

34 30 hours were recorded as dynamic points, totalling approximately 4000 sampling
35 points. The HRMS accuracy was measured at a confidence level of 63%. The HRMS
36 results for the Trimble GeoXT ranged from about 6.9 m for the Cork 1 route to 3.2 m
37 for the Cork 2 route (Table 1). Results for the Garmin GPSMAP76 varied from a
38 much higher value of about 43.0 m for the Limerick 3 route to 56.9 m for the Cork 2
39 route (Table 1). With this highly variable level of positional accuracy between the
40 two GPS units, it is clear which receiver unit can best be used for professional GPS
41 data collection (Trimble GeoXT) and which is suitable for use as a recreational device
42 (Garmin GPSMAP 76). The option to collect field data using inexpensive
43 recreational GPS units may be sufficient for outdoor enthusiasts who simply require
44 an occasional location fix of moderate (even uncertain) accuracy, but it is unlikely to
45 be sufficient for the GIS professional who requires consistently accurate locations of
46 objects, lines and polygons so that data layers can be overlaid within a GIS. A
47 position fix that is tens of metres in error can lead to distorted spatial data and hence
48 incorrect decision making. In fact, for some applications, a very inaccurate position
49 could be worse than no position fix at all.

50

51 *Keywords:* Trimble GeoXT, Garmin GPSMAP76, GPS, differential GPS, dynamic
52 positional accuracy.

53

54 **1. Introduction**

55 Within the Irish forestry sector (both private plantations and state owned) there
56 is a necessity to introduce Information Technology (I.T.) into the timber haulage
57 sector (Optilog, 2003). Specifically, Information Technology in this sector implies
58 the use of GPS for tracking of timber trucks from a forest harvesting site to sawmill

59 destination, and the incorporation of this positional information within Geographical
60 Information Systems (GIS) to determine if the truck is located at the harvesting site,
61 travelling on a national route or unloading within a sawmill (Frisk et al. 2005).
62 Precision forestry is rapidly becoming an important practice, involving many aspects
63 such as timber harvesting within the forests and subsequent timber transportation on
64 both internal forest roads and the public road network. High GPS positional accuracy
65 for internal forest applications is a prerequisite for updating the GIS forest roads
66 database.

67 This paper documents the results of the performance testing of non-differential GPS
68 (DGPS) techniques using both the Trimble GeoXT and the Garmin GPSMAP 76.
69 Both receivers were used to track an articulated truck across public roads in Ireland.
70 The results show that a recreational GPS receiver was not capable of providing the
71 accuracy necessary for the GPS tracking of trucks travelling across the Irish road
72 network, and definitely not adequate for mapping the internal forest roads. Further
73 research will involve the tracking of the articulated truck on the internal forest road
74 network. This will allow the mapping of any unknown forest road from the recorded
75 GPS data and its transfer into a GIS forest roads map layer. The authors have tested
76 two GPS receivers in an open environment and are confident that the Trimble GeoXT,
77 with its EVEREST multipath rejection technology, option to use the EGNOS
78 correction overlay service, and ability to operate in DGPS mode), is well suited for
79 generating a high level of positional accuracy in the forest canopy environment. The
80 eventual plan will be to create and update the internal forest roads database for
81 different forest compartments. This will allow the X and Y co-ordinates of harvested
82 timber stacks to be entered on the GIS map and be easily located by the truck driver.

83

84 2. Materials and Methods

85 2.1 GPS – background

86 The Global Positioning System (GPS) consists nominally of 24 satellites
87 orbiting the earth at an altitude of approximately 20,000 km (at the time of writing in
88 February 2007 there are in fact 30 satellite in orbit). GPS satellites broadcast radio
89 signals on two different frequencies, the L1 = 1575.42 MHz and the L2 =
90 1227.60MHz. Each signal contains a digital code, the Precise “P” code and the
91 Civilian Access “C/A” code. The P code is transmitted on both frequencies but
92 scrambled by the US DoD for security reasons under a policy known as “anti-
93 spoofing”. With a single receiver the P code allows geographical locations to be
94 determined with metre-level accuracy. The C/A code is broadcast on the L1 only and
95 available to any civilian GPS user as part of the Standard Positioning Service (SPS).
96 (A detailed description of the GPS, its signals, and positioning principles is beyond
97 the scope of this paper and readers are referred to an excellent range of GPS reference
98 books at the online bookshop NavtechGPS, 2007, and official literature and status
99 reports on GPS available from the U.S. Coast Guard’s NavCen website, NavCen,
100 2007.) SPS receivers can determine position, velocity and time (PVT). The P and C/A
101 codes contain signal transmission timing data that the GPS receiver uses to determine
102 how long it takes the signal to travel from the satellite to the receiver. Since radio
103 signals travel at the speed of light (299,792.458m / sec), the distance between the
104 satellite and the receiver is simply the transmission time multiplied by the speed of
105 light. This calculation must be very precise in order to obtain accurate positions.
106 Three satellites are necessary for a 2-dimensional position fix, with two satellites
107 needed for determining horizontal position and the third satellite for determining the
108 receiver clock error, with the height constrained to a known or average value. Three-

