An Accuracy Assessment of Positions Obtained Using Survey- and Recreational-Grade Global Positioning System Receivers across a Range of Forest Conditions within the Tanana Valley of Interior Alaska

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ABSTRACT

The accuracy of recreotional- and survey-grade global positioning system (GPS) receivers was evaluated across a range of forest conditions in the Tanana Valley of interior Alaska_ High-accuracy check points, established using high-order instruments and closed-traverse surveying methods, were then used to evaluate the accuracy of positions acquired in different forest types using a recreational-grade GPS unit and a Global Navigation Satellite System (GLONASS)-enabled survey-grade unit, over a range of acquisition and postprocessing alternatives, including distance to base station, or baseline length (0-1 0, 10-50, 50-100, and > 100 km), use of Russian GLONASS satellites, and occupation times (5, 10, and 20 minutes). The accuracy of recreational-grade GPS was 3-7 m across all sites. For survey-grade units, accuracies were influenced by forest type and baseline length, with lower errors observed with more open stands and shorter baseline lengths. The use of GLONASS satellites improved positions by a small but appreciable amount, and longer observation times (20 minutes) resulted in more reliably accurate positions across all sites. In general, these results indicate that if forest inventory plots in interior Alaska and other high-latitude regions of the world are occupied for 20 minutes with survey-grade instruments, positions with submeter error can be consistently obtained across a wide range of conditions.

Keywords: GPS, accuracy, measurements, inventory

The ability to acquire accurate field plot locations, even under a dense vegetation canopy, is becoming increasingly important in regional forest resource inventories, such as that carried out by the forest Inventory and Analysis (FIA) program in Alaska (Bechtold and Patterson 2005, Hoppus and Lister 2007). With the emergence of high-resolution remote sensing technologies, including hyperspectral imaging and airborne LIDAR (light detection and ranging), as important sources of data in forest inventory, there is increasing recognition of the need to accurately register remotely sensed data to field plot information for the purposes of training image classification algorithms and multiphase sampling (Schreudert et al. 1993).

At present, the Alaska FIA program uses recreational-grade global positioning systems (GPS) units to georeference field plots (US Forest Service 2008). These low-cost ($100-$500) units are 12-channel, single-frequency receivers that provide nominal accuracies of 2-7 m in good, clear-sky conditions with good satellite visibility but can be considerably less accurate (>20 m error) under typical forest inventory conditions (dense forest canopy, poor satellite geometry) (Karsky et al. 2001, Wing er al. 2005). In a test carried out under dense forest canopy in western Oregon, Wing and Eklund (2007) reported an average error of 8.9 m for locations obtained with a Garmin V recreational (or consumerr-grade unit, with errors exceeding 22 m at several points. These units track only the American GPS satellite signals and do not correct for rnultipathing errors. Recreational-grade units that are enabled to receive a correction signal from a Wide Area Augmentation System (W AAS) satellite can achieve improved accuracies in clear-sky conditions (e.g., from 20-m error to 1.5-2 m), but this signal is often blocked by the forest canopy (Karsky 2004). In general, although these low-cost units generally provide a level of accuracy that is sufficient to relocate field inventory plots, it is unlikely that they can consistently provide the

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi; kilograms (kg): 1 kg = 2.2 lb.

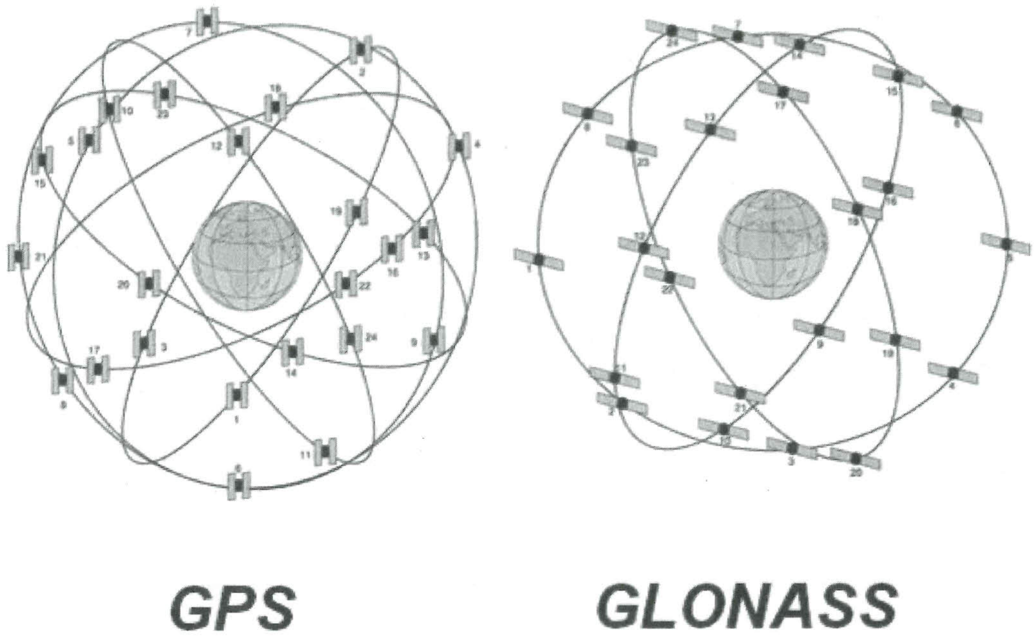

Figure 1. GPS and Global Navigation Satellite System (GLONASS) satellite constellations. The GPS consists of 24 satellites (plus 1 spare) orbiting on six planes at an inclination angle of 55° and an altitude of 20,200 km. The GLONASS system consists of 21 satellites (plus 3 spares) orbiting on three planes at an inclination angle of 64.8° and an altitude of 19,100 km (Nesheim and Ofstad 2005).

level of accuracy (1-m error) needed to accurately register high-resolution remote sensing and field plot data across a broad range of forest conditions. It should be noted that a recent test of several mapping-grade GPS receivers, with a cost ($2,000-$12,000) intermediate between the recreational- and survey-grade units tested in this study, indicated that these units provided a higher level of accuracy than recreational-grade units but still did not consistently provide positions with submeter error under dense forest canopy (Wing et al. 2008).

