

A Test of the Applanix POS LS Inertial Positioning System for the Collection of Terrestrial Coordinates under a Heavy Forest Canopy

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Abstract—The Applanix POS LS backpack-mounted inertial land positioning/navigation system was used to collect terrestrial coordinates along a previously surveyed closed traverse. A total station surveying instrument was used to establish 26 ground-level stakes along a 1 mile traverse under the dense canopy of a 70 year-old conifer forest in the Capitol State Forest near Olympia, Washington. The Applanix POS LS was initialized at a fixed monument and carried through the forest along the traverse 12 times. Coordinate readings were collected continuously both at the survey posts and between posts. Both the system's location accuracy and its potential for developing terrain profiles were evaluated. The system's average real-time position accuracy was 2.3 ft (1.6 ft Stdev., 7.0 ft max.) and average post-processed accuracy was 1.4 ft (0.9 ft Stdev., 4.0 ft max.), measured at each survey stake. An earlier study provided a 5 by 5-foot, gridded digital terrain model (DEM) derived from high-density LIDAR data. Profiles generated from the LIDAR DEM were compared with profiles measured by the POS LS system. Average post-processed elevation difference along the profiles was 0.7 ft (1.0 ft Stdev., 4.5 ft max.).

INTRODUCTION

Applanix* [a Canadian company that has developed a number of position and orientation systems (POS) based upon inertial navigation systems (INS)] has recently produced a system designed for land surveyors (Gillet *et al.*, 2001). The POS LS system combines an INS [with its embedded inertial measurement unit (IMU)], a roving global position system (GPS) unit, and a computer datalogger into a backpack system weighing about 40 pounds.

When utilizing the internal roving GPS receiver, the POS LS unit is intended to be

used with a user-supplied real-time kinematic (RTK) GPS basestation that would provide the necessary carrier-phase ambiguity resolution, thereby supplying frequent, accurate coordinate updates to the INS system.

Applanix has established with other products, such as the airborne POS AV system, that uninterrupted, post-processed data from such a GPS/INS system can deliver coordinates accurate in the range of inches. However, Applanix anticipates that the land surveyor will on occasion lose the GPS signal—for example, under a forest canopy. The question then becomes: what accuracy can one expect from the POS LS system under these less than optimal GPS conditions?

* Use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

In general, the INS and GPS components of an integrated POS system complement each other's strengths or, rather, compensate for weaknesses (Farrel and Barth, 1999). With an initial coordinate fix and the acceleration vectors sensed by the IMU, an INS can integrate the velocity vectors and compute the coordinate path as the unit moves; however, positional accuracy is eroded as instrument drift accumulates over time.

In contrast, GPS errors are not accumulated over time but, rather, GPS accuracy is maintained by regular, frequent, independent readings. In short, an INS can measure direction and distance in the short run, but benefits greatly by regular coordinate updates from the GPS to correct drift. The GPS is good over the long run, and benefits greatly from the INS data acquired between GPS recordings.

As a surveying device operating in the open under a good constellation of GPS satellites, the POS LS will deliver coordinates accurate in the range of RTK GPS capabilities—approximately 4 inches or better. However, when the GPS signal is blocked, under a forest canopy for example, it reverts to sole dependence upon its INS, and, the error due to drift will begin to diminish the position accuracy over time.

The effect of INS drift can be mitigated in two ways: 1) by position updates—the obvious technique of re-initializing the system position with either GPS readings or by periodically re-visiting known points; or, 2) by zero velocity updates (ZUPTs)—a method used to obtain a velocity re-initialization that has been incorporated into the POS LS instrument. If the INS unit is momentarily held still (at zero velocity), the POS LS software can re-initialize the velocity vector to zero and thereby correct for accumulated velocity drift. In Figure 1,

note how the operator uses a blue staff to help hold the system steady during a ZUPT.



Figure 1. Applanix POS LS system is held steady in one position during a ZUPT.

The desired time interval between ZUPTs is user defined; however, longer intervals increase position errors. When under dense canopy (when the position is being updated using only INS data) an audible announcement and text display on the POS LS datalogger informs the user when it is time for either a ZUPT or position fix (acquiring a new GPS location in a clearing or moving to a known point). A ZUPT is also automatically initiated when the INS unit senses that it is stationary. Additionally, the operator can manually initiate a ZUPT at any time.

