


Performance Evaluation of the Use of a Low-cost High Sensitivity GPS (HS-GPS) Receiver in Forests

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Abstract

For many precise navigation and surveying applications in forests, such as the navigation of tractors, harvesters and forest machines, as well as static cadastral surveys or the determination of the size of agricultural land for European Union funding, the use of low-cost GNSS receivers has become increasingly popular. High Sensitivity GPS (HS-GPS) receivers are frequently employed for these tasks because they provide higher availability and good performance even under unfavourable satellite visibility conditions. This study investigates the practicability of the usage and the achievable quality of a certain low-cost HS-GPS receiver under forest canopy in such types of applications. Different test areas in deciduous, coniferous and young forests representing variations of kind, age and form of trees were selected. Long-term observations in summer, winter and autumn over at least two days at ten selected test points were carried out. Hence, several tests under varying states of foliation could be evaluated which clearly show the influence of the type of forest, tree height and foliage moisture as a matter of the season. It was found that the performance of a HS-GPS receiver is acceptable and static single point positioning generally performs well for the above mentioned applications. For static code measurements the mean horizontal deviations range from few dm up to 2 m with a standard deviation of around 8 m depending on season and length of the observation time. In the case of carrier phase solutions from baseline observations to a virtual reference station, however, a significant reduction of signal quality is seen. Using robust estimation, the influence of outliers could be efficiently reduced. Single frequency relative positioning with robust estimation then yielded a median deviation of less than 10 cm with an interquartile range (IQR) of around 3 m.

Keywords: Low-cost HS-GPS, forest canopies, HS-GPS performance analysis

Kurzfassung

Immer häufiger werden heute low-cost GNSS-Empfänger für viele Navigations- und Vermessungsanwendungen im Wald verwendet. Typische Anwendungen sind die Navigation von Traktoren und anderen Forstmaschinen, Katasteraufgaben, sowie die Bestimmung von förderungswürdigen Flächen für Förderungsprogramme der EU. Sehr oft werden hier High-Sensitivity GPS (HS-GPS) Empfänger verwendet, da sie auch unter schlechten Empfangsbedingungen eine hohe Verfügbarkeit aufweisen und Positionslösungen berechnen können. Diese Studie untersucht die Möglichkeiten der Verwendung und die erreichbaren Genauigkeiten eines HS-GPS Empfängers im Wald. Um die Einflüsse von Art, Alter und Höhe zu untersuchen, wurden mehrere Testgebiete in Nadel-, Laub- und Jungwald bestimmt. Im Winter, Sommer und Herbst wurden Messungen über mindestens zwei Tage an zehn vorher bestimmten Messpunkten durchgeführt. Dadurch konnten in den Auswertungen der Einfluss der vorherrschenden Baumart, Baumhöhe und der saisonal bedingten Änderungen des Blätterdaches bestimmt werden. In dieser Testreihe funktionierte der HS-GPS Empfänger zufriedenstellend und auch die statische Positionsbestimmung erwies sich als einsetzbar für die betrachteten Anwendungen. Statische Codemessungen zeigten eine mittlere Lageabweichung von wenigen dm bis zu 2 m mit einer Standardabweichung von rund 8 m abhängig von der Jahreszeit und Beobachtungslänge. Werden Trägerphasenlösungen im Zuge einer Basislinienmessung zu einer Referenzstation bestimmt, ist eine deutliche Verschlechterung der Signalqualität festzustellen. Durch robuste Schätzverfahren kann der Einfluss grober Fehler effektiv reduziert werden. Relative Einfrequenzmessungen mit robusten Fehlerdetektion führt zu einem Median von unter 10 cm mit einem Quartilabstand von rund 3 m.