Satellite Geopositioning at High Latitudes

Satellite-based geopositioning technologies, specifically the N avigation Satellite Tracking and Ranging System, also called GPS, is managed by the US Department of Defense and generally allows for accurate measurement of field plot positions in the contiguous United States. At higher latitudes, however, several factors lead to GPS signal degradation. Because the orbital partcrns of the GPS satellite constellation were optimized for positioning at the middle latitudes, the position of the constellation relative to points on the earth surface changes significantly as one moves higher in latitude (Cannon et al. 2003). The ideal satellite configuration, from a purely geometric standpoint, consists of one satellite directly overhead and other satellites widely spaced in all directions around the horizon. At very high latitudes, no GPS satellites pass directly overhead, and most satellites are to the south and relatively low on the horizon, which leads to suboptimal satellite geometry (high position dilution of precision [PDOP) and an increased potential for rnultipathing (Figure 1).

Several commercially available GPS units use the Russian satellite navigation system (Global Navigation Satellite System [GLONASS]) to expand the constellation of available satellites. The use of a combined GPS+GLONASS system can be particularly advantageous at high latitudes, where, because of the different inclinations of the orbital planes in the GLONASS satellite constellation (Figure 1), there are generally improved satellite visibility and geometry.

In addition, many survey-grade GPS units have dual-frequency capability, meaning that they track both Ll (1,575.42 MHz) and L2 (1,227.60 MHz) GPS signals, which can significantly decrease the observation time required to achieve accurate positions (Wolf and Ghilani 2006). In a forested environment, these survey-grade systems will provide a postprocessed, differentially corrected, solution based on either carrier-phase-shift measurements or code ranging, or both, depending on the conditions (for more details on the different types of GPS measurements, the reader is referred to Wolf and Ghilani 2006). Although there are several options available for correcting GPS data, Karsky found that postprocessing is the most accurate method of correction (Karsky 2004). In addition, survey-grade systems often incorporate sophisticated processing algorithms to reduce multipathing errors or errors caused by multiple reflections of satellite signals in a complex environment. Previous studies carried out in Scandinavia and the Pacific Northwest of the United States have shown that dual-frequency, GLONASS-enabled survey-grade receivers can consistently acquire positions with submeter error even under dense forest canopy conditions (N aesset 1999, Clarkin 2007). Although survey-grade, GPS+GLONASS units are relatively expensive ($12,000-$15,000 each), the potential of this technology to provide consistently accurate (<1-m error) plot locations-across a wide variety of forest conditions-may justify the cost in a forest inventory application.

The objective of this study was to rigorously evaluate the accuracies of GLONASS-enabled survey-grade and recreational-grade GPS units across a range of representative site conditions within the Tanana Valley of interior Alaska, using high-accuracy survey techniques to establish the test courses for the accuracy assessment. The main factors that influence the accuracy of GPS positions were identified as follows:

