Behavior of GPS Signal Interruption Probability under Tree Canopies in Different Forest Conditions

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Abstract

Global Positioning System (GPS) surveys were conducted over one year in four different forest environments in order to observe interactions between signal interruption probability (SIP), canopy opening index, observation period, number of available satellites and positional dilution of precision (PDOP). SIP showed larger correlation to positional errors than canopy opening index or PDOP, both horizontally and vertically, which contrast with some previous studies. An observation period of up to 15 minutes provided acceptable positional accuracy in correlation with SIP. Through indexes like SIP, canopy structure itself and signal behavior can provide a better understanding of accuracy in forestry.

Keywords: GPS, survey, canopy opening, signal interruption probability, accuracy.

Introduction

The Global Positioning System (GPS) is a satellite-based navigation system widely used in positioning and orientation in diverse fields and applications. In forestry, GPS has been used since its early stages, and today is an essential tool in the application and development of precision forestry. Major advantages of using GPS in forestry are the remote location of sites of interest, easier and faster topographic and forest surveys, route determination, road construction, and general navigation and positioning of forest workers and machinery. However, a factor limiting the reliable use of GPS in forestry is that the system was planned to be used in open sky situations with minimum interference. Tree canopies and trunks increase error and interfere with the reception of the signal broadcast by the satellites. Researchers have studied the problem with the aim of identifying the factors most strongly associated with this interference and providing better positioning and error estimates under tree canopies. Naesset and Jonmeister [2002] found that reduction of basal area as well as longer survey periods increase positional accuracy. Kobayashi et al. [2001] agreed and suggested the selective use of point positioning and differential GPS techniques to improve accuracy. Sigrist et al. [1999] concluded that even small increases in canopy closure can cause huge positional errors. Often in such studies, the canopy opening index is used to quantify the
canopy gap and calculate errors caused in positioning. This index is obtained by analysis of canopy photographs that determine the amount of visible sky [Holden et al., 2001]. Another factor cited as leading to positional errors is the positional dilution of precision (PDOP) or the satellite geometry at the moment of the survey. This geometry can be influential, depending on the terrain configuration and sky view. Martin et al. [2000] attributed errors under the canopy to PDOP, while Jiang et al. [2008] asserted that a better performance is obtained with longer periods of observation that result in lower PDOP values.

Proposed solutions for improving reception range from raising the antenna height [Gandaseca et al., 2001; Sawaguchi et al., 2003; Yoshimura et al., 2006], using translocation instead of point-positioning [Tsuyuki, 1994], and increasing the survey period [Yoshimura and Hasegawa, 2006]. Hasegawa and Yoshimura [2003] developed regression models based on the observation period and canopy opening, using the canopy photographs mentioned above. Later [Hasegawa and Yoshimura, 2007], they proposed the signal interruption probability (SIP) as a value indicating the GPS signal fragmentation due to forest conditions, specifically canopy interference. SIP can resolve ambiguity by predicting errors arising from signal fragmentation, but is more practical than the canopy opening index because it is calculated during post processing, without any need for photographs. A different method with similar approach was carried by Ordonez et al. [2011], having the canopy as main factor of influence but not defining one, but many variables as source of interference in positional accuracy.

In this study, we compare SIP, the canopy opening index, PDOP, and number of available satellites as factors determining positional accuracy under tree canopies. Based on previous studies, we designed a methodology for code phase measurements and code phase differential GPS post-processing techniques regarding horizontal errors and tridimensional errors. We focused on the results of float (non-fixed) solutions, which are more common in forest environments. We propose that SIP is more predictive of interference caused by the canopy than other indices and provides a stronger scientific basis for use in surveys under tree canopies.

