Agricultural Forest Applications and Boundary Surveys Using Low-cost High Sensitivity GPS (HS-GPS) Receivers

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Key words: High sensitivity GPS (HS-GPS), forest canopy, code single point positioning, differential positioning, virtual reference station, robust estimation.

SUMMARY

GNSS is employed in numerous situations and especially the use of low-cost receivers has become very popular. The use of GNSS receivers is already standard in many applications, e.g. for precise navigation and guidance of machines, for cadastral boundary surveys or to determine the size of agricultural land for European Union funding. Often modern HS-GPS receivers are used for these tasks because they have a better performance even under unfavorable conditions like urban canyons or forests. Their accuracy and reliability is usually determined for open sky conditions. Several studies exist in which the possibilities of HS-GPS receivers in urban canyons were investigated. On the other hand, nearly no tests have been performed to determine the limitations of these receivers in forests. This study investigates the practicability of using low-cost HS-GPS for usage under forest canopies. A test area with varying types of forests, such as broad-leaved forests, coniferous forests and young forests, was selected. Long-term observations over 24 hours in three different seasons were carried out on ten survey points. It was found that the availability of HS-GPS receiver measurements in forest areas is satisfactory and static single point positioning mostly perform well. In the case of carrier phase solutions from baseline observations to a virtual reference station, however, a significant reduction of signal quality can occur. Due to a large number of outliers the number of solutions, in which the ambiguities can be solved and in which a high positioning accuracy less than one meter can be achieved, is lower than expected. Using robust estimation outliers have been efficiently detected and eliminated. In Single Point Positioning (SPP) a scattering of about 8 m for single epoch measurements and 3 m for static measurements was determined. Single frequency differential positioning with robust estimation yields to a median of less than 10 cm with an inner quartile range (IQR) of around 3 m. It can be concluded that HS-GPS measurements in forests are applicable for applications like mapping, classification and boundary surveys in most cases in dependence on a careful selection of the suitable observation time and analysis method.

ZUSAMMENFASSUNG

Satellitenpositionierung und Navigation mit preiswerten GNSS Empfängern wird heutzutage vermehrt in vielen Anwendungsfällen und Situationen eingesetzt. Der Einsatz solcher Geräte ist bei verschiedenen landwirtschaftlichen Anwendungen bereits zum Standard geworden, z.B. für präzise Navigation und Steuerung von Maschinen oder für Grenzvermessungen, um Nutzflächen für EU Förderungen zu bestimmen. Dabei ist auch der Einsatz im Wald gefragt. Aktuelle sogenannte High Sensitivity GPS (HS-GPS) Empfänger können auch Signale bei ungünstigen Sichtverbindungen zu den Satelliten empfangen. Die vorliegende Studie beschäftigt sich mit der Untersuchung der Nutzung von HS-GPS Empfängern im Wald. Dafür wurde ein Testgebiet mit Laub-, Nadel- und Jungwaldanteilen ausgewählt. Langzeitbeobachtungen über 24 Stunden in drei verschiedenen Jahreszeiten wurden auf 10 Messpunkten ausgeführt. Die Ergebnisse zeigten, dass die Verfügbarkeit der HS-GPS Messungen zufriedenstellend ist und statische Einzelpunktbestimmungen (sog. Single Point Positioning) gut funktionieren. Trägerphasenmessungen mit Beobachtung von Basislinien zu einer virtuellen Referenzstation ergaben jedoch, dass eine signifikante Reduktion der Signalqualität auftreten kann. Aufgrund der großen Zahl von Ausreißern in diesen Daten ist die Anzahl der Lösungen, bei denen die Ambiguitäten bei der Trägerphasenmessung bestimmt werden können und die Positionierungsgenauigkeit besser als ein Meter ist, geringer als erwartet. Für Einzelpunktbestimmungen wurde eine Standardabweichung von 8 m für einzelne Epochen und eine Standardabweichung von 3 m für statische Messungen ermittelt. Die differentielle Einfrequenzpositionierung ergab mit robusten Schätzverfahren einen Median von 10 cm und einen Quartilabstand von rund 3 m. Zusammenfassend kann gesagt werden, dass HS-GPS Messungen im Wald für Anwendungen wie Kartographie, Klassifikationen und Grenzvermessungen in den meisten Fällen bei Beachtung einer sorgfältigen Auswahl der Beobachtungszeiten und Auswertemethode eingesetzt werden können.

