ANALYSIS OF SIGNAL INTERRUPTION PROBABILITY FOR GNSS UTILIZATION IN FOREST CONDITIONS

ALEX SOUZA BASTOS

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1 Introduction

1.1 Problem Identification

The Global Positioning System (GPS) is a satellite-based navigation system widely used today in diversified fields, from military to recreational. Even though created in the 1970's and passed through several stages of modernization, the system still presents certain limitations when it comes to forestry work. Being developed to open-sky conditions, the GPS broadcast signal is disrupted by vegetation or any other direct obstacles, which compromises the accuracy of the coordinates obtained. Although GNSS equipment have been widely introduced and utilized in many forest works, obtained raw coordinates by GNSS are used without enough verification of error, which at large scales can lead to incorrect zoning and at small scale limits the dynamic of forest work in a more efficient, fast and cost-benefit methodology. This error management is, presently, hard to achieve with user-level receivers and lack of technical knowledge. In that sense, forest researchers have been studying for years how to increase accuracy, developing alternative techniques and implementing remote sensing tools especially focused on forest work. Studies such as the Signal Interruption Probability (SIP), which provides information about the signal behavior under tree canopies and characterizes the canopy structure, can be applied in a user-friendly interface to aid the average surveyor in order to evaluate the quality of surveys and assess information about the forest structure. If error management of GNSS coordinates would be achieved by using SIP and/or other techniques of error management, usability of GNSS would be increased also in forested areas and could be an important enhancement on field work, industry, research and conservation, benefiting all forested-related issues which deal with remote sensing and positional information. Furthermore, SIP has a great possibility to estimate stand information because obstacles which interrupt GNSS signal reception are mainly tree stems and large branches under tree canopies, as found in many studies over the years of GNSS availability for civilian users, in a progressive network of forest-oriented studies by researchers worldwide.

This study explores the under-canopy signal reception, specifically, the signal interruption probability and other factors that affect positional accuracy in the forest. We present references that explored the issue before in different perspectives with diversified results and explore our own assumptions about the problem, based on previous knowledge from these references as well as the exploration of new ideas. The main objective is to clarify the how much the signal is affected by the forest structure, specially the canopy and which results can we obtain or expect from surveys realized under forest conditions.

Another objective of this study is to observe the behavior of the GPS associated with other remote sensing technologies. GLONASS, the Russian satellite navigation system became widely used in the recent years and its usage improves greatly the dynamics of remote sensing. LIDAR data, the laser scan technology which provides tridimensional maps is being used for long now in forestry, providing detailed information about forest structure otherwise obtainable only through laborious and time-demanding techniques. To make use of these tools, which are becoming more available and less onerous with the advances of technologies is a must-do for foresters and researchers in general, which allows a better understanding of the forest dynamics and characteristics, and better planning for forest work and decision making concerning the use of natural resources.

The main objective of this research is to provide enough information about SIP and improve its scientific basis, as well as other related factors that can be used in further studies and development, in order to improve the forest work and research in a more economically viable, technologically advanced and ecologically efficient system.

1.2 Literature Review

The necessity to obtain positioning with accuracy date as far as the time of the first navigations, when the need to go further from the coast brought up the navigation through stars, dead reckoning, the study and development of the latitude and longitude concepts, nautical instruments and more reliable maps. Although many centuries were necessary to achieve such technologies, with the invention of the radio, men developed in less than a century the technologies nowadays called remote sensing. Military and communication purposes being the great influence in this fast advance and the fast-paced political events of the 1900s allied to the development of the information technologies, brought what it is today the state-of-art of positioning, being the Global Navigation Systems the most reliable and used systems for positioning and decision making.

1.2.1 Global Navigation Satellite System – GNSS

Satellite-based navigation system is a method that provides geo-spatial position based on signal reception of orbital satellites using time signals. If a satellite based system provides global coverage, it is called a Global Navigation Satellite System or its acronym, GNSS. As of May, 2013, the only GNSSs fully operational are the United States NAVSTAR-GPS and Russia’s GLONASS. Satellite-based navigations date back to the times of the cold war period (1960s to 1980s) when military development raised in face of possibly treats to national security, especially in the U.S. and former Soviet Union. With the release of first artificial satellite, the Sputnik-1 by the Soviet Union, researchers at the Applied Physics Laboratory of the

John Hopkins University noticed that the satellite signal was Doppler shifted as results of the satellite motion, which allowed to locate the satellite position in orbit. From these studies, the Transit system was developed in the U.S. following the Doppler principles which became the precursor of the GPS system and the first satellite navigation system.

Complementary to GNSSs are the Augmentation Systems or Satellite Based Navigation Systems (SBAS), which include the Wide Area Augmentation System (WAAS, North America), European Geostationary Navigation Overlay Service (EGNOS), Multi-functional Satellite Augmentation System (MSAS, Japan), Differential GPS and Inertial Navigation Systems. These systems are usually based on ground stations collecting GNSS information and verifying it, resending to satellites so it can be used by end-users, or comparing data to apply correction in the called post-processing software. We provide in this chapter a brief description of all these systems and how they work and are applied.

1.2.2 Global Positioning System

To replace and improve the Transit and other existent system, the U.S. Department of Defense (DoD) started developing a new system in the early 1970’s with the primary objective to fulfill military needs. The first GPS satellite was launched in 1978 and the system reached full operational capability status in 1995. Initially the system had an intentional degradation on its signal for civilian users, the called Selective Availability (S/A), during that period only military personal had access to the high quality signal and the precision positioning. In the year 2000, by order of former U.S president Bill Clinton, the S/A was turned off and the civilian GPS precision improved from 100 to 20 m. Since it became available to civilians and specially after the S/A, technological advances made the system widely available for the general population and with the advent of less bulky and more user-friendly receivers and integrated devices, GPS is now a known and accessible tool for anyone at anytime, anywhere.

1.2.3 Principles and aspects of GPS system

Satellite navigation, in general, follows the principles of trilateration, where a point can be located relative to other points with known coordinates, if the distance to these points can be measured or estimated. However, trilateration provides position based on distances from these fixed points while satellites are moving in the space. In order to locate a point with satellites information, the time factor is necessary.

A GPS receiver calculates its position based on the information received by the broadcast signal of each satellite available at that moment. Satellites of the GPS system are continuously transmitting the time the message was broadcast and their own position at the time of the transmission, the ephemeris. With that information, receivers are able to pinpoint their own location at that moment (Fig 1).

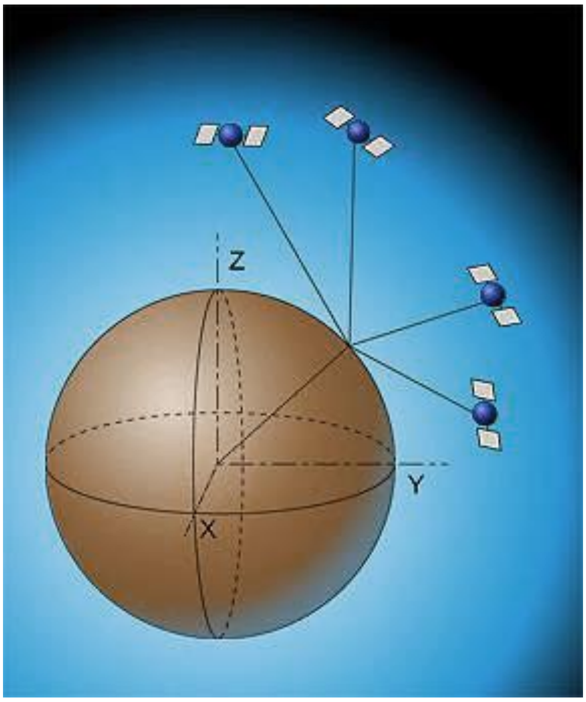


Fig 1 Simple representation of GPS location based on satellites coordinates relative to the center of the Earth (http://eoedu.belspo.be/en/guide/gps.asp)

The satellites in the GPS are part of the Space Segment, which count in number of 32 Space Vehicles (SVs) at the time of this study (USNO, 2013). The basic design positions 24 SVs in six orbitals planes on an elevation of 55 degrees relative to the equator, which provides extensive coverage for the entire planet, with the exception of higher latitudes, where the satellites appear to be on the horizon height. Satellites can be visible anywhere in the world, anytime and under any weather conditions, given that the sky is visible to the receiver and no direct obstructions block the reception. The extra satellites function as backup units and provide more precision to receivers with redundant measurements At the moment, 9 satellites are visible from any place in the planet. The Space Segment is controlled by the Control Segment, constituted by a master control station, an alternate master control station, four dedicated ground antennas and six dedicated monitor stations. The Control Segment monitors, correct and updates satellites orbits and health and can activate or deactivate a satellite for maintenance.

The User Segment is constituted by the thousands of military receivers and millions of civilian receivers making use of the satellites broadcast data. GPS receivers available for civilians are in numerous configurations, ranging from recreational models to high-end, survey-oriented devices. The accuracy desired usually dictates the price of a device, with a simple logger costing several dozens of dollars (precision >10 m) and a high-end model in the tens thousands of dollars (precision in mm). Advances in technology brought the

GPS to mobile phones, with the assisted positioning provided by the cellular network, which was successfully tested by Qualcomm in 2004 and since then incorporated in a number of devices. Other common usage became the aided road navigation in cars. Military receivers are exclusive and have encrypted access to the military frequencies of the GPS, reaching much higher precisions.

GPS satellites use Code Division Multiple Access (CDMA) transmission method, which allows multiple users to receive the signal without degradation despite the number of receivers active, similar to television and radio broadcasts. The frequencies used by GPS satellites are mainly 1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal), with each satellite identifying itself on its transmitted message through codifications unique to each satellite that the receivers must be aware of in order to capture the data. L1 and L2 are the frequencies most commonly used by civilians, with the recently added L5 signal at 1.17645 GHz. Other frequencies are used by military personel or are being studied to different purposes. Messages transmitted by the satellites to the receivers include information about the satellite health, GPS time, satellite position at the time of the transmission, the *ephemeris* or satellite orbit, and the almanac – the information of coarse orbit and status of the 32 satellites. Another important factor on the technical aspects of satellites is the orbit duration: a GPS satellite takes 11:58 to complete orbit around the planet, which means the same satellite can be seen passing through the same point 4 minutes earlier everyday.

1.2.4 GLONASS

The Russian Global Navigation Satellite System – GLONASS, acronym of *Globalnaya Navigatsionnaya Sputnikovaya Sistema* is an alternative and complement to the GPS, it was developed in the late 1960s and completed on the late 1970s, however with the political disturbances caused by the fragmentation and end of the Soviet Union in the 1980s, the system reached full operational status only by 1995 and was recently renewed and efforts to maintain and modernize the system are kept by the Russian government. As GPS, GLONASS is a GNSS and the only system at the moment that can also provide global coverage. In a similar design, the satellites are in three orbital planes with 8 satellites on each but at a higher elevation, 64.8 degrees, which provides better coverage at higher latitudes (north or south) where GPS satellites are harder to receive. Differently from GPS, GLONASS satellites utilize frequency division multiple access (FDMA), where each satellite transmits a different unique frequency with added variation based on the L1 band at 1602.0 MHz. This approach identifies each satellite by its transmitted signal, rather by its transmitted encoded message. As the GPS, GLONASS also relies on ground control stations to maintain its satellites in correct orbit and verify their health. The orbit of the satellites of GLONASS is also shorter than the GPS, 11 hours and 15 minutes. With the modernization the system and political agreements between their respective countries, GLONASS and GPS became interoperable and many receivers are now produced with the advantage of capturing both systems satellites, which gives superior coverage, faster fix possibilities and better reception in urban canyons and other environments where GPS alone might be difficult to acquire.

1.2.5 Augmentation Systems

Augmentation systems provide auxiliary information and improve (augment) the accuracy, reliability and availability of GNSSs by the usage of other satellites or ground stations. Airports and aircrafts make use of the Wide Area Augmentation System (WAAS) and of the Satellite Based Augmentation System. The ground stations on the WAAS receive GPS information, correct and resend it in GPS-like signals to users. SBAS is constituted of geostationary satellites that receive GPS corrected information form ground stations and resend it to the surface, providing a higher quality of information. Similar system is used in other countries, such as the European Geostationary Navigation Overlay Service (EGNOS) and Multi-functional Satellite Augmentation System (MSAS, Japan). Also in Japan, the Quasi-Zenith Satellite System (QZSS) is already operational with the first satellite of three orbiting and providing coverage to great part of the Asia. Fig 2 shows the MSAS system as example of augmentation system.

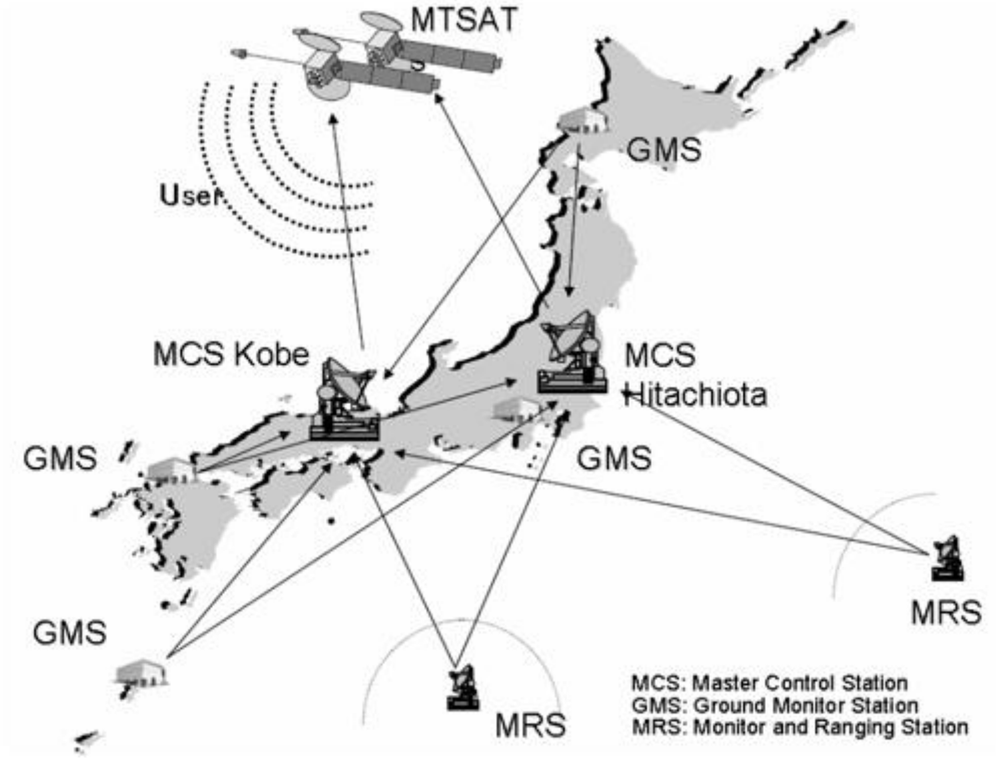


Fig 2 Japan’s MSAS Augmentation system (http://www.navipedia.org/index.php/MSAS_Ground_Segment)

On a local level, surveyors can use Differential GPS (DGPS) a technique in which one receiver is used as base station, located on a spot less prone to interference and another receiver; the rover acquires positions on the desired locations. Later the data of both receivers is compared and corrected based on the data of the base station. In some cases, both receivers keep a communication link through radio modems and correct the data on-the-fly.

1.2.6 GNSSs in forestry

GNSSs, mainly GPS, are widely used in forestry since its early stages. Even through the time of S/A, GPS allowed users to realize large area measurements faster than by traditional survey with an acceptable margin of error. With the modernization of the system and receivers, the applications in research and work became much more extensive. Studies vary from animal behavior (Rodgers, 2001) to application of GPS in forestry machinery (Taylor, 2001) and forest road planning (Abdi, 2012), as well as harvesting planning and inventory survey. Other typical applications are fire prevention, infestation control, aerial spraying and other services carried by forest services and governmental organs.