Schlüsselwörter: Low-cost HS-GPS, Waldbedeckung, HS-GPS Leistungsuntersuchung

1. Introduction

GNSS is employed in numerous situations and the use of low-cost receivers in particular has become very popular [2]. Owing to applications in challenging environments, such as in urban canyons or covered areas, it has become very important to further develop GNSS receiver technology and measurement data analysis. A strong impact came from the mobile phone sector in which new more powerful electronic components have been developed. It was possible to build receivers which have a much better performance and higher positioning capabilities. These are called High Sensitivity GPS (HS-GPS) receivers. In contrast to conventional receivers they have millions of integrated correlators. The u-blox LEA-6T receiver used in this study has two million correlators and can acquire signals as low as –178 dBW. Owing to improved calculating capacities new 'deep' GPS signal search techniques, such as non-coherent integration (see [1]), can be used. Owing to higher calculating capacity the time-to-first-fix can be reduced to less than one second. Under severe conditions, however, the integration time can be extended up to thousand milliseconds [3].

In forests particularly GPS signals are scattered by foliage. Multipath is the major problem due to signal reflections and diffraction effects. This causes that conventional low-cost GPS receivers have serious problems in acquiring and tracking GPS signals. HS-GPS receivers, on the other hand, can acquire signals and track them even under these unfavourable conditions. This study investigates the practicability of a low-cost HS-GPS for usage under forest canopies. The research hypothesis is that low-cost HS-GPS receivers are suitable for applications such as the navigation of forest machines, static cadastral surveys or the determination of the size of agricultural land for European Union funding. The performance is demonstrated by providing general information of accuracy and reliability.

2. Test set-up and data processing

In cooperation with the Austrian Federal Forest Department (ÖBF) a test area near Pressbaum in the Wienerwald west of Vienna was selected. The Wienerwald is a mixed forest with heterogeneous variations in kind, age and form of trees in a relatively small area. As the definition of forest varies also the physical characteristics of wood vary. Therefore ten survey points were established in the test area located in miscellaneous types of forest, i.e., deciduous, coniferous and young forest. The height of the trees was 10 to 20 m in the deciduous and coniferous forest and 5 m in the young forest. The ten test points were conventionally surveyed with traversing using a total station and embedded into a local GPS network. Their standard deviation is in the range of around 1 cm. Long-term static observations of 24 h periods were performed at least twice on each survey point in different measurement campaigns. To cover the whole vegetation cycle measurement campaigns were carried out in three different seasons with different states of foliage. The first one was in summer with moist foliage, the second in October with dry foliage and the last in March without leaves on the trees. In this study a u-blox LEA-6T receiver which also logged the raw data for post processing was used with its standard antenna. For the static measurements the antenna was mounted on a tripod. A thorough analysis of the great number of observations was done in post processing using Leica GeoOffice (LGO) in several ways, i.e., code single point positioning (SPP) solutions using broadcast ephemeris with and without EGNOS corrections, relative carrier phase positioning solutions using baselines to a virtual reference station in the Austrian EPOSA CORS network and the use of either broadcast or precise ephemeris. The different solutions are compared with the absolute coordinates of the survey points. In the following sections selected results of the extensive study are presented.

3. Code solutions

First of all, real time C/A code solutions under open sky and with foliage were carried out to analyse the receiver general performance. Figure 1 on the right visualizes the deviations from the ground truth for the code single point solution of a 24 h session on two survey points, one under open sky (left) and one with coniferous canopy (right). The elevation cut-off angle was set to 15°. The loss of positioning accuracy under forest canopy can easily be seen in the deviation maps. The standard deviation of 2.9 m under open sky increased crucially with foliage. This loss of accuracy is a consequence of the lower signal to noise ratio (SNR). The average C/N_0 as indicator of the SNR decreased from 42.2 dB under open sky to 34.8 dB under canopy.