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1. INTRODUCTION AND MOTIVATION

Low-cost GNSS receivers have become a common tool in navigation but they are also employed for geodetic purposes and many other types of applications (see e.g. Weston and Schwieger, 2010). In agriculture they are used for precise navigation and guidance of tractors, harvesters, forest machines, etc. and even for static boundary surveys. Working under difficult conditions, such as in urban canyons, or covered areas, where satellite signals are very weak (lower than -172 dBW), it became important to further develop the GNSS receiver technology and the measurement data analysis. Due to the fact that the signal power of the satellite signals may not be changed, the noise power that is a function of bandwidth and noise density has to be reduced to improve the signal-to-noise ratio (SNR).

Modern receivers reach an improved SNR (see Schwieger, 2007). But to further improve the "sensitivity" of a GPS receiver a longer integration time for the acquisition of a signal is required to reduce the effect of the noise on the correlation process for the C/A-code. Due to the limitation by the Doppler effect as well as the length of the data bits of the navigation message, conventional GPS receivers integrate the received GPS signals for one millisecond only, using only 24 to 36 correlators. This limits the ability to acquire and track signals, only able to operate with signal strengths down to around the -160 dBW level. The ability to predict a bit transition and the use of non-coherent integration techniques additionally helps to raise the integration time up to 0.1 s (Lachapelle et al., 2004; Schwieger, 2007). To acquire signals with low dBW values by only increasing the integration time, however, leads to an intolerably long searching period which can take up to several minutes. By increasing the number of correlators it was ensured that this "deep" signal search techniques achieve an excellent performance and a high availability in an accurate time (Zhang et al., 2011). These are called High Sensitivity GPS (HS-GPS) receivers and have millions of correlators, e.g. the u-blox LEA-6T receiver used in this study has two million correlators and can acquire signals as low as -178 dBW with time-to-first-fix (TTFF) faster than 1 s.

A side effect of the non-coherent integration is that even single frequency GPS receivers can track the carrier phase, if the signal is not attenuated (Wieser and Hartinger, 2006). Schwieger (2007) showed experimentally that for static, differential observations in post processing positioning accuracies on the few centimeter level for baselines up to around 1 km over measurement times of approximately 30 minutes can be achieved. He concluded that these results are sufficient for surveying applications like cadastral boundary surveys and for construction works.

The improved sensitivity induces a better availability so that current receivers with HS-GPS chips, however, can acquire signals and track them in forests where GPS signals are attenuated and delayed by the foliation (see e.g. Zhang et al., 2011; Wieser and Hartinger, 2006). This is sketched in Figure 1. The study at hand investigates the practicability und usability of low-cost HS-GPS as well as their performance under different kind of forest canopy.

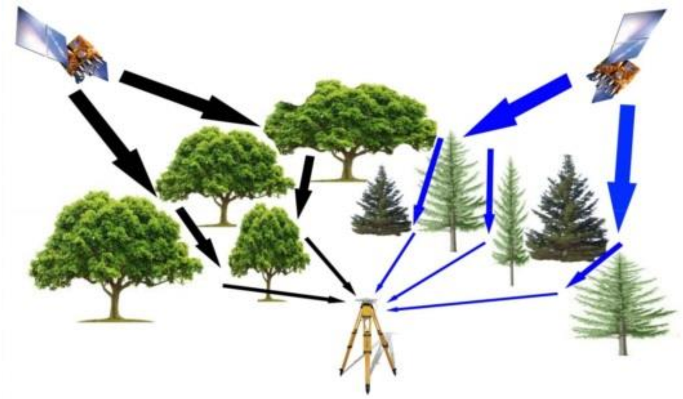

Figure 1: Influence of forest canopy on the received GNSS signals

In previous studies carried out by other researchers (e.g. Ramm and Schwieger; 2004; Bettinger and Fei, 2010; Ransom, Rhynold and Bettinger, 2010) different type of applications were investigated to test the performance of low-cost receivers under forest canopy. Ramm and Schwieger (2004), for instance, have investigated the use of five different low-cost GPS receivers under broad-leaved forest at different hillside situations. Their considered application concentrated on the use of low-cost receivers for timber extraction. For this application a low positioning accuracy of around 10 m was sufficient. For other applications, like mapping or determination of areas for example, a positioning accuracy of less than one meter is required. Cadastral applications, as determination of border points, require a positioning accuracy on the dm-level. Some low-cost HS-GPS receivers, like the used u-blox receiver, are able to store raw data and so differential GNSS-methods can be performed, similar to geodetic dual frequency receivers (Lanzendoerfer, 2007). This study focuses on the possibilities and limitations of HS-GPS differential methods under forestal conditions.