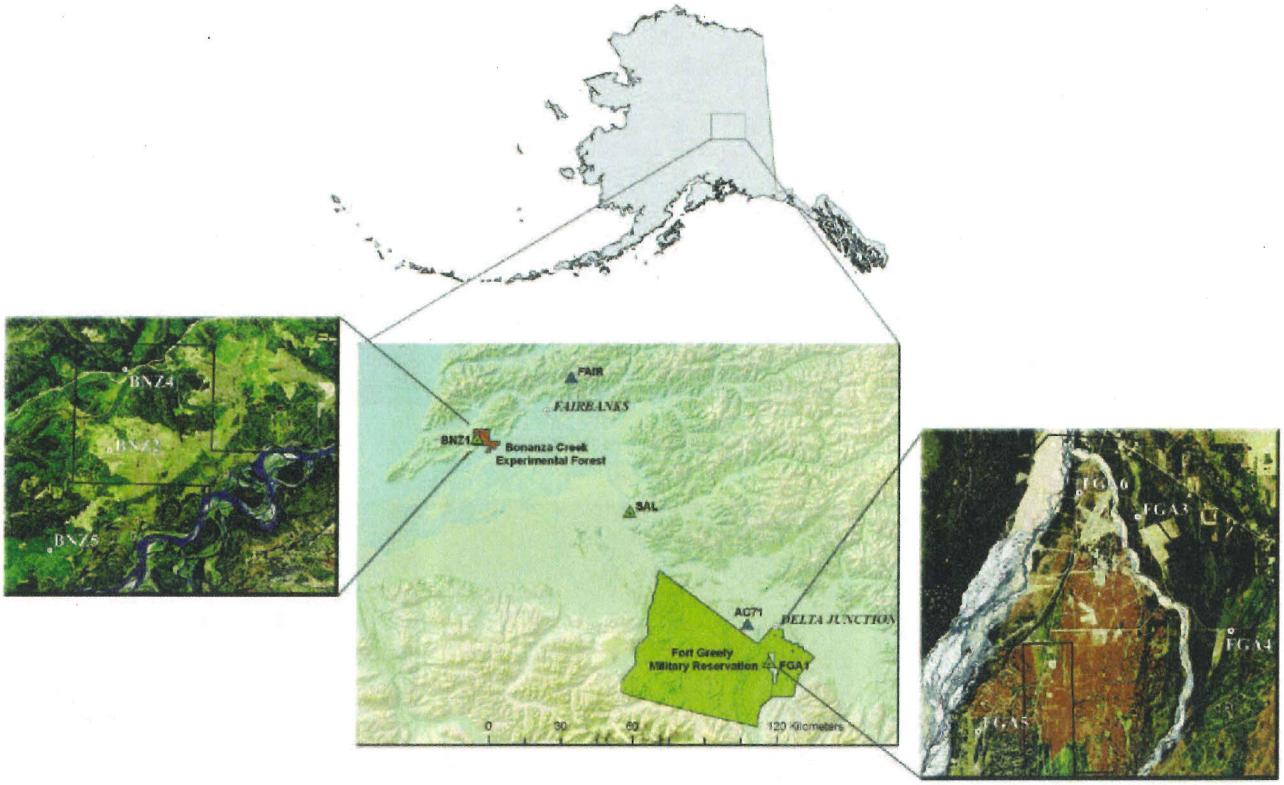

Figure 2. Location of study areas (Bonanza Creek and Fort Greely) in Tanana Valley of interior Alaska. Location of study sites (white circles in left and right images) and location of GPS base stations (colored triangles in center map) are also indicated. Black outlines in images indicate boundaries of Bonanza Creek Experimental Forest (BNZ) and Fort Greely Military Reservation (FGA).

- Forest canopy conditions (density, species composition),
- Type of instrument (handheld versus survey-grade),
- Baseline length or distance to base station (for survey-grade unit),
- GPS+ GLONASS versus GPS only (for survey-grade unit), and
- Length of occupation time (for survey-grade unit).

FIA currently records the precision of the GPS coordinate ("estimated position error") as a measure of reliability. As this is a measure of precision-not accuracy-it is uncertain how closely this metric relates to the accuracy of the coordinate. In this study, we used conventional surveying techniques to rigorously evaluate the accuracy of GPS-derived plot coordinates recorded using alternative types of GPS instruments and postprocessing techniques across various forest sites in interior Alaska. Although the results are presented in the context of a forest inventory in Alaska, the conclusions are broadly applicable to forest survey in high-latitude, boreal regions throughout the world. We also investigated the relationship between true accuracy of the GPS measurement and the measure of precision provided by the instrument.

Study Area

This study was carried out at two sites, Bonanza Creek Experimental Forest (BNZ) (64.75°N, 148.27°W), approximately 30 km southwest of Fairbanks, Alaska, and Fort Greely Military Reservation (FGA) (63.97°N, 145.75°W), just south of Delta Junction, Alaska. These sites are approximately 160 km apart and therefore cover a wide geographic range within the Tanana Basin (Figure 2). The topography at each study area was generally hilly, and slopes ranged from flat to greater than 100%. At some sites, especially those on steep slopes, the sky view was partially blocked by the local terrain.

Table 1. Summary of site conditions for Tanana GPS tests.[a]

Site	Forest type	Stand size class	Canopy density	Slope class	Aspect
BNZ2	Birch	Reprod.	Open	Medium	S
BNZ4	Black spruce	Reprod.	Closed	Medium	N
BNZ5	Birch	Pole.	Closed	Medium	W
FGA3	White spruce/ birch/aspen	Pole.	Closed	Low	NW
FGA4	Black spruce/ aspen	Reprod.	Closed	Low	NE
FGA5	Birch	Pole.	Closed	High	SE
FGA6	Balsam poplar	Pole.	Closed	Low	W

[a] Stand size classification is based on diameter: reproduction (Reprod.): 0–12.7 cm dbh; poletimber (Pole.): 12.7–22.9 cm dbh (conifer), 12.7–27.9 cm dbh (deciduous). BNZ, Bonanza Creek Experimental Forest; FGA, Fort Greely Military Reservation.

Several sites were identified within both BNZ and FGA that covered a range of forest types, canopy densities, slope classes, and aspects (Table 1). The density of the forest canopy at each site is indicated by the representative hemispherical photographs shown in Figure 3.

Methods

To georeference the survey traverses, local base stations were established at secure sites with open-sky conditions within 30 km of each study area (BNZ1, FGA1). To test the effect of various baseline