As the main limiting factor of the precise application of GNSS in forestry, the low quality of signal received under tree canopies is the main focus of this study. This issue has been studied from early times since before S/A was turned off. Notable examples of studies involving the canopy or the basal area as main source of interference are Tsuyuki (1994), D'Eon (1996), Phillips (1998), Naesset (1999 and 2001), Naesset & Jonmeister (2002), Wing (2005). Although contrasting at times, these studies agree about the canopy structure as source of signal disruption and source of errors such as multipath, where a signal reflected on another surface is received and causes positional error. While these are all factors caused by the environment where the receiver is located, the signal interruption itself was not studied until the first work of Hasegawa & Yoshimura (2007 a) on that matter, which explored the disruption of the signal in forest conditions and its relation to positional accuracy.

1.2.7 Signal Interruption Probability

Hasegawa & Yoshimura found out that the signal interruption probability (SIP) could predict positional errors on post-processing and improve accuracy. Moreover, SIP could inform about the canopy structure, being proportional to the density of the canopy and providing information about the period of time necessary for acquire positioning with acceptable errors. The following descriptions are excerpts from the original work of Hasegawa & Yoshimura (2007 a):

"To evaluate the frequency of GPS signal interruption, we extracted portions of continuously received signals and counted their frequencies according to the length" – this procedure is possible post-processing software provided with the receiver or Receiver Independent Exchange Files (RINEX), in which detailed information about a signal reception can be analyzed. The extraction of this data can be done accurately using

software that shows in details the behavior of the signal reception in the desired period of time.

“The (following) example shows a total of 60 epochs from three GPS satellites of which 31 signals were received successfully”

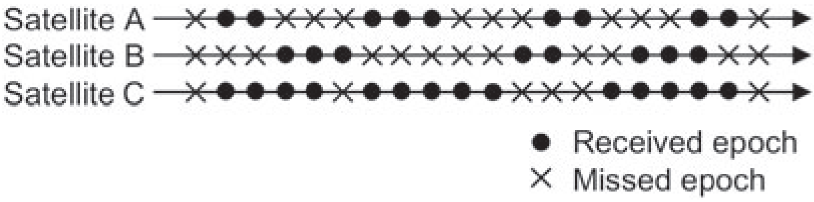


Fig 3 Example of a 20-epoch observation of global positioning system (GPS) signals from three satellites fragmented due to the forest canopy

“As shown in Fig 4, there are four sections of two continuous received signals (in red), *three sections of three continuous signals* (green), *one section of four continuous signals* (purple) *and two sections of five continuous signals* (blue)”

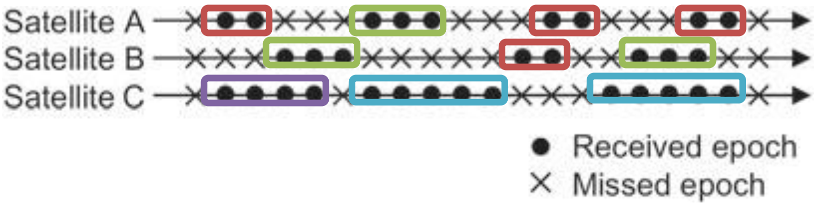


Fig 4 Distribution of continuously received signals in sections for SIP calculation

“We evaluated the frequency of GPS signal interruption as the cumulative probability of such interruption, which indicates the probability that any signal randomly sampled from all received GPS signals will be included in a section of continuously received signals interrupted within k epochs. A cumulative probability for GPS signals interruption (Pk) was then calculated using the following equation:

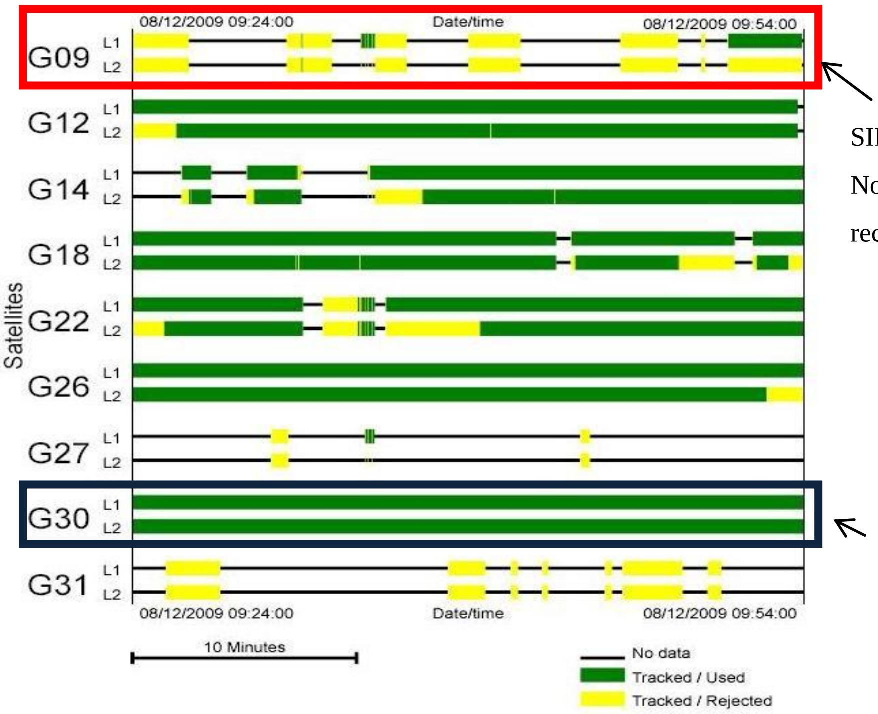
$$P_k = \frac{\sum_{i=1}^{k}(i \cdot N_i)}{\sum_{i=1}^{K}(i \cdot N_i)} (1 \le k \le K)$$

(Eq. 1)

“where k indicates the number of continuously received epochs, Pk indicates the cumulative GPS signal interruption at k-th epochs, Nk indicates the number of sections of GPS signals continuously received for k

epochs, and K indicates the total number of epochs for each satellite (20 in the example shown in Fig. 2). The numerator of Eq. 1 represents the number of received signals interrupted within k epochs, while the denominator represents the total number of received signals during the observation period from all satellites. In the example shown in Fig. 2, Pk is calculated as P1 = 0, P2 = 8/31, P3 = 17/31, P4 = 21/31, P5 = 1, P6 = 1, . . . , P20 = 1 on the condition of K = 20, N1 = 0, N2 = 4, N3 = 3, N4 = 1, N5 = 2, N6 = 0, N7 = 0, . . . , N20 = 0."

Another way to understand SIP is as a percentage index for the amount of interruption suffered by the signal on its way to the receiver. Figure 1 shows the analysis of GPS data received in this research in the graphical format presented by the software Leica Geo Office 6.0.



SIP10= 100%

No signal

reception

SIP10= 0%

Signal fully

received

Fig. 5 Graphical representation of a GPS signals reception by Leica Geo Office 6.0. In this picture the green and yellow bars represent signal reception/rejection, SIP10 can be understand as the percentage of signals with lengths less than 10 minutes.

SIP10 means SIP at ten minutes of observation. Since SIP is related to the epochs (time measurements) for its calculation, a determined period of observation should be attributed to the value. In the previous work of Hasegawa, the SIP at 10 minutes, or SIP10 was showed as an ideal index for correction of accuracy errors.

Another role of SIP is on the ambiguity resolution, or the correction of GPS data that couldn't have a Fix condition, usually referred as Float data. The float data is by definition a not accurate position that the receiver could not establish correctly even in the post processing step or with DGPS techniques these coordinates don’t have acceptable errors; therefore a correction is necessary to obtain positional accuracy. As showed in the same publication, SIP can be used effectively as predictor of this error than the canopy opening index. SIP is also an index related to the period of observation. In its first publication, SIP10, or SIP at 10 minutes observation was found significant for the ambiguity resolution. In posterior works (Hasegawa & Yoshimura, 2007 b) other periods of observation were tested and again it was found that SIP10 as a significant predictor of GPS positional errors.

Another advantage of SIP is that it can be used to make on-site calculations on the appropriate receivers, thus obtaining information about the forest environment surveyed, such as the canopy structure and its level of interference on the signal reception while using only the receiver itself or the post-processing software. SIP values may have relationship with stand condition such as stand volumes. Actually, Wright et.al (2008) and later Liu et al. (2011) clarified the relationship between the GPS signal attenuation and length of vegetation through which GPS signals were received by using LIDAR (Light Detecting an Ranging) data. SIP analysis may provide additional information for that study, as well as in other factors which affect the GNSS usability and functionality under tree canopies.

2 - GPS Accuracy in Using Antenna Pole under Tree Canopies and Usability of Signal Interruption Probability (SIP) for Accuracy Estimation

2.1 Introduction

The Global Positioning System (GPS) has become increasingly popular in recent years, but its application in forestry is still challenged by interference caused by tree canopies, which disrupts the signal; errors are introduced by multipath effects, loss of lock, tree movement caused by wind, and the canopy structure itself, including trunks, leaves, and branches. Different studies attribute positional errors obtained during forest surveys to canopy opening indexes and increments in basal area and propose corrections of horizontal and tridimensional errors based on this assumption (Frair, 2004, Naesset & Jonmeister, 2002). Moreover, these and other studies have been searching for methodologies that can improve reception under tree canopies. Raising the antenna height to avoid interference from shrubs and regenerating trees is a known but not deeply studied enhancement (D’Eon & Stephen, 1996, Gandaseca, 2001, Yoshimura, 2008). Other studies attempted to another improvement, based on an earlier study (Hasegawa & Yoshimura, 2006), it was proposed the Signal Interruption Probability (SIP), an index of signal fragmentation that can be obtained during post-processing and that can be used to correct positional errors based on the continuity of signal reception (Hasegawa & Yoshimura, 2007). SIP has proved efficient in predicting positional errors and has the potential to estimate canopy structure at an observation point. In connection with an effect of GPS accuracy on stand conditions, Naesset (1999) clarified that basal areas and tree species were statistically significant among the forest-related independent variables. These procedures are important for the modernization of forest operations, having multiple applications, including reduction of time necessary to survey a forest area. They can generally increase the quality of forest work.

The objective of this study was to clarify the response of SIP values to different variables, particularly forest type and antenna height. In this study, we analyzed the positional errors caused by different forest types using different antenna heights, the effects of forest type on the results, and the variation in SIP values at different heights.

2.2 Methodology

2.2.1 Study Site

The study was conducted at Kamigamo Experimental Station, Kyoto University (35°04′N, 135°46′E) a forested mountainous area in Kyoto City, Japan. Four observation points on plain ridges in different forest types were chosen: Open sky/Forest road, Coniferous plantation, Deciduous forest, and Evergreen forest.

Kyoto University has placed a marker with known coordinates at the P1/Open Sky point; it was therefore used as a control point. P1 is located at the highest point on the station and is surrounded by buffering vegetation with a canopy up to 10 m high at a distance of 3–5 m (in diameter) from the marker. The marker is placed on a plain, well-preserved forest road and is subject to weather conditions because it is exposed to the open sky. The P2/coniferous observation point is located in a plantation of coniferous Japanese Hinoki Cypress (*Chamaecyparis obtusa*), which have an average canopy height of 15 m. The characteristic foliage of the species provides enough sunlight, but sky visibility is highly fragmented. Although this survey point is subject to rain, wind is a minor issue due to the height of the trees and canopy. The P3/Deciduous observation point is located in a regenerating forest near the southern border of the station. One of the dominant species near this point is the Konara Oak (*Quercus serrata*). The canopy in this area reaches 12 m in height and the survey point is placed on a slightly elevated south-facing slope. Weather impacts this point more severely during the defoliation period (November–March). The P4/Evergreen observation point is located near a forest road in a plantation of mixed Japanese oaks dating from the 1950’s (e.g., *Q. stenophylla, Q. acuta,* and *Q. myrsinaefolia*). The canopy has an average height of 15 m with dense foliage and thick branches; this survey point is situated on a north-facing slope with trees buffering the forest road but rarely present on the slope.

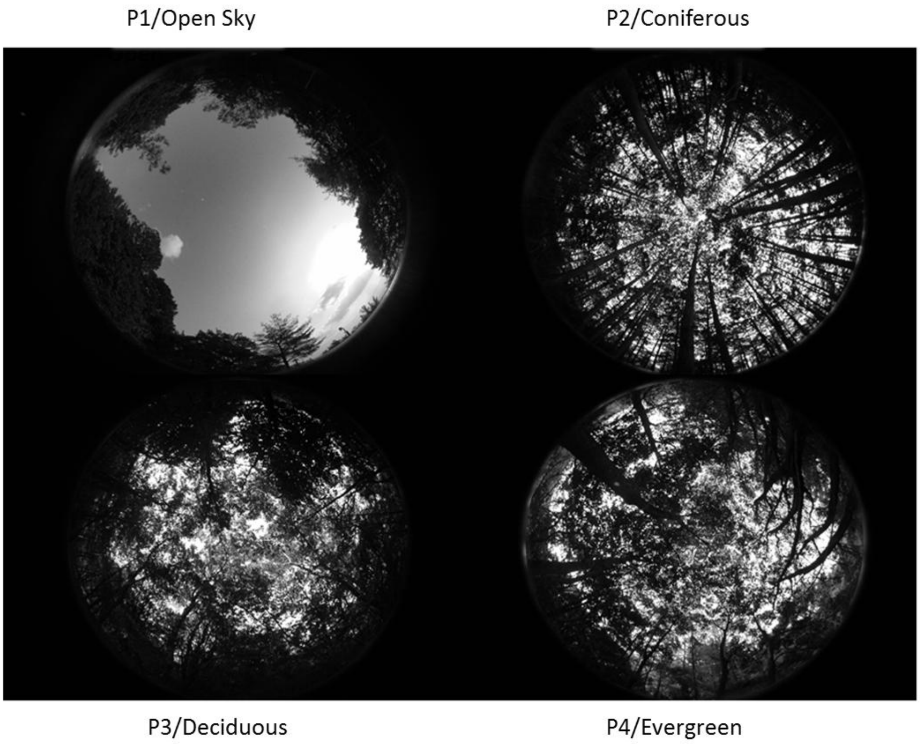


Figure 1: Hemispherical pictures of survey sites at 1.5-m camera height.

2.2.2 Data Collection

Surveys were conducted every two months between August 2009 and July 2010. For each forest type, we conducted four surveys using four different antenna heights (1, 5, 8 and 11 m) on four days. When the weather conditions were unacceptable (windy, rainy or snowy) we conducted the survey on the next weather-favorable day, respecting the satellites rotation, i.e. 4 minutes earlier for every day passed. Details of each point are shown in Table 1. In total, we had 32 observations per point, each observation lasting 15 minutes, twice per point per hour observed.

Table 1: Survey schedule, antenna heights used on each day at each survey point.

Survey	Day 1		Day 2		Day 3		Day 4	
order	Ant. h. (m)	Point	Ant. h. (m)	Point	Ant. h. (m)	Point	Ant. h. (m)	Point
1	1.5	P1	1.5	P2	1.5	P3	1.5	P4
2	5	P2	5	P3	5	P4	5	P1
3	8	P3	8	P4	8	P1	8	P2
4	11	P4	11	P1	11	P2	11	P3

A Leica GPS, model SR530 (Leica Geosystems, Heerburg, Switzerland) was used as a rover; this receiver has differential capabilities, 12 channels and an accuracy of 3 mm + 0.5 ppm according to the manufacturer. As base station we used a Trimble GPS Total Station, model 4700 (Trimble Navigation Ltd., Sunnyvale, USA), a differential GPS enabled receiver with 9 channels and an accuracy of 5 mm + 1 ppm. The base station was set at Kyoto University Main Campus, logging at 1 epoch per second, identical to the rover. The baseline was of 4.84 km between the closest point and the base and 5.23 km between the furthest point and the base. The elevation mask was set at 10 degrees and the total observation time at each point was 1 h. A tripod with tribarch was used to fix the height at 1.5 m, and a telescopic pole was used to position the antenna at heights of 5 m, 8 m, and 11 m. This pole was ordered by us for research purposes (Yoshimura, 2008), it is made of carbon fiber, weighing 4.2 kg with 1 m of height for each sub-pole, with the diameter of the first pole being 22 cm and the last pole 5 cm. To obtain a canopy opening index for each point and height, a camera equipped with a hemispherical (fish-eye) lens was used to take photographs of the canopy prior to the survey in the same positions and at the same heights used for the antenna; canopy opening indexes were calculated using the software Gap Light Analyzer (GLA) 2.0 (Frazer, 1999) and are shown in Figure 2.