The paper is organized as follows: The disposition of the study including the selection criterias for the test area and test realization is described in chapter 2. Then three different processing solutions are discussed and analyzed in chapter 3. Finally, some concluding remarks and an outlook about the further data processing and evaluation is given.

2. DISPOSITION AND REALIZATION OF THE STUDY

2.1 Test area and disposition

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 scattering in kind, age and form of trees in a relatively small area. In the test area ten survey points were established and conventionally surveyed with a total station. They were located in miscellaneous types of forests, i.e., in broad-leaved forest, coniferous forest and young forest. Broad-leaved forests are in this study classified as areas with mainly deciduous trees and a closed canopy about 8 to 10 m. The major tree types are beeches, oaks and ashes. In coniferous forest pine trees with a similar height dominate. Young forests are mixed tree types with less than five metres height. The canopy is not fully closed.

2.2 Realization

On each point the HS-GPS receiver was installed in summer, in autumn and in winter. The intention was to cover a whole annual vegetation's cycle with thick foliation in summer thin foliation in autumn and without leaves in winter. By performing each measurement over at least 24 hours it was secured that all satellite configurations were investigated and the results are a cross section of possible satellite constellations.

The receiver, a LEA 6T by u-blox, was mounted on a tripod and connected to a notebook for data logging and first analyses. It was essential, that the receiver was able to log raw data for the conducted post processing analyses. The receiver was used with its original patch antenna to investigate the performance in a real life situation, as rarely a high-end antenna would be employed for the types of application we are interested in.

3. PROCESSING AND RESULTS

Using a HS-GPS receiver different positioning methods are possible. In our study the following three positioning solutions were investigated: Firstly, a code solution using the u-blox's software (so-called u-center) was obtained. SBAS-aided corrections (i.e. EGNOS) were applied in the case of their availability in this solution. Secondly, a Single Point Positioning (SPP) solution, with precise ephemeris was calculated. This solution serves as a good reference for the first solution. It can be expected that a higher positioning accuracy is achieved in differential mode. The third solution is therefore based on differential carrier phase positioning. Here baselines to a virtual reference station were processed. The virtual reference station observations were obtained from an Austrian wide CORS-network, i.e. EPOSA. In this solution the disturbing effects of the broadcast ephemeris, ionosphere and weather are reduced and only the influence of the canopy was significant for the test results. The three processing solutions are analyzed with the dataset obtained in summer. In addition the three seasons are also compared.
Observations on a test point under open sky conditions showed that it is possible to achieve a

positioning accuracy of better than 80 cm for SPP and 10 cm for differential positioning with a scattering of less than 1.8 m for the SPP and half a meter of the baseline solution, depending on the observation time for the employed HS-GPS receiver. The absolute coordinates obtained from conventional surveying always serve as reference and can be considered as ground truth. A division into the three different forest types is performed to see the different effect of the canopy.

3.1 SPP solution from the u-center

Most applications of HS-GPS receivers use the integrated software for positioning and take the resulting coordinates for the continuing computations. In this chapter two different analyses are performed. On the one hand the single epoch code SPP solutions calculated with the u-center were analyzed and on the other hand this single epoch solutions were averaged over three hours for static solutions, which were analyzed in the second part of this chapter. Table 1 shows the resulting arithmetic mean and standard deviation of the horizontal deviations from the ground truth in the three different forest types of a single epoch solution. For the 3 h static observations the results in Table 2 are obtained. In both solutions, the arithmetic mean of the deviations is similar to the results achieved under open sky, but the standard deviation differs significantly from the result under open sky. Only a standard deviation of about 8 m for the single epoch solution was obtained. By averaging over 3 h the standard deviation was reduced to about 3 m. The results for the heights, however, are worse. Here the arithmetic mean is around 9.7 m for both solutions with a standard deviation of around 10.1 m for the SPP respectively 5.1 m for the averaged 3 h solution.

Table 1:Performance of single epoch code solutions from u-center depending on the forest type

Forest type	Broad-leaved	Needle	Young
Arithmetic mean [m]	0.66	0.41	0.86
Std. deviation [m]	8.31	7.90	7.45

The results in Table 1 are similar to the studies of Ramm and Schwieger (2004) and Bettinger and Fei (2010). A standard deviation of 7 to 10 meters seems to be the limit of code receivers.