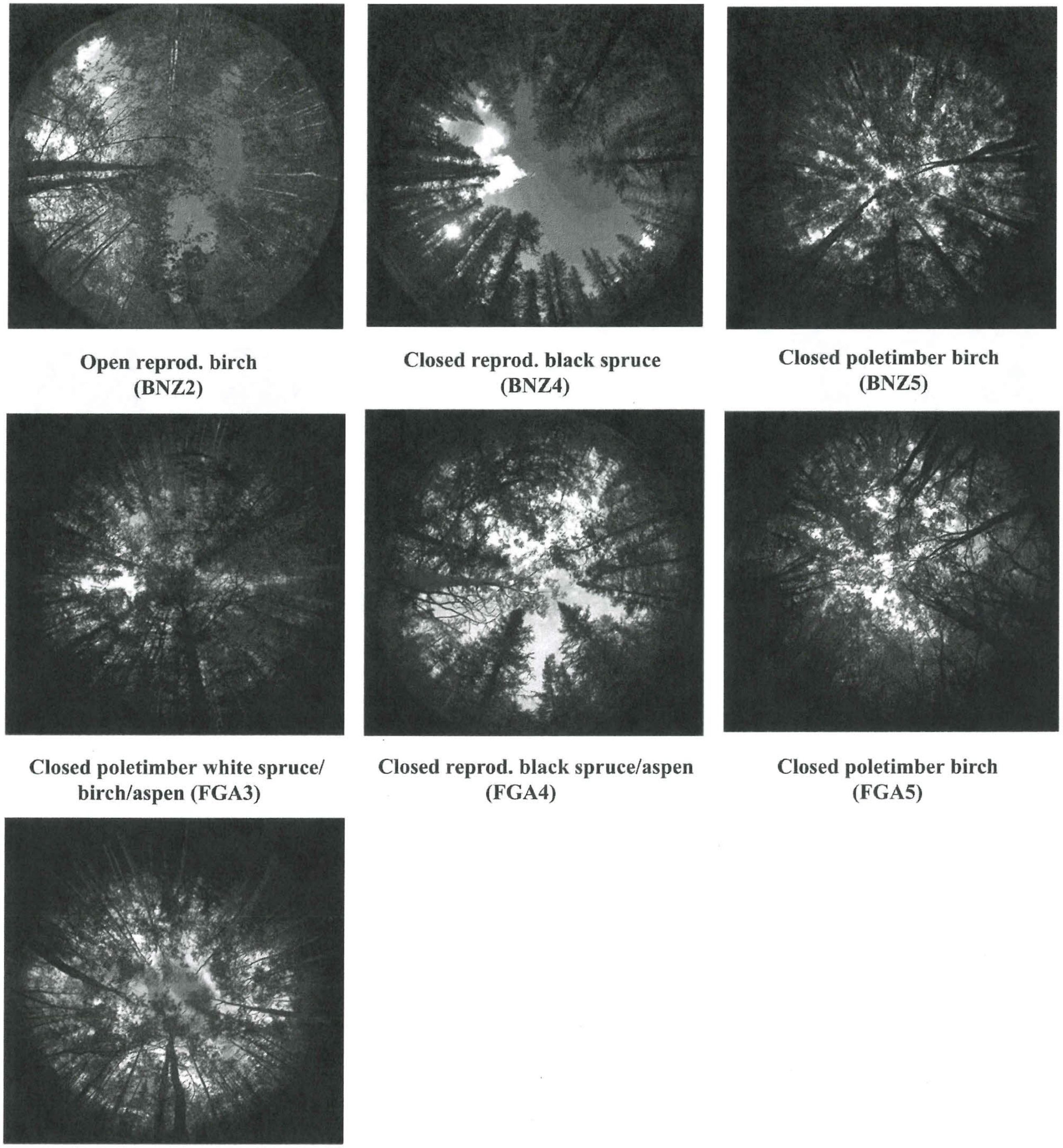

Figure 3. Representative hemispherical photographs taken within study sites in the Tanana Valley, Alaska. BNZ, Bonanza Creek Experimental Forest; FGA, Fort Greely Military Reservation.

distances on the accuracy of GPS coordinates and the potential benefit of recording GPS and GLONASS data, an additional secure site was identified at Salcha Bluff (SAL), approximately halfway between Bonanza Creek and Fort Greely (approximately 70 km from BNZ and 80 km from FGA; Figure 2). Local base stations established at BNZI, FGAI, and SAL consisted of a Javad Maxor survey-grade unit set up on a surveying tripod and logging data at a 1-second interval. In addition, to test the effect of correcting GPS data using data from continuously operating reference stations (CORS) at various distances, RINEX GPS data from a National

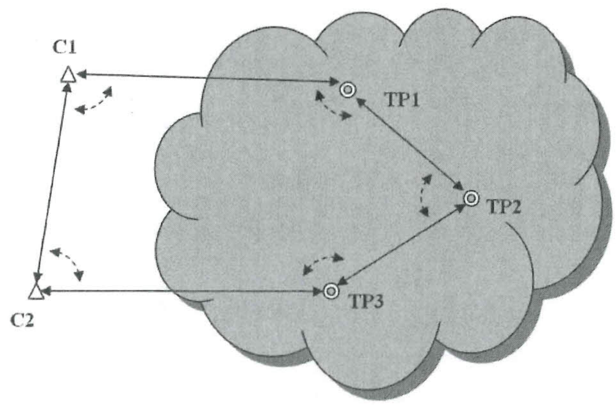

Figure 4. Closed-polygon traverse survey. Solid lines indicate distance measurements, and dashed lines indicate angular measurements. Triangles indicate high-accuracy control points (C) (<1-cm error), and circles are traverse points under canopy (<10 cm error). Traverse points (TP) were used to test GPS units. Gray area represents forest canopy.

Geodetic Survey (NGS) CORS site near Fairbanks (Fair) and a UNAVCO plate boundary observation (PBO) site near Delta Junction (AC71) were downloaded from the Web and used to differentially correct the GPS data (Figure 2) (National Geodetic Survey 2008, UNAVCO 2008). It should be noted that these NGS CORS and UNAVCO PBO sites do not collect GLONASS observations.

Closed-Traverse Surveys

To establish a network of highly accurate check points within these seven representative forest stands, a high-order Topcon ITS-l total station instrument was used to establish a closed-traverse survey course at each site in late July and early August 2007. Two intervisible control points, preferably 25-40 m apart, were established in a clearing adjacent to the forest condition of interest at each site (Cl and C2 in Figure 4). Using these points as a baseline, a closed-polygon traverse survey was carried out at each study site, where a series of traverse points was established under forest canopy (TPl, TP2, and TP3 in Figure 4). Traverse points were established that were generally at least 25 m apart and at an adequate distance from the edge of the stand, to capture a range of representative stand conditions. A closed-polygon traverse survey consists of a closed network of distance and angular measurements; if every angle and distance were measured without error, the algebraic sum of the east-west and north-south components (called *departures* and *latitudes,* respectively) of all survey measurements would equal zero. In reality, measurements are never acquired without error, and the difference between the theoretical sum (zero) and the measured sum provides a measure of the accumulated error of the survey. This accumulated error is then distributed over the entire network, resulting in a new *adjusted* survey. The Compass Rule (Bowditch Method) was used to adjust departures and latitudes of the traverse survey measurements in proportion to their lengths (Wolf and Ghilani 2006). The *linear misclosure,* calculated as

$$\sqrt{(\text{departure misclosure})^2 + (\text{latitude misclosure})^2},$$

provides an indication of the precision of each traverse survey; these values are given in Table 2, along with the total length of the traverses and the number of traverse points. It should be noted that the linear misclosures for all traverses was less than 10 cm.