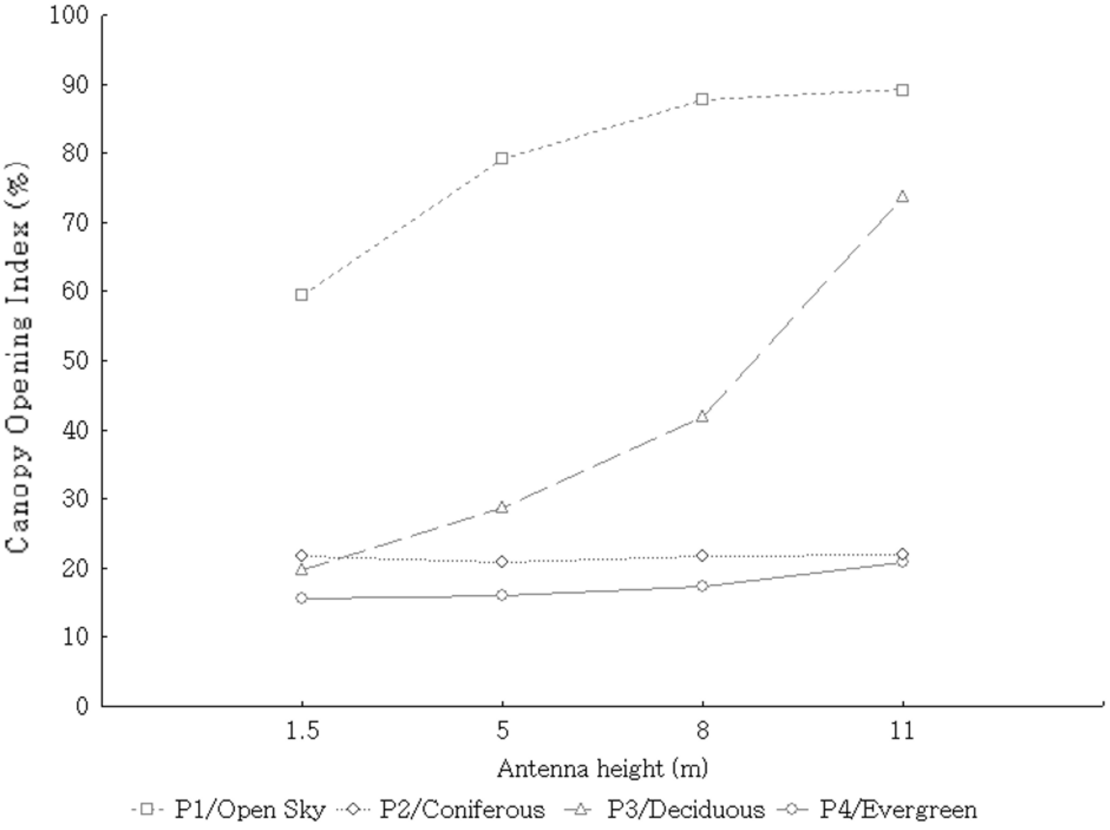


Figure 2: Average of canopy opening index according to antenna height.

The results show the variation of the canopy opening on each site for each antenna height used to photograph the canopy. The canopy opening index is more noticeable at the Deciduous point because of the defoliation period and the short canopy, which provided a larger gap at higher heights. Results of the survey were post-processed using the proprietary software Leica Geo Office 6 with Receiver Independent Exchange Format (RINEX) files from the base station, comparing the coordinates between the rover and the base and correcting the rover data accordingly. In this study we use code-differential measurements on the L1 frequency of the GPS signal for all analysis.

2.2.3 Positional Errors and Signal Interruption Probability

In this study, horizontal (2D) errors were calculated based on true coordinates obtained from a previous static GPS survey and total station survey with three-dimensional network adjustment method to a relative accuracy of 5 mm. Errors were calculated using the equation:

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

Where *x* and *y* are the coordinates obtained by the rover and *xt* and *yt* are the coordinates obtained in the total station survey (“true” coordinates). Signal fragmentation for a given GPS observation is usually evaluated as SIPt (Hasegawa & Yoshimura, 2007). SIP is the probability of GPS signal interruption within a certain period of time and is defined as the ratio of a number of signals, which were successfully received at a period less than t min, to a number of all received signals. SIP can be calculated using receiver logs and are entirely obtained after post-processing using the custom-developed software SIPCalc, which allows RINEX files of post-processed data to be used for the calculations. The factor t should be determined by the operator. In this study, we used SIP10 because Hasegawa & Yoshimura (2007b) specified that *t* should be set at 3–18 min in 1 Hz (1 epoch per second) observation for estimating horizontal error. In this study, we use two periods of 15 minutes, extracted from each hour of observation in the 0 to 15 minutes and 30 to 45 minutes intervals.

2.3 Results and Discussion

2.3.1 Horizontal Errors

At first, we conducted Smirnov-Grubbs test with significance level of 5% for detecting outliers because one data observed on December at Evergreen point was too far apart from others. The result of the test indicates that this data was detected as an outlier, so we excluded this data in the following analysis.

Table 2 shows the results of the ANOVA analyzing the factors affecting horizontal error of code-phase GPS. Point and antenna height were significant at 1% level, and interactions between point and antenna height, and among all factors, were also significant at 1% level. Interaction between point and month was also significant at 5% level. In the result of contribution rate, half of variance was produced as error, which indicates that satellite arrangement and other factors are largely affected on GPS accuracy. It should be noted that all factors relating antenna height showed large contribution rates, so that antenna height was important factor affecting GPS accuracy.

Figure 3 shows the effect of interaction on the average results for horizontal errors in all points. Open Sky and Evergreen points achieved better results at 5 m. In the case of Open Sky point, the buffering vegetation causes interference at lower heights, whereas at 8 and 11 m, the error increases owing to the instability of the pole used and the stronger influence of the wind. In the case of the Evergreen point, antennae placed at lower heights suffer high interference from the surrounding trees; when the antenna is placed at mid-heights, it gets better reception owing to its better position relative to the tree trunks. Antennae placed at the Coniferous point achieved better results at 8 m because at that height inside the forest plantation the antennas were above the shrubs and the thickest parts of the tree trunks, in addition, the stability of the pole was not much affected by winds inside this dense plantation site. In case of the Deciduous point, the lower antenna height offered better distance from the branches and leaves of the regenerating forest, which increased positional accuracy. In all cases, the error rate of antennas placed at a height of 11 m was accentuated by the carbon-fiber pole bending under its own weight and the weight of the antenna; at this height, the antenna is also more subject to wind, causing greater variation and less accurate results.

Table 2: Result of ANOVA for horizontal errors.

Source of Variation	Sum of square	df	Mean square	F	p		Contribution rate (%)
Point (A)	1.736	3	0.5785	4.846	0.004	**	2.86
Antenna height (B)	6.132	3	2.0440	17.123	<0.001	**	12.08
Month (C)	0.618	5	0.1236	1.035	0.402		
A x B	6.985	9	0.7761	6.502	<0.001	**	12.30
A x C	3.854	15	0.2570	2.153	0.013	*	4.17
B x C	2.351	15	0.1567	1.313	0.210		
A x B x C	14.680	45	0.3262	2.733	<0.001	**	19.04
Error	11.340	95	0.1194				49.55
Total	47.680	190					100.00

*Significant at 5% level; **significant at 1% level; Contribution rates are calculated by using pooled data.

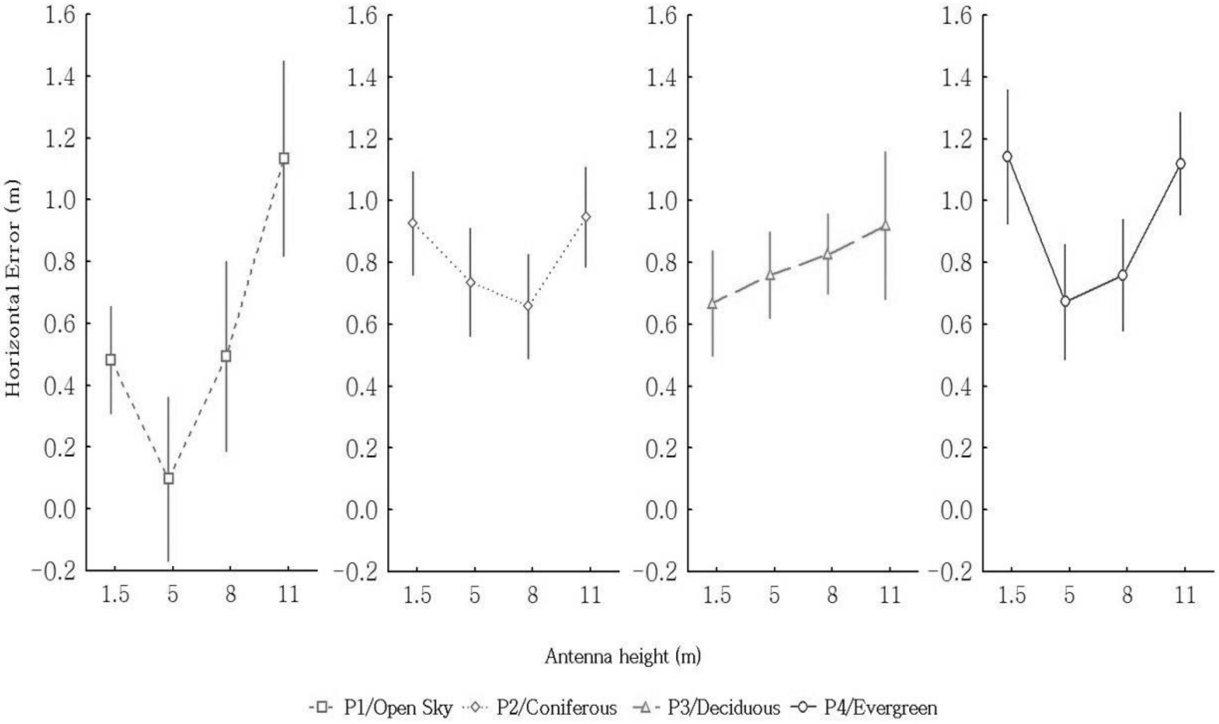


Figure 3 Mean horizontal errors according to antenna height for each point. Bars indicate standard deviation.

Another complex interaction revealed by ANOVA is between forest type, antenna height, and the month. Figure 4 shows the horizontal error, antenna height, and the month at an observation rate of 15 min. It should be noted that seasonal change of GPS positioning accuracy is not clear because of the difference of satellite arrangement among the seasons. Of the four antenna heights chosen for this study, the intermediate heights of 5 and 8 m offered the least variation in horizontal error.

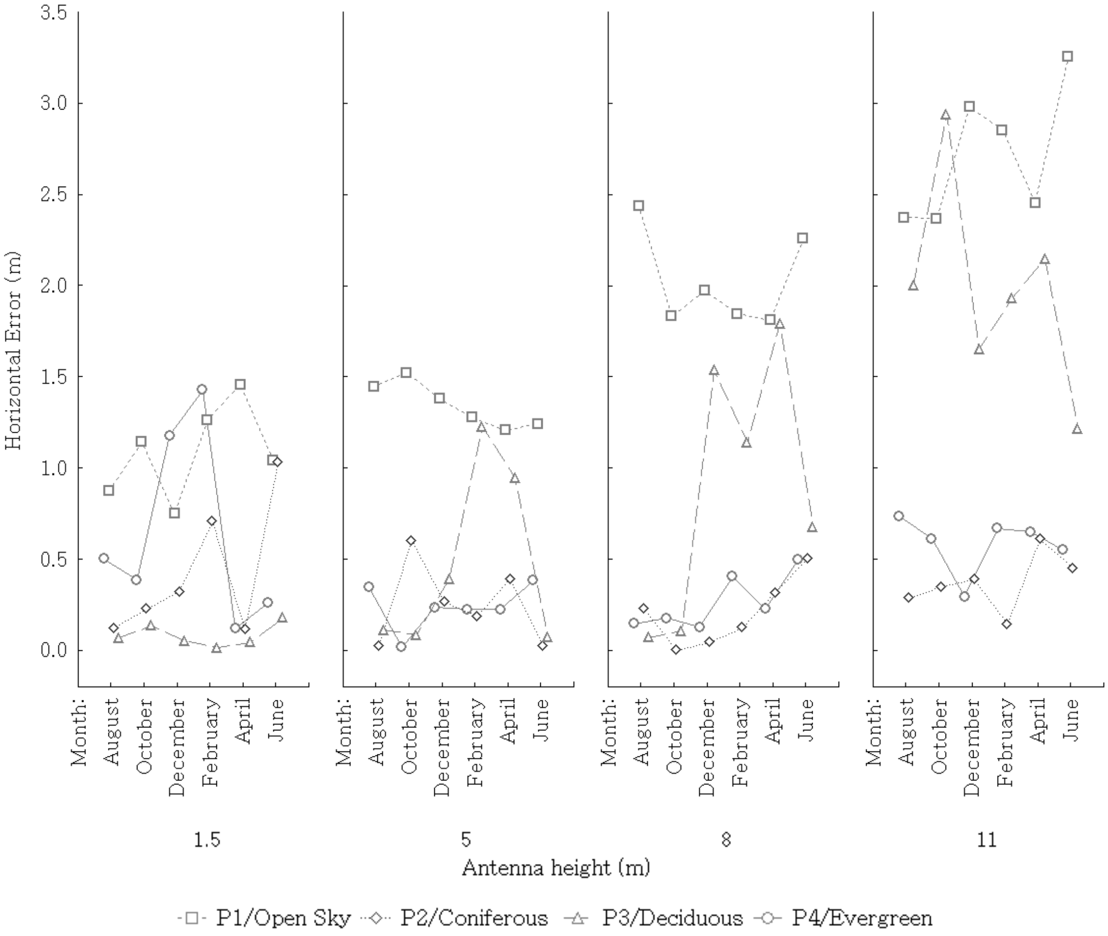


Figure 4 Mean horizontal errors during one year’s observation relative to antenna height and forest type.

As previously mentioned, the increased rate of error at 1.5 m can be explained by the greater prevalence of shrubs, short trees, thicker parts of tree trunks, and other sources of interference. Even though 1.5 m offered the most stable antenna position due to the use of the tripod instead of the pole, interference was stronger. As mentioned by Karsky *et al*. (2001), the decrease in accuracy is caused by low SNR values, a relationship often encountered in code-phase measurements where there are obstacles to clear reception. Evergreen has particularly strong variance due to its closed canopy (<20% visible sky), which can also be said for the Coniferous site with its highly fragmented canopy. The Evergreen forest had the highest errors due to the higher and thicker trees surrounding the area. At the Coniferous forest site, the highly fragmented canopy of Japanese cypress caused high levels of multipath error and signal fragmentation. However, even at these points, antenna heights of 5 and 8 m strongly influenced the results.

2.3.2 Factors Affecting Estimation of GPS Positional Errors

The effects of antenna height on SIP10 measured at L1 frequency and on the canopy opening index are shown in Figures 5 and 6, respectively. SIP follows a different pattern when compared at individual antenna heights, with less interruption at the highest levels; this does not imply that it provides better accuracy, only that reception improves as the antenna gets closer to the canopy. As we know that at a height of 11 m, antenna instability increases the rate of error, it can be seen that accuracy is influenced by the sum of the factors that comprise a forest environment.

