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Tetsuhiko Yoshimura · Hisashi Hasegawa

Comparing the precision and accuracy of GPS positioning in forested areas

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Abstract The objective of this study is to clarify the performance of the Global Positioning System (GPS) in forested areas after selective availability (SA) was turned off. In this study, we conducted a field test on horizontal and vertical positional errors of GPS positioning at different points in forested areas. The precision and accuracy of GPS positioning at different points were then calculated and compared. Furthermore, the effect of differential GPS (DGPS) on precision and accuracy was analyzed using analysis of variance (ANOVA), and the necessity for DGPS after SA was turned off was discussed. As a result, the largest horizontal precision errors were found to be in the plantation forest, followed by the natural forest and forest road. On the other hand, precision errors were smallest at the landing, around which there were no obstacles. Horizontal accuracy errors were greatly improved by using the DGPS. Large vertical precision errors were produced in the plantation forest, on the forest road, and in the natural forest, while those at the landing were much smaller. Vertical accuracy errors were also relatively small at the landing. In conclusion, tree canopies greatly affected precision errors, and the DGPS improved not horizontal precision but horizontal accuracy. The autonomous GPS is sufficiently useful for purposes in which horizontal positional errors of a maximum of 10 m are allowable. However, the DGPS should be used for surveying and mapping, for which higher accuracy is necessary.

Key words Accuracy · ANOVA · DGPS · GPS · Precision

T. Yoshimura (✉)
Biosphere Informatics, Graduate School of Informatics, Kyoto University, Kyoto 606-8501, Japan
Tel. +81-75-753-3131; Fax +81-75-753-3133
e-mail: yoshimu@bre.soc.i.kyoto-u.ac.jp

H. Hasegawa
Graduate School of Agriculture, Kyoto University, Kyoto, Japan

Introduction

The Global Positioning System (GPS) is a satellite-based navigational system designed and operated by the US Department of Defense for military and civilian use. There were difficulties in getting accurate positional data because of selective availability (SA), which degraded the signal available to nonqualified GPS receivers and introduced a positional error of about 100 m by dithering the time and ephemerides data provided in the navigation message for reasons of US national security. Therefore, the differential GPS (DGPS) had been used to improve positioning or navigation accuracy. However, SA was turned off a few minutes past 4:00 a.m. on May 2, 2000 (UTC). As a result, the horizontal positional error of the autonomous GPS was officially said to have been reduced to about 33 m (Assistant Secretary of Defense for Command, Control, Communications, and Intelligence 2000).

The objective of this study is to clarify the performance of the GPS in forested areas after SA was turned off. It is known that tree canopies adversely affect the accuracy of GPS positioning because they attenuate GPS signals. Many studies have shown the performance of the GPS and DGPS in forested areas. Martin et al. (2001) evaluated DGPS positional accuracy and precision on Irish forest roads with typical peripheral canopies and discussed the relationship between position dilution of precision (PDOP) and the percentage of open sky. This study also showed that both DGPS accuracy and precision improved with decreasing peripheral obstruction. Næsset (1999) showed that the accuracy of GPS positioning was significantly higher with the 12-channel GPS receiver than with the 6-channel GPS receiver and was significantly higher with the combined use of the C/A code and carrier phase than with the use of the C/A code only. Kobayashi et al. (2001) evaluated five GPS receivers' performance by comparing the positional accuracy of the autonomous GPS, real-time DGPS, and carrier phase GPS. Results indicated that the autonomous GPS and real-time DGPS produced positional errors of 15.4–48.6 m and 2.7–21.7 m, respectively, which were based on the condition that

SA was on. Sawaguchi et al. (2001) discussed the effect of stand conditions on positioning precision with real-time DGPS and found factors that affected positional precision by using multiple regression analysis. Mori and Takeda (2000) showed the effects of SA removal on positional accuracy of the DGPS. However, Sawaguchi et al. (2001) and Mori and Takeda (2000) partially discussed accuracy in forested areas under different peripheral conditions after SA was turned off. Many other studies were done when SA was on. In addition, almost all studies discussed only horizontal errors of GPS positioning but not vertical errors. In this study, we conducted a field test on horizontal and vertical positional errors of GPS positioning at different points in forested areas. Then the precision and accuracy of GPS positioning at these different points were calculated and compared. Furthermore, the effect of DGPS on precision and accuracy was analyzed using analysis of variance (ANOVA), and the necessity for the DGPS after SA was turned off was discussed based on the results of the field test.