A survey-grade GPS receiver (javad Maxor GGD) was then set up on a tripod on each control point, and GPS measurements were logged for 20 minutes (Figure 5; Table 3). These control points were differentially corrected using a local base station (BNZI for BNZ sites and FGAI for FGA sites). Because these control points were established in the open, occupied for a sufficiently long period of time, and differentially corrected using a relatively nearby base station, a carrier-phase, ambiguity-fixed solution with an expected error of less than 1cm was obtained for each control point. These points were then used to georeference the closed-traverse survey (coordinates in Universal Transverse Mercator projection, Zone 6 North, North American Datum of 1983).

GPS Test Protocol

Once the closed-traverse survey was established at each site, both survey- and recreational-grade GPS units were tested at each traverse point. At each traverse point, a vertical prism pole with bipod attachment was set up. The survey-grade GPS (rover) receiver was set to a height of2 m to improve the satellite visibility and minimize the effects of stems and branches near the ground. GPS data were then collected at 1-second epochs for 20 minutes on each traverse point. A coordinate was also recorded for each traverse point using a recreational-grade Magellan Explorisr 210 GPS unit soon after the site was occupied with the survey-grade receiver (Figure 5; Table 3). In addition, it was noted if the recreational-grade unit was applying a correction based on the WAAS signal at a particular point.

The elevation-angle masks, which prevent signals received from satellites below a certain angle above the horizon from being used in the position solution, set for GPS receiver operations during this fieldwork were *15°* and 12° for the rover and base receivers, respectively. The elevation angle on the base station receiver was set lower than the roving receiver to ensure that all rover satellites were received by the base for differential correction. It is well known that the signal received at a low elevation angle can be more affected by multi path, ionosphere, and troposphere errors, as well as receiving antenna gain patterns (Parkinson and Spilker 1996, Le and Tiberius 2007). The effect of low elevation angle can be even more severe when collecting GPS information in heavily forested environments

The PDOP mask of 6 was set for GPS receiver operations in this study, as is recommended for average types of GPS surveys (Wolf and Ghilani 2006). Accuracy decreases as PDOP increases (Karsky et al. 2001), so filtering out occupations with high PDOP values can be vety important when taking GPS positions and is especially important in obstructed environments. Piedallu and Gegout (2005)

Table 2. Linear misclosures of closed-traverse surveys at Tanana study sites.

	BNZ2[a]	BNZ4	BNZ5	FGA3	FGA4	FGA5	FGA6
Linear misclosure (m)	0.093	0.042	0.082	0.016	0.005	0.086	0.018
Total length of traverse (m)	473.34	520.50	355.00	489.28	255.05	356.08	351.93
Number of traverse points	8	13	8	9	8	7	8

[a] BNZ, Bonanza Creek Experimental Forest; FGA, Fort Greely Military Reservation.

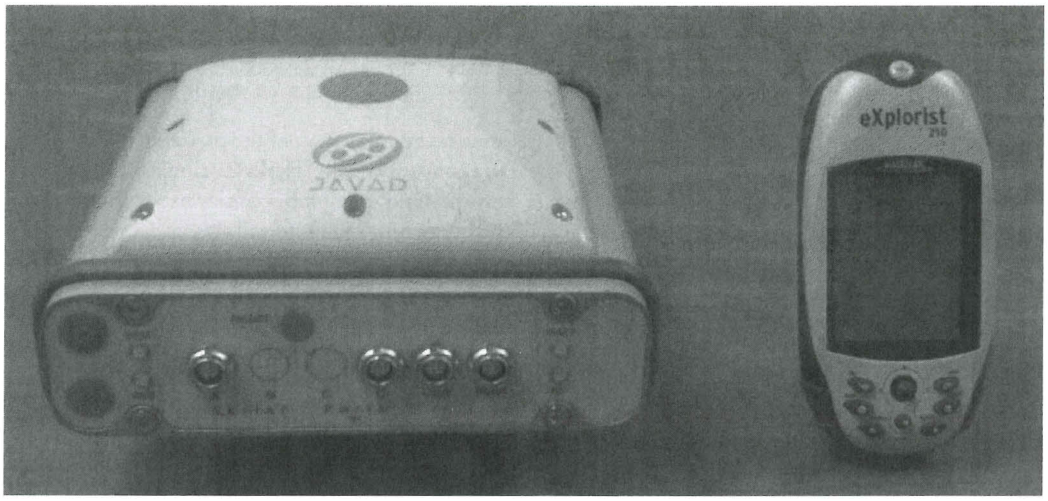

Figure 5. Survey-grade Javad Maxor GGD (left) and recreational-grade Magellan Explorist 210 (right) GPS units used in this study.

Table 3. Specifications of survey-grade and recreational-grade GPS units used in this study.

	Javad Maxor GGD (survey-grade)	Magellan Explorist 210 (recreational-grade)
Satellite tracking specifications	20-channel GPS + GLONASS[a] L1/L2	14 channel GPS L1
Antenna	Microstrip	Patch
Dimensions	16.0 cm × 17.3 cm × 11.4 cm	11.7 cm × 5.3 cm × 3.3 cm
Weight	1.8 kg	0.1 kg
Construction	Ruggedized aluminum housing, waterproof	Wraparound rubber armor, weatherproof
Approximate cost	$12,000	$200

[a] GLONASS, Global Navigation Satellite System.

Table 4. Accuracy (RMSE)[a] of Magellan Explorist 210 recreational-grade GPS across various forest types (RMSE [m], with minimum and maximum errors [m] in parentheses). The proportion of points using the WAAS signal is also indicated.