109 dimensional positioning requires three satellites for determining the 3-D coordinates,
110 with the fourth satellite used for determining the receiver clock error. The clocks
111 within GPS receivers are not as accurate as the satellite atomic clocks and it is for this
112 reason that the receiver clock error must be continually determined as part of the
113 position fix calculations. (In fact a GPS receiver, after a position fix, is the most
114 accurate portable clock ever built, giving absolute time to sub-microsecond accuracy.)
115 Differential GPS (DGPS) is an advanced GPS technique that cancels out any errors
116 associated with satellite clock timing errors and atmospheric refraction effects. DGPS
117 involves running a reference receiver at a known location to calculate the satellite
118 timing and atmospheric errors and to then relaying these as corrections to the roving
119 GPS receiver for enhanced positional accuracy, in real - time.

120 Not all receivers that use differential corrections flag their solution coordinates with
121 the correction status, hence it is impossible to distinguish between the corrected data
122 and the uncorrected data in some cases. This is not an issue with more advanced
123 professional receivers, which provide additional information about each position fix.
124 This data about GPS data is known as *metadata*. Metadata provides information
125 about the GPS PVT fix such as date, time, dilution of precision (DOP), speed, the
126 datum in which the coordinates were transformed, and other information. The
127 recorded coordinates can also be used with Environmental Systems Research
128 Institute's (ESRI's) Tracking Analyst extension for ArcMap. This extension software
129 allows the playback of GPS recorded data. Features such as GPS quality control,
130 electromagnetic shielding, antenna technology, quality of the housing and user
131 interface, size of screen and onboard memory are just some of the design features that
132 may distinguish a professional receiver from a low-cost recreational receiver.

133 The Trimble GeoXT and Garmin GPSMAP 76 used for this experiment are twelve-
134 channel, SPS (L1-only) GPS receivers. They were both used in the non - differential
135 mode to determine how accurate the positions of an articulated truck travelling across
136 Irish roads could be determined. The recorded data showed that a maximum of nine
137 satellites and a minimum of four satellites were tracked during the experimental
138 period, which implies that good quality GPS position fixes should be possible (Prisley
139 et al. 1995). Both GPS receivers were used with external magnetic antennas fixed
140 side by side to the roof of the cab of the truck. An external antenna can significantly
141 improve the signal strength in difficult environments, which consequently results in a
142 higher number of positions recorded and less degradation of the signal and positional
143 accuracy.

144

145 *2.2 Software and data used*

146 The GIS used in this research is ESRI's Arcview 8.3 (ArcCatalog, ArcToolbox and
147 ArcMap) to explore, query and analyse the data geographically. The development
148 platform was Windows XP for PC's. The main tools used to create, manage and edit
149 the geodatabase are found in ArcCatalog and ArcMap. ArcCatalog has the tools for
150 creating and modifying the geodatabase schema while ArcMap is used to analyse and
151 edit the contents of the geodatabase.

152 The Trimble GeoXT handheld receiver can provide sub-metre accuracy in real-time
153 through space-based augmentation systems such as WAAS (North America) and
154 EGNOS (in Europe only) and DGPS. However, the results of this paper attempt to
155 quantify the HRMS dynamic positional accuracies of both the Garmin GPSMAP76
156 and the Trimble GeoXT *without* DGPS correction. The GeoXT receiver includes
157 EVEREST multipath rejection technology for optimal performance in difficult GPS

158 environments. Multipath occurs when the signal picked up by the GPS antenna has
159 been reflected off a surface (in this case, the top of the trailer or the wind – deflector
160 on the roof of the cab), rather than being received directly from the GPS satellite.
161 Because the signal has been delayed, it introduces errors into the position calculation,
162 therefore reducing the accuracy performance of the GPS. Antenna technology is one
163 of the key methods to reduce multipath and to bolster signal strength. The GPS data
164 was recorded through the ESRI ArcPAD software on the GeoXT. The GPSMAP 76
165 records its positions through connection to a PDA via the HGIS (StarPal) software
166 version 7.25. This requires a cable connection to the PDA, which has a poor battery
167 life, especially when recording GPS data.