In the following, three different code SPP solutions of the observations in the forest were analyzed (see Table 1). Solution 1 is a single epoch real-time SPP solution over a 24 h session which was then divided into 3 h observation windows (solution 2) to analyse how static measurements perform over shorter time spans. From the 24 h observation time the resulting deviations of a certain 3 h window are given in the Table. In these tests SBAS-aid (i.e., EGNOS) and receiver autonomous integrity monitoring (RAIM) for blunder detection were used. From the resulting coordinates deviations to the absolute coordinates of the survey test points were calculated. The average horizontal deviations of solution 2 are similar to the one of solution 1, but their standard deviations are far better, i.e., they are around 3 m. The reason for this is that in the certain 3 h session fewer outliers are present. Solution 3 is a post processed SPP solution over 24 h without SBAS and RAIM. The larger horizontal deviations

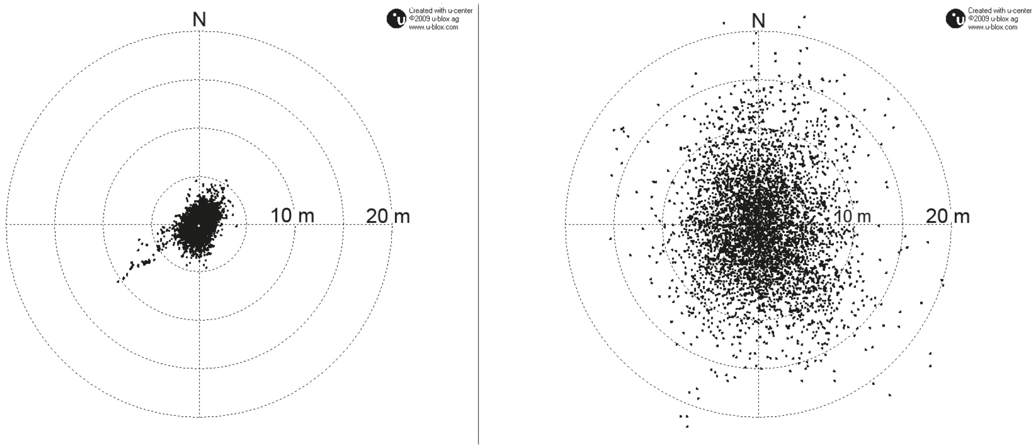

Fig. 1: Comparison of deviation maps of real-time code solutions under open sky on the left and with foliage on the right

of this solution remarkably show that the use of EGNOS and RAIM for blunder detection yields a much better result (i.e., in solution 1). In addition, it can be seen from Table 1 that the results in the coniferous forest are slightly better than in the deciduous and young forest, especially for solution 3.

Furthermore the code SPP solution performance of the receiver in the three different seasons was analysed in more detail. Table 2 shows the results for summer, autumn and winter. The deviations from ground truth of SPP solutions for session lengths of 24 h are given in the Table. In the measurement campaign these sessions were repeated at least twice in all three seasons. Mean horizontal deviations of better than 1 m with a standard deviation of around 8 m are achieved in summer and winter in all three forest types. In autumn, however, the mean horizontal deviations are around 2 m in deciduous and young forest. In the coniferous forest they are 1.1 m. Thus these results indicate that dry leaves cause a higher reduction in positioning accuracy than freshly soaked leaves. As expected, the deviations in height are much larger and the reach over 15 m in the deciduous forest, again in autumn.

4. Differential carrier phase solutions

In this section the results of the L1 carrier phase measurements are discussed. Due to the attenuation and delay by the foliage the carrier phase observations are heavily biased. In the paper we use the term 'phase solution' if all ambiguities can be fixed as integers. If ambiguities cannot be fixed to integers a 'float solution', or if no ambiguities could be fixed a 'code solution' is obtained. This differentiation is an effective way to evaluate the performance and the improvement achieved for measurements under forest canopy, because all three solutions show different behaviour patterns. Due to immense influence of the canopy baseline solutions under high canopy are even worse than the code solutions presented in chapter 3. Table 3 shows a comparison of mean, standard deviation, median and interquartile range (IQR) of the horizontal deviations from ground truth for static baseline solutions in 3 h observation windows over two days. An immense difference in mean and median (which is the largest in deciduous forests) indicates a large number of outliers. Table 4 shows a comparison of horizontal and vertical deviations exemplarily in summer with varying session lengths from 15 minutes up to