Table 2 Performance of 3h static code solutions from u-center depending on the forest type

Forest type	Broad-leaved	Needle	Young
Arithmetic mean [m]	0.71	0.34	0.98
Std. deviation [m]	2.99	2.13	3.20

3.2 Post processed code SPP solution

A post-processed SPP solution was computed with Leica GeoOffice using precise ephemeris. This solution is compared with the results from the u-center to investigate the u-center’s performance. This comparison is made here because different types of ephemeris are employed in the two solutions to see their influence on the result. No significant differences were detected.

3.3 Differential GPS solutions

The ability of the u-blox receiver to log raw observation data enables differential positioning. In this chapter baseline solutions to a virtual reference station with a length of less than 500 m are analyzed. In differential positioning three cases can be distinguished, i.e. a phase solution, where all ambiguities are fixed, a float solution, where the ambiguities are not fixed for all satellites and a code solution, where no ambiguities are fixed and a SPP solution is calculated.

3.3.1 General baseline performance

From the resulting percentage of the different solution the quality of the signal can be easily determined. The results for different session lengths from 15 minutes up to 6 hours are presented in Table 3. The parameter 'number' in the Table shows the count of session results over the duration of the whole measurement campaign in the three seasons and for all forest types. For the arithmetic mean and the standard deviations the results are devastating. Arithmetic means between 1 and 4 m in the horizontal deviations from the ground truth and standard deviations of around 30 to 250 m show the significant influence of forest canopies. A median of less than 0.2 m in the horizontal deviations and an inner quartile range of less than 5 m indicate a large number of false measurements.

Table 3: Comparison of Least Mean Square (LMS) (arithmetic mean and standard deviation) and robust estimation (median and inner quartile range IQR) for baseline measurements to a virtual reference station depending on different observation times

	15 Min.		30 Min.		1 Hr.		2 Hr.		3 Hr.		6 Hr.	
Number:	998		505		252		135		93		52	
[m]	Hor.	Height	Hor.	Height	Hor.	Height	Hor.	Height	Hor.	Height	Hor.	Height
Ar. 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	208.67	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

Due to the negative influence of the canopies and the resulting outliers least squares method fails. Robust methods, however, perform much better. Another important fact can be seen in Table 3. The mean and standard deviation significantly decrease with a session length longer than one hour. This is caused by the ability of the post processing software to compute a usable ionosphere model after an observation time length of 1 h.

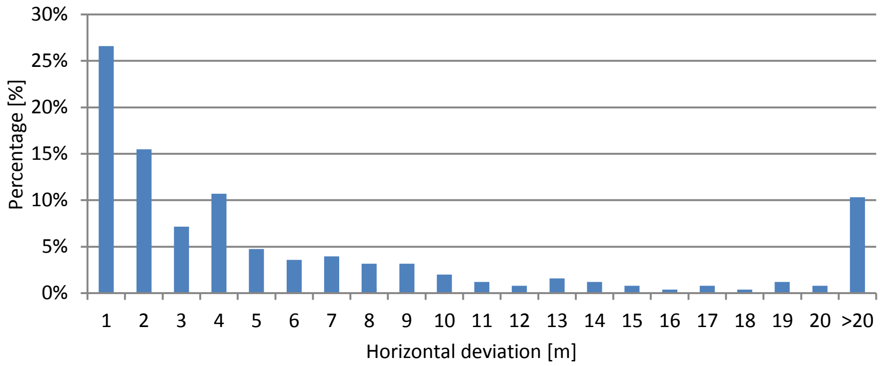

Figure 2: Histogram of deviations of 1 h static observation

In Figure 2 the histogram of the horizontal deviations from the ground truth of 252 one hour static observations is shown. More than 25 % of the results have a deviation of less than 1 m, more than 50 % less than 5 m. On the other side there are more than 10 % with a deviation higher than 20 m, nearly 20 % with more than 10 m. A significant part of the observations is affected heavily by the foliation. As a consequence the number of measurements taken on a single point has to be raised to detect outliers. This is only possible by an extension of the observation time. Only robust estimation is an appropriate tool to reduce the influence of outliers.