168 The data was recorded in the World Geographic System 1984 (WGS84) datum, i.e.
169 the GPS reference frame. Since the digital road map data is in Irish National Grid
170 (ING) form, the GPS data had to be transformed into the Irish National Grid reference
171 frame (Ordnance Survey Ireland, 1996; Ordnance Survey Ireland, 1999; Bray, 2001).
172 As well as this, WGS84 records the latitude and longitude in decimal degrees. In
173 order to compare the accuracy of the GPS data with the underlying road vector
174 network in units of metres, each GPS data point was to be converted from WGS84
175 decimal degrees to Eastings and Northings of the Irish National Grid in metres. This
176 data conversion was carried out with Grid Inquest 6.0 software, which is available
177 from the Ordnance Survey Ireland website (Quest Geodetic Software Solutions Ltd).
178 Map projection onto the Irish National grid was necessary in order to eliminate
179 alignment and accuracy errors when adding the layers of GPS route data for eventual
180 analysis within the GIS (Ordnance Survey Ireland, 2000; Ordnance Survey Ireland,
181 2001). This projection of coordinate systems was carried out within ArcCatalog. The
182 digital road network of Ireland was used within the GIS, which comprised motorway,

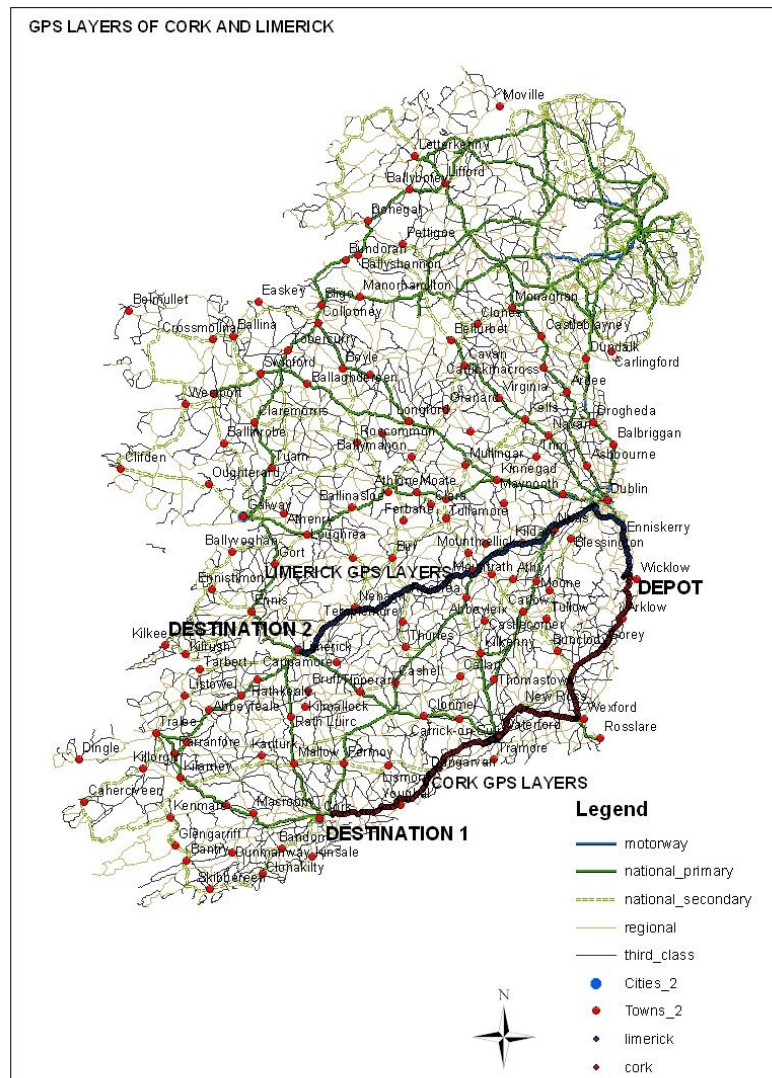
183 national primary, national secondary, and regional and third class roads. The road
184 network was represented as connections of 5917 nodes and 8941 links together. The
185 nodes represent the road intersections and the links represent homogeneous road
186 segments. Geometric networks are built in the GIS model to construct and maintain
187 topological connectivity.

