Analysis of the accuracy of GPS Trimble JUNO ST measurement in the conditions of forest canopy

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ABSTRACT: GPS Trimble JUNO ST was tested at 16 points under forest canopy. The measurements were done on three different dates of the growing seasons in 2007 and 2008. On each date, 4 recordings were measured in the length of 1, 2, 5, and 10 minutes with the recording frequency of 5 seconds. The resultant data were statistically evaluated by analysis of variance (ANOVA) both for data before corrections and for data after post-process corrections from the reference station. The tested GPS receiver reaches the average mean square error of the measurement of *XY* coordinates in the interval of 2.7 up to 5.1 m (without corrections and depending on the time of observation). The error of the altitudinal (*Z*) coordinate measurement is three times the average MSE *XY*. The use of corrections from reference stations turns out to be ineffective. No statistically significant relationship was proved between the PDOP value and the error of measurement of the position or height, and there was no significant relationship of the type of stand or stand density or the type of relief. By contrast, the age of stand was statistically significant and there are higher MSE *XY* values in older stands, depending, however, on the stand density.

Keywords: forest canopy impact; GPS; GPS device accuracy; location precision; mean square error; Trimble JUNO ST

The history of a satellite positioning system goes back to the 1960s, when the US navy launched the Transit system. In the former USSR the Cyklon system with the same disadvantages was used as a counterweight. In the early 1970s, after the experience with these systems both superpowers started to build systems of a new generation. In the USA it was the project called GPS – NAVSTAR (*Global Positioning System – Navigation System using Time and Ranging*) and in the USSR the GLONASS project (*Globalnaja Navigacionnaja Sputnikovaja Sistema*). Nowadays the GPS system is mostly used, although the European project of the GALILEO system was launched as early as in 1999. The GALILEO system should have been in operation since 2008 but prolonged discussions with private companies which should take part in the project co-financing postponed the launching of the project. At the moment there are only 2 test satellites in orbit (Giove-A and Giove-B) and the last assessment for launching the GALILEO system into operation is planned for the end of 2013.

GPS consists of three basic segments: (a) cosmic – 24 satellites on 6 orbits with the slope of 55°, (b) control – 5 terrestrial monitoring stations, and (c) user – GPS receivers. Measurement with the help of positioning systems can be done on the basis of code or phase measurements. Determining the absolute position right in the terrain follows from relationships (1), when solving a system of 4 equations with 4 unknowns. On the left side of the equations there are apparent distances of the receiver to individual satellites r_i. X, Y, and Z are coordinates of the receiver which we want to determine and x_i, y_i, z_i are coordinates of satellites at the time of measurement of apparent distances (from the calculations of data in navigational messages),

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c is the speed of light and ΔT is the unknown clock difference of the receiver as opposed to the system time.

These equations are simultaneously solved so that the receiver could provide the output in coordinates – the position is determined in geocentric coordinates, but it is normally converted into geographic coordinates of any map projection. Height above ellipsoid H (HAE) converted from the WGS-84 rectangular coordinates is referred to the surface of the reference ellipsoid (Fig. 1). For mapping and technical work the height h is more important, corresponding to the height above the geoid ($h = H - N$). In the Czech Republic, the geoid height above the ellipsoid N ranges approximately in the interval from 42.5 m in the east to 47 m in the west (Hrdina et al. 1996).

$$r_1 = \sqrt{(X - x_1)^2 + (Y - y_1)^2 + (Z - z_1)^2 - c\Delta T}$$

$$r_2 = \sqrt{(X - x_2)^2 + (Y - y_2)^2 + (Z - z_2)^2 - c\Delta T}$$

$$r_3 = \sqrt{(X - x_3)^2 + (Y - y_3)^2 + (Z - z_3)^2 - c\Delta T}$$

$$r_4 = \sqrt{(X - x_4)^2 + (Y - y_4)^2 + (Z - z_4)^2 - c\Delta T}$$

A number of factors influences the position and time accuracy, especially the control of the access to signals from the satellite, satellite state, measurement precision rate, signal-to-noise ratio (SNR), multipath effect, number of visible satellites, positional dilution of precision (PDOP), type of receiver, diligence of the measurement plan preparation, validity of ephemeris, ephemeris accuracy, clock accuracy on satellites, ionosphere and troposphere impacts, receiver clock error and the measurement and evaluation methods. Improvement in GPS measurement can be done in several ways:
- averaging,
- differential correction and post-processing,
- augmentation systems.