Methods

GPS positioning

The study site was located on the mountain ridge forming the boundary of Kyoto University Forest in Wakayama, western Japan, at a latitude of 35°4′24.4″–31.6″N and a longitude of 135°31′47.3″–32′17.6″E (WGS-84) with an elevation of 1045–1112 m above sea level. Before starting the field test, the reference coordinate of each positioning point was determined as an average of fixed resolutions obtained by static surveying with dual-frequency GPS receivers.

The field test was conducted on August 25 and 26, 2000. The field test was conducted for 2 days only, because we are aware that ionospheric and atmospheric conditions that affect GPS positional errors change as time goes on. The base station (Trimble 4600LS) was set up where there were no tree canopies or other obstacles, and the rover (Trimble Pathfinder Pro XR) was set up at a landing, in a plantation forest, on a forest road, and in a natural forest (Fig. 1). At each point, GPS positioning was repeated four times using the rover. The observation period of each session was only 20 min, in order to repeat observations as many times as possible. Næsset (1999) analyzed positional accuracy by changing observation periods from 2.5 to 30 min. The observation period of 20 min falls within this range.

At the landing, the rover was set up under a completely open sky without any obstacles, such as trees or slopes; this point was a reference to compare the precision and accuracy of GPS positioning under different peripheral conditions. In the plantation forest, the rover was set up under canopies of Japanese cedars (*Cryptomeria japonica*) that were planted in 1958. The average tree height, average diameter (dbh), and stand density in the plantation forest were 17.0 m, 30.7 cm, and 1200 trees/ha, respectively. On the forest road, the rover was set up at a point 1.0 m from the

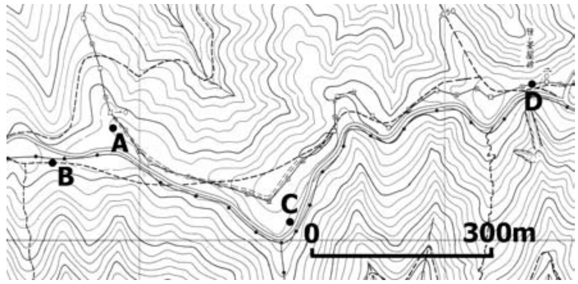

Fig. 1. Study site. *A* landing, *B* plantation forest, *C* forest road, *D* natural forest. The map was provided by the Kyoto University Forests

Table 1. Receiver settings

GPS receiver	PDOP mask	SNR mask	Elevation mask (°)	Logging interval (s)
Pathfinder Pro XR	20	0	15	5
4600LS	12	0	15	15

Table 2. Order of GPS positioning in the field test

Date	Times	Starting time	GPS positioning point
August 25, 2000	1	09:33:02	Landing
		10:12:51	Plantation forest
		10:52:07	Forest road
		11:38:57	Natural forest
	2	13:25:31	Forest road
		13:57:01	Landing
		14:35:41	Natural forest
		15:09:52	Plantation forest
August 26, 2000	3	09:26:57	Natural forest
		10:03:57	Forest road
		10:35:21	Plantation forest
		11:05:52	Landing
	4	12:32:52	Plantation forest
		13:13:17	Natural forest
		13:47:12	Landing
		14:26:26	Forest road

base of the cut slope. On the other side, there were some natural trees along the fill slope. The forest road was 5.5 m wide, and the cut slope was 5.2 m high. In the natural forest, the rover was set up under the natural forest canopy, which consisted of *Fagus*, *Carpinus*, *Parabenzoin*, *Acer*, etc. Table 1 shows the receiver settings used in this field test, and the order of GPS positioning is shown in Table 2. As shown in this table, eight observation sessions were conducted on each day, and observation time of each session was set to be almost the same between the two days. In addition, observation at each point was repeated at different times of the day because the geometric distribution of GPS satellites, which changes according to time, affects GPS positional errors. The number of visible GPS satellites during the field test is shown in Fig. 2. According to Fig. 2 and Table 2, this field test was done only when the number of available GPS satellites was equal to or more than 5. The GPS data were differentially corrected using Trimble Pathfinder Office, version 2.80, after GPS data were collected each day.