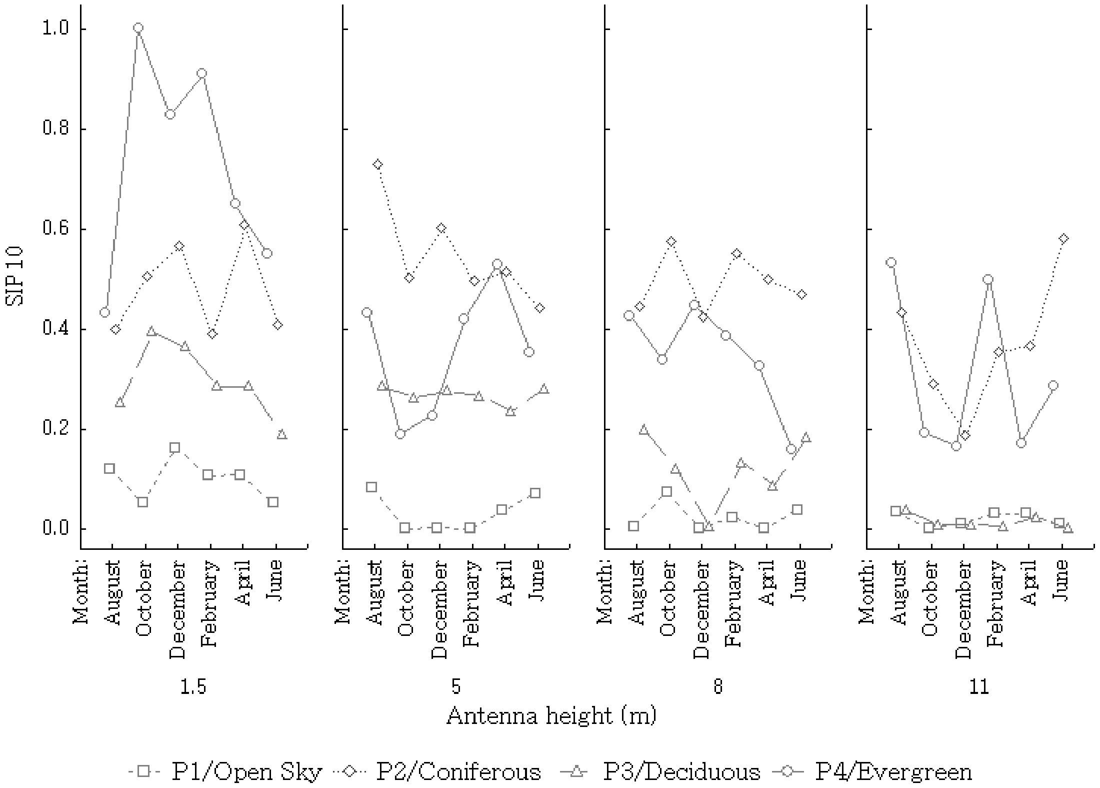


Fig 5 Average of SIP10 according to antenna height during the period of one year.

Although the canopy opening index calculated from hemispherical photographs reflects the canopy structure (Evans, 1959), SIP10 shows a higher correlation with 2D errors than the canopy opening index (r = 0.25 and -0.07, respectively). By comparing the effects of antenna height on SIP10 and the canopy opening index in deciduous forest at heights of 1.5 m and 5 m, it can be said that SIP10 remains the same whereas the canopy opening index increases at a height of 5 m. According to the results of the horizontal error analysis, shown in Figure 4, no difference can be observed between them, indicating that SIP10 is less subject to horizontal error than the canopy opening index.

Table 3 shows the results of multiple regression analysis, which is used for comparison effects of SIP10 and the canopy opening index on horizontal errors. Although SIP10 and the canopy opening index have high correlation (r=-0.72), multicolinearlity can be ignored because VIF (variance inflation factor) was enough low (VIF=2.06).

Standard partial regression coefficient of SIP10 is higher than that of the canopy opening index. This result indicates that SIP10 is a better indicator than the canopy opening index, regardless of antenna height or season. We hypothesize that the canopy opening index is not a good indicator of horizontal error because GPS radio waves can pass through thin leaves and small branches, which are evaluated as obstructions in hemispherical photographs. Therefore, the canopy opening index tends to overestimate the effect of the canopy on GPS reception. SIP is thus a more informative value than the canopy opening index because it more accurately represents the amount of signal that can be received.

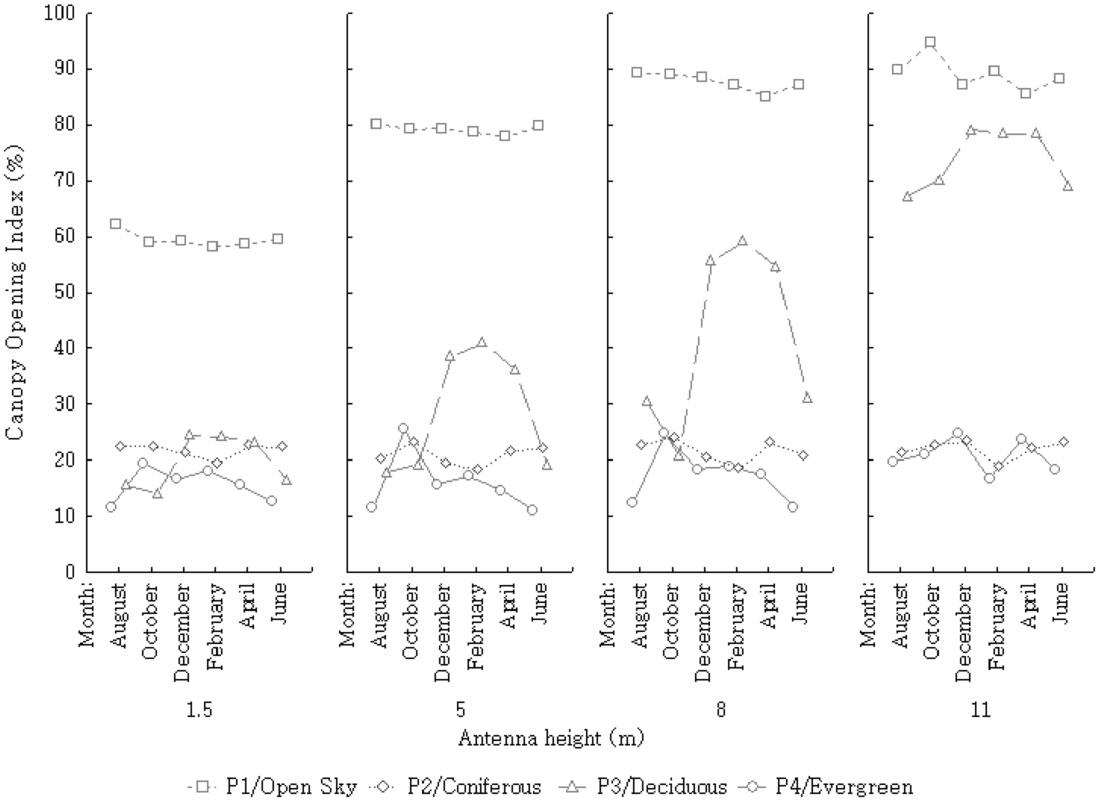


Figure 6 Canopy opening index variations according to antenna height during the period of one year.

Table 3 Result of multiple regression analysis for horizontal errors.

Variable	Estimate	SE of Estimate	Standard partial regression coefficient	*p*	
Intercept	0.3726	0.1253		0.003	**
SIP10	0.8104	0.2070	0.3946	<0.001	**
Canopy Opening	0.0043	0.0018	0.2397	0.018	*

*Significant at 5% level; **significant at 1% level; R^2=0.067; VIF=2.06

2.4 Conclusions

An increase in antenna height can provide better reception with less error compared with a very stable but shorter antenna (tripod heights, usually less than 1.8 m) or a taller but unstable antenna. Our results show that if the pole used to raise the antenna is stable and unaffected by the wind, the height range between 5 and 8 m can provide reliable data, even in forest types with a naturally high interference level. SIP is directly related to the canopy opening index, as previously stated by the original authors and has a tendency to decrease as antenna height increases, and is not necessarily related to the accuracy of observation. We recommend that surveys, whenever possible, utilize taller antenna heights or at least position the antenna above the sources of interference in the surrounding area. Compared to the canopy opening index, SIP values are a better indicator of error management regardless of antenna height and time of the year and are a recommended parameter for canopy structure analysis, more efficient than the canopy opening index itself, providing information on the signal structure and easier to obtain on site, without the need of extra equipment such as camera. Furthermore, SIP may express the forest structure, especially in a stem and branches because SIP was not highly influenced by seasonal changes of canopy condition as same as GPS accuracy, that is differently from canopy opening index. This usability reflects better the quality of reception that can be achieved in a determined site regardless of the conditions, making SIP a reliable value to determine data quality.

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

3.1 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 & Jonmeister (2002) found that reduction of basal area as well as longer survey periods increase positional accuracy. Kobayashi (2001) agreed and suggested the selective use of point positioning and differential GPS techniques to improve accuracy. Sigrist (1999) cited even small increases in canopy closure as causing 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, 2001). Another factor cited as leading to positional errors is 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 (2000) attributed errors under the canopy to PDOP, while Jiang (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, 2001; Sawaguchi, 2003; Yoshimura, 2006), using translocation instead of point positioning (Tsuyuki, 1994), and increasing the survey period (Yoshimura & Hasegawa, 2006). Hasegawa & Yoshimura (2003) developed regression models based on the observation period and canopy opening, using the canopy photographs mentioned above. Later (Hasegawa & Yoshimura, 2007), 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 (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.

3.2 Methodology

3.2.1 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) 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 and 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.

Table 1 – Observation point details

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

3.2.2 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.

Table 2 – Survey schedule with adjusted time for every survey

Day 1	Point	Day 2	Point	Day 3	Point	Day 4	Point
10:00	P1	9:56	P2	9:52	P3	9:48	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, 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

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

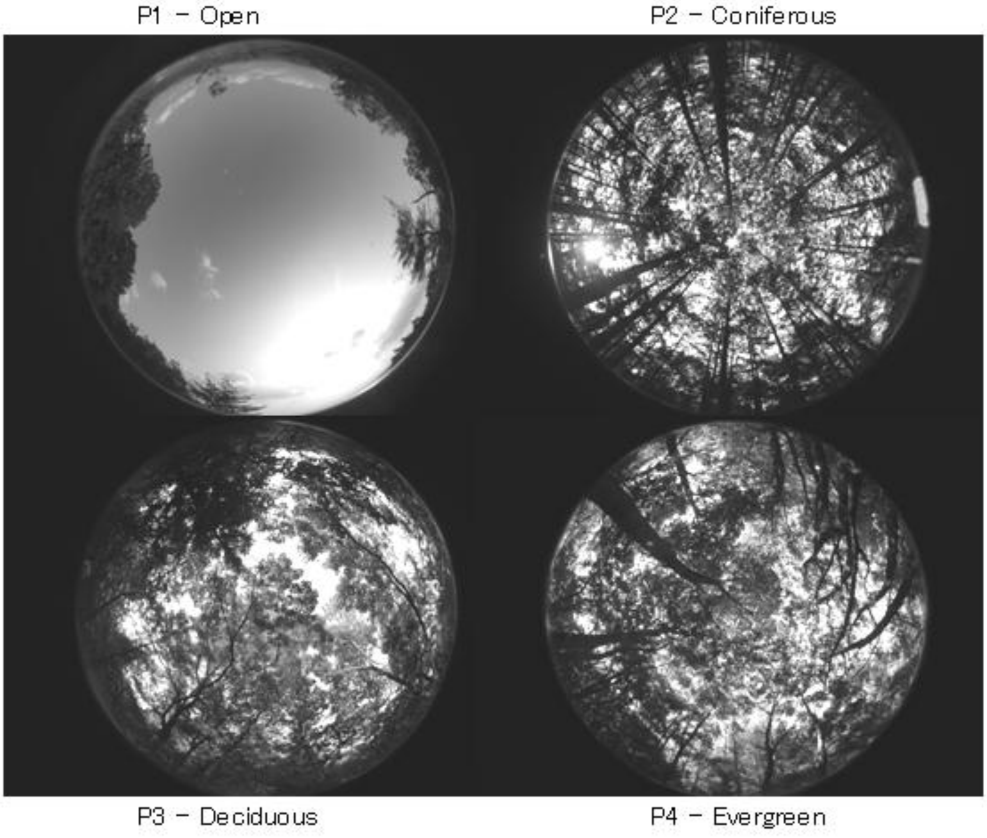


Figure 1 - Hemispheric pictures taken at surveying spots at 5m, September 2009

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. Elevation mask of the rover was set at 10 degrees.

3.2.3 Baseline analysis

To calculate errors in the coordinates acquired by the rover within the station data, we first divided 1-h observation data into two sets of 30 min each and extracted smaller periods of 1, 5, 15, and 30 min for the first half an hour and a repetition of the same periods for the second half an 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:

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

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.

3.2.4 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:

$$P_k = \frac{\sum_{i=1}^{k}(i * N_i)}{\sum_{i=1}^{K}(i * Ni)} (1 \leq k \leq K) \qquad (3)$$

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.

3.3 Results and Discussion

3.3.1 Mean errors

Table 4 and 5show 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, 2005; Andersen, 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 & 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 & 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. 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 4 – Mean horizontal errors

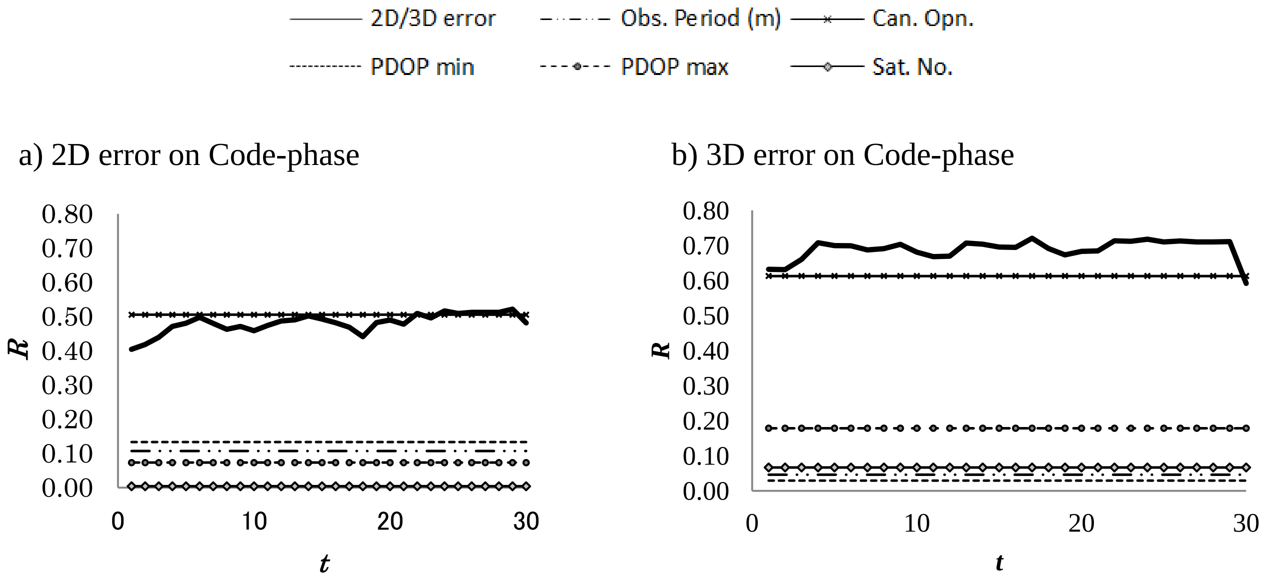
Mean horizontal errors (m)										
Observation Point	Observation Period (min)	L1(fix)	# of Fixes	L1(float)	# of Float	L1+L2 (fix)	# of Fixes	L1+L2 (float)	# of Float	Code
P1	1	-	-	0.3278	12	0.1320	12	-	-	0.0869
	5	0.0952	2	0.4321	10	0.1317	12	-	-	0.1341
	15	0.1314	12	-	-	0.1326	12	-	-	0.0817
	30	0.1303	11	0.1480	1	0.1323	12	-	-	0.1178
P2	1	-	-	0.7506	12	-	-	0.8002	12	1.0319
	5	-	-	0.8198	12	-	-	0.7119	12	0.8383
	15	-	-	0.5843	12	0.2854	2	0.6036	10	0.7880
	30	0.3776	2	0.6659	10	0.2191	2	0.9444	10	0.5623
P3	1	-	-	0.6605	12	0.2976	3	0.6315	9	0.4662
	5	-	-	0.5066	12	0.2074	6	0.4670	6	0.5389
	15	0.0864	1	0.4544	11	0.2010	9	0.5652	3	0.6858
	30	0.1378	5	0.4032	7	0.2258	12	-	-	0.5665
P4	1	-	-	0.7315	12	0.1769	1	0.8673	11	1.0387
	5	-	-	0.6529	12	0.1478	2	0.6252	10	0.8015
	15	-	-	0.6496	12	0.2207	5	0.7586	7	0.5780
	30	0.4037	4	0.8213	8	0.2137	9	0.9508	3	0.5680