If we do not consider the largest obstacle of GPS measuring in a forest stand – adverse geomorphological conditions, then the measurement is significantly influenced especially by the structure and age of the stand (expressed by its volume parameters), which have a greater impact than if the stand is in foliage. The forest stand thus influences GPS measurement because the trees (trunks and branches) are an obstacle for the sheer signal reception and these objects cause a multipath effect which increases the measurement error (Tuček, Ligoš 2002). Forest stands also make the phase measurement impossible and it is often also impossible to receive EGNOS corrections because the low earth orbiting geostationary satellite (about 30° above horizon) is shaded.

Much time has been devoted to the issue of GPS measurement in forest stands and its accuracy. Unfortunately, a number of results of individual authors are ambiguous and the results in many works actually contradict each other. The explanation can be found in a mutual comparison of the results with regard to the measurement methodology, momentary observation conditions, setting up user parameters, methodology of result processing and especially to the influence of technological progress on the used GPS receivers (hardware and producer technologies). It is possible to assume that these factors may exert a greater influence in a number of cases than the forest canopy itself.

Most authors agree (see also Tuček, Ligoš 2002) that the general set up of parameters for a GPS measurement under the forest canopy makes use of PDOP 6–8, SNR up to 4 and of an elevation mask up to 10–15°. GPS performance standards guarantee 98% of the daily PDOP 6 and better, and functionality of at least 21 satellites with 98% probability on the annual average. In general, the relevant accuracy of the GPS measurement in the space is assessed according to the PDOP value, but some researchers reported (Yang, Brock 1996) that there were no statistically provable differences in the accuracy if

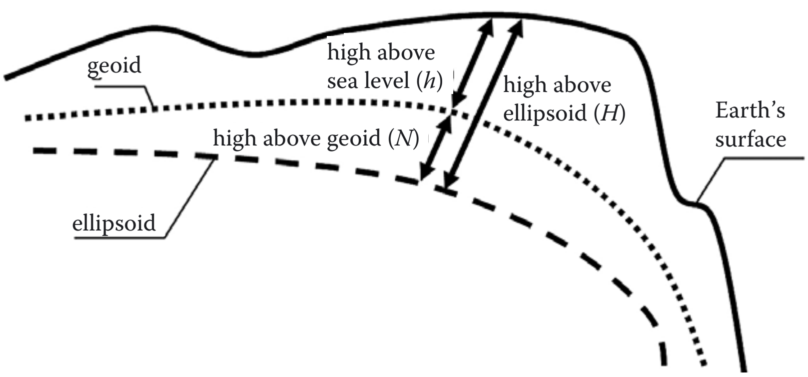

Fig. 1. Relation between the system ellipsoidal height WGS-84 (H) and the altitude (h)

the PDOP value decreased, and that even the opposite may occur, i.e. a lower PDOP value might generate a less precise measurement (Sigrist et al. 1999). Similarly, other authors did not prove any statistically significant difference in the data measured in the forest stand before and after the post-process correction (Wing et al. 2008).

It is then certain that although the forest canopy influences the measurement but that despite this fact it is nearly always possible to proceed with the surveying (the forest stand does not limit the use of GPS to such an extent as e.g. an adverse relief configuration does). However, the published sources cannot provide any concrete conclusions as their data are ambiguous and often even contradictory. As a result, only general recommendations may be derived that are as follows: the planning of measurements (checking of the satellite unavailability time, determining the PDOP value for the given location, etc.), the use of the most technologically advanced GPS device including an external antenna, which is best to be placed higher above the terrain, and finally, a suitable measurement methodology (in particular the number of records for the measured point). Unfortunately, none of these recommendations necessarily produces the desired effect. For instance, Wing and Eklund (2008) reported that during their testing measurements they did not note any statistically significant difference in the use of the GPS receiver with an internal antenna or external antenna. Analogically, other researchers (Tuček, Ligoš 2002) did not prove any statistically significant difference in the accuracy of the GPS measurement and the species composition of forest stand (categorized as conifers, broadleaves and mixed stand).