Forest type	Horizontal mean and standard deviations in [m]					
	Solution 1		*Solution 2*		*Solution 3*	
Deciduous	0.66	8.31	0.71	2.99	2.27	3.21
Coniferous	0.41	7.90	0.33	2.13	0.53	3.11
Young	0.86	7.45	0.98	3.20	2.58	5.80

Tab. 1: Comparison of horizontal mean deviations from ground truth and their standard deviations in [m] of three different code solutions

Summer	Deciduous		Coniferous		Young	
	horiz.	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*
Mean	0.66	12.91	0.42	11.45	0.87	4.38
Std. dev.	8.31	10.19	7.90	9.39	7.45	8.24
Autumn	**Deciduous**		**Coniferous**		**Young**	
	horiz.	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*
Mean	1.97	15.80	1.09	13.82	2.23	8.34
Std. dev.	7.54	8.81	7.13	8.19	7.42	7.78
Winter	**Deciduous**		**Coniferous**		**Young**	
	horiz.	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*
Mean	0.18	14.07	0.58	8.98	0.65	4.82
Std. dev.	7.38	8.93	5.95	7.19	5.27	5.99

Tab. 2: Comparison of mean horizontal and vertical deviations and their standard deviations in [m] in three different seasons over 24 h session lengths

Forest type	Mean / Std. dev.	Median / IQR		
Deciduous	16.61	72.67	0.74	8.06
Coniferous	8.91	49.93	0.46	5.05
Young	0.50	2.98	0.03	0.91

Tab. 3: Comparison of mean, standard deviation, median and interquartile range (IQR) of horizontal deviations in [m] for static baseline solutions in 3h observation windows

Summer	15 min.		30 min		1h		2h		3h		6h	
	horiz.	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*	*horiz.*	*vert.*
Mean	1.06	12.19	3.50	–7.43	2.29	1.32	3.36	–15.96	3.77	–11.55	2.63	6.39
Std. dev.	254.42	471.44	148.97	345.83	39.11	164.32	43.92	208.70	53.23	254.37	31.44	41.71
Median	0.16	1.77	0.14	1.54	0.07	1.52	0.07	1.33	0.02	1.12	0.03	1.07
IQR	4.32	6.13	4.67	6.03	4.97	6.28	4.93	4.63	3.49	5.68	4.02	4.28

Tab. 4: Comparison of mean, standard deviation, median and interquartile range (IQR) of horizontal and vertical deviations in [m] in summer with varying session lengths

6 h in all forest types. As can be seen, many outliers cause high standard deviations and they are not normally distributed. Median and IQR, on the other hand, show that a high positioning accuracy can be achieved if outliers are eliminated. The percentage of phase, float and code solutions over different observation times can be seen in Figure 2. Focusing on the percentage of phase solutions in deciduous and coniferous forests, the percentage reaches its maximum after two to three hours at around 12%. Float solutions are dominant and nearly no code solutions occur. In young forests the number of phase solutions increases with the length of observation time and nearly all ambiguities can be solved in observations over 24 h.

Further analyses of phase and float solutions are shown in Figure 3. Here standard deviations and IQR are compared in the three forest types over different observations windows from 15 minutes up to 6 h. The cause for high standard deviations in the float solutions are the large number of outliers. When looking at the IQR it can be seen that robust filters can reduce this influence significantly by eliminating the outliers.