188

189

190 2.3 Data collection procedure and study area

191 The experiment involved the truck travelling two main routes across the whole of
192 Ireland, on different occasions throughout the month of August 2005. Each route was
193 travelled three times from the haulage depot in the east of the country to two
194 destinations in the south and southwest of the country (Figure1).



195
196 Figure 1. Digital road map of Ireland showing GPS routes to Limerick and Cork.

197 The GPS receivers were set to record data every thirty seconds along the route. Each
198 route averaged a total of 1000 sample points, but averaging 650 dynamic sample
199 points. There was on average seven satellites acquired for each sample point recorded
200 (a maximum of nine satellites and a minimum of four satellites). The GeoXT can also

201 record data as a shapefile (.shp), which allowed easy transfer of data between GPS
202 and the ESRI ArcView GIS software installed on the laptop. The same method of
203 data transfer applied to the GPSMAP 76. Data can be transferred using Microsoft's
204 Active Sync. Dilution of precision values are influenced solely by the geometry of
205 the satellites. Low values of Horizontal Dilution of Precision (HDOP) mean high
206 precision, which in turn implies increased accuracy of the recorded data if there are no
207 systematic biases affecting the measurements (Table 1).

208

209 **3. Results and Discussions**

210 *3.1 Measuring Accuracy*

211 Over 50 hours of data, totalling approximately 6000 data points were recorded at 30-
212 second sampling intervals under open sky conditions by both the Trimble GeoXT and
213 Garmin GPSMAP 76 (that is, about 100 hours of data totalling approximately 12000
214 data points). Of these 50 hours, over 30 hours were recorded as dynamic points,
215 totalling approximately 4000 sampling points for each receiver. The tests were
216 carried out across two separate routes, each route being travelled three different times
217 during August 2005.

218 The objectives of these tests were to determine:

219 1). How accurate are the sampled points in relation to the underlying road
220 vector network.

221 2). How does the non-DGPS positional accuracy of both GPS receivers
222 compare to each other.

223 From within the GIS, the data recorded from each route can be added as a shapefile
224 (.shp) layer to the map (Figure 1). The map contains the underlying road network in

225 Irish National Grid (ING) coordinates. The GPS points are converted from the
226 WGS84 datum into ING in order to correctly overlay and align with the road network.
227 Using GIS tools, a spatial join was carried out. This implies calculating how close
228 each GPS point is to the underlying road vector. To measure accuracy, it is necessary
229 to compare a known and unknown location. If there is no known location then only
230 *precision* can be quantified. In this experiment, the known location is assumed to be
231 the road network. The distance of the GPS fix from the known location was then
232 calculated. From the statistics tools within the GIS, the mean and the standard
233 deviation of the distance values between the recorded GPS points and the underlying
234 road vector data can be calculated accordingly for each of the six specific routes. The
235 root mean square is determined from the square root of the sum of the squares of the
236 mean and standard deviation. This calculation is repeated for each route recorded by
237 both of the receivers, i.e. six routes for the GeoXT and six routes for the GPSMAP 76.
238 The results of the HRMS accuracy are shown in Tables 1 and 2.

239 The accuracy is expressed as a Horizontal Root Mean Square (RMS) value and is a
240 measure of the spread of data around the known location. The HRMS value
241 represents the horizontal distance from the known position on the road network and it
242 defines the distance within which 63% of the position errors will fall.

243 Another related accuracy specification is 2dRMS or twice the distance HRMS. The
244 confidence level for 2dRMS is 95%. A third accuracy specification is Circular Error
245 Probable (CEP), which has a 50% confidence level. These three different measures
246 can be used to describe a GPS receiver's accuracy. They all describe the same spread
247 of errors, but in different ways.

248 From Table 1 and Figure 2 it can be seen that the results of the accuracy of dynamic
249 non-differential GPS prove quite favourable to the GeoXT, with a minimum HRMS

250 accuracy of about 6.9 m for the Cork 1 route and a maximum HRMS accuracy of 3.2
251 m for the Cork 2 route. The GPSMAP 76, however, resulted in a minimum HRMS
252 accuracy of about 43.0 m for Limerick 3 and a maximum HRMS accuracy of 56.9 m
253 for Cork 2. It is worth noting that: 1) the width of the truck is approximately 2.5 m, 2)
254 the total length of the truck and trailer is approximately 16.75 m, 3) the lane widths of
255 a motorway are 3.5 m with hard shoulders, 2.5 m in width, and 4) the centre median is
256 a minimum of 4.0 m. The same dimensions apply for dual carriageways. Single lane
257 roads have a total range width from approximately 5 m to 8 m. (National Roads
258 Authority). This implies a very high level of accuracy for the Trimble GeoXT GPS
259 but not as impressive a performance for the GPSMAP 76.