Despite the above, many researchers (Naesset, Jonmeister 2002; Bolstad et al. 2005; Wing et al. 2008) are unanimous in that the present technological equipment of the GPS receivers in the GIS application category commonly allows surveying under forest canopy in the horizontal (*XY*) component of the position with error allowance up to 5 m without corrections, and up to 2 m when using post-process corrections. In the vertical (*Z*) component of the position the quoted error increases approximately twice or three times and displays a decisively greater variance. When natural conditions of the forest stand are considered, the attained horizontal accuracy (after corrections) is sufficient for many applications in forestry, and further improvement of accuracy is also to be expected.

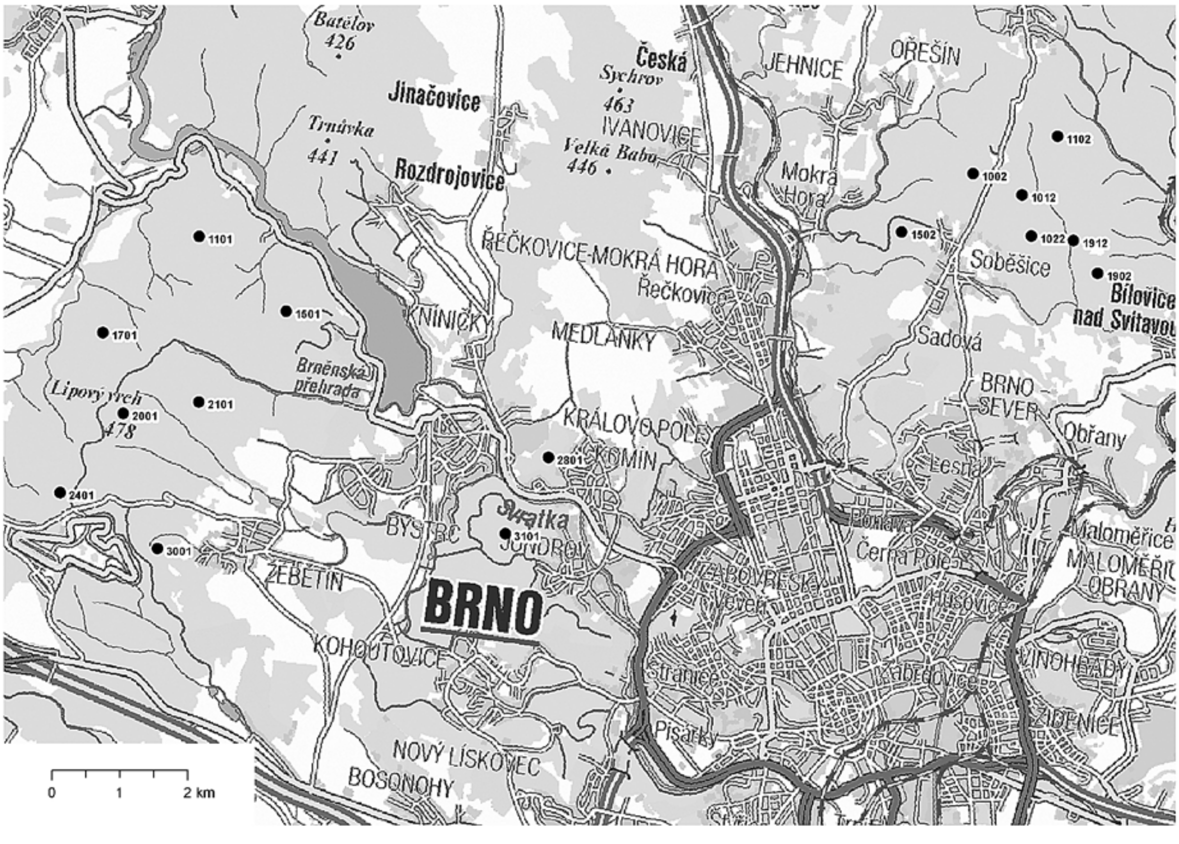

Fig. 2. Location of the tested points for the GPS measurement

MATERIAL AND METHODS

JUNO ST is a compact (size 10.9 × 6.0 × 1.9 cm) and light (133 g including the battery) GPS receiver integrated within the field computer, and serves especially for data collection in the field (mobile GIS solution). It was first marketed by Trimble in 2007. The battery (Li-Ion 1,200 mAh) allows 6 to 10 working hours, depending on the outside temperature (operation temperature spans from –10 to +50°C) and also on the battery age. JUNO ST is equipped with a 64 MB RAM- and 128 MB-internal flash disc and a 300 MHz processor. It offers a number of communication options, from the SD card slot and USB connector (which also acts as a recharger of the JUNO ST), to the Bluetooth and WiFi (802.11 b/g) technology. The integrated GPS receiver has 12 channels, and supports the NMEA-0183 protocol and the WAAS expanding system. JUNO ST is fitted with a SiRF chip to improve the signal reception under difficult measurement conditions. The operation and control are based on a 2.8" touch display with the resolution of 240 × 320. With its qualities and favourable price (approximately 16, 000 CZK including software) JUNO ST then functions as a great aid in field surveys where the position of the recorded objects plays a key role. At the end of 2008 Trimble introduced two new models of JUNO to the market: JUNO SB and JUNO SC, which have a number of technological improvements (larger display, faster processor, integrated camera or a modem etc.). However, there are no substantial differences in the integrated GPS module parameters.