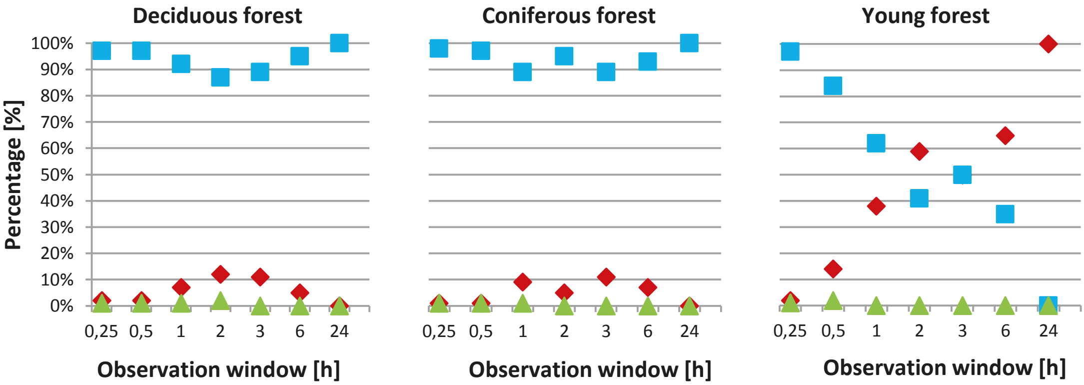

Fig. 2: Comparison of the percentage of phase (red), float (blue) and code (green) solutions over different observation time lengths in the three forest types

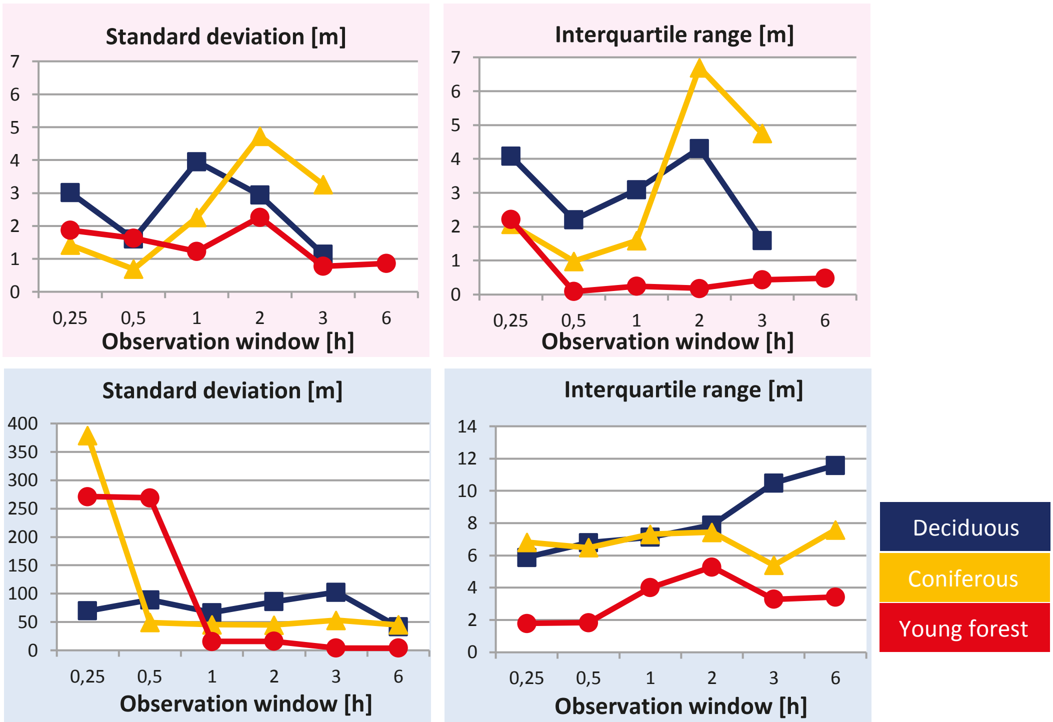

Fig. 3: Comparison of standard deviations and IQR of horizontal deviations of phase (top) and float solutions (below) in [m] in dependence of the observation time length [h]