3.3.2 Changes in different types of forest

The dataset was distinguished in dependence of the forest type. Figure 3 shows the percentage of phase solutions in the different types of forests. Forests with high canopy only have a low percentage of phase solutions, where all ambiguities can be solved. The maximum lies about by 10 %. In contrast young forests show a rising percentage with the extension of observation time. Most of the solutions, however, are float solutions. The percentage of code solutions is only 1-2 % for an observation time shorter than two hours. There are only phase and float solutions and no code solutions for longer observation times.

Focusing on accuracy and scattering of these different types of solutions, a clear difference between phase and float solutions is obvious. In Figure 4 it can be seen that the mean and median deviation show a similar behavior. The accuracy is below 2 m up to 3 h observation time. The inner quartile range is also in the same range as the standard deviation. It is almost below 5 m (see Figure 5). For an observation time from 30 minutes to 6 hours the values of measurements in young forest reaches similar quality as measurements under open sky conditions.

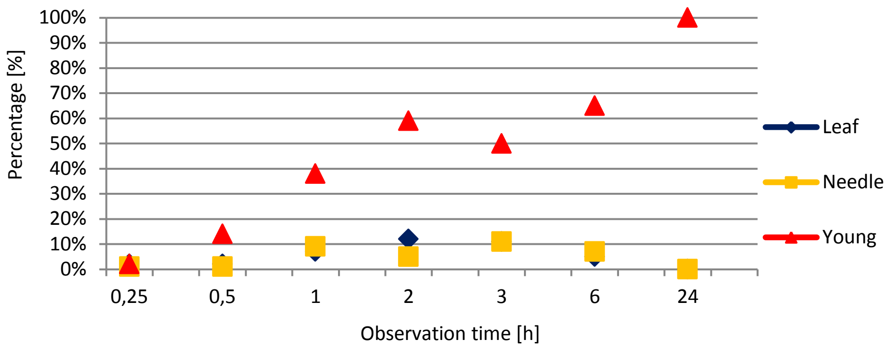

Figure 3: Percentage of phase solutions in broad-leaved, needle and young forest depending on the observation time

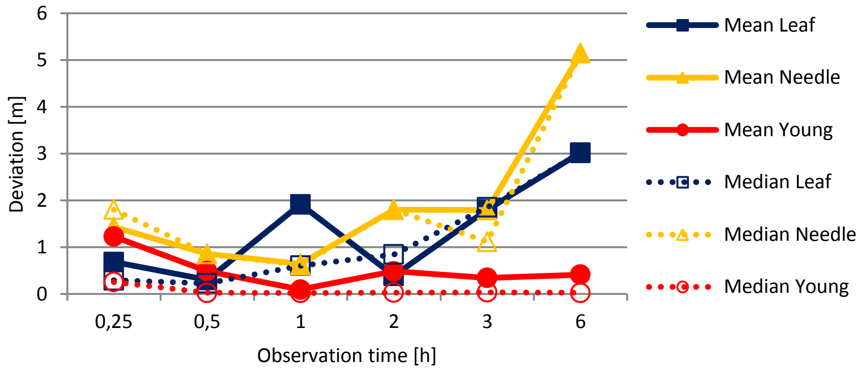

Figure 4: Comparison of mean (solid line) and median (dotted line) deviations of phase solutions in broad-leaved, needle and young forest depending on the observation time

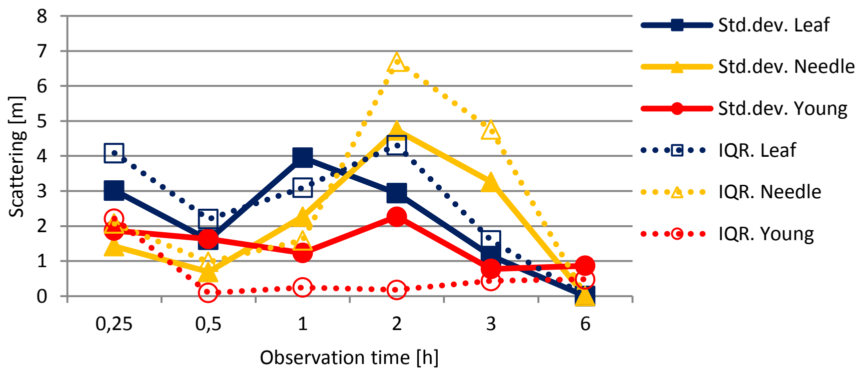

Figure 5: Comparison of standard devation (solid line) and inner quartile range IQR (dotted line) of phase solutions in broad-leaved, needle and young forest depending on the observation time

The float solutions behave totally differently. While the mean deviation varies between 1 to 25 m the median is almost less than 1 m (see Figure 6). As can be seen from Figure 7 the standard deviation reaches up to several hundred meters for short observation times while 50 % of the data is almost better than 10 m. The float solutions are affected by a large number of outliers. Unfortunately this part is the largest one.