The testing of measurement accuracy with the help of GPS Trimble JUNO ST was carried out from May to August in 2007 and 2008 in a forest stand on the outskirts of Brno. The first experimental area (area A) was located west of Brno, in the vicinity of the Brno Dam, and the second area (area B) was situated northeast of Brno, on the southern border of the forest ground belonging to the Křtiny Training Forest Enterprise (Fig. 2). The measurement in area A was tested at 9 points of known coordinates and in area B at 7 points. Individual points were selected so as to represent the variable conditions of the forest stand (species composition, stand age, stand density). The selection included both stabilized trigonometric points and points located in the space especially for this purpose (Table 1). The stabilization accuracy of the tested points was determined by the mean coordinate error of 1.5 cm and the marginal deviation up to 3.5 cm; the vertical component accuracy was up to 10 cm. This accuracy level proved fully sufficient for testing the aforementioned GPS JUNO ST, as the accuracy quoted by the manufacturer is 1 to 5 m after post-process correction.

Table 1. List of testing points

Point No.	Forest stand type (%)		Age (years)	Stocking	Relief	
	broadleaved	coniferous			slope (%)	type
1101	100	0	35	10	5	elongated ridge
1501	100	0	153	7	10	hillside under peak
1701	5	95	35	8	30	hillside of ridge
2001	90	10	70	9	0	peak
2101	100	0	17	10	0	flat plane
2401	99	1	90	9	10	convex hillside
2801	90	10	76	8	5	hillside under peak
3001	100	0	45	10	20	concave hillside
3101	100	0	63	7	0	peak
1002	50	50	54	9	5	hillside
1012	30	70	31	10	45	hillside of ravine
1022	40	60	42	10	55	hillside of ravine
1102	90	10	29	10	15	hillside under peak
1502	90	10	93	5	0	peak
1902	100	0	69	10	10	elongated ridge
1912	60	40	35	10	60	hillside of ravine

Table 2. Measurement accuracy at all points without the observation length differentiation

	ΔX (m)	ΔY (m)	ΔZ (m)	MSE XY (m)
Without correction				
Average	0.5	0.3	11.2	4.0
SD*	4.0	2.8	6.6	2.8
Minimum	–14.3	–13.8	–5.3	0.2
Maximum	9.9	6.9	27.2	15.5
With post-process corrections				
Average	–0.1	0.7	8.2	3.8
SD*	3.8	2.6	5.7	2.7
Minimum	–12.3	–6.6	–7.0	0.1
Maximum	8.8	8.8	21.3	12.4