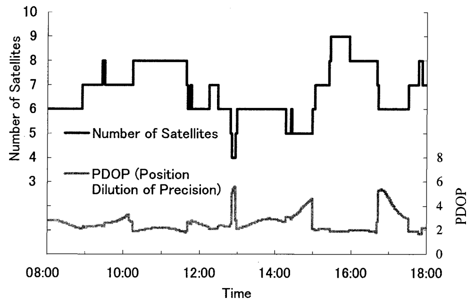

Fig. 2. Number of visible GPS satellites on August 26, 2000

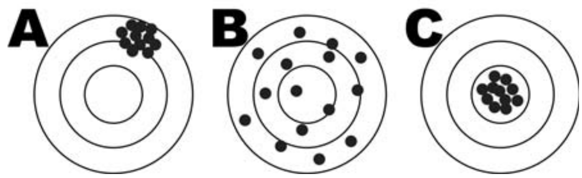

Fig. 3A–C. Precision and accuracy. **A** high precision and low accuracy, **B** low precision and high accuracy, **C** high precision and high accuracy

Horizontal positional errors

In this study, horizontal positional errors were calculated in terms of precision and accuracy. Accuracy refers to the closeness of the sample mean to the true value, and precision refers to the closeness of repeated observations to the sample mean. Precision and accuracy are briefly explained in Fig. 3A, B, and C, the centers of which indicate the true location. Points distributed in these figures indicate those measured using the GPS. Fig. 3A indicates high precision and low accuracy and, conversely, Fig. 3B indicates low precision and high accuracy. Fig. 3C indicates high precision and high accuracy.

In this study, horizontal precision was calculated and compared using the root mean square (RMS), which has 64%–77% probability (Leick 1995). The RMS is calculated by the following equation:

$$\sigma_{H\_precision} = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{1}$$

where $\sigma_{H\_precision}$ indicates RMS; σ_x and σ_y indicate the standard deviation of the positional error along the x and y axes, respectively, and are calculated by the following equations:

$$\sigma_x^2 = \frac{\sum_{k=1}^{n}\left(x_k - \bar{x}\right)^2}{n-1} \tag{2}$$

$$\sigma_y^2 = \frac{\sum_{k=1}^{n}\left(y_k - \bar{y}\right)^2}{n-1} \tag{3}$$

In Eqs. 2–3, n indicates the total number of epochs; x_k and y_k indicate the location of kth epochs along the x and y axes, respectively; $\bar{x}$ and $\bar{y}$ are the sample mean of the positional error along the x and y axes, respectively.

On the other hand, horizontal accuracy was calculated using the following equation:

$$\sigma_{H\_accuracy} = \sqrt{\left(\bar{x} - x_{true}\right)^2 + \left(\bar{y} - y_{true}\right)^2} \tag{4}$$

where $\sigma_{H\_accuracy}$ indicates horizontal accuracy; x_{true} and y_{true} indicate the true location along the x and y axes, respectively.

Vertical positional errors

Vertical positional errors were also calculated in terms of precision and accuracy as shown below:

$$\sigma_{V\_precision} = \sqrt{\frac{\sum_{k=1}^{n}\left(z_k - \bar{z}\right)^2}{n-1}} \tag{5}$$

$$\sigma_{V\_accuracy} = \left|\bar{z} - z_{true}\right| \tag{6}$$

where $\sigma_{V\_precision}$ and $\sigma_{V\_accuracy}$ indicate vertical precision and accuracy, respectively; $\bar{z}$ is the sample mean of the positional error along the z axis; z_{true} is the true location along the z axis.

Results and discussion

Horizontal positional errors

Horizontal precision at the landing, in the plantation forest, on the forest road and in the natural forest is shown in Table 3. As shown in the table, the largest precision errors were in the plantation forest, followed by the natural forest and forest road. On the other hand, precision errors were smallest at the landing, around which there were no obstacles. The larger precision errors were caused by degradation and/or interruption of GPS signals that traveled through tree canopies and by multipath errors that were caused by the reflection of GPS signals due to nearby structures in the plantation and natural forests, and on the forest road. According to the Table 3, it was also found that there were slight differences in precision errors between the autonomous GPS and DGPS.

Horizontal accuracy at the four positioning points is also shown in Table 3. According to this table, accuracy errors were greatly improved by using the DGPS. It should be noted that the DGPS improved accuracy errors at the landing more than on the forest road, in the plantation, and natural forests.

Vertical positional errors

Vertical precision and accuracy errors at the four positioning points are shown in Table 4. Large precision errors were

Table 3. Horizontal positional errors of precision and accuracy

GPS positioning point	Times	Precision (m)		Accuracy (m)	
		Autonomous GPS	DGPS	Autonomous GPS	DGPS
Landing	1	0.87	0.79	2.42	0.44
	2	0.15	0.21	5.35	0.09
	3	0.35	0.24	4.44	0.16
	4	0.34	0.22	6.67	0.18
Plantation forest	1	6.79	7.35	4.97	0.77
	2	4.39	4.30	3.26	1.38
	3	2.16	2.21	4.99	1.18
	4	4.96	3.74	6.19	1.92
Forest road	1	1.17	1.23	3.17	0.69
	2	4.35	4.39	6.11	5.02
	3	1.36	1.44	5.02	0.41
	4	1.34	1.22	6.72	0.55
Natural forest	1	2.99	1.57	2.95	0.51
	2	5.43	4.54	3.35	1.23
	3	2.88	3.29	6.23	0.91
	4	2.93	1.81	6.09	1.04