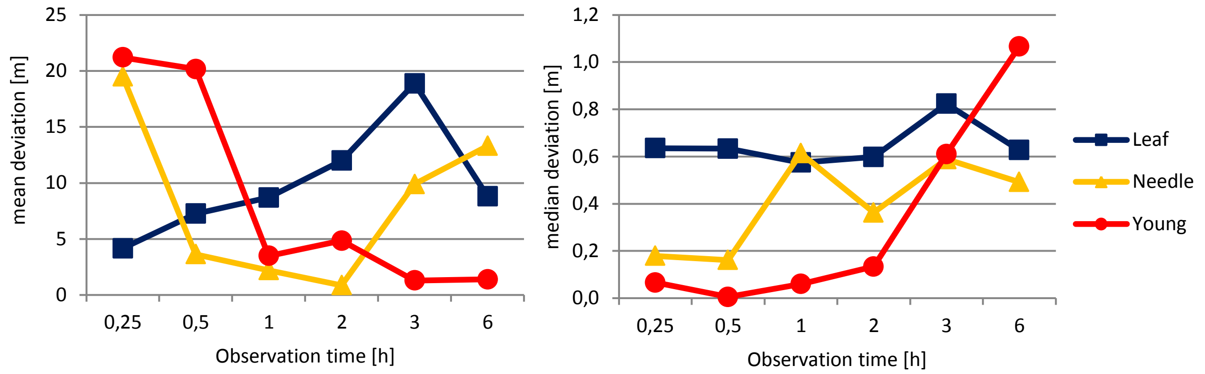

Figure 6:Comparison of mean (left) and median (right) deviations of float solutions in broad-leaved, needle and young forest depending on the observation time

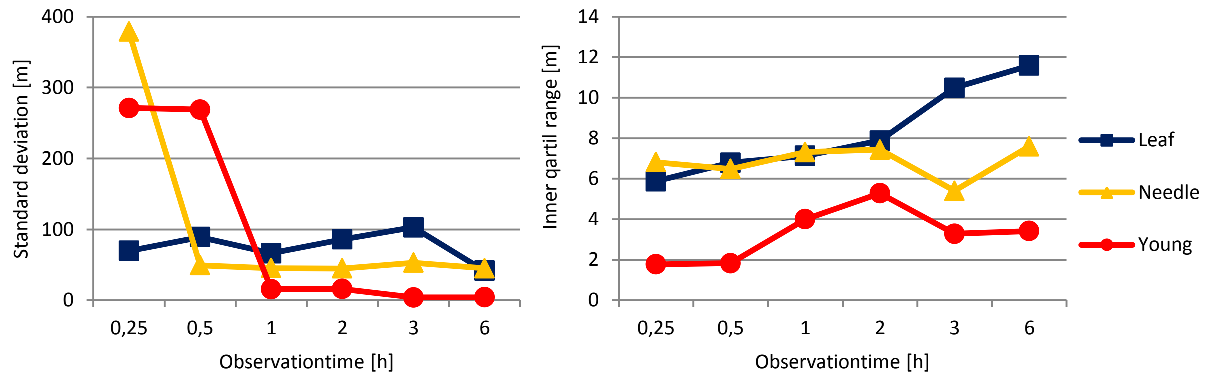

Figure 7: Comparison of standard devation (left) and inner quartile range (right) of phase solutions in broad-leaved, needle and young forest depending on the observation time

The results of the code solutions are not presented here as they are similar to the ones already presented in chapter 3.1 and there are only one to two percent code solutions.

Concluding on the differences between the different kinds of forest a clear influence of the height of the canopy can be seen. In young forests with low canopy the percentage of phase solutions is the highest (see Figure 3). Most of the time the deviations and scatterings are the lowest (see Figures 4 to 7). This is in contrast to the results of the single positioning code solutions. Comparing needle and broad-leaved forests one of the most important differences appears in the scattering of the float solutions (see Figure7). The standard deviation of broad-leaved forests is significantly higher and varies more than the one in needle forests does. The effects of outliers are larger in broad leaved forests than in needle forests. This is remarkable as in the broad-leaved forests the scattering of the phase solutions is as constant as in needle forests.