*SD – standard deviation

At each of the testing points measurements were taken at three different times in the course of the vegetation period of 2007 and 2008. Each time 4 recordings were done (at each point) lasting 1, 2, 5, and 10 minutes, with the 5-second recording frequency (i.e. 12, 24, 60, and 120 recordings). Each time GPS JUNO ST was placed on a single tripod 1.30 m high above the measured point and so no external antenna was used. The surveyor was standing south of the device so that comparable measurement conditions were ensured for each point (the surveyor creates an obstacle and shades the satellite reception of the signal). The measurements were done with the use of the software Trimble TerraSync 3.01 Professional edition. The S-JTSK coordinates system was implemented and the conversion of coordinates from WGS-84 into S-JTSK was performed directly by the TerraSync programme. The conversion accuracy was tested earlier on an experimental polygon and did not exceed the error tolerance applied at the tested points. The measured data were finally processed in the software Trimble GPS Pathfinder Office 4.00. In this programme the post-process correction of data was also processed from the CZEPOS network, more specifically from the external station VESOG Brno (TUBO). The TUBO station distance did not exceed 11 km (4–11 km) from the measured points. The resultant data were evaluated by the analysis of variance (ANOVA) on the basis of several factors (stand characteristics, PDOP and measurement time), both before and after the post-process correction. The evaluation was processed in SW STATISTICA Cz version 8.0.

RESULTS AND DISCUSSION

The average value of the mean square error in the position (*XY*) component of the coordinates (MSE *XY*) was 4.0 m for measurements without the application of the post-process corrections (the minimum 0.2 m, maximum 15.5 m and standard deviation 2.8 m) and the average error in the vertical (*Z*) coordinate measurement was 11.2 m (minimum –5.3 m, maximum 27.2 m and standard deviation 6.6 m), i.e. approximately a triple of the average error in the position (Table 2). When post-process corrections were applied, the average value of the MSE *XY* component of coordinates dropped to 3.8 m (the minimum 0.1 m, maximum 12.4 m and standard deviation 2.7 m). The average error in the vertical coordinate measurement decreased to 8.2 m (minimum –7.0 m, maximum 21.3 m and standard deviation 5.7 m), i.e. approximately a double of the average error in the position. The measurement error correction with the use of post-process corrections provided a varied rate for individual observations at testing points, ranging from 0.1 to 1.8 m. Needless to say, three of the tested points were negatively influenced by the application of the post-process corrections, whereby the average measurement error rose by 0.1 to 0.7 m. If we take into account the fact that the application of the post-process corrections reduced the average measurement error only by 0.2 m and at the same time, that this reduction varied greatly with individual observations (including a negative influence occurrence), it may be argued that the application of the post-process corrections is ineffective (in terms of

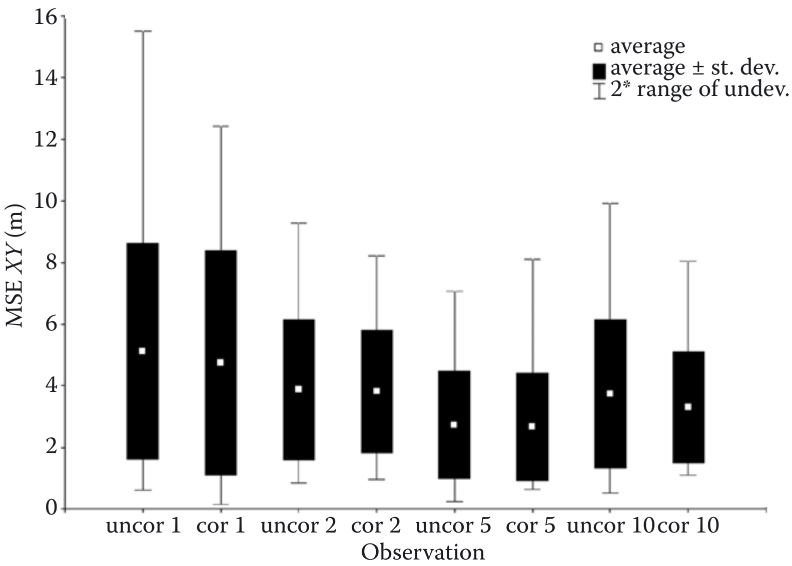

Fig. 3. Mean square error of the measurement of *XY* coordinates (MSE *XY*) without corrections (uncor) and with post-process corrections (cor) at 1, 2, 5, and 10 minutes observations