At the end of a survey, the location of the POS LS unit is accurately established by either acquiring a high-accuracy GPS position in an opening, or by returning to a

known reference point. This allows the traverse data to be post-processed to derive more accurate, adjusted positions.

Objectives

It is well established that GPS is not reliable for surveys under or near a forest canopy due to obstruction of GPS satellite signals or signal multi-path problems (Darche, 1998; Elosegui *et al.*, 1995; Firth and Brownlie, 1998; Lachapelle and Henriksen, 1995). The POS LS unit offers an alternative method for collecting geographic positions under such adverse conditions. The accuracy of the POS LS system is a function of the frequency of coordinate updates—from either a GPS signal or the input of known coordinates—and the frequency of ZUPTs.

In this initial study, we only examined POS LS coordinate accuracy at a fixed ZUPT interval (nominally 30 seconds) under forest canopy. We examined both real-time accuracy of the POS LS unit and accuracy obtained by post-processing POS LS positions after each trial run (traverse) was closed on a known point.

It is also important to note that in our test, because of extremely dense canopy conditions, GPS positions were not collected with the POS LS unit. Instead, the unit was initialized over previously surveyed reference points for each trial run. These reference points were located in a clearcut adjacent to the forested area. In practice, the GPS unit in the POS LS could have been used in the clearcut to accurately establish the initial location of the instrument before entering and after emerging from dense forest.

METHODS

On May 21-22, 2002, Applanix technical personnel brought a POS LS instrument to

the Capitol State Forest near Olympia, Washington for trials under the canopy in our forest test site. The forest is managed by the Washington State Department of Natural Resources. Our test site has a mix for forest canopy cover, ranging from 70-year-old conifer cover to recently clearcut areas. It has been the site of several other geomatic (Reutebuch *et al.*, *in press*) and forestry (Curtis, *et al.*, *in press*) research trials.

LIDAR data sets were collected in 1998, 1999, and 2000, and a high resolution, 5x5-ft gridded digital terrain model (DTM) was produced from the 1999 data. Additionally, a closed traverse, total station survey was performed under a full-canopy segment of the forest and the staked-points were available for use in assessing the accuracy of the POS LS system. Our test of the POS LS unit was build primarily around re-visiting these surveyed points. A comparison was also conducted between POS LS position elevations and elevations interpolated from the LIDAR-based DTM.

The closed traverse survey loop consisted of 26 points, marked with 2x2-inch wooden pegs driven into the forest floor down to ground level. Two reference points, marked as 1A and 2A, were established from local HARN points with a carrier-phase, survey-grade GPS instrument. Other points, spaced around a roughly circular traverse of approximately 1 mile in length, were established with a Topcon ITS-1 total station survey instrument. Closure calculations showed the horizontal accuracy was 1:2840 and vertical closure was 1.1 inches. After adjustment, the horizontal and vertical accuracy of the ground points were within 6 inches and 1 inch, respectively.

Sets of POS LS coordinate data were collected continuously at a once per second rate over the course of the closed traverse.

Most of the readings were collected while in transit between survey stakes; however, specific blocks of recordings were noted. These blocks were:

- 1) Alignment Fix: The operator set the backpack at reference point 1A to establish the initial position and allow the system to determine true north.
- 2) Point Visitation: After alignment, with the instrument on his back, the operator located himself over a survey point (i.e., the 2x2-inch peg) and held himself steady enough to record several seconds of consistent coordinate readings. (Note: A vertical bias of 3.0 ft was subtracted during data reduction to account for the height of the unit's recording point above the peg in these standing positions).
- 3) ZUPTs: When alerted by the unit, the operator stopped with the instrument still on his back and held steady—at zero velocity—for several seconds.
- 4) Position Fix: The operator took the instrument off his back and set it on a survey stake for several seconds and commanded the system to update position. (A survey stake approximately midway through our closed traverse, was used as this intermediate point).

