5.4 kph to 9.1 kph. For example, mean position errors in data collected by the ProXR were I .56 m and 1.65 m for high speed and low speed, respectively. Similarly, the mean position errors in data collected by the GeoExplorer were 4.41 m and 4.14 m for the high and low speed. respectively. Analysis of variance results confirmed that there were no significant differences in data collected at the two different machine speeds. Part of the reason that there were little differences in accuracy at the two machine speeds may have been due to the fact that the differences in the two speeds were relatively small.