measurement with GPS Trimble JUNO ST in the forest stand conditions). This conclusion is also supported by the fact that corrections from the reference station network are almost always charged for, which increases the measurement cost. For example, the CZEPOS network charges 80 CZK for reference

Table 3. Measurement accuracy with the observation length differentiation at all points without post-process corrections

	Δ*X* (m)	Δ*Y* (m)	Δ*Z* (m)	MSE *XY* (m)
1 minute				
Average	0.2	–0.4	10.3	5.1
SD*	5.2	3.4	7.5	3.5
Minimum	–14.3	–13.8	–1.4	0.6
Maximum	7.8	4.3	27.2	15.5
2 minutes				
Average	–0.3	0.9	11.1	3.9
SD*	3.5	2.8	6.2	2.3
Minimum	–7.3	–6.2	–5.3	0.8
Maximum	9.2	6.9	20.6	9.3
5 minutes				
Average	0.7	-0.2	11.8	2.7
SD*	2.3	2.3	5.4	1.7
Minimum	–3.5	–4.9	4.0	0.2
Maximum	5.0	5.4	26.8	7.1
10 minutes				
Average	1.7	1.2	12.1	3.7
SD*	3.8	1.3	6.7	2.4
Minimum	–5.7	–1.0	–1.3	0.5
Maximum	9.9	3.8	20.1	9.9

*SD – standard deviation

Table 4. Measurement accuracy with the observation length differentiation at all points with post-process corrections

	ΔX (m)	ΔY (m)	ΔZ (m)	MSE XY (m)
1 minute				
Average	–0.7	0.1	7.7	4.8
SD*	5.2	3.0	5.6	3.6
Minimum	–12.3	–6.6	–1.7	0.1
Maximum	8.8	8.8	19.7	12.4
2 minutes				
Average	–1.2	1.5	8.0	3.8
SD*	2.6	3.0	6.1	2.0
Minimum	–4.7	–6.1	–7.0	1.0
Maximum	7.2	8.2	21.2	8.2
5 minutes				
Average	0.7	0.3	8.4	2.7
SD*	2.1	2.3	5.3	1.7
Minimum	–3.2	–3.5	–2.3	0.6
Maximum	5.3	6.1	21.3	8.1
10 minutes				
Average	1.2	1.3	9.1	3.3
SD*	3.0	1.4	5.8	1.8
Minimum	–4.5	–0.8	–5.4	1.1
Maximum	8.0	3.5	16.5	8.0

*SD – standard deviation

data per hour (for one station) with the sample interval of 1 s. One-shift measurement would then cost another 640 CZK. (On the other hand, it is also possible to use a longer sample interval in order to reduce the costs; 1 hour with the sample interval of 15 s is charged with 8 CZK.)

In individual selected time-lengths of the observations at tested points a gradual decrease in the average MSE *XY* was detected up to the observation lengths of 5 minutes. With a 10-minute observation the error value grew similarly like that of a 2-minute observation (Fig. 3). With a 1-minute observation MSE *XY* already moves around a 5-m limit, a value quoted by the manufacturer for the present technological equipment of the GPS receivers in the GIS application category (Table 3). However, it has to be emphasized that the standard deviation is relatively high (3.5 m) and the local extreme values reach up to three times the average. With a 5-minute observation approximately a half the average rate of MSE *XY* (2.7 m) was reached in comparison with a 1-minute observation, and the standard deviation was also significantly lower (1.7 m). Even so, here too local extreme values linger, obtained from individual observations at tested points and exceeding the average twice or three times. Neither does the application of the post-process corrections generate any notable improvement (Table 4). It follows from the attained accuracy that the use of this GPS device is debatable for forestry thematic mapping, in the sense of collecting background material for forest maps. Forest maps are classified as thematic, purpose-oriented maps and are defined in Regulation No. 84/1996, § 5 of the Ministry of Agriculture of the Czech Republic on Forestry Management Planning. Forest maps must be based on cadastral maps or state maps – 1:5,000 scale. When higher units of the spatial division of the forest are projected, i.e. the compartment and the subcompartment, geodetic accuracy of $m = 0.0004 \times M$ is applied, with M as the map scale. In terms of an management map of a 1:5,000 scale it entails generating accuracy of ± 2 m.