**Methodology**

**Study site**

The field test was conducted at Kamigamo Experimental Station, Field Science Education and Research Center, Kyoto University (35°04′ N, 135°46′ E). The station has a history of degradation by forest operations, but its diversity of forest environments makes it an ideal site for comparative analysis. We specified four observation points, P1, P2, P3, and P4, in the station. Details of each point are presented in Table 1. Each point was chosen with the intent of simulating real forest operating conditions, and not for convenience of signal reception as usually recommended by manufacturers. Observation point P1 was located on a forest road (4 m wide) and afforded an “open sky” condition and control point. It was also located at the highest spot of the station (265 m above sea level) and was accordingly subject to all weather conditions such as wind, rain, and snow. P2 was located in a plantation of Japanese hinoki cypress (*Chamaecyparis obtusa*), an evergreen coniferous species with a canopy over 15 m high and highly fragmented visibility due to the characteristic foliage of cypresses. The canopy potentially increases multipath effects but is highly protective against wind. P3 was located on a deciduous strip of regenerating forest along the southern border of the station. This point is most subject to seasonal changes, with moderate to dense vegetation, a canopy reaching 12 m, and lies on a south-facing slope dominated by *Quercus serrata*. P4 is located
on an evergreen strip of forest near a forest road, with a steep (30°-45°) slope facing north; species here had high (up to 18 m) and dense canopies, with a gap caused by the forest road and buffering vegetation. Coordinates for each point were collected with a total station, referencing from several previously surveyed marks along the site.

| Observation Point | Condition                          | Main Obstacle for Reception | Mean Canopy Opening Index (%) |
|-------------------|------------------------------------|-----------------------------|-------------------------------|
| P1                | Forest road, open sky              | None                        | 79.1                          |
| P2                | Coniferous plantation              | Closed canopy               | 20.8                          |
| P3                | Deciduous regeneration forest      | Closed canopy               | 28.7                          |
| P4                | Evergreen forest                   | Closed canopy and cut slope | 15.9                          |

**Data collection**

GPS surveys were performed every two months between August 2009 and June 2010 with a total of 6 surveys. Every observation point was surveyed for one hour with the antenna set at 5 m height to avoid interference from nearby shrubs, people, and vehicles. The total number of surveyed hours was of 24 hours, logging at 1Hz (1 epoch per second) rate. To set the antenna, a telescoping pole provided by researchers of Kyoto University was used. The pole was fixed to a tripod for stability and to level the antenna center as well as possible. In order to receive the same satellites every day of the survey, we scheduled the data acquisition according to the satellite orbit periods (4 minutes earlier everyday) as shown in Table 2. In case of rain or snow, the survey would be adjourned for the next day with the proper time correction.

| Day 1   | Point | Day 2   | Point | Day 3   | Point | Day 4   | Point |
|---------|-------|---------|-------|---------|-------|---------|-------|
| 10:00   | P1    | 09:56   | P2    | 09:52   | P3    | 09:48   | P4    |
| 12:00   | P2    | 11:56   | P3    | 11:52   | P4    | 11:48   | P1    |
| 14:00   | P3    | 13:56   | P4    | 13:52   | P1    | 13:48   | P2    |
| 16:00   | P4    | 15:56   | P1    | 15:52   | P2    | 15:48   | P3    |

Prior to each survey, hemispherical pictures were taken to calculate the canopy opening index for each point, giving a clear image of seasonal changes and visible sky. Table 3 shows these changes over time. The camera used was a Nikon Coolpix 995 with a hemispherical fisheye lens (Nikon, Japan), and the remote shutter trigger was controlled by the open-source software Krinnicam 2.02 (available at http://www.softpedia.com/get/Multimedia/Graphic/Digital-Photo-Tools/krinnicam.shtml). The canopy opening index for each picture was calculated using the hemispherical-photograph-processing software Gap Light Analyzer (GLA) 2.0 [Frazer et al., 1999] to determine the percentage of visible sky on each point. Figure 1 shows the hemispheric photographs for each point at 5 m height to give the same panorama as the GPS antenna that was analyzed.
Table 3 - Canopy opening changes over one year at 5 m height.

| Observation Point | Canopy Opening Index (%) - 2009/2010 |
|-------------------|--------------------------------------|
|                   | August | October | December | February | April | June |
| P1/Open sky       | 80.1   | 79.2    | 79.3     | 78.7     | 77.9  | 79.8 |
| P2/Coniferous     | 20.3   | 23.2    | 19.4     | 18.2     | 21.7  | 22.1 |
| P3/Deciduous      | 17.8   | 19.2    | 38.6     | 41.1     | 36.2  | 19.2 |
| P4/Evergreen      | 11.4   | 25.5    | 15.1     | 17.1     | 14.5  | 11.1 |

Figure 1 - Hemispheric pictures taken at surveying spots at 5 m height, September 2009.