Coordinate and orientation data were collected continuously while following the closed traverse through several loops. We divided this continuous stream of data into runs. Each run was initiated at a Position Fix and terminated later at another Position Fix with Position Visitations and ZUPT updates registered in between. Twelve runs were made during our test.

Data Management and Reduction

During the two days of POS LS field testing, our operator (Joel Gillet from Applanix)

tramped through our rough, forested terrain for a total of nearly 6 miles while stopping at 175 known positions to either re-initialize the instrument or record points as coordinate data. The task took over ten hours and the instrument, recording constantly at the rate of one coordinate set per second, collected nearly 40,000 points.

From these data, Applanix delivered to us two types of coordinate files: 1) the 'real-time' files that held lists of field recorded 'time, X, Y, Z' data, and 2) the 'post-processed' files of the same data after adjustment. All coordinate data had been transformed into the State Plane System, Washington South Zone, NAD83, Mean Sea Level Elevation, NAVD88 datum, International Feet.

The 'real-time' and 'post-processed' data are purposely distinguished in this report. The 'real-time' data are those that the operator would see on the datalogger coordinate read-out in the field as the POS LS is being carried in the forest. Each real-time data file begins with an initial Position Fix. The data from that initial point forward were computed by dead reckoning based upon the IMU readings and INS projections augmented by the operational ZUPTs.

The 'post-processed' data result from the same recordings, but they depend upon a final Position Fix at the end of each run. An algorithm implemented in the Applanix POSpac software is designed to adjust to zero the error at this fixed terminus and to minimize the error over each run. Both these data sets were examined in this study to quantify the real-time point-by-point accuracy that one can expect in the field, and the accuracy obtainable from further POSpac refinements accomplished after data collection in the office.

RESULTS

Both the ‘real-time’ and ‘post-processed’ data from this test are presented similarly. Tables 1 and 2 summarize the basic results, including average of coordinate errors at all survey stakes, standard deviation, and maximum error associated with each run. Plots display error accumulation over time for ‘real-time’ and ‘post-processed’ data and differences between them (fig. 1 and 2).

Run descriptions

A ‘run’ is defined by an initial Position Fix and, with the exception of Run 5, is terminated by a final Position Fix. (Run 5 was terminated by an unexpected battery failure and, therefore, did not have a terminal fix and could not be post-processed). Each run took a certain time—recorded and shown in seconds—and covered a certain point-to-point distance—computed as the accumulated, straight-line distance between the points visited. The count of the actual number of points visited is shown in the tables as well. The average run time, number of points, and length was 48 minutes, 2,440 points, and 2,472 ft, respectively.

Coordinate errors at survey stakes

Tables 1 and 2 present the average coordinate errors (defined at each point as the coordinates collected over the survey stake (generally the average of ten readings) minus the survey stake coordinates) for each run for the ‘real-time’ and the ‘post-processed’ data, respectively. The overall error means and standard deviations, weighted in proportion to the number of points visited within each run, are computed and displayed at the bottom of each table.

For the ‘real-time’ runs, the mean horizontal error at the stakes was only 2.3 ft (1.6 ft

stdev, 7.0 ft max). The mean real-time elevation error was: 1.4 ft (1.0 ft stdev, 5.4 ft max).

For the ‘post-processed’ runs, the mean horizontal error at the stakes was only 2.3 ft (1.6 ft stdev, 7.0 ft max). The average post-processed elevation error was a remarkable: 0.4 ft (0.3 ft stdev, 1.4 ft max).

Error Plots at survey stakes versus time

Figures 1 and 2 display the coordinate error as it accumulated over time during each run. The plots distinguish each run and are organized to contrast error drift in the ‘real-time’ data (fig.1) and the ‘post-processed’ (fig.2) data.

Comparisons with a LIDAR DTM

As noted earlier, coordinates were being collected constantly at a one second interval while the operator traveled between points. We have distinguished these ‘between-points’ blocks of data by noting the operator movements. By our definition, any point with a coordinate (X, Y) that differs by a tenth of a foot from the average of coordinates over a range of plus and minus 5 seconds, is taken as a point where the operator is in motion and between points. Table 3 summarizes the post-processed data in this “between-points” class. The table shows the total number of points recorded in a run, and the total number of points recorded while moving.

