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# Horizontal accuracy and applicability of smartphone GNSS positioning in forests

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This study focuses on the evaluation of horizontal accuracy of smartphones for collecting and using spatial data in forests in comparison with other Global Navigation Satellite Systems (GNSS) devices. Accuracy evaluation was conducted at 74 points in a mixed deciduous-coniferous forest (during leaf-on and leaf-off season) and additionally at 17 points under open area conditions. Total station theodolite measurements served as a reference for all point positions. Positional accuracies of three smartphones (one with two differing OS versions), a tablet, a mapping- and a survey-grade receiver were compared. Root mean square errors of positional accuracies ranged from 4.96–11.45 m during leaf-on and 4.51–6.72 m during leaf-off season in the forest plots to 1.90–2.36 m under open area conditions. Differences in positional accuracy between leaf-on and leaf-off conditions were only significant in some cases, while differences between forest and open area were always significant. Differences between devices were only significant under leaf-on conditions except for the survey-grade receiver, which was significantly more accurate than all other devices in all tested cases. In a second experiment, two smartphones, a handheld receiver and satellite imagery were used to measure the area of wind damage in disturbed forests. The results obtained with the GNSS devices showed a significantly higher accuracy of area and timber volume assessment compared with visual estimation, particularly in larger disturbed areas. Generally, the results suggest that current smartphones can be successfully used for some tasks in forest management where precision of the spatial data is not of highest priority.

## Introduction

Many tasks in forestry are related to spatial data. Apart from classical geodetic methods, it is possible to use remote sensing or the Global Navigation Satellite Systems (GNSS). Only a few forestry organizations can afford the acquisition and processing of remote sensing data at short notice; therefore, GNSS measurement can be an applicable method for obtaining accurate spatial data in cases of short-term demands. Handheld GNSS receivers do not achieve the accuracy of survey-grade geodetic GNSS receivers, but may still be a useful tool for decision support. However, studies on the positional accuracy of handheld GNSS receivers in forests are needed as forests cause a significant decrease of the GNSS positioning accuracy. The main reason for this is the interaction of the GNSS signal with the complex canopy structure, which can either block the signal or reflect the signal multiple times (multipath effect). Despite advances in technology, these issues are still not resolved.

The accuracy of smartphone GNSS positioning under forest conditions is poorly documented despite the wide availability and prevalence of this technology. The few earlier conducted experiments were often averaging a large number of GNSS measurements to obtain the position (e.g. Zandbergen and Barbeau, 2011). This procedure was found to increase the GNSS accuracy of point objects in forests (Grala and Brach 2009; Valbuena *et al.*, 2010) but also increases the time and cost of post-processing the data, especially when these points are subsequently used to generate lines or polygons. Nowadays, ‘smart’ devices (e.g. smartphones, tablets) often use the so-called ‘assisted GPS’ (A-GPS). Predicted ephemeris data (broadcasted using mobile networks) are used to eliminate sections of the signal search space. The time required for signal acquisition and the ‘Time to First Fix’ is therefore shorter (Zandbergen and Barbeau, 2011). However, until now it is unclear whether ‘close-to-real-time’ GPS measurements (no averaging of multiple measurements) can achieve satisfactory accuracy under forest conditions.

One of the typical examples where the rapid collection of spatial data can improve the decision making in forestry is the occurrence of disturbances. As an example, storm ‘Žofia’ caused major damage to forests in Central Europe on 14 and 15 May 2014 and the wood volume of damaged trees in Slovakia (being one of the most affected countries) was 4 072 000 $m^3$ according to preliminary reports (Gubka *et al.*, 2014). After the storm, rapid information on the extent of the damaged areas and the corresponding volume was required, especially as much damage occurred in beech stands which increased the risk that the timber would rapidly deteriorate during the summer. One of the first tasks after any disturbance is the determination of the correct area of damage, since the timber volume can be consequently determined if per hectare volumes are known. Visual estimation of the area of damage in forests, which is a still used and an accepted method in Slovakia (but also other European countries), may be very difficult just after the disturbance where the situation is often characterized by confusing mosaics of dead and living trees, and inaccessible terrain due to large amounts of dead wood and coarse woody debris. Under such circumstances, it is therefore desirable to use more objective methods for the collection of spatial information and estimates of areas affected.

The aim of our study was to assess the feasibility of smartphones – which can be much more versatile devices compared to dedicated consumer-grade GNSS receivers – for obtaining operational spatial data in forests. The study consisted of two experiments. The objective of the first experiment was the assessment of real-time (i.e. neither averaged nor post-processed position measurements) accuracy of smartphone GNSS measurements by comparing the determined position of points to their position acquired using a more accurate device. Positional accuracy differences in forest environments compared to open area, as well as the influence of the vegetation period (leaf-status) on the resulting accuracy was also evaluated. In the second experiment, the aim was to examine the application of smartphone positioning for a realistic forest management task, namely the measurement of the extent of wind-disturbed sites.