3.3.3 Changes in seasons

By analyzing the changes of positioning over a vegetation cycle the differences caused by the moisture of the canopy can be seen clearly. In Figure 8 the distribution of phase, float and code solutions for the three different seasons can be seen. The percentage of phase solutions is higher in summer than in autumn and it is, as supposed, best in winter. As already mentioned, code solutions are very rare.

Median and inner quartile range are good tools to evaluate the changes of accuracy and scattering as they do not include outliers. The median in autumn varies more than in winter and in summer, when it is the smallest (see Figure 9). The scattering in summer and autumn is around 5 m, in winter about 3 m. Thick foliation does not seem to influence the signal as dry foliation does.

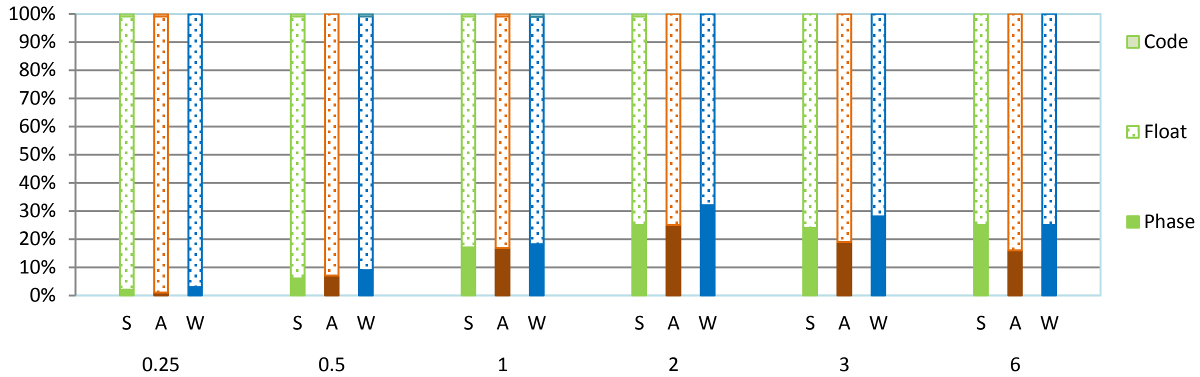

Figure 8: Percentage of phase, float and code solutions in broad-leaved, needle and young forest depending on the observation time in different seasons (summer (S), autumn (A), winter (W))

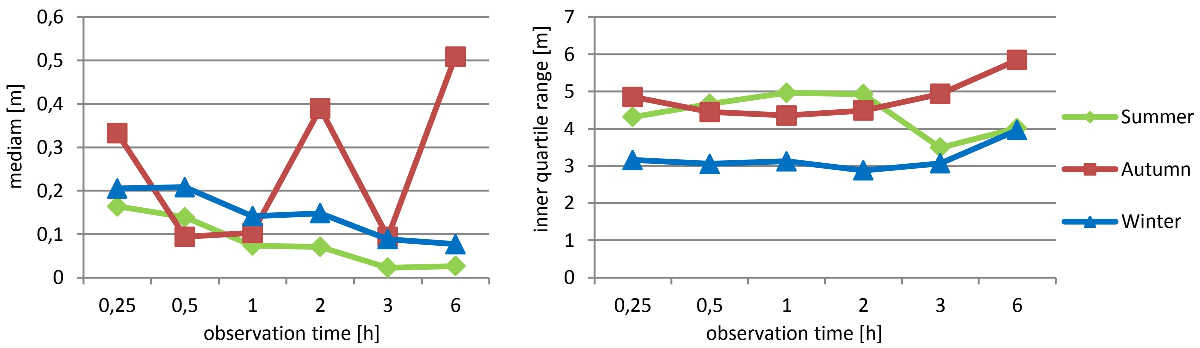

Figure 9: Comparison of median (left) and inner quartile range (right) in different seasons depending on the observation time

The GPS-signal depends on the seasonal changes. Not only the presence or absence of leaves is important, also the state of the vegetation cycle changes the leaves influence on the signal. So is the median, as indicator for the accuracy, in summer better than in winter, even if the inner quartile range is smaller in winter. The inner quartile range in winter shows, that bending effects through trunks and branches also have a large influence on the signal.