	Forest type						
	BNZ2	BNZ4	BNZ5	FGA3	FGA4	FGA5	FGA6
RMSE (m)	3.8073	5.5566	6.7229	5.5782	3.6204	4.0832	6.1794
	(1.05, 5.01)	(0.64, 14.01)	(3.74, 9.07)	(2.11, 8.69)	(1.91, 6.43)	(1.50, 7.67)	(3.38, 8.04)
With WAAS	7/8	10/13	1/8	3/9	5/8	5/7	2/8

[a] BNZ, Bonanza Creek Experimental Forest; FGA, Fort Greely Military Reservation; RMSE, root mean squared error; WAAS, Wide Area Augmentation System.

found that in closed forest canopies, GPS positioning error were directly related to PDOP. However, in practice PDOP values rarely exceed 6 when using a GPS+GLONASS survey-grade receiver.

Signal-to-noise ratio (SNR) is a ratio of satellite signal strength to the strength of the surrounding noise, measured in decibel-hertz. The canopy has been shown to have a substantial effect on total signal loss and the reduction of SNRs (Gerlach and Jasumback 1989, Grewal et al. 2001, Karsky et al. 2001, Rodriguez-Perez et al. 2006). GPS signals become unusable when the ratio falls below approximately 25 dB-Hz (Grewal et al. 2001). The SNR minimum was set to 30 for GPS receiver operations during this fieldwork to ensure that at least a minimum qualiry signal was obtained.

The survey-grade GPS observations at each site were differentially corrected using various postprocessing alternatives, including various distances to base stations (0-10,10-50,50-100, and more than 100 km) and occupation times (5, 10, and 20 minutes). In addition, observations at three of the Fort Greely sites (FGA4, FGA5, and FGA6) were postprocessed with and without Russian GLONASS satellites.

Results

Accuracy of Recreational-Grade GPS

The root mean squared error (RMSE) of the recreational-grade GPS unit was between 3 and 7 m across all sites (Table 4). The relationship between the precision, or estimated position error (given by the instrument), and the true error is shown in Figure 6. The results indicate that the estimated error, in general, seems to overestimate the true error.

Accuracy of Survey-Grade GPS

The RMSE values for the survey-grade GPS coordinates, collected for various occupation times and differentially corrected using various baseline lengths, were generally less than 1 rn, as shown in Table 5. As expected, results indicate that accuracies decreased with shorter occupation times and at longer baseline distances, although not dramatically. At a 20-minute occupation, accuracies were seemingly related to forest rype, as positional errors obtained in the open stand (BNZ2) were generally lower than sites with denser canopy conditions. The accuracy of the Fort Greely sites corrected

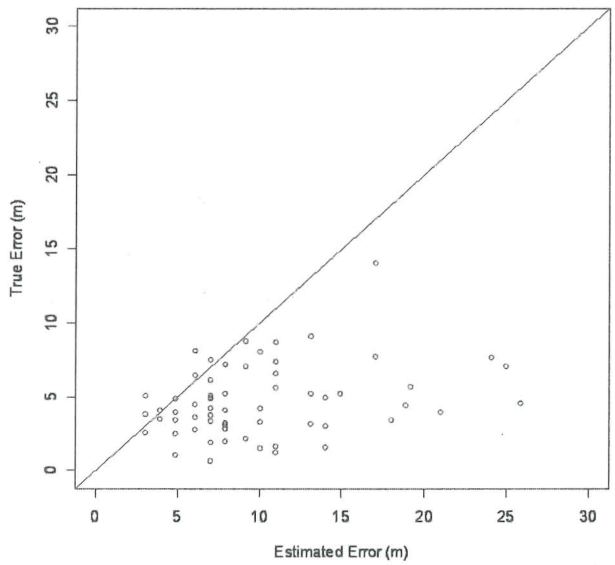

Figure 6. Relationship between precision (estimated position error, provided by instrument) (*x*-axis) and true accuracy (*y*-axis) for recreational-grade GPS (all points).

with and without the Russian GLONASS satellites is shown in Table 6. Results indicate that on average, the use of GLONASS satellites tends to improve the accuracy of positions by approximately 10 cm at a baseline distance of 80 km. The relationship between the estimated horizontal precision for each position, as provided in the postprocessed solurion, and the true error for each

Table 6. Influence of using GPS + GLONASS[a] versus GPS only on accuracy of survey-grade GPS positions in various forest types.

		Forest Type		
	SAL	FGA4	FGA5	FGA6
RMSE (m)	with GLONASS	0.3078	0.4855	0.4049
	without GLONASS	0.4728	0.5600	0.4712

[a] FGA, Fort Greely Military Reservation; GLONASS, Global Navigation Satellite System; RMSE, root mean squared error; SAL, Salcha Bluff.

traverse point is shown in Figure 8. This graph indicates that there is an evident, if relatively weak, relationship between estimated precision and the actual error for survey-grade GPS-derived positions.

Discussion

The accuracy of the coordinates obtained from the recreational-grade GPS units was more consistent than expected, with very few errors exceeding 10 m across all site conditions (Table 4). However, this level of accuracy is still not at the sub meter level that is required to coregister FIA plot data to high-resolution remotely sensed data. Not surprisingly, accuracy of the recreational-grade coordinates tended to improve on those sites where a W AAS signal was available. Unfortunately, it was impossible to disable the W AAS correction on this low-cost recreational-grade unit, so we were not able to evaluate the influence of the WAAS correction at specific points. The results indicate that the "estimated error" as provided by the unit is a very poor measure of the true error of the position and generally overestimates the true error by an appreciable amount-in several cases, the estimated error was on the order of 25 m, whereas the true error was approximately 5-7 m (Figure 6).

Table 5. Errors of survey-grade positions across various forest types, baseline distances, and occupation times (root mean squared error [m], with minimum and maximum errors [m] in parentheses).