Table 5 – Mean tridimensional errors

Mean Tridimensional Errors (m)										
Observation Point	Observation Period (min)	L1(fix)	# of Fixes	L1(float)	# of Float	L1+L2 (fix)	# of Fixes	L1+L2 (float)	# of Float	Code
P1	1	-	-	0.5779	12	0.1342	12	-	-	0.1227
	5	0.0973	2	0.4820	10	0.1336	12	-	-	0.3223
	15	0.1334	12	-	-	0.1347	12	-	-	0.1666
	30	0.1323	11	0.1481	1	0.1341	12	-	-	0.2309
P2	1	-	-	2.0552	12	-	-	1.7112	12	2.5400
	5	-	-	1.0115	12	-	-	1.0436	12	2.2360
	15	-	-	1.2870	12	0.4052	2	1.7389	10	1.7344
	30	0.3956	2	3.8179	10	0.3285	2	4.9657	10	1.7366
P3	1	-	-	0.9267	12	0.3441	3	0.8135	9	0.8863
	5	-	-	0.7754	12	0.2861	6	0.9237	6	0.9737
	15	0.1893	1	0.5205	11	0.2877	9	0.6325	3	1.1378
	30	0.2171	5	0.4809	7	0.3010	12	-	-	0.9225
P4	1	-	-	1.1406	12	0.2243	1	1.0468	11	1.5044
	5	-	-	1.2616	12	0.4859	2	1.1017	10	1.8654
	15	-	-	1.0660	12	0.7079	5	0.8438	7	1.9054
	30	1.7274	4	1.1893	8	0.8199	9	1.0031	3	2.1006

3.2.2 Correlations between positioning errors and SIP

Considering the data for float and code solutions (Figure 2a–2d), 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.



a) 2D error on Code-phase

b) 3D error on Code-phase

c) 2D error on L1 (Float values)

d) 3D error on L1 (Float values)

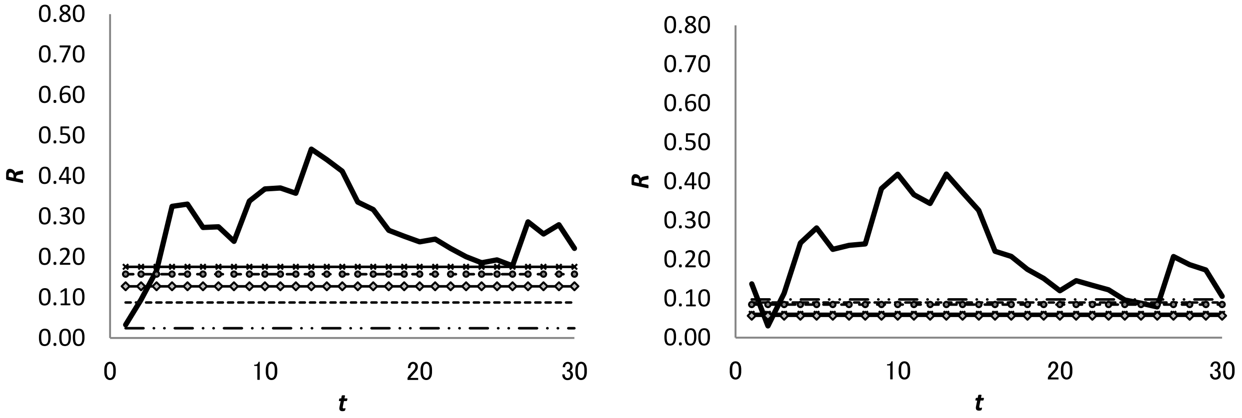


Figure 2a–2d: SIP correlations with 2D and 3D errors and other factors. Values of canopy opening are shown as absolute values, due to negative correlation with positional errors.

Code-phase values showed more stability, regardless of the *t* value, while Float solutions had higher values in the periods between 10 and 15 minutes. The observation period is another factor from which SIP evolves directly. As shown in Table 4 and Figure 2 and 3, 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.

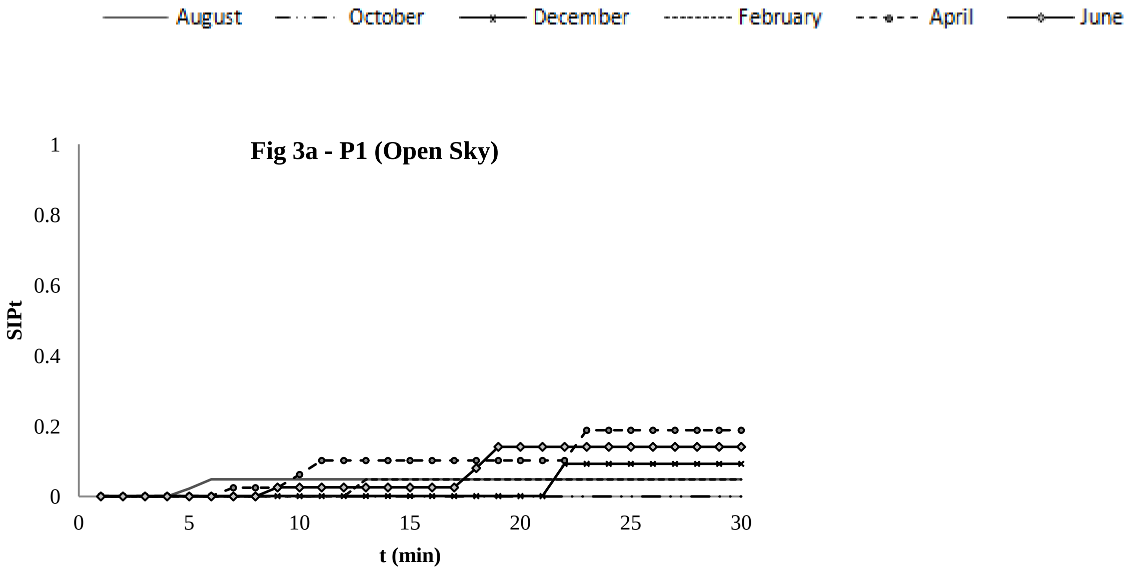


Fig 3a - P1 (Open Sky)

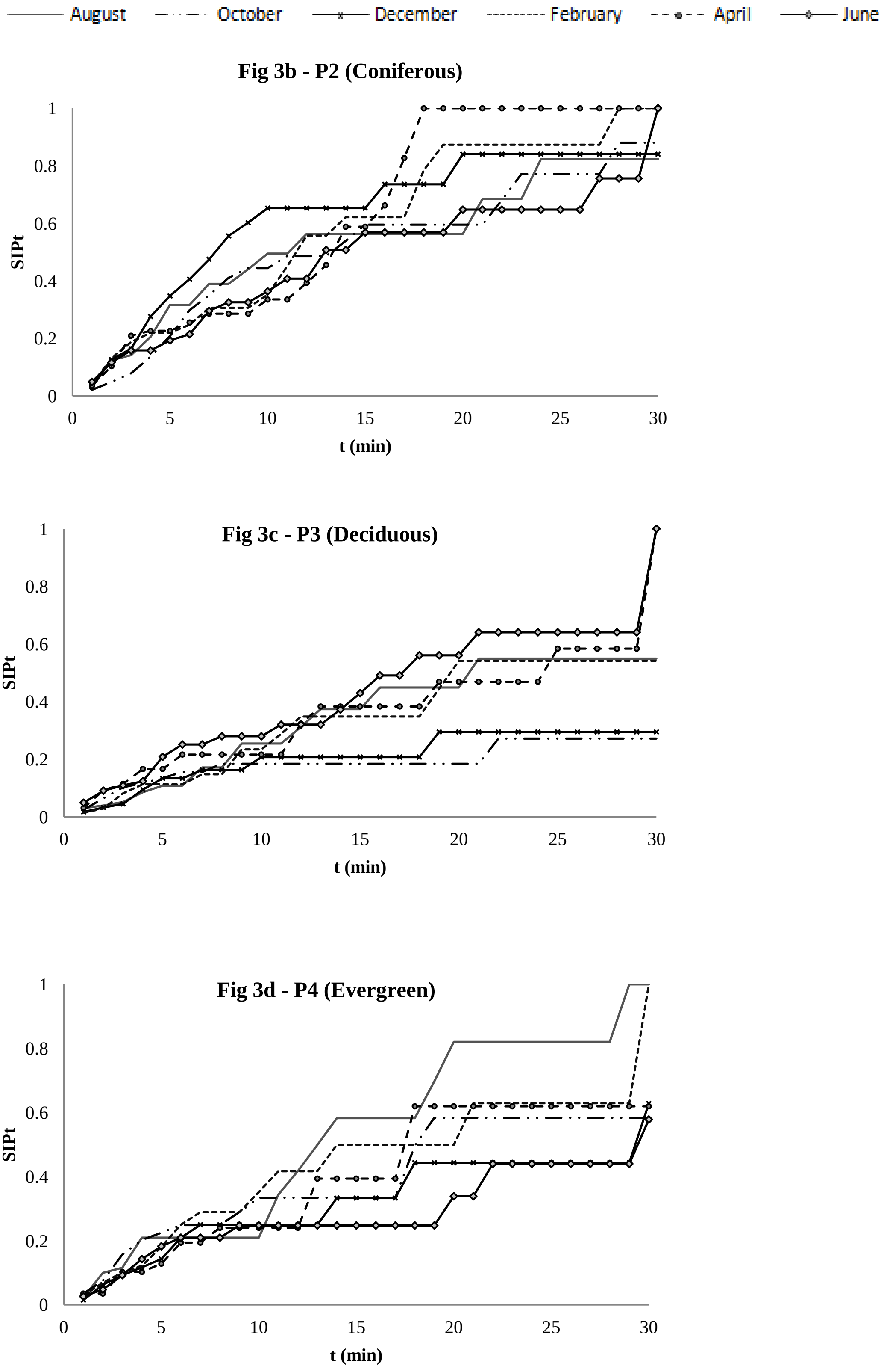


Figure 3a–3d: SIP behavior under seasonal changes in periods of 30 min

3.4 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.

4 – Characteristics of Signal Interruption Probability in Multiple Use of GPS and GLONASS Satellites

4.1 Introduction

Global Positioning System, GPS, and the Russian Global Navigation Satellite System, GLONASS, are currently the only GNSSs fully operational on a global scale and offering service for any capable receiver. Even though the systems have different designs and technologies, interoperability was made possible and nowadays the usage of both systems provides higher coverage and better accuracy for users. These advantages became clear along the years in different studies and for different applications. For instance, Ong (2009) found that GPS+GLONASS data provides better accuracy; and availability, as well as float solutions with accuracy in vehicle positioning in roads and highways than GPS-only. The combination of both GNSSs also provided better kinematic solutions in the European Permanent Network but not better daily solutions, in which GPS performed better (Ineichen, 2008) and for Real-Time Kinematic (RTK) surveys under forest environments (Pirti, 2010). Still, some contrasts were found, for example Cai (2009) states that in when there is a low number of available satellites, combined GNSS has lower accuracy than GPS only. However, when it comes to reception under forest canopies, GLONASS suffers the same problems as GPS. A combination of both systems in such specific situation was studied by Naesset (2000), who found that under canopy GLONASS+GPS accuracy is superior for float solutions, with accuracy improve after 15 minutes for low and moderate densities. Later, utilizing the combination of system, Naesset (2008) found that shorter observation periods, especially less than 30 minutes increases error and degrades accuracy, especially in dense forest, but the same kind of receiver tend to provide better accuracy in short periods when it comes to under canopy surveys. Andersen (2009) found similar results about observation periods, recommending a minimum of 20 minutes of survey. Hasegawa & Yoshimura (2007a) studied the effects of canopy and the signal interruption probability (SIP) on positional accuracy for GPS receptions and found that SIP could represent these effects and predict positional errors through regression analysis.

Based on these studies, we designed a survey to test the behavior of SIP under forest canopies using the combination of GPS+GLONASS and compare to a GPS-only receiver in static survey and propose that SIP for mixed GNNSs can be as predictive as GPS-only and for the first time, observe the index on the case of GLONASS.

4.2 Methodology

4.2.1 Study Site

This study was conducted at Kyoto University Ashiu Forest Research Station, a mountainous area in the northeastern part of Kyoto Prefecture in Central Japan. The area is characterized by its high reliefs, with attitudes varying from 355 to 959 m above sea level. Two of the sub-forests at the Station were chosen to conduct surveys: Miyanomori, a forest plantation located in an accented slope facing north, and Chouji, a forest plantation located at a plain area surrounded by slopes facing east. Both forests are populated by Japanese cedar (*Cryptomeria japonica*) only. Canopy Opening Index values and details of each site set for survey are shown on Table 1.

Table 1 – Value of Canopy Opening Index on each forest and each point.

Chouji

Point	Condition	Main Obstacle for Reception	Canopy Opening Index
B1	Plain, Forest plantation	Surrounding tree, high canopy	16.1%
B2	Plain, Forest plantation	Surrounding tree, high canopy	12.9%
D1	Mountain, Forest plantation	Surrounding tree, high canopy, slope facing	12.2%

Miyanomori

Point	Condition	Main Obstacle for Reception	Canopy Opening Index
C1	Mountain, Forest plantation	Surrounding trees, cut slope to the south	11.3%
C2	Mountain, Forest plantation	Surrounding trees, cut slope to the south	11.9%
S1	High valley, harvested forest	Cut slope to the south	20.8%
S2	High valley, harvested forest	Cut slope to the south	21.5%
V1	Low valley, harvested forest	Buffering vegetation, cut slope to south	22.8%
V2	Low valley, harvested forest	Buffering vegetation, cut slope to south	18.2%

Six points were set at Miyanomori forest distributed along the slope. C1 and C2 were located inside the permanent plot of the forest plantation, surrounded by trees in high points of the slope, between 700 to 720 m. S1 and S2 were located at the same heights but in the harvested area with buffering vegetation at north and south but low presence of trees. V1 and V2 were located in the lower part of the harvested area (680 and 700 m) of the slope.

Three points were set at Chouji forest. B1 and B2 were set at the plain area of the forest plantation, and the surrounding trees had and average DBH of 43 cm and heights up to 20 m with low canopy opening. B1 was set at the slope facing east, also with low sky visibility and surrounding trees with an average of 38 cm

DBH.

4.2.2 Data Collection

For this data collection, a Leica GR-10 (Leica Geosystems, Herrburg, Switzerland) receiver was used as base station. According to the manufacturer, this model has 10mm + 1ppm accuracy, up to 120 channels and GPS/GLONASS mixed operation capabilities. We set the base at a forest road at 737 m above sea level with high sky visibility, logging at 1Hz rate (1 epoch per second) and with an elevation mask of 10 degrees.

The first rover was a Leica 530 GPS (Leica Geosystems, Heerburg, Switzerland), a receiver with differential capabilities, dual L1+L2 reception over 12 channels and an accuracy of 3 mm + 0.5 ppm; the second rover was an Ashtec Promark 100 (Spectra Precision, Westminster, USA) a receiver with differential L1/E1 frequency reception for GPS and GLONASS with an accuracy of 0.5cm + 1ppm. Both receivers were logging at 1 Hz rate and elevation mask of 10 degrees. The average baseline between the base station and the rovers at Miyanomori and Chouji forests was of 2 km and 1.6 km respectively. Surveys had an observation period of 30 minutes per point with no fixed schedule. After each survey, a hemispheric photograph was taken in order to evaluate the Canopy Opening Index of each point using a camera equipped with fisheye lens. To obtain the canopy opening index of the pictures, we used the software Gap Light Analyzer (GLA) 2.0 (Frazer, 1999). Canopy hemispheric pictures are shown on Figures 1 and 2.