The average PDOP value during the measurement under the forest stand conditions reached 3.1 (the minimum 1.4 and the maximum 9.4). No statistically significant relation between the PDOP value and the measurement error in the positional or altitudinal coordinates has been proved. In fact, despite the identical PDOP value, considerably varied measurement errors were generated. Often, a higher PDOP value generated a greater measurement accuracy and *vice versa*. Therefore, it cannot be argued that the PDOP value has a decisive impact on the measurement accuracy but it should only be considered as directory when measurement is not encouraged for values higher than 10. Likewise, no statistically significant relation has been detected in the species composition, stand density and the relief type. In contrast, the stand age was proved to be statistically significant, and in older stands higher values of MSE *XY* can be observed, though depending on the stand density. These results may be interpreted in relation to the volume characteristics of the stand, where the wood substance blocks or modifies the received signal and thus reduces accuracy with which the GPS locates the position.

As a conclusion it may be stated that the tested GPS receiver generates an average square error in the interval of 2.7 to 5.1 m in the forest stand conditions, without the corrections and depending on the length of the observation. However, it is necessary to count with up to a triple of the quoted average in local extreme values. The measurement error of the altitudinal (*Z*) coordinate is approximately a triple of the average MSE *XY*, with a substantially higher variance. The application of corrections from reference stations appears ineffective. The measurements were intentionally carried out in the vegetation period when the maximal use of the GPS in the field research is to be expected and the forest canopy of deciduous woody species is in foliage. It is to be expected that under extreme conditions of the relief (deep and narrow mountain valleys, ravines and castellated rocks) the attained accuracy will be reduced further; however, such conditions were not the subject of research.

References

Bolstad P., Jenks A., Berkin J., Horne K., Reading W.H. (2005): A comparison of autonomous, WAAS, real-time and post-processed global positioning systems (GPS) accuracies in northern forests. Northern Journal of Applied Forestry, ***22***: 5–11 (in Czech).

Hrdina Z., Pánek P., Vejražka F. (1996): Radio positioning (satellite system GPS). Praha, ČVUT: 267 (in Czech).

Naesset E., Jonmeister T. (2002): Assessing point accuracy of DGPS under forest canopy before data acquisition, in the field, and after postprocessing. Scandinavian Journal of Forest Research, ***17***: 351–358.

Sigrist P., Coppin P., Hermy M. (1999): Impact of forest canopy on quality and accuracy of GPS measurements. International Journal of Remote Sensing, ***18***: 3595–3610.

Tuček J., Ligoš J. (2002): Forest canopy influence on the precision of location with GPS receivers. Journal of Forest Science, ***48***: 399–407.

Wing M.G., Eklund A., Sessions J., Karsky R. (2008): Horizontal Measurement Performance of Five Mapping-Grade Global Positioning System Receiver Configurations in Several Forested Settings. Western Journal of Applied Forestry, ***23***: 166–171.

Wing M.G., Eklund A. (2008): Vertical Measurement Accuracy of Mapping-Grade Global Positioning Systems Receivers in Three Forest Settings. Western Journal of Applied Forestry, ***23***: 83–88.

Yang X., Brock R. (1996): Comparison between RDOP and PDOP. Proceedings of the 1996 American Society for Photogrammetry and Remote Sensing, Baltimore, 22 to 25 April 1996, ***2***: 162–171.

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