（ 続紙 1 ）

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論文題目	ANALYSIS OF SIGNAL INTERRUPTION PROBABILITY FOR GNSS UTILIZATION IN FOREST CONDITIONS （森林域におけるGNSS利用のための信号分断度（SIP）の分析）		

（論文内容の要旨）

In this study, the Signal Interruption Probability (SIP) applied to GNSS surveys under tree canopies was analyzed. The main objective was to assess the information that SIP provides about the reception in forest conditions and compare this data to other factors pointed by previous studies to find the applicability of the SIP as index. Allied to that some tests were also performed on different antenna heights, different observation periods and different GNSSs, under different forest environments, emulating as much as possible the scenario presented by surveyors and forest workers.

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

At first, the behavior of GPS signal under tree canopies using different antenna heights, which is an improvement previously explored in other studies. Allied to that factor, the observation of the SIP compared to other factors directly related to GPS survey, such as the canopy opening index and its variations in the seasonal changes were explored within four different forest environments in Kyoto University Kamigamo Forest Research Station. The results show that horizontal errors decrease with higher antenna heights, given that the antenna pole is stable. The lowest height (1.5m) suffers interference of surrounding vegetation and thickest parts of the tree, even though it was very stable. The highest height (11m) was highly affected by the instability of the antenna pole utilized, which curved over the antenna weight as well as its own, being also subject to wind and providing results with high positional errors. The mid-heights of 5 and 8 m provided the results with less error, which gives the conclusion that at these heights, if the pole is stable, lower vegetation and the thickest parts of the trees are eliminated from the reception path, providing favorable results. SIP could provide information about the signal structure more efficiently than the canopy opening index, because it is not affected by the seasonal changes, reflecting the interfering elements of the canopy regardless of the season. The results show clearly that simple techniques can improve the traditional survey and allow us to assess the reliability of the signal received. It is recommended that the usage of higher antenna heights be incorporated on surveys and usage of SIP to determine the quality of data survey.

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

In this part, a deeper analysis of SIP was realized comparing it to other factors associated with GPS data reliability, such as PDOP, canopy opening index, observation period and number of available satellites. The period of observation, which would provide the data with higher positional accuracy, was analyzed based on SIP observations. The research was conducted using an antenna height of 5 m in four different forest environments Kamigamo Forest Research Station. The results show that SIP has a higher correlation to horizontal and tridimensional errors than all other factors, which highly increases its usability and potential as assessment tool for data quality assurance either on-site or during post-processing. It was also found that mean positional errors do not necessarily increase with a longer period of time, as previously stated in other studies. Instead, periods of time between 10 and 15 minutes of

observation yielded acceptable results according to the signal analysis using SIP. These results give SIP a stronger background to its application in the future.

III. Characteristics of Signal Interruption Probability in Multiple Use of GPS and GLONASS Satellites

Finally, comparison between effects SIP and other factors on GNSS surveys including both GPS and GLONASS was analyzed to estimate usability of SIP with other GNSS. The effects of SIP was compared with the number of available satellites, canopy opening index, observation period and the usage of GPS dual frequency vs. GLONASS singles frequency, plus the combination of both systems. The data collection was conducted at Kyoto University Ashiu Forest Research Station, in two different Japanese cedar forests, with different topographical characteristics and different forest age. The results show that SIP was, as in the other chapters, a significant index to obtain information about the canopy structure and reception conditions, reflecting the quality of the data according to the terrain and forest characteristics of each place. SIP was also successfully utilized with GLONASS utilizing a slightly modified version of the software utilized on the previous chapters. Combined systems performed with less positional error in more dense forests but dual-frequency GPS performed with higher accuracy in relatively open sites. In the analysis, GPS+GLONASS had an overall better performance than GPS only. By this study, it was clarified that the usability of SIP also with other GNSS, and the results give SIP background to be applied in GNSS forest surveys.