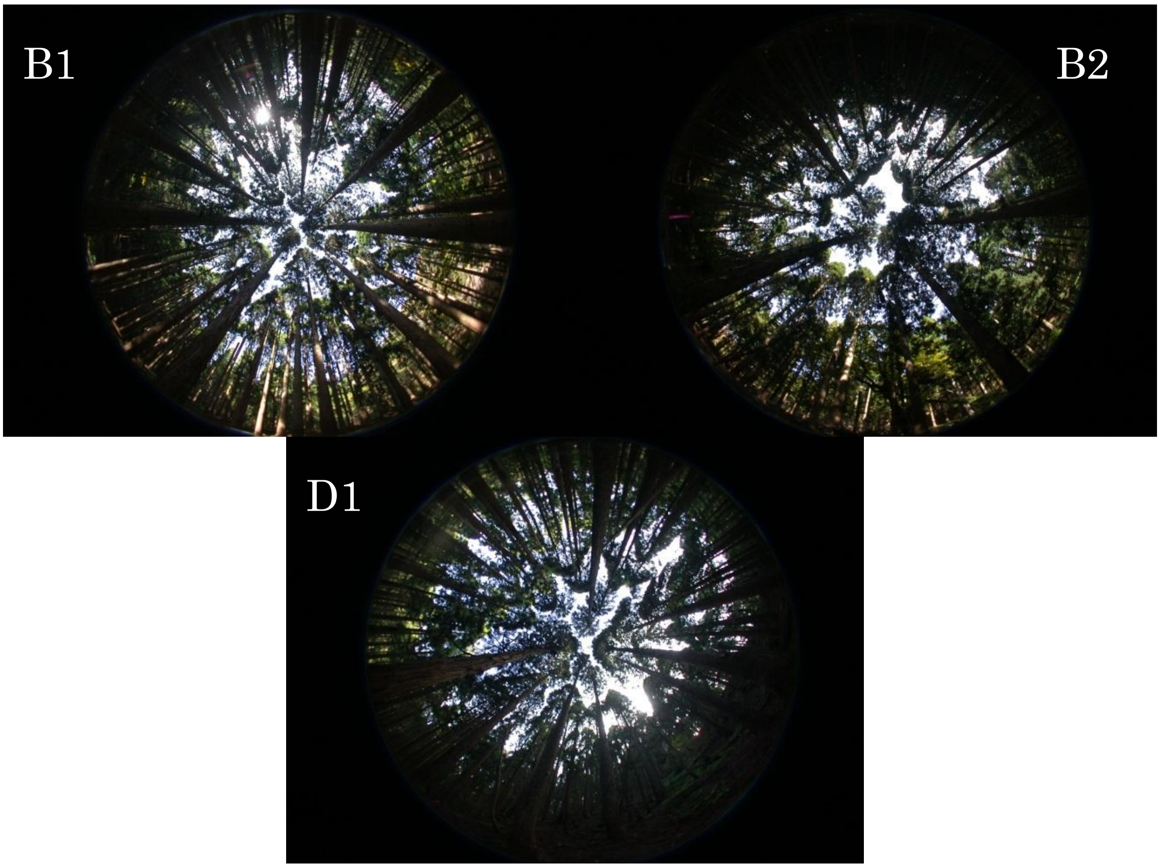


Figure 1 - Canopy Hemispheric Photographs for Chouji Forest

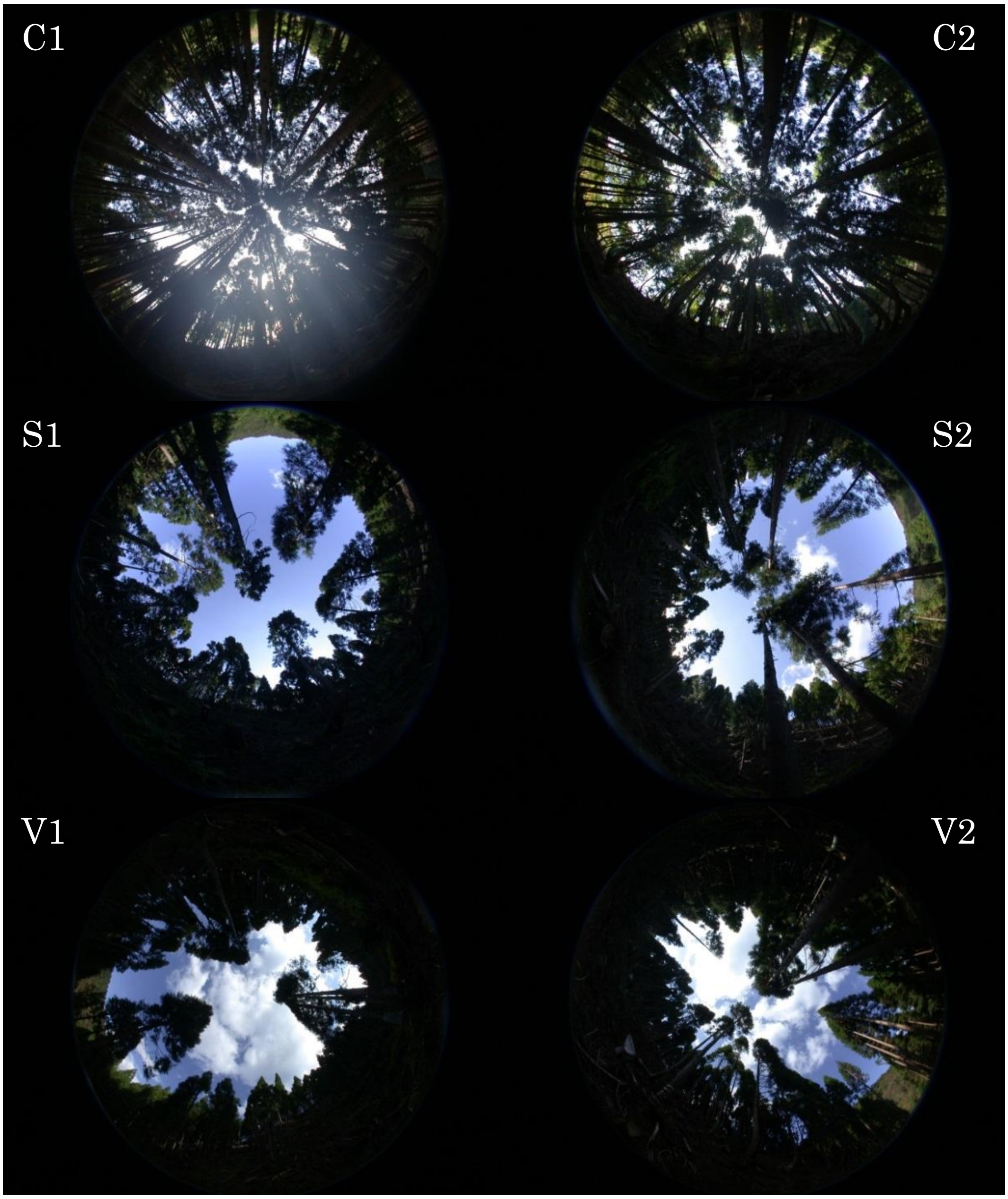


Figure 2 – Canopy Hemispheric Photographs for Miyanomori Forest

After the surveys, post-processing operations were taken using the proprietary software Leica Geo Office 8.3 and GNSS Solutions 3.8. In post-processing we divided the 30 minutes observation period in smaller amounts of 1, 5, 10 and 15 min with a repetition on the next 15 minutes, totalizing 1800 epochs of received data. In this study we analyze positional results for the GPS Code-phase, L1 and L1+L2 bands for the Leica receiver and Code-phase and L1/E1 band for GPS and GLONASS measurements on the Ashtec receiver. As common data pattern between receivers, we used the GPS-only L1 band.

4.2.3 Baseline Analysis and Signal Interruption Probability

Positional errors were calculated after the post-processing. After plotting all the positions of each observation period, we eliminated the most discrepant points (i.e. the points with further distance from the average position) in order to obtain the precise position for each point and avoid “false” fix solutions (Naesset, 2001). Assuming this position as the precise true position we calculated the average horizontal and tridimensional using the same equations mentioned on chapter 3. For SIP we used the same methodology mentioned in chapters 2 and 3, with the difference that SIP was also calculated for GLONASS satellites, obtaining the reception patterns of both GNSSs.

4.3 Results and Discussion

4.3.1 Mean Errors

Tables 2 and 3 show the average horizontal and tridimensional errors for each forest and each point, considering the average results of both receivers but separating the solutions that each receiver can achieve. Code solutions are the results of Code-phase measurements on the L1 band of both GPS and GLONASS. Float solutions are positions which even the post-processing was unable to pinpoint as accurate, therefore prone to have errors. Fix solutions are positions which the post-processing could confirm as accurate or acceptable, based on the differential measurements. L1 results corresponds to the measurements of the L1 band for GPS only, L1+L2 corresponds to the dual-band measurements of GPS only, available only on the Base Station and Leica receivers in this case. GPS+GLONASS are the measurements of both GNSSs, available at the Base Station and the Ashtec receivers. The number of observations represents the number of obtained solutions for Float and Fixed solutions. In Code and L1 solutions the maximum number of observations can be four, two repetitions of each receiver. In other cases that number has a maximum of two observations, due to the unique capabilities of each receiver. Unless data loss occurs, results should be shown distributed in either solution (Float or Fix) but not exceeding the maximum number expected.

For Chouji Forest, no Fix solution was obtained in any of the cases. The main reason can be associated with the high and dense canopy of the surrounding forest and the surrounding mountains. GPS and combined GPS+GLONASS observations tend to increase in accuracy with longer observation periods (Andersen, 2009) and that is most of the cases here presented. However, the lower positional errors were acquired on the combination of GPS+GLONASS. Only one case of sub-meter position was detected on the dual-frequency for point B1. This reflects how much interference the canopy and other elements caused on the reception, a high number of data loss was observed in this survey results, especially for the GPS-only Leica rover. Tridimensional errors are substantially higher due to the vertical element included on the calculation. Vertical aspects of a terrain have a larger level of error than horizontal elements (El-Rabbany, 2006).

In Miyanomori Forest, results yielded less errors than in Chouji Forest, despite the forest being located on a valley facing north – GPS surveys in general are recommended to face south in the northern hemispheres due to the satellites orbit configuration. The observation period had mixed results; however, most of the Fix positions were obtained with 15 minutes observation and in the configurations of dual-frequency or GPS+GLONASS. In Float solution, GPS+GLONASS provided the best results with sub-meter accuracy, showing that how much improvement of a mixed system can achieve, even in the case of a single frequency receiver. It is important to observe that Fix solutions were obtained only in the harvested areas, but even in the forested areas, no data loss was experienced.

For multiple comparison tests, the values of horizontal error were converted to logarithmic values because horizontal errors have a logarithmic distribution. Then the Tukey-Kramer test was applied among single-frequency GPS code solutions, single-frequency GPS float solutions, dual-frequency GPS float solutions, single frequency GPS+GLONASS float solutions (Figure 3). Results show that there was a significant difference only between single-frequency GPS code solutions and single-frequency GPS+GLONASS float solutions ($p = 0.0097$). However not significant, there was difference between single-frequency GPS float solutions and GPS+GLONASS float solutions ($p = 0.1894$) and between dual-frequency float solutions and GPS+GLONASS float solutions ($p = 0.1770$).

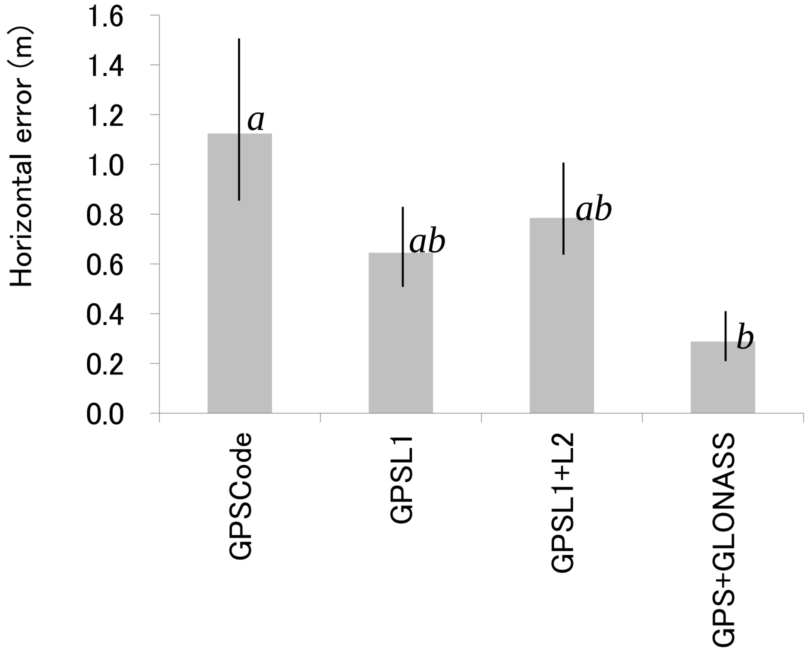


Figure 3 – Multiple comparison test using Tukey-Kramer method

Table 2 Mean horizontal errors

Mean Horizontal Error															
Observation Point	Observation Period (m)	Code Solution		Float solution						Fix Solution					
				L1		L1+L2		GPS+ GLONASS		L1		L1+L2		GPS+ GLONASS	
B1	1	6.59	(4)	6.50	(4)	-	-	2.73	(2)	-	-	-	-	-	-
	5	5.40	(4)	2.27	(4)	3.27	(1)	1.57	(2)	-	-	-	-	-	-
	10	1.74	(4)	9.21	(3)	1.38	(1)	1.42	(2)	-	-	-	-	-	-
	15	1.85	(4)	6.96	(4)	0.49	(1)	1.33	(2)	-	-	-	-	-	-
B2	1	2.95	(4)	12.14	(3)	-	-	2.88	(2)	-	-	-	-	-	-
	5	3.96	(4)	2.45	(4)	1.42	(1)	1.23	(2)	-	-	-	-	-	-
	10	3.45	(4)	1.19	(2)	-	-	1.11	(2)	-	-	-	-	-	-
	15	2.94	(4)	3.66	(4)	-	-	3.02	(2)	-	-	-	-	-	-
D1	1	4.34	(4)	4.34	(4)	-	-	2.54	(2)	-	-	-	-	-	-
	5	3.51	(4)	2.03	(4)	2.54	(2)	2.15	(2)	-	-	-	-	-	-
	10	2.62	(4)	2.05	(4)	-	-	1.69	(2)	-	-	-	-	-	-
	15	1.89	(4)	2.04	(4)	2.40	(1)	1.66	(2)	-	-	-	-	-	-
C1	1	2.27	(4)	2.29	(4)	1.49	(2)	3.91	(2)	-	-	-	-	-	-
	5	2.19	(4)	1.45	(4)	0.93	(2)	1.04	(2)	-	-	-	-	-	-
	10	1.88	(4)	0.60	(4)	0.97	(2)	1.14	(2)	-	-	-	-	-	-
	15	2.05	(4)	0.62	(4)	0.80	(2)	1.21	(2)	-	-	-	-	-	-
C2	1	1.24	(4)	1.24	(4)	1.49	(2)	0.88	(2)	-	-	-	-	-	-
	5	0.85	(4)	1.10	(4)	1.04	(2)	0.83	(2)	-	-	-	-	-	-
	10	1.18	(4)	0.72	(4)	0.68	(2)	0.55	(2)	-	-	-	-	-	-
	15	1.25	(4)	0.57	(4)	0.77	(2)	0.39	(2)	-	-	-	-	-	-
S1	1	2.73	(4)	2.71	(4)	0.75	(2)	4.64	(2)	-	-	-	-	-	-
	5	1.96	(4)	0.92	(4)	0.84	(2)	0.99	(2)	-	-	-	-	-	-
	10	1.19	(4)	0.86	(4)	-	-	0.13	(2)	-	-	0.42	(2)	-	-
	15	0.86	(4)	0.78	(4)	-	-	0.11	(1)	-	-	0.38	(2)	0.40	(1)
S2	1	1.00	(4)	1.00	(4)	1.08	(1)	0.94	(2)	-	-	-	-	-	-
	5	1.43	(4)	0.92	(4)	1.20	(2)	0.48	(2)	-	-	-	-	-	-
	10	1.08	(4)	0.53	(4)	0.97	(1)	0.16	(2)	-	-	0.00	(1)	-	-
	15	0.97	(4)	0.38	(4)	-	-	0.16	(2)	-	-	0.01	(2)	-	-
V1	1	1.40	(4)	1.38	(4)	0.93	(2)	2.31	(2)	-	-	-	-	-	-
	5	0.86	(4)	0.58	(4)	0.37	(2)	0.62	(2)	-	-	-	-	-	-
	10	0.21	(4)	0.64	(4)	0.55	(1)	0.24	(2)	-	-	0.03	(1)	-	-
	15	0.26	(4)	0.63	(4)	-	-	0.23	(2)	-	-	0.04	(2)	-	-
V2	1	1.44	(4)	1.44	(4)	1.79	(2)	0.67	(2)	-	-	-	-	-	-
	5	0.87	(4)	0.85	(4)	0.90	(2)	0.36	(2)	-	-	-	-	-	-
	10	0.67	(4)	0.29	(4)	0.72	(2)	0.43	(2)	-	-	-	-	-	-
	15	0.62	(4)	0.31	(3)	0.32	(1)	0.38	(1)	0.04	(1)	0.33	(1)	0.47	(1)