The receiver used as the rover was a Leica GPS model SR530 (Leica Geosystems, Heerburg, Switzerland), with differential capabilities (DGPS), receiving both L1 and L2 frequencies of the GPS signal through an external choke-ring antenna and an extension cable. This model has 12 channels for each frequency (L1 and L2) and is specified by the manufacturer to have an accuracy of 3 mm + 0.5 ppm of baseline distance in long-term observations. The reference station was a Trimble GPS Total Station (model 4700, Trimble Navigation Ltd., Sunnyvale, USA) a 9-channel-per-frequency receiver station with DGPS capabilities and 5 mm + 1 ppm accuracy for static surveys. The elevation mask of the rover was set at 10 degrees.

Baseline analysis
To calculate errors in the coordinates acquired by the rover within the station data, we first divided the 1-hour observation data into two sets of 30 min each and extracted smaller periods of 1, 5, 15, and 30 min for the first half-hour and a repetition of the same periods for
the second half-hour. The position of each point was then calculated by baseline analysis using three types of data classified by GPS frequencies: L1, L1 + L2, and code phase data (C/A code extracted from the L1 frequency), allowing us to observe the difference between each data point of each frequency acquired at the same time. We used the proprietary software Leica Geo Office 6.0 for this analysis and RINEX files to work with both rover and station files, given the differences between the original file types. The elevation mask was set at 10° to capture satellites just above the antenna to avoid interference from nearby trees and branches and avoid receiving signals from satellites positioned at lower angles; these satellites are subject to higher errors of multipath and signal interference. Finally, the horizontal and three-dimensional errors were calculated using the following equations:

For horizontal errors:

$$E_{2D} = \sqrt{(x - xt)^2 + (y - yt)^2} \quad [1]$$

and for three-dimensional errors:

$$E_{3D} = \sqrt{(x - xt)^2 + (y - yt)^2 + (h - ht)^2} \quad [2]$$

where $xt, yt,$ and $ht$ are the true coordinates acquired by total station surveys at their respective observation points. For every observation, both values were calculated with the aim of identifying errors present even after post-processing.

**Signal Interruption Probability**

SIP can be defined as the percentage of interruption that a signal suffers in a determined period of time or the fragmentation of the GPS signal over an elapsed time of $t$ min. The following formula is used to obtain SIP:

$$P_k = \frac{\sum_{i=1}^{k} (i \times N_i)}{\sum_{i=1}^{k} (i \times N_i)} (1 \leq k \leq K) \quad [3]$$

where $P_k$ is the cumulative probability $P$ of signal reception in $k$ continuously received epochs divided by the total of received epochs for each satellite $K$; we can obtain the values for SIP as the amount of time representing the percentage of interrupted signal. In brief, lower values of SIP indicate lower signal fragmentation, whereas values close to 1 (100%) indicate a high-interference condition. In $k$ epochs there is a probability $P$ that the signal will be disrupted by a satellite loss-of-lock or signal loss due to interference. To calculate SIP for every observation period for every survey for all the observation points, we first obtained the raw data from the rover for the entire observation period of 1 h and divided it into the same intervals used in the baseline analysis (1, 5, 15, and 30 min). We generated a new RINEX file for each smaller period of time (8 files per hour of observation for each point observed) and calculated the SIP for every minute of observation using SIPCalc, an application developed
by Hisashi Hasegawa for his original SIP research and updated to read RINEX files. Results from SIPCalc are transferred to text files and can be used in standard spreadsheet software. SIP calculations consider the number of total signals received continuously over the total number of epochs for that observation period. We set the receivers, both rover and base station, to log one epoch per second, so our SIP results were calculated for 60, 300, 900, and 1800 epochs, respectively, twice per hour including repetitions.