There here is remarkably little difference between the LIDAR DTM elevations and the POS LS elevations (DTM elevation minus the POS LS elevation). The mean, standard deviation, and root-mean-square difference over all the moving points were 0.7, 1.0, and 1.3 ft, respectively. With differences ranging from –4.1 to 4.5 ft.

Table 1. Real-time POS LS system error computed from ground survey stakes.

Run No.	Run Length (ft)	Stakes Visited (no.)	Total Time (sec)	Horizontal Error (ft)			Vertical Error (ft)			Combined Error (ft)			Time per Stake* (sec)		
				Avg.	Stdev.	Max.	Avg.	Stdev.	Max.	Avg.	Stdev.	Max.	Avg.	Stdev.	Max.
1	3732	20	6931	1.9	1.2	3.9	1.4	0.8	2.4	2.4	1.4	4.6	328	397	1912
2	2241	15	2496	1.7	1.2	5.2	1.4	0.9	2.8	2.2	1.4	5.7	162	127	529
3	3799	20	5201	2.4	2.1	5.8	2.6	1.6	5.4	3.7	2.5	7.1	256	198	893
4	2141	12	2553	1.9	1.1	3.7	2.0	1.8	4.6	2.8	1.9	5.4	207	137	522
5	2597	12	3103	3.5	2.2	6.9	1.1	0.4	1.6	3.7	2.2	7.0	259	208	797
6	957	7	1290	4.0	2.5	7.0	0.8	0.4	1.4	4.1	2.5	7.1	177	62	256
7	2237	12	2018	2.7	1.5	4.6	1.2	0.7	2.3	3.0	1.6	5.0	165	101	374
8	253	3	806	1.4	0.7	1.9	0.7	0.4	1.1	1.5	0.8	2.2	254	226	515
9	3486	17	3104	2.7	1.8	5.3	1.6	0.8	3.1	3.1	1.9	5.7	180	98	402
10	2239	13	2245	2.0	1.1	3.6	1.2	0.6	1.8	2.4	1.2	3.9	167	100	351
11	3739	19	3192	1.9	1.5	4.8	0.8	0.7	2.0	2.1	1.5	5.1	165	95	415
12	2239	12	1819	1.6	0.6	2.4	1.3	0.8	2.3	2.2	0.9	3.1	148	87	312
Weighted Avg., Stdev., Max. Error--all runs				2.3	1.6	7.0	1.4	1.0	5.4	2.8	1.8	7.1			

*Time spent collecting data at each stake and traveling to next stake.

Table 2. Post-processed POS LS system error computed from ground survey stakes.

Run No.	Run Length (ft)	Stakes Visited (no.)	Total Time (sec)	Horizontal Error (ft)			Vertical Error (ft)			Combined Error (ft)			Time per Stake* (sec)		
				Avg.	Stdev.	Max.	Avg.	Stdev.	Max.	Avg.	Stdev.	Max.	Avg.	Stdev.	Max.
1	3732	20	6931	1.1	0.6	2.6	0.3	0.3	0.8	1.2	0.6	2.7	328	397	1912
2	2241	15	2496	2.3	1.1	4.0	0.5	0.3	1.0	2.5	1.1	4.0	162	127	529
3	3799	20	5201	1.5	0.9	3.1	0.5	0.4	1.4	1.7	0.9	3.1	256	198	893
4	2141	12	2553	1.3	0.8	2.4	0.6	0.5	1.3	1.5	0.8	2.7	207	137	522
6	957	7	1290	0.9	0.4	1.4	0.2	0.2	0.5	0.9	0.3	1.4	177	62	256
7	2237	12	2018	1.2	0.9	2.6	0.2	0.2	0.7	1.3	0.9	2.6	165	101	374
8	253	3	806	0.4	0.2	0.6	0.1	0.1	0.3	0.4	0.2	0.6	254	226	515
9	3486	17	3104	1.3	1.2	3.4	0.3	0.3	0.8	1.4	1.2	3.5	180	98	402
10	2239	13	2245	0.9	0.6	1.8	0.3	0.3	0.9	1.0	0.7	2.0	167	100	351
11	3739	19	3192	1.5	1.1	4.0	0.4	0.3	1.2	1.6	1.1	4.0	165	95	415
12	2239	12	1819	1.3	0.8	2.5	0.4	0.3	0.7	1.4	0.8	2.5	148	87	312
Weighted Avg., Stdev., Max. Error--all runs				1.4	0.9	4.0	0.4	0.3	1.4	1.5	0.9	4.0			

*Time spent collecting data at each stake and traveling to next stake.