Table 3 Mean tridimensional errors

Mean Tridimensional Errors																	
Observation Point	Observation Period (m)	Code Solution		Float solution						Fix Solution							
				L1		L1+L2		GPS+ GLONASS		L1		L1+L2		GPS+ GLONASS			
B1	1	24.00	(4)	23.87	(4)	-	0	15.72	(2)	-	-	-	-	-	-		
	5	20.73	(4)	6.00	(4)	8.20	(1)	5.62	(2)	-	-	-	-	-	-		
	10	14.20	(4)	12.30	(3)	9.39	(1)	6.27	(2)	-	-	-	-	-	-		
	15	12.81	(4)	12.10	(4)	11.39	(1)	6.63	(2)	-	-	-	-	-	-		
B2	1	15.76	(4)	36.98	(3)	-	0	13.73	(2)	-	-	-	-	-	-		
	5	21.37	(4)	11.34	(4)	30.15	(1)	6.73	(2)	-	-	-	-	-	-		
	10	14.02	(4)	8.96	(2)	-	0	6.99	(2)	-	-	-	-	-	-		
	15	9.56	(4)	8.37	(4)	-	0	8.97	(2)	-	-	-	-	-	-		
D1	1	11.41	(4)	11.41	(4)	-	0	4.90	(2)	-	-	-	-	-	-		
	5	7.23	(4)	5.45	(4)	4.11	(2)	6.15	(2)	-	-	-	-	-	-		
	10	5.50	(4)	5.45	(4)	-	0	6.34	(2)	-	-	-	-	-	-		
	15	4.40	(4)	5.12	(4)	4.08	(1)	6.01	(2)	-	-	-	-	-	-		
C1	1	4.57	(4)	4.59	(4)	2.08	(2)	5.69	(2)	-	-	-	-	-	-		
	5	3.55	(4)	2.31	(4)	1.21	(2)	1.12	(2)	-	-	-	-	-	-		
	10	2.55	(4)	1.69	(4)	1.93	(2)	1.90	(2)	-	-	-	-	-	-		
	15	2.69	(4)	1.84	(4)	1.76	(2)	2.09	(2)	-	-	-	-	-	-		
C2	1	3.07	(4)	3.08	(4)	2.29	(2)	1.25	(2)	-	-	-	-	-	-		
	5	2.54	(4)	2.31	(4)	2.43	(2)	2.29	(2)	-	-	-	-	-	-		
	10	1.92	(4)	1.77	(4)	1.74	(2)	2.38	(2)	-	-	-	-	-	-		
	15	1.86	(4)	1.92	(4)	1.96	(2)	2.59	(2)	-	-	-	-	-	-		
S1	1	5.17	(4)	5.19	(4)	2.40	(2)	6.23	(2)	-	-	-	-	-	-		
	5	5.25	(4)	1.60	(4)	1.21	(2)	1.71	(2)	-	-	-	-	-	-		
	10	3.47	(4)	1.24	(4)	-	-	0.40	(2)	-	-	0.61	2	-	-		
	15	2.40	(4)	1.12	(4)	-	-	0.29	(1)	-	-	0.44	2	0.40	1		
S2	1	3.64	(4)	3.63	(4)	1.08	(1)	4.58	(2)	-	-	-	-	-	-		
	5	4.96	(4)	1.62	(4)	1.30	(2)	1.34	(2)	-	-	-	-	-	-		
	10	2.77	(4)	0.73	(4)	1.23	(1)	0.43	(2)	-	-	0.00	1	-	-		
	15	2.58	(4)	0.53	(4)	-	-	0.35	(2)	-	-	0.07	2	-	-		
V1	1	1.84	(4)	1.81	(4)	1.11	(2)	2.59	(2)	-	-	-	-	-	-		
	5	1.40	(4)	1.35	(4)	0.72	(2)	1.21	(2)	-	-	-	-	-	-		
	10	0.98	(4)	1.00	(4)	0.55	(1)	0.49	(2)	-	-	0.03	1	-	-		
	15	0.85	(4)	0.91	(4)	-	-	0.35	(2)	-	-	0.05	2	-	-		
V2	1	3.28	(4)	3.28	(4)	2.36	(2)	2.64	(2)	-	-	-	-	-	-		
	5	2.49	(4)	1.25	(4)	1.70	(2)	0.48	(2)	-	-	-	-	-	-		
	10	2.49	(4)	0.42	(4)	0.89	(2)	0.45	(2)	-	-	-	-	-	-		
	15	2.51	(4)	0.36	(3)	0.65	(1)	0.43	(1)	0.12	1	0.33	1	0.53	1		

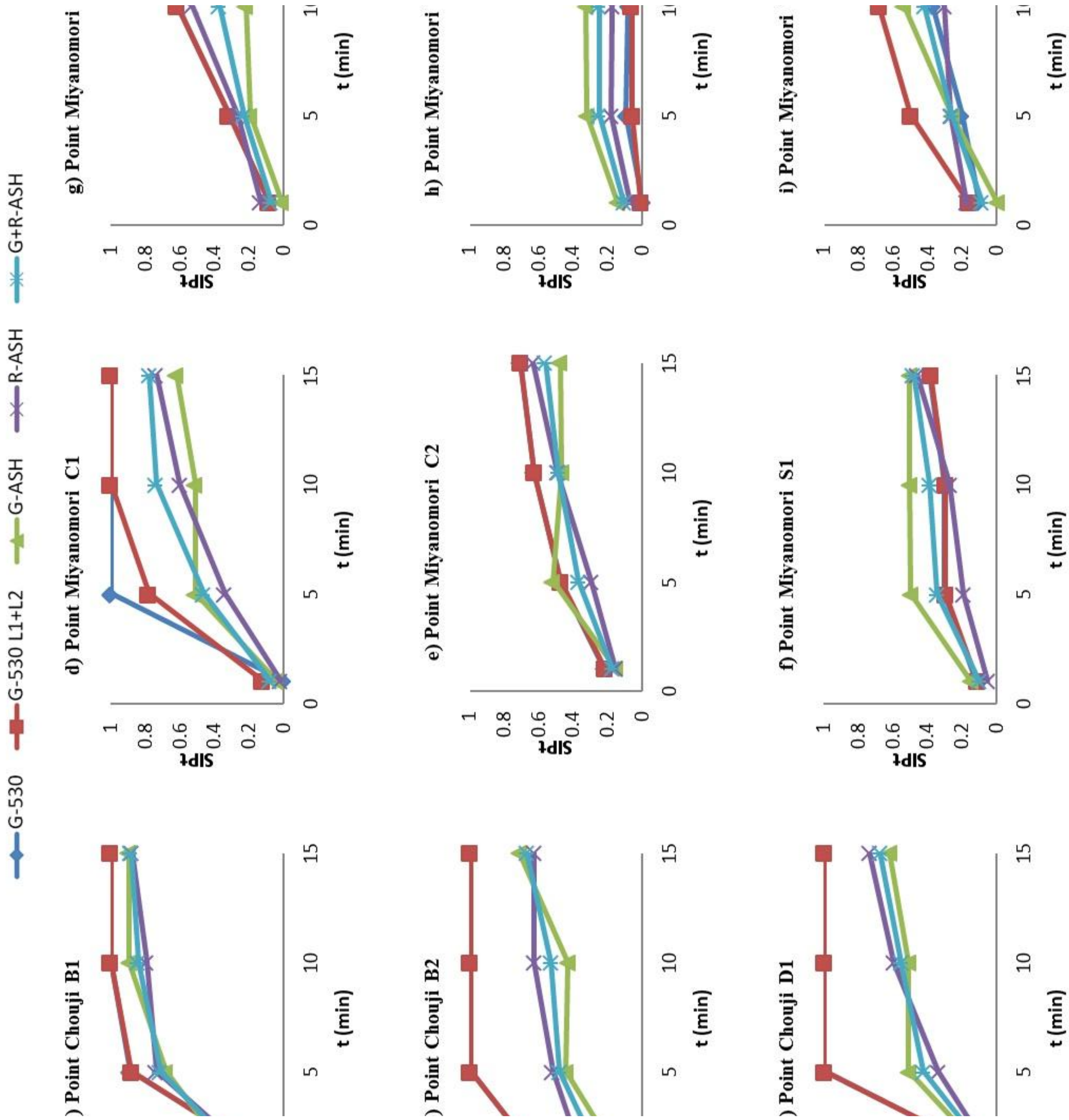
4.3.2 SIP and Observation Period

In the Figures 4a to 4i it is possible to observe the behavior of SIP along the observation period of 15 minutes (plots include repetition data) in each point separately and visualize the conditions of each site for GPS/GLONASS reception. “G” corresponds to the results of GPS L1 data, Code-phase measurements included; “G-530 L1+L2” is the Leica receiver in dual-frequency mode; “R” is the GLONASS-only measurements on L1/E1, including Code-phase measurements and “G+ R” includes both GNSSs.

Based on the data, GLONASS satellites suffered less interruption than GPS; GPS L1 and L1+L2 had a higher index of interruption and the combination GPS+GLONASS provided stable results. GLONASS only data is also in lower indexes compared to GPS. Results up to 10 minutes observation yield less interruption, even if the positional accuracy shown on Tables 2 and 3 is not high.

For Chouji forest (Figures 4a, 4b and 4c), the Leica receiver in single and dual-frequency modes suffered high rates of interruption, which was caused by the low number of GPS satellites at the moment of the survey. That is clearly shown on the figures, where the Ashtec receiver, with GPS and GLONASS capabilities had a lower interruption rate. Another factor that should be considered is that SIP is based on the reception rate, as in the number of logged observations for each satellite received, with a low number of observations in the area for GPS-only satellites, the Leica receiver performed poorly with the settings utilized in this survey. Also there is the possibility that the technological difference between receivers, which have a difference of 10+ years of release, allows the newest model (Ashtec Promark 100) to have a better performance in such extreme condition of that forest.

That is also shown on Miyanomori forest, where in the most closed canopy sites (C1, C2 and V2) had similar results to Chouji forest. In the cases, for relatively open points S1 and V1, dual-frequency performed better but not on S2, where the lowest interruption was acquired by the Ashtec receiver using only GPS satellites. Overall the GPS+GLONASS set of the Ashtec receiver yielded lower interruptions than the GPS-only Leica. It is important to remember that while reception can be higher for one receiver, the solution obtained might not be necessarily with a lower positional error, what can be seen on tables 2 and 3, where dual-frequency sets had a higher number of Fix solutions than the GPS+GLONASS. That can be attributed to the fact that, given the adequate conditions, a dual-frequency GPS-only receiver will perform better than a single-frequency receiver (Naesset, 2001; Cosser, 2003).

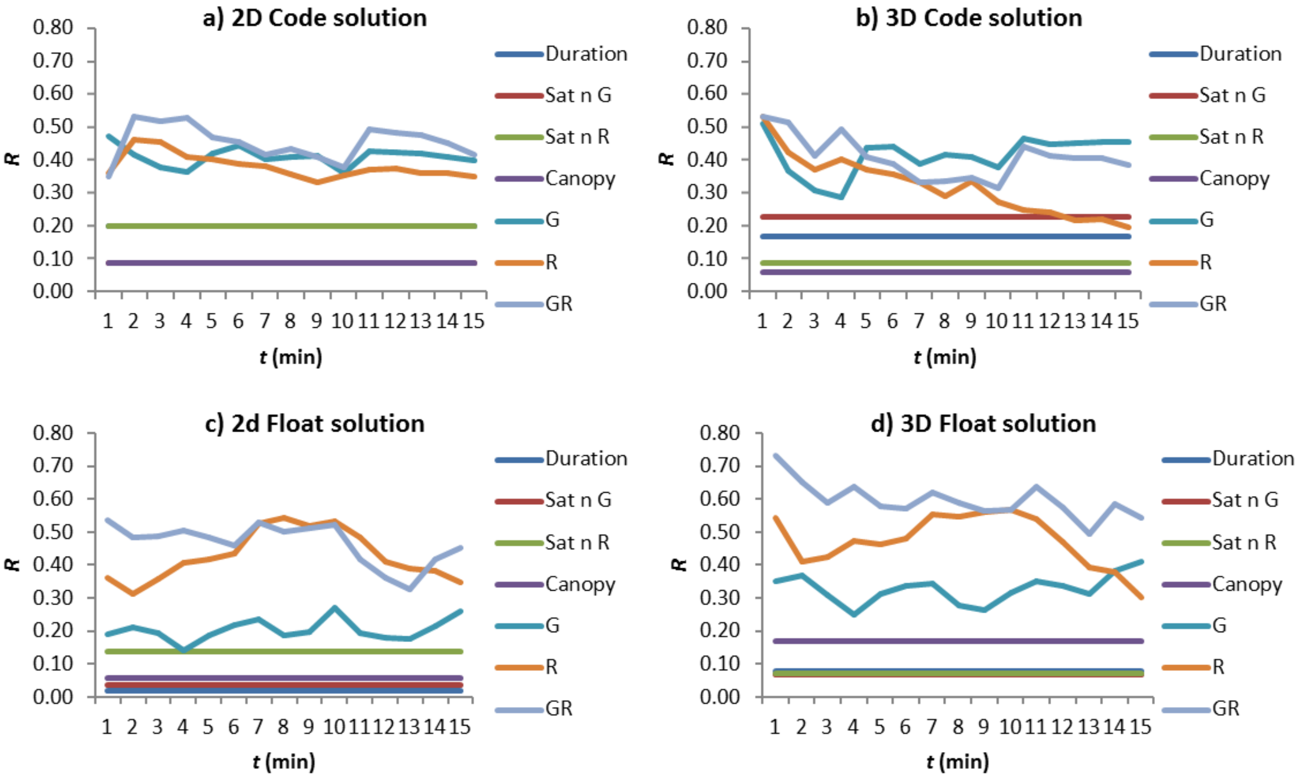


Figures 4a to 4i SIP behavior along the time for each individual point according to receiver and GNSS used. G = GPS, R = GLONASS, 530 = Leica GPS530 receiver, ASH = Ashtec Promark 100

4.2.3 Correlation of factors affecting positional accuracy

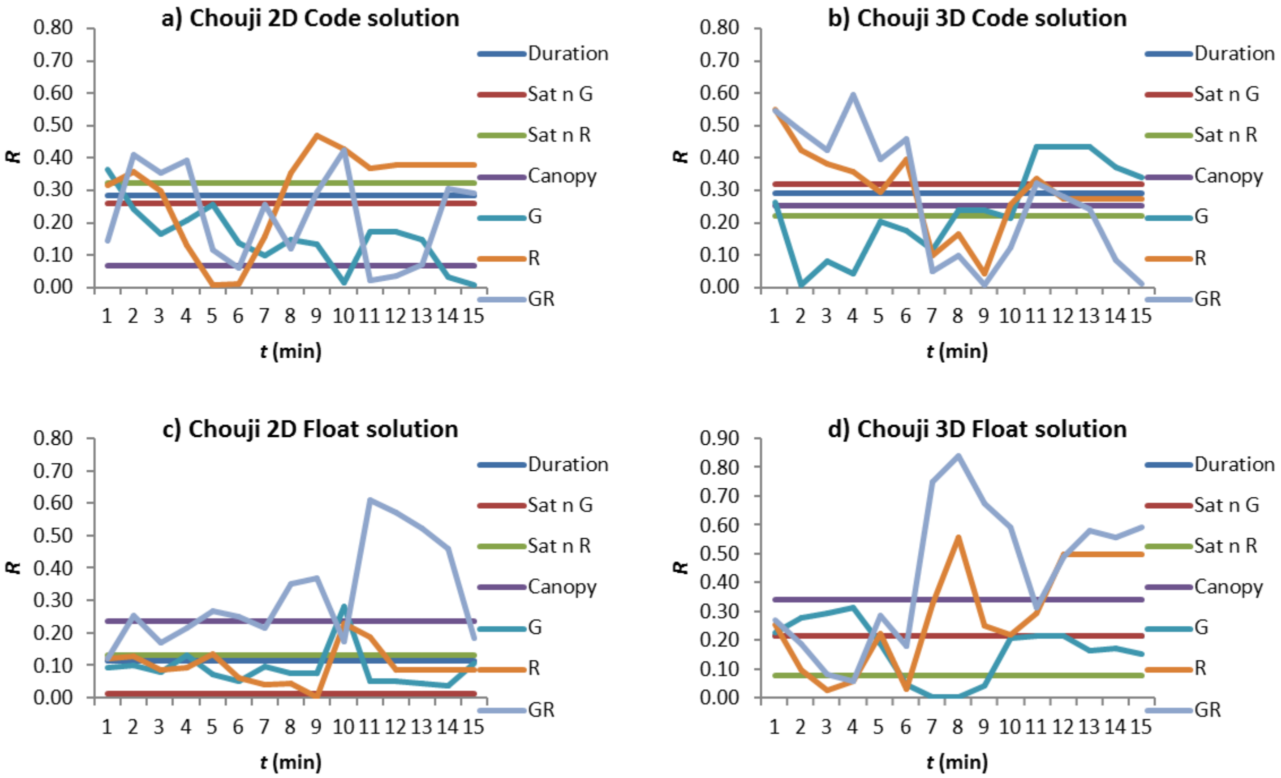
In figures 5, 6 and 7 we provide several correlation tests in diverse conditions in order to analyze SIP within other elements commonly associated to positional accuracy, both horizontal and tridimensional. At first we test the correlations for both forest type in Code and Float solution, the most commonly obtained solution in forest conditions. In Fix solutions, it is most important whether the ambiguity is resolved or not because Fix solution is accurate enough in forest work (Hasegawa & Yoshimura, 2003). Then Code and Float solutions will be discussed in this study.