In this study, SIP in all cases was shown as factor directly related to horizontal and tridimensional error and has a higher correlation than previously studied factors such as PDOP, observation period, number of available satellites and canopy opening index. SIP also provides more reliable information than the canopy opening index because it is not influenced by the seasonal changes, giving information of the real interfering elements of the canopy regardless of forest type and time of the year. SIP is also as applicable to other GNSS as it is for GPS, having being successfully used with GLONASS and giving important data for the system's signal reception quality. In conclusion, SIP has the potential to be used in field to evaluate the quality of the data acquired, can give important information about the canopy structure and the site's reception conditions. It is highly recommend SIP use and application in the field and research as a quality and error management tool.

The characteristics of SIP, which is hardly affected by seasonal changes, can be applied to the forest inventory such as stand volume estimation. This is agree with the results of some researches indicating relationship between forest canopy structure and GPS signal condition by using LIDAR (Light Detection and Ranging) analysis. The combination analysis of SIP and LIDAR may produce new forest inventory techniques in the future. For example, forest workers can simultaneously obtain positional data by GPS positioning and stand volume at that point by analysis of SIP.

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（続紙 ２ ）

（論文審査の結果の要旨）

森林での位置情報の取得は，多様かつ複雑な生態系を有する森林の持続的管理・利用において，大変重要な問題である。近年はGPSをはじめとするGNSS技術の発達によって，森林内でも容易に絶対座標を得ることができるようになったが，GNSSは単に観測された座標を表示するのみで，その観測精度を明らかにするためには，高度な測量計算や高価な測量機器を使用するほかなかった。特にGNSSは障害物のない状況での使用を想定して開発されており，森林のように複雑な障害物を有する環境での精度管理は長年の課題とされてきた。本研究は，信号分断度（SIP）を指標としてGNSSによって取得された位置情報の精度管理を目指すものであり，これまで提唱はされてきたものの，その挙動や有用性等について十分に議論されてこなかったSIPに関する貴重な研究であり，応用面・社会への波及性も含めて極めて重要な業績である。

評価できる点は次のとおりである。

第一に，GNSS測位精度およびSIPの挙動を多面的に評価している点である。GNSS測位はばらつきが非常に大きく，複数の林分環境や異なった観測高，異なった季節における測位試験を実施することが困難であるが，これらを統一的に実施した例自体がこれまでになく，大変貴重なものである。

第二に，様々な林分におけるGNSS測位精度およびSIPの挙動に関する季節変化を明らかにした点である。GPS測位精度に関する季節性については，既存の研究例がいくつかあるが，落葉樹林，常緑樹林，人工林といった比較例はほとんどなかった。中でも全天写真の撮影による解析例では，落葉樹林における落葉が測位精度に与える影響の過大評価が問題となっていたが，SIPでは適正に評価されることを明らかにした点は，大変重要である。

第三に，SIPの挙動を明らかにした点である。SIPは信号の分断を評価する時間設定によって，測位精度との相関が大きく変化することが知られていたが，これをコードディファレンシャルと干渉測位の各手法別に，明らかにした。

第四に，GNSS観測精度推定におけるSIPの有用性を明らかにした点である。開空度やPDOPなどのこれまで提唱されてきた指標に比べ，SIPがより高い相関を有することを明らかにし，これらの組み合わせによってより高度な精度管理が可能になった。

その他，SIPがGPSだけでなくGLONASSなど他のGNSSにも適用可能であることを示した点，およびSIPとLIDARとの組み合わせによって新たな森林資源調査の可能性を示した点も評価できる。

以上のように，本研究は今後の研究および実地への応用，波及性の点から，非常に価値が高く，林学ならびに林業工学、森林経理学の発展に寄与するところが大きい。

よって，本論文は博士（農学）の学位論文として価値あるものと認める。

なお，平成２５年７月１２日，論文並びにそれに関連した分野にわたり試問した結果、博士（農学）の学位を授与される学力が十分あるものと認めた。

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