260 The HDOP (2-D) values are also indicators of the quality of the GPS position. This
261 value takes into account each satellite's location relative to the other satellites in the
262 constellation and their geometry in relation to the GPS receiver. A low HDOP value
263 indicates a higher probability of accuracy. The HDOP values recorded for each of the
264 routes are summarised in Table 2 and correspond with those predicted from Trimble's
265 satellite almanac 'Mission Planning Software' for each separate recording date
266 (Trimble Mission Planning Software - Table 2 and Figure 3). The GPSMAP 76 does
267 not provide any information regarding any DOP values, hence no comparisons can be
268 made with the HDOP values recorded by the GeoXT.

269

270

	DATE	TRIMBLE GeoXT (m)	GARMIN GPSMAP 76 (m)	MAX SATS	MIN SATS
Limerick1	11/08/05	5.2734	45.9426	9	5
Limerick2	15/08/05	4.393	45.4082	9	5
Limerick3	16/08/05	6.8017	43.024	9	5
Cork 1	25/08/05	6.9197	54.8437	9	4
Cork 2	26/08/05	3.1926	56.9076	9	4
Cork 3	29/08/05	4.303	56.4808	9	5

271

272 Table 1. Summary of HRMS positional accuracy for single receiver (i.e. non-
 273 differential) GPS across each of the six routes for the Trimble GeoXT and Garmin
 274 GPSMAP 76.

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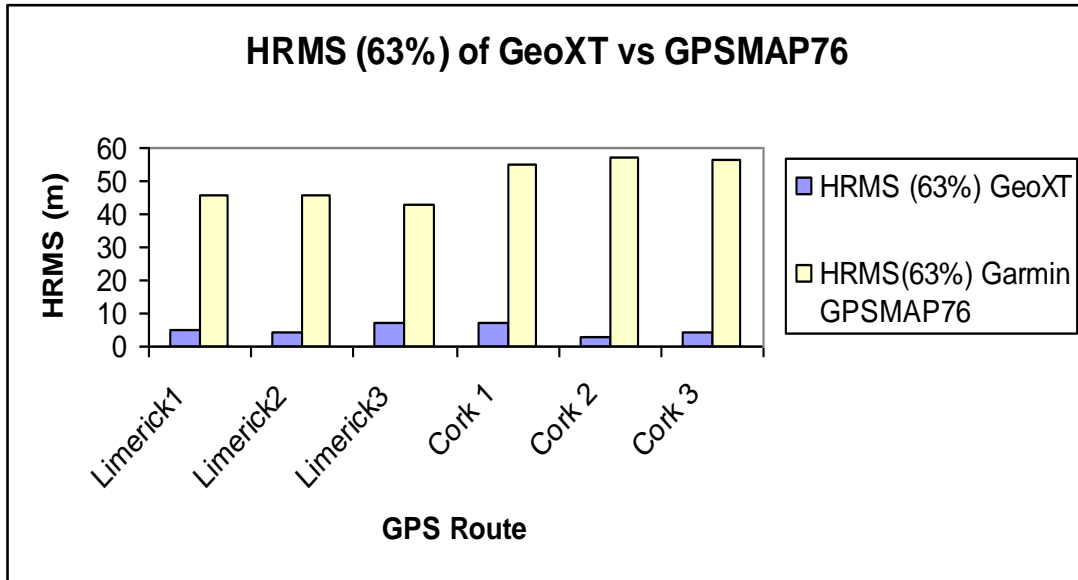
	DATE	HRMS (63%)	MEASUR ED HDOP	TRIMBLE HDOP	GeoXT MAX SATS	GeoXT MIN SATS	TRIMBLE MAX SATS	TRIMBLE MIN SATS
Limerick1	11/08/05	5.2734	1.375	1.364	9	5	9	5
Limerick2	15/08/05	4.393	1.173	1.448	9	5	9	5
Limerick3	16/08/05	6.8017	1.335	1.369	9	5	9	6
Cork 1	25/08/05	6.9197	1.389	1.537	9	4	9	5
Cork 2	26/08/05	3.1926	1.306	1.485	9	4	9	6
Cork 3	29/08/05	4.303	1.298	1.552	9	5	9	5