By evaluating seasonal trends of the phase, float and code solutions it can be recognized that positioning results in summer with moist foliage are better than in autumn when the foliage is dry. As expected, in winter the performance is best. One of these indicators is the percentage of phase solutions which is presented in Figure 4 over different observations windows from 15 minutes up to 6 h. In the longer observation windows it can clearly be seen that in autumn the number of phase solutions is lower than in the other two seasons. For observation windows of longer than 2 h the number of phase solutions reaches around 25 % in summer and up to 30 % in winter. In deciduous and coniferous forests float solutions are usually obtained. These are highly affected by outliers caused by biased carrier phase observations. This analysis also shows that the number of phase solutions is lowest in deciduous and the highest in young forest. As an example the IQR of the phase and float solutions for the deciduous forest over the three different seasons with varying observation windows ranging from 15 minutes up to 6 h is shown in Figure 5. The IQR of the float solutions is very similar in all seasons whereas the phase solutions vary significantly, but on a lower level. In winter the lowest IQR for the phase solution of less than 1 m occurs for observation windows of 6 h.

5. Statistical analysis of raw data

In the following, a statistical analysis of raw data is presented and discussed. For post processing RINEX files of raw observations were used. The loss-of-lock indicator (LLI) in these files describes if a loss of the carrier phase ambiguity occurred and a new unknown ambiguity has to be introduced and solved for. In case of dual frequency receivers LLI-flags indicate not only if the phase ambiguity is lost, but also if a change of the wavelength factor occurred. For single frequency receivers, however, this distinction is not possible. In the following analysis the LLI flags

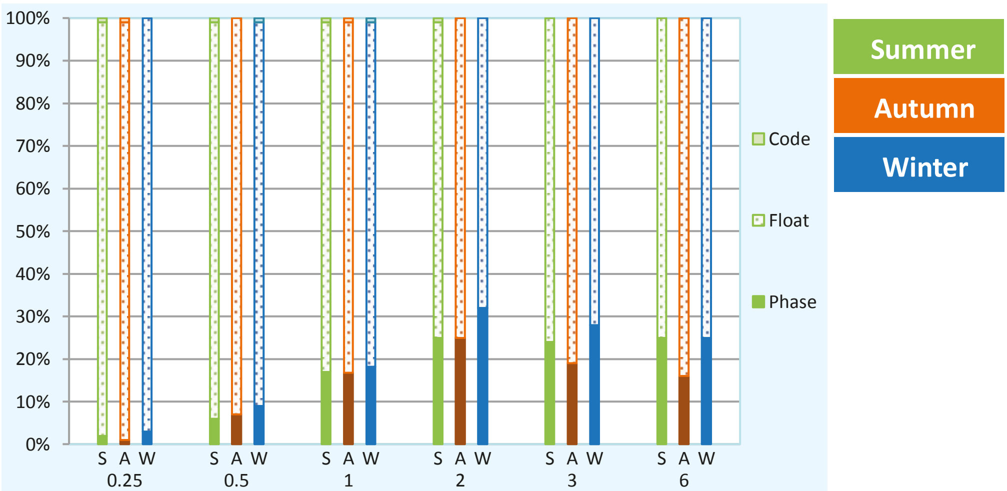

Fig. 4: *Comparison of percentage of phase-, float-, and code solutions in summer, autumn and winter depending on the observation time length [h] averaged over all forest types*