4. CONCLUSIONS AND OUTLOOK

4.1 Conclusions

HS-GPS receivers mostly perform well in forests as there were no completely failures detected. As the received signal is affected, however, accuracy and scattering are worse. The standard deviation of code solutions is about three times larger than under open sky conditions. The u-blox receiver with its standard antenna achieves about 8 m standard deviation in forests for code SPP. These results accord to the results of Ramm and Schwieger (2004) and Bettinger and Fei (2010). Using static measurements the standard deviation can be reduced to around 3 m.

Differential single frequency baseline measurements reduce the obtainable standard deviation to about 30 cm in line of sight situations. Under forest canopy it can increase up to several hundred meters due to a great number of outliers. Robust methods, in contrast, show that 50 % of the positioning results lie within 10 m (IQR).

Analyzing the dataset according to different aspects, like forest type or season, it can be seen that the influence of forest canopy on the signal is dependent on many factors. Not only the type of forest, but also the height of canopy, the form of the trees, or their moisture can affect the result. In autumn the influence of the dry canopy is more intense than in summer when the leaves are soaked with water or in winter without leaves. With long observation times and robust estimation a high quality positioning results on sub-meter level in forests and their direct surrounding can be achieved. Analyses of the raw data have shown that up to 50 % of the satellite observations in RINEX-data are flagged by a Loss-of-Lock Indicator. More detailed investigation is presented in the master thesis of Severin Heuboeck (2014) and will be published elsewhere.

4.2 Outlook

The previous tests showed that carrier phase measurements under forest canopy suffer from a large number of outliers. With robust estimation better results can be achieved, as most outliers are eliminated. A first attempt was made in this study to cut of outer quantiles of the coordinates in each direction. That means that the coordinates along each axis, below and above a certain threshold, are eliminated. This threshold is defined by the chosen quantile. The advantage of this method is that no deviations to mean coordinates of the measurement point have to be calculated. The disadvantage, however, is that up to four times of the quantile value in case of 2-D coordinates and six times in case of 3-D coordinates is eliminated in the dataset. If a 5 % quantile is chosen, for instance, up to 20 % of the 2-D coordinates and up to 30 % in 3-D coordinates may be eliminated.

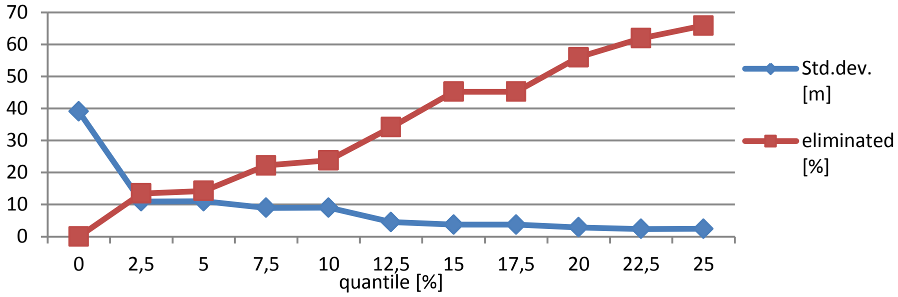

Figure 10:Comparision of the reduction of standard devation (blue, [m]) and the loss of data (red, [%]) depending on the quantiles of the sample

Figure 10 compares the loss of horizontal coordinates with the improvements of the standard deviation in differential positioning with 1 hour observation time in summer. It shows that a small quantile of 2.5 % already has a huge impact on the standard deviation which decreases from about 40 m to about 10 m. At a 12.5 % quantile all outliers are eliminated, according to the histogram shown in Figure 10, i.e. about one third of the dataset. The standard deviation of the coordinates is reduced to 4.5 m. Higher quantiles reduce the standard deviation even more by further reducing the measurement sample. Again the IQR is much better with about 2.8 m. The median of 9 cm is again smaller than the arithmetic mean with about 40 cm. This shows that the robust estimation is a better estimation method for measurements in forests.

As a consequence to the great number of affected satellite signals, more satellites have to be available to secure availability of a GNSS-receiver under forestal conditions. With the increasing number of satellites due to the installation of GALILEO and other GNSS-Systems it will be possible to run even geodetic receivers under canopy. Further analyses will be done, such as the performance test of other robust outlier detection algorithms. Tests with different antennas and receivers are planned.

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BIOGRAPHICAL NOTES

Severin Heuböck is a final year master student at the Vienna University of Technology, Austria. In his study of Geodesy and Geoinformation his main research interests are in the fields of geodesy as well as GNSS positioning and navigation.

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