276

277 Table 2. Summary of mean measured HDOP (GeoXT) Vs Trimble Planning Software
 278 mean HDOP values.

279

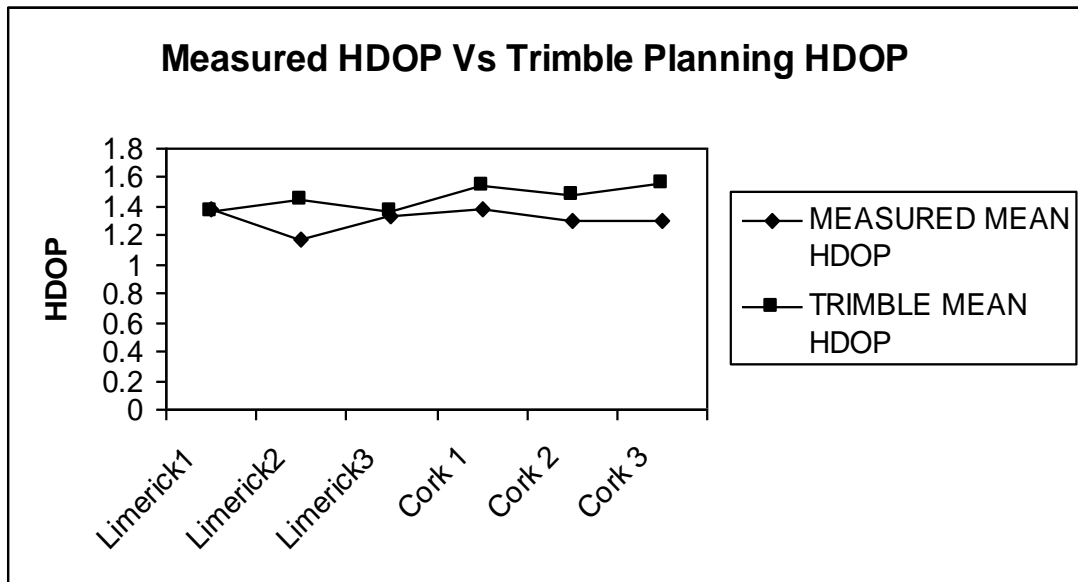
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281

282 Figure 2. Graph of HRMS (63%) of Trimble GeoXT Vs Garmin GPSMAP 76.

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284

285 Figure 3. Graph of Measured HDOP (GeoXT) Vs Trimble Planning Software HDOP.

286 **4. Conclusion**

287 From this study of the dynamic performance of two GPS receivers, the
288 Trimble GeoXT clearly demonstrates increased positional accuracy compared to the
289 Garmin GPSMAP 76 receiver when both run in non-differential mode. There is no
290 direct evidence to suggest that Trimble’s antenna technology and the advanced
291 EVEREST multipath rejection technology played a pivotal role in ensuring high
292 accuracy. However, by rejecting the multipath signals before computing positions,
293 the GeoXT would be expected to offer increased HRMS accuracy compared to the
294 GPSMAP 76. Of course the performance of the GeoXT compared to the GPSMAP
295 76 cannot be solely attributed to the more advanced GPS technology within one
296 receiver. Other factors such as atmospheric refraction effects, satellite ephemeris and
297 clock errors and the dilutions of precision also impact on the final results. Ephemeris
298 and clock errors, for example, can introduce errors in the range of approximately 2.5
299 m and 2 m respectively. Propagation delays in the troposphere and ionosphere can
300 introduce errors ranging from approximately 2.5 m at the zenith and increasing to 28
301 m at the horizon. However, both receivers would have been influenced by the same
302 external effects, and although they affect absolute accuracy, the GeoXT is clearly
303 more accurate than the GPSMAP 76 in a “relative” sense.

304 This positional technology can monitor the movement of the trucks on the agreed
305 routes for timber extraction and impose any penalties if these routes are not followed.
306 Security of the timber can be increased by tracking the exact movement of the truck
307 from harvesting site to destination mill, and identifying any unexplained stops that
308 could indicate timber removal for personal gain. Back-loading of trucks can be
309 implemented more efficiently by determining which truck is closest to the pick-up
310 point and diverting it accordingly. In an environment where operating costs are rising

311 continuously, the timber haulage sector must implement such technology in order to
312 remain competitive and to maximise the time a truck is travelling while loaded. The
313 next part of the research will involve using the Trimble GeoXT for in-forest GPS
314 mapping of any unknown forest roads, and the updating of the GIS roads database
315 accordingly.

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