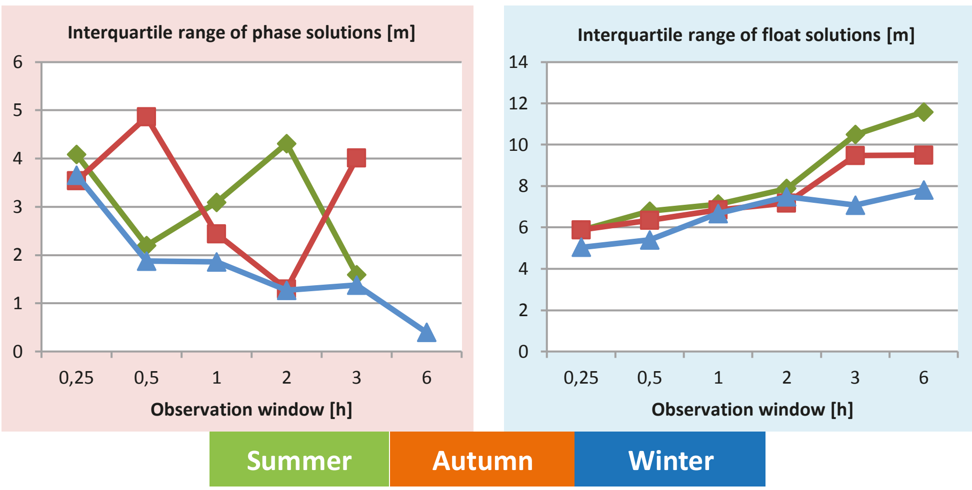

Fig. 5: *Comparison of IQR of phase and float solutions in [m] in the deciduous forest in dependent on observation time length [h]*

were only regarded as an indication if a loss of the ambiguities occurred or not. Hence it is distinguished between two cases, i.e., one with and the other without LLI flags in the RINEX raw data file. Figure 6 depicts histograms of the carrier-to-noise density ratio C/N_0 distribution showing the magnitude of the signal strength. The percentage of LLI flags corresponds to the dominating signal quality. Looking at the distribution of observations (blue distribution) it can be seen that this distribution can be split into two sub-quantities, i.e., unaffected signals without LLI (green distribution) and affected signals with LLI flags (red distribution). Reference observations under open sky conditions showed that most observations have a C/N_0 ratio of above 35 dBHz. In contrast to these observations the number of observations with LLI flags increases to 43% in forests and the mean of the C/N_0 ratio of all observations decreases from 42.16 to 34.80 dBHz. For the observations without LLI flags it decreases to 40.67 dBHz whereas the mean of the observations with LLI flags increases slightly. This means that the signal-to-noise ratio is weaker in forests than under open sky conditions which can be compensated only partially when employing HS-GPS receivers. But the observations with LLI flags show a significant rise between 20 and 40 dB which most likely causes the high scattering of the position estimates (compare Figure 1). Furthermore it was investigated if there are major differences depending on the type of forest. The results showed that there are no significant differences in high forest (i.e., deciduous and coniferous) in which about half of the satellite observations are flagged with LLI flags. In the young forest the number of observations with LLI flags is significantly lower, it is at around 30%. When analyzing the observations in dependence of the season it could be seen that the number of observations without LLI flags is higher in winter than in the other two seasons. To summarize it can be said that the signal-to-noise ratio is 4 dBHz lower in forests than under open sky.

6. Conclusions and outlook

The aim of this study was to investigate the performance of HS-GPS receivers in forests. Measurement campaigns in three different seasons with long-term static observations of 24 h periods were repeatedly performed at each of ten selected survey points serving as ground truth. The coordinates of these test points were obtained from conventional surveying with traversing using a total station with a standard deviation of 1 cm. They are located in deciduous, coniferous and young forests with tree heights ranging from 5 to 20 m. The results were compared according to the forest type and season to the absolute coordinates of the survey points. Code SPP solutions using broadcast and precise ephemeris as well as EGNOS corrections and differential carrier phase baseline solutions to a virtual reference station in the Austrian CORS