Baseline length (km)		Forest type						
		BNZ2[a]	BNZ4	BNZ5	FGA3	FGA4	FGA5	FGA6
0–10	BNZ1							
	20 min	0.0578 (0.02, 0.09)	0.0383 (0.01, 0.06)	0.1175 (0.00, 0.32)				
	10 min	0.0594 (0.02, 0.09)	0.0446 (0.01, 0.07)	0.0868 (0.00, 0.21)				
	5 min	0.0539 (0.01, 0.09)	0.2110 (0.01, 0.68)	1.2128 (0.02, 2.43)				
	FGA1							
	20 min				0.0770 (0.03, 0.10)	0.0476 (0.02, 0.09)	0.0670 (0.04, 0.09)	0.0927 (0.02, 0.17)
	10 min				0.0844 (0.03, 0.15)	0.0629 (0.01, 0.10)	0.0748 (0.04, 0.09)	0.4208 (0.01, 1.13)
	5 min				0.2496 (0.04, 0.72)	0.4242 (0.01, 1.11)	0.8052 (0.03, 1.96)	0.6512 (0.02, 1.33)
10–50	FAIR							
	20 min	0.2751 (0.11, 0.49)	0.4628 (0.09, 0.90)	0.5480 (0.27, 0.95)				
	10 min	0.3451 (0.23, 0.50)	0.5307 (0.04, 0.88)	0.7289 (0.35, 1.18)				
	5 min	0.4789 (0.07, 0.78)	0.7634 (0.24, 1.54)	0.8859 (0.10, 1.52)				
	AC71							
	20 min				0.3620 (0.07, 0.73)	0.4742 (0.00, 1.29)	0.0620 (0.02, 0.10)	0.2994 (0.02, 0.59)
	10 min				0.3833 (0.06, 0.65)	0.8508 (0.01, 1.84)	0.0846 (0.03, 0.15)	0.2722 (0.02, 1.05)
	5 min				0.5086 (0.06, 1.07)	5.09 (0.01, 14.25)	0.2814 (0.03, 0.73)	0.6593 (0.01, 1.22)
50–100	SAL							
	20 min					0.3102 (0.01, 0.43)	0.4855 (0.01, 0.84)	0.4049 (0.11, 0.78)
	10 min					0.4309 (0.16, 0.64)	0.6988 (0.16, 1.51)	0.5402 (0.16, 1.07)
	5 min					0.5825 (0.32, 0.86)	0.7094 (0.12, 1.21)	0.6920 (0.28, 1.51)
>100	AC71							
	20 min	0.3822 (0.11, 0.58)	0.5962 (0.13, 1.25)	0.5846 (0.14, 1.09)				
	10 min	0.4471 (0.06, 0.67)	0.6399 (0.15, 1.42)	0.6765 (0.18, 1.13)				
	5 min	0.8089 (0.13, 1.92)	0.7633 (0.19, 1.49)	0.6760 (0.25, 1.21)				
	FAIR							
	20 min				0.6018 (0.20, 0.95)	0.4356 (0.12, 0.86)[b]	0.6494 (0.08, 0.88)	0.5931 (0.21, 0.93)
	10 min				0.7130 (0.06, 1.06)	0.6045 (0.28, 1.09)[b]	0.9924 (0.37, 2.04)	0.6985 (0.21, 1.02)
	5 min				0.8852 (0.27, 1.75)	0.6114 (0.19, 1.16)[b]	0.9790 (0.29, 1.95)	0.7169 (0.25, 1.49)

[a] AC7, Delta Junction; BNZ, Bonanza Creek Experimental Forest; FAIR, Fairbanks; FGA, Fort Greely Military Reservation; SAL, Salcha Bluffs.
[b] Positions with two failed processes.