Table 4. Vertical positional errors of precision and accuracy

GPS positioning point	Times	Precision (m)		Accuracy (m)	
		Autonomous GPS	DGPS	Autonomous GPS	DGPS
Landing	1	0.48	0.12	3.54	0.38
	2	0.66	0.42	2.07	0.41
	3	0.56	0.31	1.90	0.85
	4	0.51	0.36	1.17	0.10
Plantation forest	1	7.63	8.16	6.36	8.59
	2	3.74	3.68	1.69	2.59
	3	6.25	6.04	1.10	2.96
	4	4.72	3.08	7.77	3.93
Forest road	1	4.20	4.06	3.27	4.08
	2	10.33	10.60	7.45	12.21
	3	3.51	2.75	1.35	2.14
	4	3.06	1.78	2.52	1.17
Natural forest	1	3.12	2.51	2.28	1.75
	2	7.25	6.29	7.20	7.68
	3	5.06	5.50	4.13	3.44
	4	4.59	4.24	1.37	3.79

produced in the plantation forest, on the forest road, and in the natural forest, while those at the landing were much smaller. Accuracy errors were also relatively small at the landing. The DGPS seems to have improved precision and accuracy errors only at the landing.

Factors affecting positional errors

ANOVA was used to clarify the effect of GPS positioning points and measurement methods on positional errors. In this analysis, the independent variables were the GPS positioning points, that is, landing, plantation forest, forest road and natural forest, and the GPS measurement methods, that is, autonomous GPS and DGPS. The dependent variables were positional errors. Tables 5 and 6 summarize the analyses of horizontal precision and accuracy, respectively, and Tables 7 and 8 of vertical precision and accuracy, respectively.

According to Table 5, horizontal precision among the GPS positioning points differed significantly ($P < 0.001$) but there were no significant differences among GPS measurement methods. The interaction effect of the two factors was also not significant. Therefore, horizontal precision differed according to the condition surrounding the rover receiver, and the DGPS did not improve horizontal precision. Conversely, horizontal accuracy differed significantly between the GPS measurement methods ($P < 0.001$) but not among the GPS positioning points (Table 6). The interaction effect of the two factors was also not significant. As a result, it can be concluded that the DGPS did not improve horizontal precision but did improve horizontal accuracy, and that horizontal accuracy was not greatly affected by conditions surrounding the rover receiver.

Table 5. Results of ANOVA for horizontal precision

Source of variation	Sum of squares	*df*	Mean square	*F* statistic	*P* value
GPS positioning point	72.24	3	24.08	11.53	<0.001
GPS measurement method	0.48	1	0.48	0.23	0.635
GPS positioning point × GPS measurement method	0.73	3	0.24	0.12	0.949
Error	50.11	24	2.09		
Total	123.56	31	26.89		

Table 6. Results of ANOVA for horizontal accuracy

Source of variation	Sum of squares	*df*	Mean square	*F* statistic	*P* value
GPS positioning point	4.29	3	1.43	0.74	0.538
GPS measurement method	118.03	1	118.03	61.07	<0.001
GPS positioning point × GPS measurement method	1.20	3	0.40	0.21	0.890
Error	46.39	24	1.93		
Total	169.92	31	121.80		

Table 7. Results of ANOVA for vertical precision

Source of variation	Sum of squares	*df*	Mean square	*F* statistic	*P* value
GPS positioning point	131.75	3	43.92	8.48	<0.001
GPS measurement method	1.04	1	1.04	0.20	0.658
GPS positioning point × GPS measurement method	0.05	3	0.02	0.00	1.000
Error	124.28	24	5.18		
Total	257.12	31	50.15		

Table 8. Results of ANOVA for vertical accuracy

Source of variation	Sum of squares	*df*	Mean square	*F* statistic	*P* value
GPS positioning point	51.19	3	17.06	2.10	0.127
GPS measurement method	0.02	1	0.02	0.00	0.957
GPS positioning point × GPS measurement method	9.63	3	3.21	0.39	0.758
Error	195.24	24	8.14		
Total	256.08	31	28.43		

Table 7 shows the results of ANOVA for vertical precision. Similar to results for horizontal precision, vertical precision differed significantly among the GPS positioning points ($P < 0.001$), while that between the GPS measurement methods did not. The interaction effect of the two factors was also not significant. Moreover, it was found that vertical precision was not improved by the DGPS. As shown in Table 8, vertical accuracy was not affected by either GPS positioning points or the GPS measurement method.