Table 3. Differences between LIDAR DTM and POS LS elevations while unit was in motion (excludes data collected while the POS LS unit was at rest.

Run (no.)	Total Points	Moving Points	Elevation Difference (LIDAR DTM elevation minus the POS LS elevation, ft)				
			Avg.	Stdev.	RMS*	Min.	Max.
1	4986	3111	0.6	1.0	1.2	-3.0	4.3
2	2324	1628	0.4	0.9	0.9	-2.7	3.9
3	4222	2649	0.8	1.1	1.3	-4.1	4.2
4	2345	1434	1.5	1.0	1.8	-1.8	4.0
6	1065	710	1.1	0.7	1.3	-1.5	3.1
7	1896	1309	0.8	0.9	1.2	-1.0	4.4
8	253	154	0.9	0.4	1.0	-0.1	1.7
9	2982	2113	0.8	1.0	1.3	-2.3	3.9
10	2079	1187	0.4	0.8	0.9	-2.0	3.6
11	3033	2159	0.8	0.9	1.4	-1.5	4.5
12	1660	1181	0.5	0.9	1.0	-1.4	3.3
Weighted Avg., Stdev., RMS, Max., Min. Difference--all runs			0.7	1.0	1.3	-4.1	4.5

*Root-mean-square difference between LIDAR and POS LS elevations

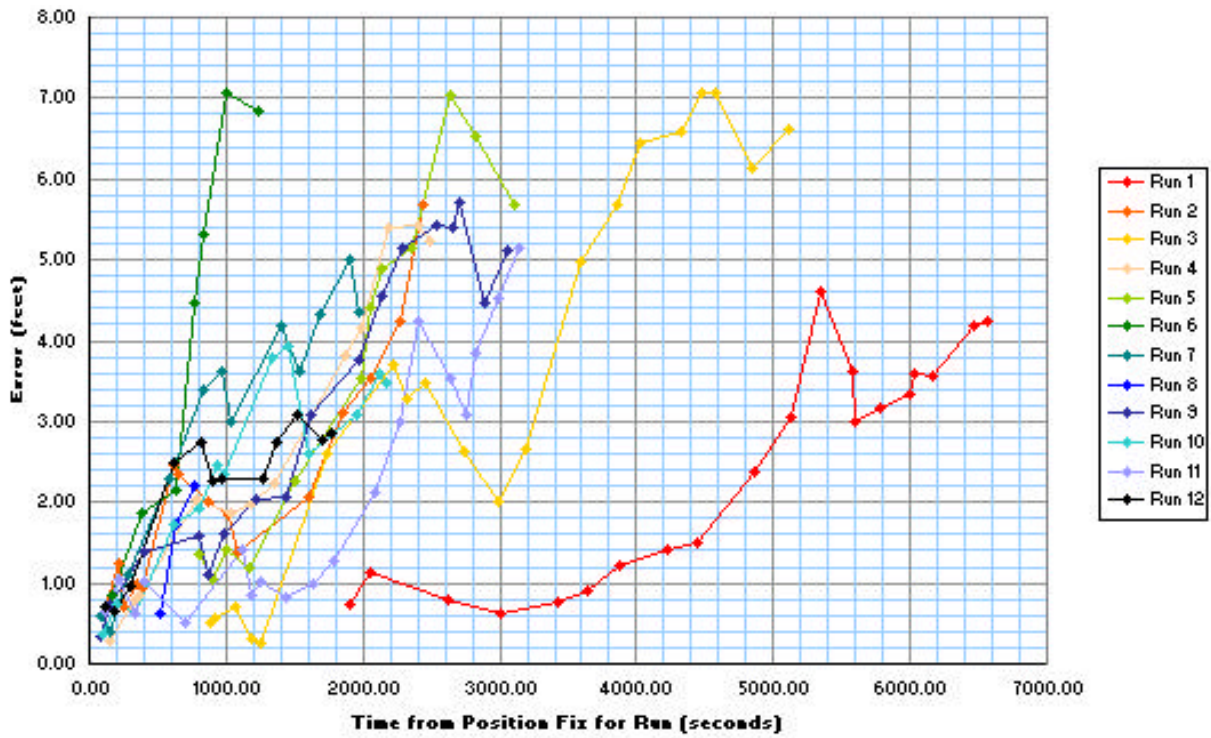


Figure 1. Real-time combined (horizontal and vertical) position error over time.

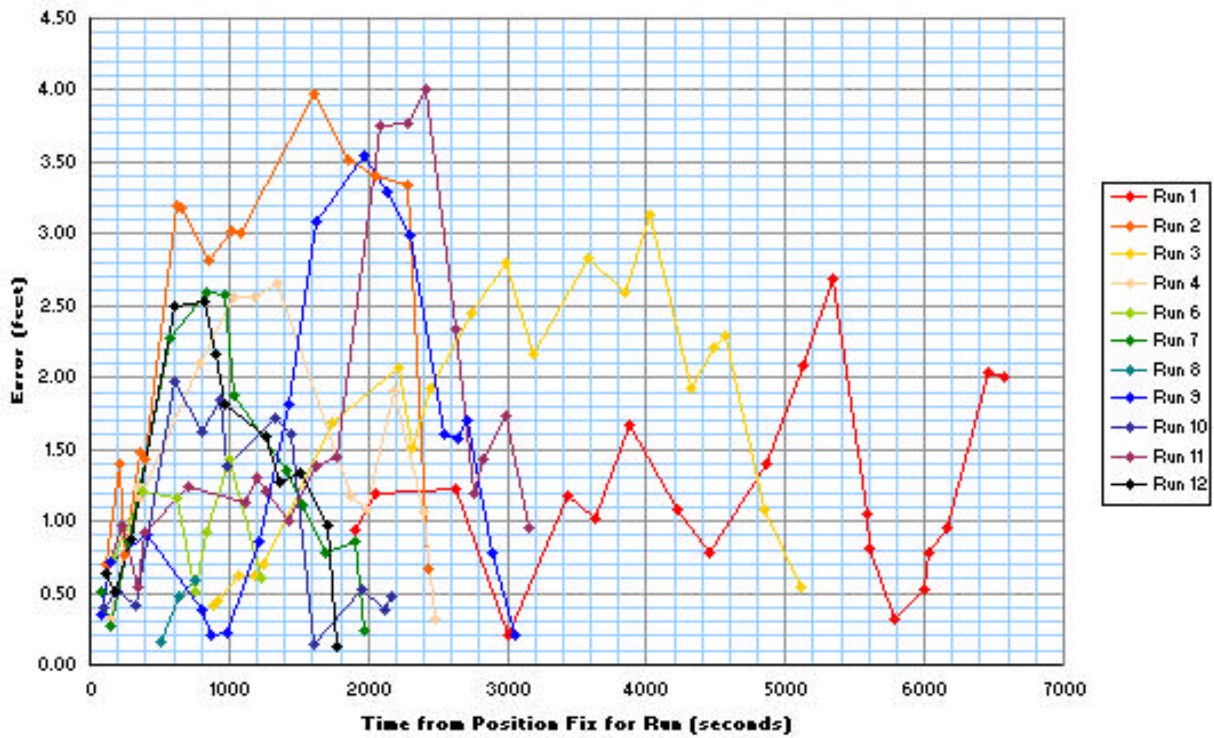


Figure 1. Post-processed combined (horizontal and vertical) position error over time.