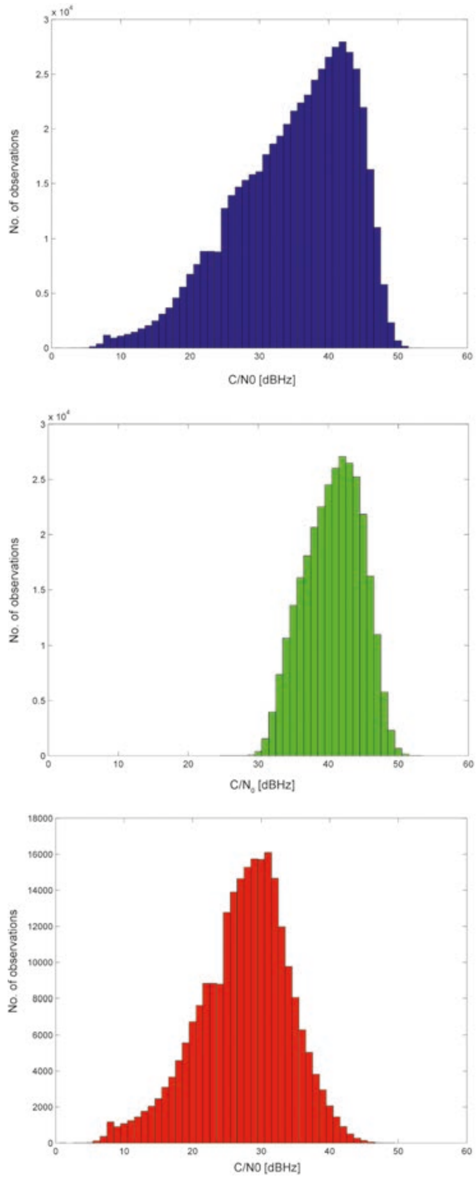

Fig. 6: Histograms of C/N0 ratio distribution for the whole observations (blue), without LLI (green) and with LLI (red) flags of the summer campaign

network EPOSA were processed and analyzed. The employed receiver generally performed well as no complete failures were detected.

For static code SPP the mean horizontal deviations on the ten survey points from the ground truth ranged from few dm up to 1 m with a standard deviation of around 8 m in summer and winter depending on the length of the observation time. In autumn, however, the mean horizontal deviations increased to around 2 m. Reasons for this could be the fact that dry leaves cause a higher reduction in positioning accuracy than freshly soaked leaves. Further investigation regarding this matter has to be carried out. By analyzing the observations depending on the kind of canopy, it could be seen that the positioning results under leaves were inferior to the one under coniferous canopy. In addition, the influence of the foliation in the different seasons could be clearly seen as in winter in deciduous forest, for instance, where there were no leaves on the trees the positioning accuracies were significantly better than in summer or autumn. As expected the code SPP solutions using EGNOS corrections and RAIM were significantly better than the one without.

In the case of carrier phase solutions of baselines to a virtual reference station, however, a significant reduction of signal quality occurred. Due to the influence of the foliation the carrier phase information was heavily disturbed. The analysis indicated that up to 50 % of the observations in a 24 h time period were affected by a loss-of-lock. Hence, the results were divided in carrier phase solutions where all ambiguities could be fixed to integers (referred to as phase solutions in the paper) and float solutions where they are no integers. The results indicated that three quarters of all solutions were float solutions and these showed a large number of outliers. A standard deviation of less than 1 m could only be achieved in the case where nearly all ambiguities could be fixed. Robust estimation is an appropriate tool to eliminate the influence of outliers in the observations. Single frequency relative positioning with robust estimation yielded a median of less than 10 cm with an IQR of around 3 m.

The study clearly shows the influence of the type of forest, tree height and foliage as a matter of the season. Code SPP is suitable for applications ranging from navigation of tractors, harvesters and forest machines to the determination of the size of agricultural land for European Union funding. On the other hand, static differential positioning is usable for applications such as mapping and forest classification, depending on a careful selection of the suitable observation time length and analysis method. In such applications extreme care has to be undertaken to achieve acceptable results.

In this study an investigation of the performance of a certain HS-GPS receiver was conducted. Further investigations and analyses will concentrate on the use of other different geodetic and navigation type receivers and antennas. Particularly with regard to the increasing number of available GNSS satellites the achievable performance, availability and increase in positioning accuracy which goes along with a careful selection and weighting of suitable unbiased satellite signals will be investigated. For single or dual carrier phase observations a first approach is the development of a sound algorithm for a careful selection and weighting of satellite signal observations which are marked with LLI flags resulting in a loss of ambiguities in differential positioning.

Acknowledgements

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