**Results and Discussion**

**Mean errors**

Table 4 and 5 show the average horizontal and vertical errors, respectively, for the surveys. We present here the mean errors per solution type: fix, when there is enough information to resolve ambiguities of coordinates, and float, when the information is insufficient to determine an accurate coordinate. By separating the results based on data type we can verify which solution type provides more stable results. With longer observation periods, errors tend to decrease [Wing et al., 2005; Andersen et al., 2009], but this is not the case for fix data under canopies, as is shown for observation points P3 and P4, both located in lower areas and facing slopes, respectively. This behavior can be seen in a similar form in the work of Yoshimura and Hasegawa [2006] where longer periods of time did not necessarily reduce positional errors in similar conditions. Errors in fix solutions for this study are higher than those in the work of Hasegawa and Yoshimura [2007]. We attribute this difference to the location of the antenna in a higher and less stable position because of the telescoping pole, preventing the antenna center from being placed in the exact center of the point mark.

**Table 4 - Mean horizontal errors.**

| Observation Point | Observation Period (min) | L1(fix) | # of Fixes | L1(float) | # of Float | L1+L2 (fix) | # of Fixes | L1+L2 (float) | # of Float | Code |
|-------------------|--------------------------|---------|------------|-----------|------------|-------------|------------|--------------|------------|------|
| A1                | 1                        | -       | -          | 0.328     | 12         | 0.132       | 12         | -            | -          | 0.087 |
|                   | 5                        | 0.095   | 2          | 0.432     | 10         | 0.132       | 12         | -            | -          | 0.134 |
|                   | 15                       | 0.131   | 12         | -         | -          | 0.133       | 12         | -            | -          | 0.082 |
|                   | 30                       | 0.130   | 11         | 0.148     | 1          | 0.132       | 12         | -            | -          | 0.118 |
| C1                | 1                        | -       | -          | 0.751     | 12         | -            | -          | 0.800        | 12         | 1.032 |
|                   | 5                        | -       | -          | 0.820     | 12         | -            | -          | 0.712        | 12         | 0.838 |
|                   | 15                       | -       | -          | 0.584     | 12         | 0.285       | 2          | 0.604        | 10         | 0.788 |
|                   | 30                       | 0.378   | 2          | 0.666     | 10         | 0.219       | 2          | 0.944        | 10         | 0.562 |
| D1                | 1                        | -       | -          | 0.661     | 12         | 0.298       | 3          | 0.632        | 9          | 0.466 |
|                   | 5                        | -       | -          | 0.507     | 12         | 0.207       | 6          | 0.467        | 6          | 0.539 |
|                   | 15                       | 0.086   | 1          | 0.454     | 11         | 0.201       | 9          | 0.565        | 3          | 0.686 |
|                   | 30                       | 0.138   | 5          | 0.403     | 7          | 0.226       | 12         | -            | -          | 0.567 |
| E1                | 1                        | -       | -          | 0.732     | 12         | 0.177       | 1          | 0.867        | 11         | 1.039 |
|                   | 5                        | -       | -          | 0.653     | 12         | 0.148       | 2          | 0.625        | 10         | 0.802 |
|                   | 15                       | -       | -          | 0.650     | 12         | 0.221       | 5          | 0.759        | 7          | 0.578 |
|                   | 30                       | 0.404   | 4          | 0.821     | 8          | 0.214       | 9          | 0.951        | 3          | 0.568 |
Nevertheless, it is important to examine the behavior of float and code solutions, since they reflect the majority of results obtained in surveys in forested points. Other factors involved, such as the elevation mask used, PDOP numbers, canopy opening, and the surrounding forest, can also interfere with the signal lock and cause positional errors even within long observation periods. This interference can be well visualized in the number of fixed signals obtained on the L1 band for all of the points and the error sizes for float solutions in both bands. The expected behavior of the results with longer observation periods and smaller positional error is not present in all the forested points, possibly due to multipath signal mitigation for points with denser canopies and signal loss-of-lock.