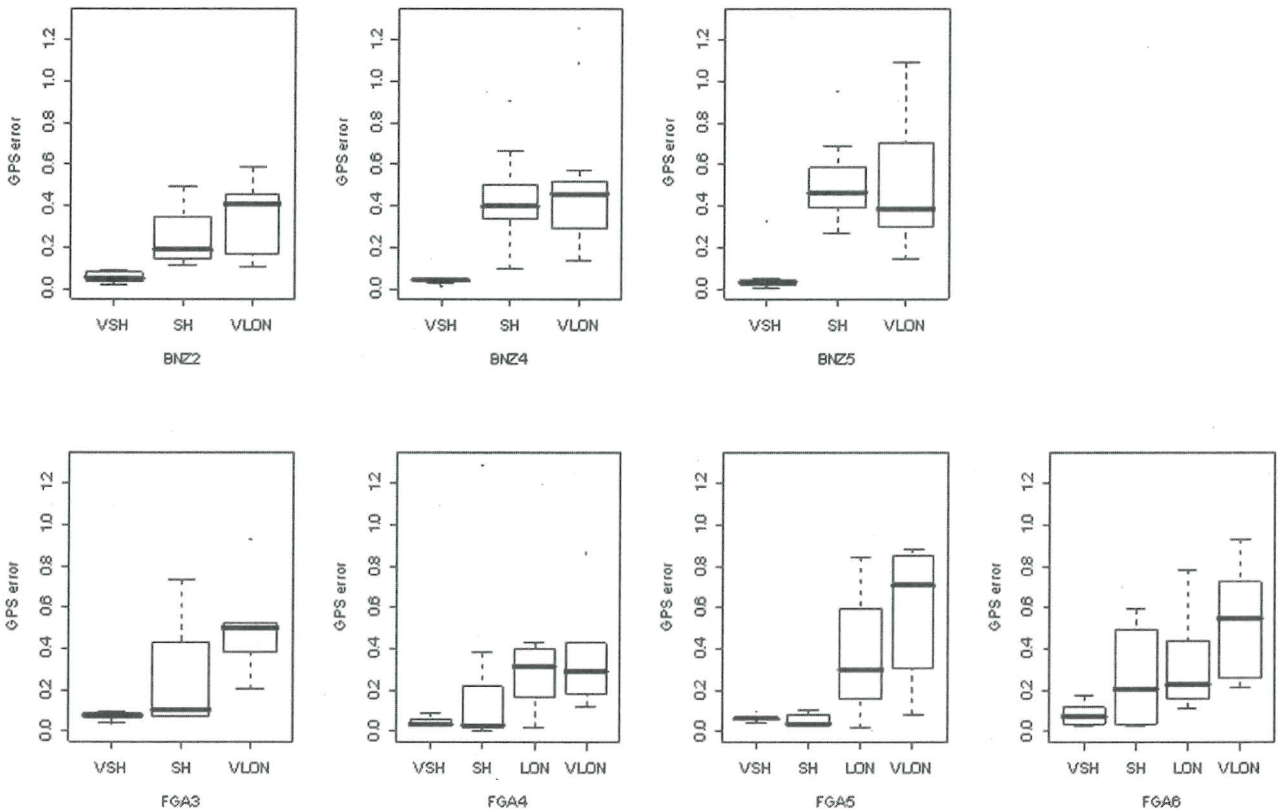

Figure 7. Box-and-whisker plots showing distribution of survey-grade GPS error by study site and baseline length for 20-minute occupations (VSH, very short baseline [0–10 km]; SH, short baseline [10–50 km]; LON, long baseline [50–100 km]; VLON, very long baseline [>100 km]).

The results indicate that the size class and density of the stand does have an effect on the accuracy of under-canopy, survey-grade GPS coordinates (Figure 7; Table 5). The lowest errors were observed at the most open stand in the study, BNZ2, whereas sites in poletimber-size stands with closed canopy generally had higher GPS errors; with more variability (BNZ5, FGA5, FGA6). Since the wavelength of the L-band GPS signal is on the order of 20 em, the signal is much more affected by canopy features at this scale (large branches and stems) than by small branches and foliage. This may explain why GPS errors were relatively low in black spruce stands with dense, closed canopy, but in a smaller size class « 12.7 em dbh) (BNZ4, FGA4). Errors generally increased with longer baselines, although maximum errors for 20-minute occupations very rarely exceeded 1 m even at very long baselines (more than 100 km) (Figure 7). The capability of logging GLONASS data had a small but appreciable effect on the accuracy ofGPS coordinates (Table 6). These results indicate that using dedicated base stations with GPS+GLONASS capability at fairly long baselines (50-100 km) would be the most cost-effective option for a FIA inventory in the interior, although using publicly available data from continuously operating base stations (NGS CORS or UNAVCO PBO) would be an acceptable, ifless-preferred, option. It should also be mentioned that Canadian Differential GPS, based on algorithms developed by Natural Resources Canada and positioning data from Canadian reference stations, is another GPS correction option in interior Alaska (Karsky 2004).

Although in some cases the average accuracy did not significantly degrade with shortened occupation times (5 or 10 minutes), the reliability of the solutions tended to decrease, with maximum errors increasing to well over 1 m for many of the 5-minute occupations (Table 5) and one case of a very large error (14.25 mat FGA3). In contrast, there were very few cases of maximum errors exceeding 1 m at the 20-minute occupation time. These results indicate that occupations of 15-20 minutes would be recommended to reliably obtain accurate coordinates in an inventory context. Although the precision (RMSE) from the postprocessing procedure provides an indication of the accutacy of the survey-grade GPS positions (Figure 8), this relationship is probably not strong enough to recommend use of the RMSE reported in the postprocessed solution as a reliable indicator of accuracy.

Conclusions

The results from this study indicate that if inventory plots in interior Alaska are occupied for 20 minutes with GPS+GLONASS survey-grade instruments, plot locations with submeter error can be consistently obtained across a range offorest conditions. The level of accuracy of recreational-grade units tested in this study was higher than expected but was still not high enough to match high-resolution remote sensing data to FIA plot data. We recommend that observations at the plots be differentially corrected using dedicated, GLONASS-enabled base stations located 50-100 km away from the plots, although GPS-only, publicly available reference station data could be used as a lower-cost, but less-preferred, option. As FIA continues to explore options to decrease the cost of inventory in remote regions such as interior Alaska-while continuing to provide a high-quality product-the ability to accurately georegister and

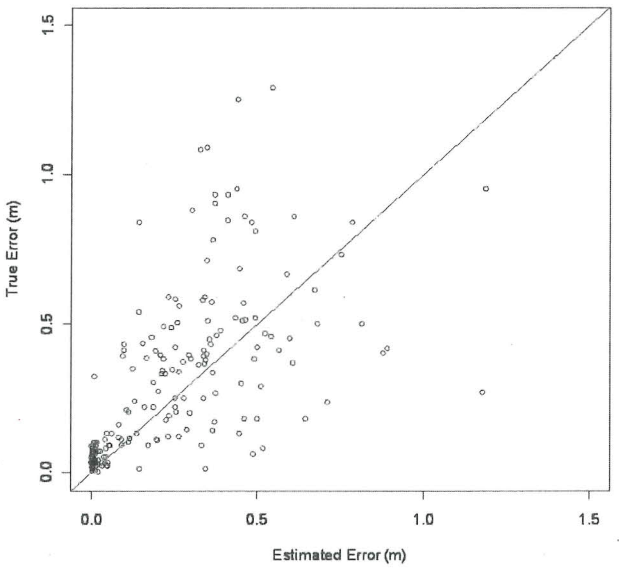

Figure 8. Relationship between precision (*x*-axis) and true error (*y*-axis) for survey-grade GPS (one outlier with precision of 4.98 m and true error of 14.25 m was excluded from graph).

inregrate plot data with high-resolution remote sensing data will become increasingly important. The acquisition of more accurate plot locations (submeter error across all forest conditions)-through the use of more sophisticated, survey-grade geopositioning equip-menr-willlikely lower costs and further leverage the value of the FIA national forest invenrory data.

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