DISCUSSION

Our tables and plots were developed to help evaluate the usefulness of the POS LS instrument in a forestry context, particularly in those situations where GPS is unreliable or known to be inaccurate. Three situations are of interest:

- 1) How well would the instrument serve as a tool for locating specific field coordinates—a plot center, for example, or the boundary points of a unit—in real-time?
- 2) How well would the instrument serve as a tool for collecting and post-processing coordinates to record, for example, an existing plot center or stream bed under a riparian canopy?
- 3) How well would the instrument serve as a tool for collecting and post-processing the coordinates necessary to define or evaluate a terrain profile or a digital terrain model in areas of dense canopy?

In the first situation, the operator would use the POS LS in a ‘real-time’ mode—out in the forest, using the real-time coordinate read-out to navigate. With the other situations, the operator would collect data and then post-process in the office to prepare an accurate coordinate file.

Both Table 1 and Figure 1 demonstrate typical error patterns in runs initiated at a known point and accumulated over time in the field. The total time lapse varies from 806 seconds (about 13 minutes) in Run 8, to 6931 seconds (almost 2 hours) in Run 1. The errors are generally dependent upon time, however, as is apparent in both Table 1 and Figure 1, there are exceptions. It does seem safe to expect a total vector error of less than 3 ft with a maximum error less than 8 ft for operations under 30 minutes in length.

Table 2 and Figure 2 show the results when the same data are post-processed. Generally, as is apparent from the results, one can expect the error to be cut by half—total vector errors less than 1.5 ft and maximums under 4 ft for a 30 minute operation.

Table 3 presents results in a format that should aid in our evaluation of the instrument’s potential for collecting data for a local DTM or linear profiles (stream, roads, trails, etc.). As mentioned above, the elevation difference statistics in Table 3 are based upon POS LS ‘moving points’ (17,635 points in total) compared to elevations interpolated from our LIDAR DTM. The DTM is gridded at 5 by 5 ft. Its accuracy was scrutinized closely and reported by Reutebuch, et al. (*in press*). The statistics in this LIDAR DTM evaluation were based upon the differences between the DTM and the elevations of a larger set of surveyed ground locations.

Using a subset of 121 points under the same portion of the forest canopy where this POS LS test was conducted, we computed a mean LIDAR DTM error of 1.02 ft, a standard deviation of 0.95 ft, and minimum, maximum error of -1.97 and 4.30 ft.

Clearly, the weighted means and standard deviations for the POS LS system (Table 3) are very comparable. As Reutebuch et al. (*in press*) make clear, the elevation differences are small and, most likely, can be attributed primarily to the smoothing effect of the DTM, the slight positive bias that was noted in the LIDAR DTM, the operator climbing over large logs, small random errors in the ground survey, and/or micro-topography of the actual forest floor.

CONCLUSIONS AND RECOMMENDATIONS

The POS LS does seem to have great potential in forestry. In an operating mode that is typical for forestry and, unimpeded by heavy canopy cover, the POS LS post-processed data are considerably better than that of a roving GPS instrument. This is true for its 'real-time' mode as well. Therefore, whether a forester is navigating to a point or preparing to record and later post-process coordinate data, the POS LS offers a considerable accuracy improvement over a roving GPS instrument. Currently, the unit is quite expensive and heavy compared to conventional GPS units. However, when accurate positions under heavy canopy were needed in the past, foresters have been forced to use more labor-intensive, expensive and heavy ground survey methods and equipment. And, as happened with GPS units, it is expected that both the cost and weight of the POS LS unit will decrease as the system is miniaturized in the future.

It is clear that ZUPTs are very important to the accuracy of the POS LS system, as they are the only means of compensating for IMU drift when reliable GPS signals are unavailable and known points are not nearby. However, ZUPTs will in some circumstances be an operational impediment—requiring the operator to stop too frequently and thus slow down progress of both navigation and data collection. The average time between ZUPTs in the runs of this test was 38.2 seconds, and the average time spent stopped for a ZUPT was 16.6 seconds. One can expect to erode the accuracy if the ZUPTs are less frequent; however, there are many operations in forestry where less accuracy would be acceptable. Therefore, we would recommend that a series of tests be designed to test the positional accuracy versus ZUPT

frequency relationship. There are certain to be many situations where this relationship will be of interest.

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