Table 5 - Mean tridimensional errors.

| Observation Point | Observation Period (min) | L1(fix) # of Fixes | L1(float) # of Floats | L1+L2 (fix) # of Fixes | L1+L2 (float) # of Floats | Code |
|-------------------|--------------------------|-------------------|-----------------------|-------------------------|---------------------------|------|
| P1                | 1                        | -                | 0.578                 | 12                      | 0.134                     | 0.123 |
|                   | 5                        | 0.097            | 2.482                 | 10                      | 0.134                     | -    |
|                   | 15                       | 0.133            | 12                    | -                       | 0.135                     | -    |
|                   | 30                       | 0.132            | 11                    | 0.148                   | 1                         | 0.134 |
| P2                | 1                        | -                | 2.055                 | 12                      | -                         | 1.711 |
|                   | 5                        | -                | 1.012                 | 12                      | -                         | 1.044 |
|                   | 15                       | -                | 1.287                 | 12                      | 0.405                     | 2    |
|                   | 30                       | 0.396            | 2                     | 3.818                   | 10                        | 2.540 |
| P3                | 1                        | -                | 0.927                 | 12                      | 0.344                     | 9    |
|                   | 5                        | -                | 0.775                 | 12                      | 0.286                     | 6    |
|                   | 15                       | 0.189            | 1                     | 0.521                   | 11                        | 0.633 |
|                   | 30                       | 0.217            | 5                     | 0.481                   | 7                         | 1.138 |
| P4                | 1                        | -                | 1.141                 | 12                      | 0.224                     | 1    |
|                   | 5                        | -                | 1.262                 | 12                      | 0.486                     | 2    |
|                   | 15                       | -                | 1.066                 | 12                      | 0.708                     | 5    |
|                   | 30                       | 1.727            | 4                     | 1.189                   | 8                         | 1.003 |

Correlations between positioning errors and SIP

Considering the data for float and code solutions (Figs. 2a-d), SIP is more relevant than the other factors, with the exception of canopy opening in horizontal errors using code phase solutions. This can be explained by the modular nature of the values presented here, since in all analyses the canopy opening index resulted in a negative correlation with positional errors and SIP. We concentrate on float and code errors because these are the errors often present in forest surveys. Our results show that the canopy opening index alone may not be the best option for evaluating GPS performance in forests. Also, in practical terms SIP can be calculated during the post-processing step of the survey and requires no more than software and GPS data, so that this choice is much easier to implement in the field. We conclude that in GPS analysis, SIP is an evolution of the canopy opening index that affords a more practical solution with stronger relevance for predicting errors and understanding the canopy structure without the need for hemispheric photographs.
Another factor from which SIP evolves directly is the observation period. As shown in Table 4 and Figure 2, longer periods of observation do not necessarily improve accuracy, which is in accordance with previously demonstrated mean error analysis. SIP values (SIPt) in the period of 15 min of observation appear to define the ideal period of observation time for static surveys and forestry operations. It is also an acceptable amount of time (for the current technology and/or high-precision demands), either for establishing a temporary station for a short survey or for defining boundaries with high accuracy, always considering the demands of each situation. SIP varies depending on the forest environment, while at the forest road (P1) point these variations were short; higher interference patterns are present in conifer plantations (P2). This difference can be explained by the highly fragmented canopy of the Japanese hinoki cypress and its uniform trunk distribution on the plantation, a strong source of multipath and signal fragmentation. Deciduous environment (P3), being a regenerating area also causes high levels of multipath and poor reception, as does Evergreen forest (P4) which has the presence of tall trees with thick trunks.

**Conclusions**

In this study we analyzed data from one year of surveys to determine the fragmentation of GPS signal under tree canopies as a more predictive factor than the previously employed canopy opening index and PDOP. SIP is the index of this fragmentation and can be easily obtained during post-processing or, in the future, on-site if integrated with the receiver’s algorithms. Mean errors in surveys do not necessarily decrease with longer observation periods, and in that aspect SIP also appears strongly indicative of the ideal amount of time necessary to obtain better data. We recommend observation periods of between 10 and 15
min whenever possible in under-canopy conditions if post-processing is being used. Given that we found that satellite-related factors such as PDOP are not predictive as previously stated, further investigations should be focused on the canopy itself as the main source of errors and signal fragmentation, as previously observed in a number of studies conducted both during and after the Selective Availability era. Future studies aiming to decrease the time needed to obtain better signal and the modernization of the GPS itself will improve accurate positioning inside forests.

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