Figures 5a to 5d show the results obtained in that case, with the combination of GPS+GLONASS having a higher correlational value for Float solutions and 2D/horizontal Code; GLONASS alone does not correlate to horizontal or tridimensional errors better than the combination of GNSSs. The peak of values are mostly before the first 5 minutes and around the 10 minutes mark, which agrees with previous studies (Naesset, 2001; Andersen 2009) in which longer observation periods provided better accuracy. That is also related to the Tables 2 and 3, in which those periods of time, especially 15 minutes yielded Fix solutions or lower positional errors on Code and Float solutions.



Figures 5a to 5d: Correlations between SIP, Observation Period (Duration), number of satellites and canopy opening index. G = GPS, R = GLONASS.

In figures 6a to 6d, we have the differences between solutions in Chouji forest. These mixed results are a portrayal of the reception conditions in the dense canopy of Chouji forest, with trees at an average age of 80 years old and an average DBH of 42 cm. Code solution had a high decrease in the periods of 5 to 10 minutes, but recovered values over time and at 15 minutes observation had higher correlation values for GPS. GPS+GLONASS performed better at Float solutions, with the peaks at 10 to 15 minutes observation.



a) Chouji 2D Code solution

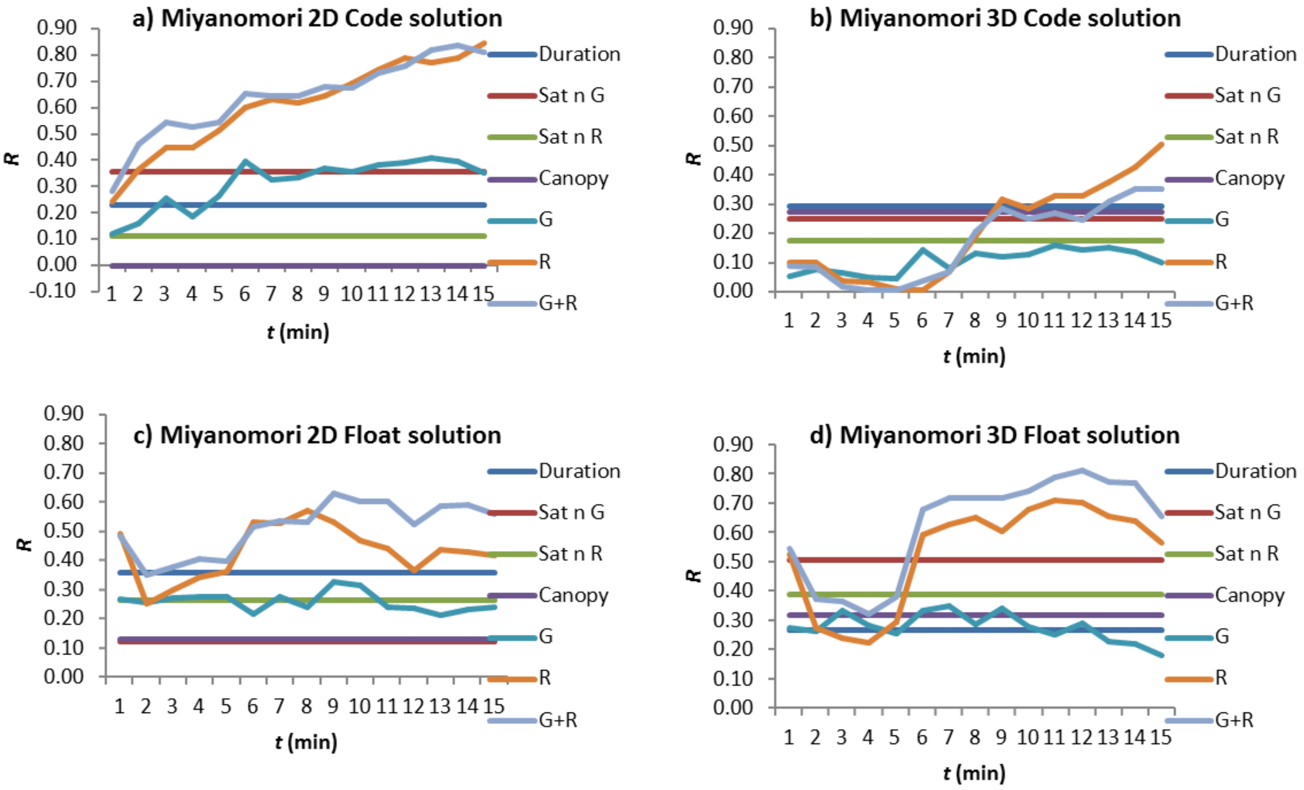
b) Chouji 3D Code solution

c) Chouji 2D Float solution

d) Chouji 3D Float solution

Figures 6: Correlations between SIP, Observation Period (Duration), number of satellites and canopy opening index in Chouji forest G = GPS, R = GLONASS.

In figures 7a to 7d we have the differences between solutions for Miyanomori forest. The overall performance had more clear results than in Chouji, especially for horizontal/2D code colution, where results are similar of Chapter 3, with Code results being stable for both systems but performing increasingly better for the GPS+GLONASS. Also as in chapter 3, Float solutions were less stable but overall presented higher correlational values, especially on the period between 10 and 15 minutes. In all cases GPS only performed on lower levels, which can be caused by the topography of the region, a cut slope facing north, as opposed as of the recommended for GPS receivers in the northern hemisphere – a factor where GLONASS has the advantage due to the higher angle of its satellites.



Figures 7a to 7d: Correlations between SIP, Observation Period (Duration), number of satellites and canopy opening index. G = GPS, R = GLONASS.

Overall, our results show SIP having a higher correlational value than all the other factors in most of the cases, such as Canopy Opening Index, Observation period and number of available satellites for each GNSS. These results explain better the mixed results of Tables 2 and 3, clarifying that in observation periods between 5 and 15 minutes, SIP tends to have higher correlation to positional errors, in accord to the original work by Hasegawa & Yoshimura (2007a). The correlations of SIP for combined GPS+GLONASS is also higher in most of cases. Combining the present data, it is safe to assume that SIP data obtained from GPS+GLONASS can provide important information about the signal reception under the tree canopies.

4.4 Conclusions

In this study, the combination of single-band GPS+GLONASS provided less Fix solutions than dual-frequency GPS-only, but has the tendency to provide Float solutions with smaller positional errors than GPS-only single-frequency or dual-frequency data. Accuracy was increased with the observation period, with the best positioning obtained between 10 to 15 minutes. Large positional errors on tridimensional results are expected because of the vertical factor and should also take in account the highly irregular topography of the terrain. SIP could reflect the reception of the signal clearly, with indexes of interruption higher for the GPS-only receiver. The mixed system receiver had higher correlational values errors on GLONASS-only or GPS+GLONASS, even though it is only single-band. SIP indexes also reflected well the reception conditions on each site, with lower values on the sites with better positional accuracy and higher canopy opening. Related to other factors such as canopy opening and number of available satellites, SIP also had larger representation on the positional errors in both receivers, Code and Float solutions and both GNSSs, combined or not, which shows that SIP can be used for combined systems like GPS and GLONASS. We suggest the usage of mixed systems whenever possible in order to achieve better accuracy, even under low reception conditions and observation periods of at least 10 minutes to achieve acceptable results. Further studies in more varied forest environments should be realized in order clarify the behavior of SIP under different conditions.

5. General Discussion and Final Conclusions

5.1 General Discussion

In Chapter 2 we analyzed and discussed about different antenna heights affecting GPS positional errors and its improvements over signal reception, regarding specifically SIP, along one year of observations. Although not a standard operation in traditional GPS surveys, which often rely on bipods or tripods, the latter with the advantages of using a tribrach to position the antenna center accurately on the desired survey point; raising the antenna height proved to offer improved results with less interruptions, as discussed on previous studies by different scholars. Operationally, the telescopic pole used for this survey offers the advantages of being light and of easy transportation and setting, but also becoming very instable on higher heights (>8 m) and having no possibility of centering the antenna center to a fixed point. However, the gains in positional accuracy, considering the heights which offered more stability, 5 and 8 m, outperform even the traditional tripod with tribrach. That happens due to the high number of elements surrounding the lower heights, such as smaller trees, shrubs, etc. SIP also proved to have lower rates on higher heights, decreasing considerably with the proximity of the antenna to the canopy, given that the canopy is not too dense. SIP also represents the canopy structure, especially stem and branches, which can be seen in our results due to the effect of seasonal changes for the canopy opening index but not for SIP. We recommend that whenever possible in forest surveys, to raise the antenna height in order to acquire less positional errors and obtain a higher reception rate, and consider SIP as more reliable index to define the structure of the canopy

In Chapter 3 we analyzed and discussed SIP under forest canopies within other factors commonly associated with positional errors, such as Positional Dilution of Precision (PDOP), or the satellite arrangement in the sky at the moment of the survey, observation period, Canopy Opening Index and number of available satellites. Raising the antenna at 5 m high, based on previous studies, we performed baseline analysis and correlations of SIP to positional errors within the aforementioned factors. SIP is shown with higher correlational values than all the other factors, what contrasts with previous studies in which PDOP and canopy opening were attributed to positional errors. Scholars had been studying for years the relationship between the canopy and GPS reception, often proving that the decrease of basal area increased positional accuracy, but utilizing SIP we can visualize that for every epoch on the survey, another advantage which can provide the level of reliability of a survey. We also found that observation periods between 10 and 15 minutes produce acceptable results, which complies with the previous study of Hasegawa (2007b) where SIP10 or SIP at 10 minutes of observation was used to predict positional errors.

In Chapter 4 we analyzed the SIP within GPS and GLONASS. The modernization of GLONASS and its interoperability with GPS provides a higher number of available satellites, which can be very advantageous for the forest survey, where often, are experienced loss-of-lock or lack of visible satellites to acquire signal. In this research we set the points to be surveyed on sites very common on forest operations in Japan, mountainous areas with low sky visibility and high canopy coverage of forest plantations. Such conditions rendered a challenge to acquire accurate positioning as shown in our data. Regardless of that, we could obtain SIP values for all sites, but not necessarily accurate positions. Our trials with two different receivers, one dual-frequency and one with GPS+GLONASS capabilities yielded results showing that in situations of dense forest, the mixed GNSS receiver performed better, while the dual-frequency receiver performed better in relatively open areas. Both receivers delivered results showing SIP as highly correlated to positional errors and to the canopy condition. Also, an observation period of 15 minutes provided the best results, which agrees with a number of studies on the matter. Furthermore, GPS+GLONASS showed higher correlational values to horizontal errors than GPS only and this indicates that SIP can be applied to other GNSS, increase the usability of the index with other active systems available in the near future. However, further studies should be made in the subject with a greater number of surveys and in different conditions to provide stronger basis to the matter.

5.2 Final Conclusions

GNSSs can provide this efficiency if reliable results can be extracted from such surveys. SIP provides information previously unavailable, such as the level of interference of the canopy or surrounding vegetation and the behavior of the signal during the survey, which reflects the canopy structure itself. This information is not obtainable in other practical or detailed form, since the Canopy Opening Index provides only the visibility levels of the canopy and satellite-related factors such as PDOP proven to be not relevant for the GPS survey. With this study we find important points about SIP, such as its relationship with the antenna height, reflecting the level of interference the lower vegetation can cause; it’s strong relationship with the canopy structure, regardless of seasonal changes; its direct correlation with positional errors and finally, its interoperability with GLONASS.

5.3 Future Works

Light Detection and Ranging – LIDAR is a remote sensing technique in which a laser scanning device attached to an aerial vehicle (usually referred as Airborne Laser Scan, ALS) or to a stationary/rotational base. Scans use laser pulses/beams of light and capture the return of these pulses (referred as returns or echoes) in order to construct spatial data, usually Digital Terrain Models (DTMs) or Digital Elevation Models (DEMs) of the area scanned; these models are tridimensional reproductions of the scanned surfaces based on horizontal and vertical coordinates given by these returns. LIDAR is a very efficient tool to capture forest elements due to its capacity to reach under the canopies and quantify its structure (Means, 2000; Lim, 2003; Niemann, 2007; Gatziolis, 2008). Applications of LIDAR in forest canopy research vary from estimation of volume and biomass (Popescu, 2004), estimation of leaf area index (Riano, 2004), prediction of light interception (Lee, 2009), among others.

Based on these studies, SIP and the study herein presented the relationship of SIP and LIDAR data can be further explored in order to provide deeper information about the canopy structure. SIP characterizes the main elements of interference on the canopy (large branches and stem) and the studies of Wright et al. (2008) and Liu et al. (2011) explored the attenuation level of the vegetation on the L-band of GNSS using LIDAR data. Wright et al. (2008) explored the relationship of the density of the canopy obtained using LIDAR data with the disruption of the GPS signals by correlating the changes on the SNR (signal-to-noise ratio) of the GPS signals received in forest conditions and found that the LIDAR point cloud could be used to predict the attenuation of the GPS signals. Liu et al. (2011) based on that study proposed to observe the direct line of sight in the vegetation attenuating the signal for each satellite considering the Fresnel zone, developing a Directional Vegetation Density model which correlates the vegetation structure to the signal attenuation. In a similar study, Hasegawa & Yonetsu (2006) calculated the vegetation resistance for each satellite available using LIDAR data to quantify the vegetation quantity along the signal’s path and developed an algorithm based on that data that could reduce positional errors.

With that information, the combination SIP and these techniques has the possibility to characterize the canopy using remote data. Since the signal attenuation was explored using SNR for individual satellites, using SIP to characterize the level of signal disruption for each individual satellite (individual SIP) we can obtain similar results in characterizing the canopy structure. Such study would deviate from the standard SIP, which considers the total number of signals received for all satellites and explore the interruption for each satellite supposed to being captured by a receiver at the survey moment, an information that can be obtained by the almanac and ephemerides of GNSS.

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