The main effects of the GPS positioning points on horizontal precision, the GPS measurement method on horizontal accuracy, and the GPS positioning points on vertical precision are shown in Figs. 4, 5, and 6, respectively. The positional errors of horizontal precision in the plantation forest were the greatest, followed by the natural forest, forest road, and landing (Fig. 4). This indicates that horizontal precision was greatly affected by tree canopies, especially in the plantation forest. As shown in Fig. 5, the DGPS greatly improved horizontal accuracy regardless of the GPS positioning points. According to Fig. 6, the positional errors of vertical precision in the plantation forest, on the forest road, and in the natural forest were much greater than at the landing. This result also indicates that vertical precision was greatly affected by tree canopies.

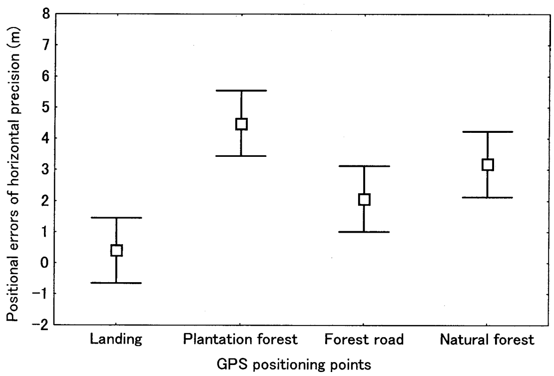

Fig. 4. Main effect of the GPS positioning point in horizontal precision with a 95% confidence interval

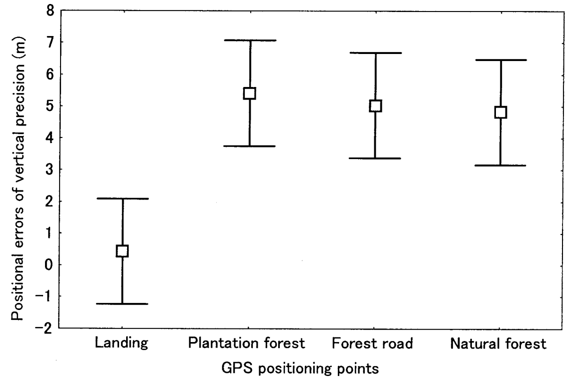

Fig. 6. Main effect of the GPS positioning point in vertical precision with a 95% confidence interval

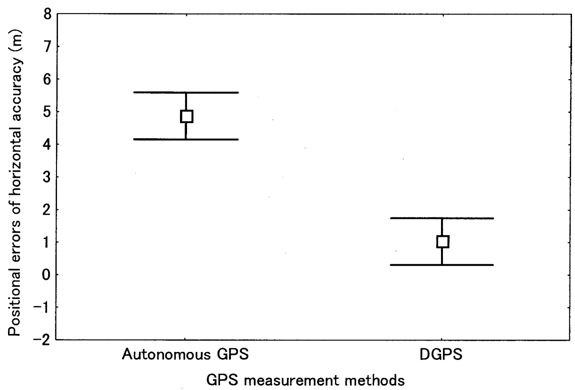

Fig. 5. Main effect of the GPS measurement method in horizontal accuracy with a 95% confidence interval

Conclusions

Our study showed that horizontal precision and accuracy of the autonomous GPS were 0.15–0.87 m and 2.42–6.67 m, respectively, at the landing, around which there were no obstacles, and that these errors were smaller than those in the plantation forest, on the forest road, and in the natural forest. For example, horizontal precision and accuracy errors of the autonomous GPS in the plantation forest were 2.16–6.79 m and 3.26–6.19 m, respectively. The cause of such large errors can be considered to be signal degradation and/or interruption when GPS signals travel through tree canopies. It should be noted that horizontal precision and accuracy errors on the forest road were larger than at the landing because the cut slope interrupted the GPS signals, and because it might have caused multipath errors at the same time. We also found that the DGPS, which was known to have been very effective in reducing positional errors before SA was turned off, did not improve horizontal precision but did improve horizontal accuracy. On the other hand, vertical precision and accuracy were affected by tree canopies or the cut slope, and were not improved by the DGPS except at the landing.

In summary, tree canopies greatly affected precision errors, and the DGPS improved not horizontal precision but horizontal accuracy. Therefore, the autonomous GPS is sufficiently useful for purposes in which horizontal positional errors of a maximum of 10 m are allowable. However, the DGPS should be used for surveying and mapping, for which higher accuracy is necessary.

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