## Methods

### *Experiment 1: evaluation of real-time horizontal accuracy of point measurements*

A geodetic point network established in a mixed deciduous-coniferous forest was used at the approximate location 48°37′20″N, 19°05′20″E. It consists of 74 points, which represent skid roads passing through young and mature forest stands, a boundary between mature and young forest stands, a boundary between forest and non-forested areas, and other points in various forest settings (Figure 1a). These points cover different conditions in a forest with minimal changes of relief that could influence the GNSS measurements. The closer surroundings of the points were documented using the Field-Map technology (Figure 2). However, the extent (diameter) of the documented plots was not sufficient to analyse the influence of basic dendrometric characteristics on the resulting GNSS accuracy as a much wider area influences such a measurement. Therefore, the documentation serves only as an illustration of conditions where the measurements actually took place. Also, a set of 17 points under conditions with obstacle-free GNSS signal reception on a meadow was included. Four polygonal traverses surveyed using the Topcon GPT3002 total station were used to determine the positions of the points in forest; the points in the open area were surveyed from a single observation point. The data obtained by this method were used as a reference for the GNSS measurement. Previous experimental measurements using Topcon GPT3002 confirmed the possibility of achieving point measurements with the accuracy of a few centimetres (e.g. Žíhlavník *et al.*, 2013). In the present case, the resulting traverse accuracies were better than 10 cm.

The selection of ‘smart’ devices was limited by their availability at the time of the study. The basic characteristics of the devices examined in the

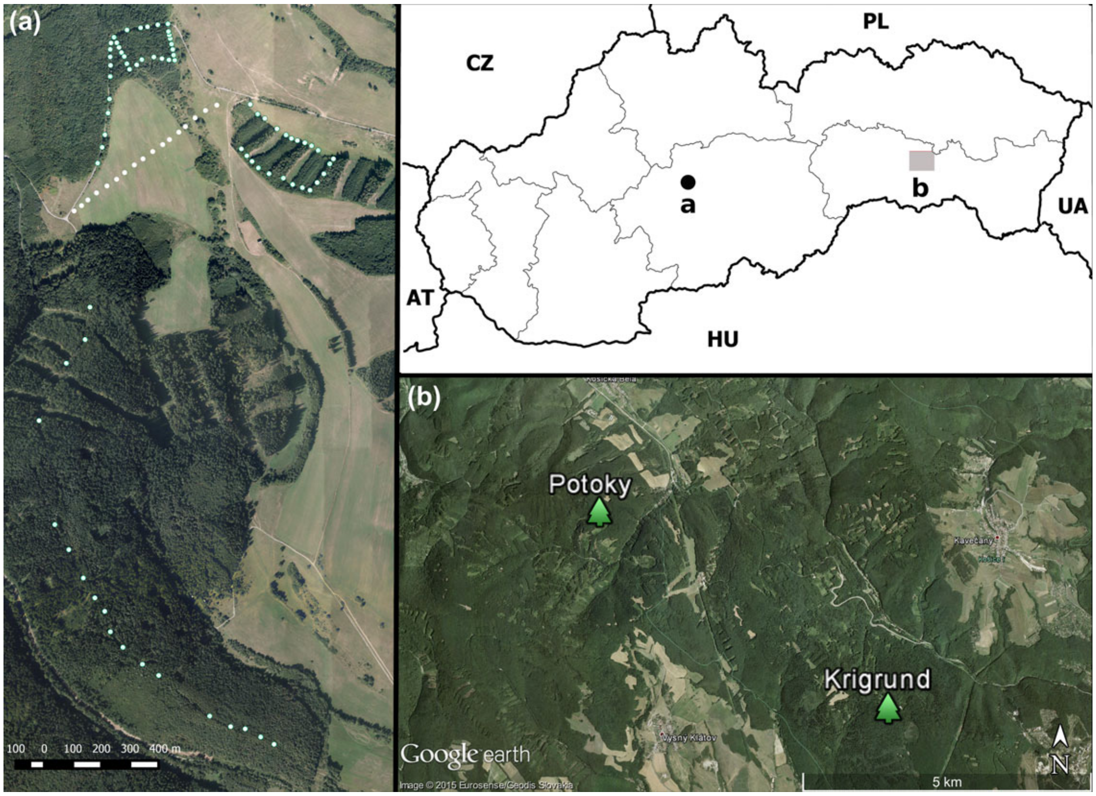

**Figure 1** Location of experimental areas (a) first experiment, (b) second experiment.

study are shown in Table 1. Most of the mobile devices used in the experiment can be considered mid-class with a decent price-performance ratio. The only exception is the ZTE Blade, which is an older telephone and was used to evaluate the development of smartphone positioning technology. The LG G2 smartphone was used with two differing operating systems, Android 4.4 (Kitkat) and Android 5.0 (Lollipop) to evaluate the influence of the operating system version on the resulting accuracy. Because GIS handheld GNSS receivers are today probably the most widespread tool for operative positioning in forests, the Trimble Nomad 900GLE receiver was used for comparison. A Topcon HiperGGD survey-grade receiver was also used in this experiment. The measurements with this receiver were conducted using the real-time kinematic method with differential corrections of the GNSS signal. The data needed for the differential corrections were acquired from the Slovak real-time positioning service SKPOS (http://skpos.gku.sk/en/) using a mobile data connection.

The selection of applied software was based on the experience of the authors. The Locus Map Pro application was chosen for the measurements with Android smartphones. The Trimble Nomad receiver used preinstalled TerraSync software. 'Add new point' option with no averaging was used in the Locus Map Pro application. The measurement in TerraSync software was conducted using 3 sec observation time for each individual point. The reception of the GNSS signal was switched on without a break even when moving between points. The measurements were conducted first during the growing season under leaf-on conditions (June 2015) and subsequently during the dormant season under leaf-off conditions (November 2015). Sunny days with minimal wind were chosen to minimize the impact of weather conditions. All acquired positions were transformed to the S-JTSK coordinate system, which is the obligatory coordinate system for mapping in Slovakia, using the official transformation service (https://zbgis.skgeodesy.sk/zbgistransform/).

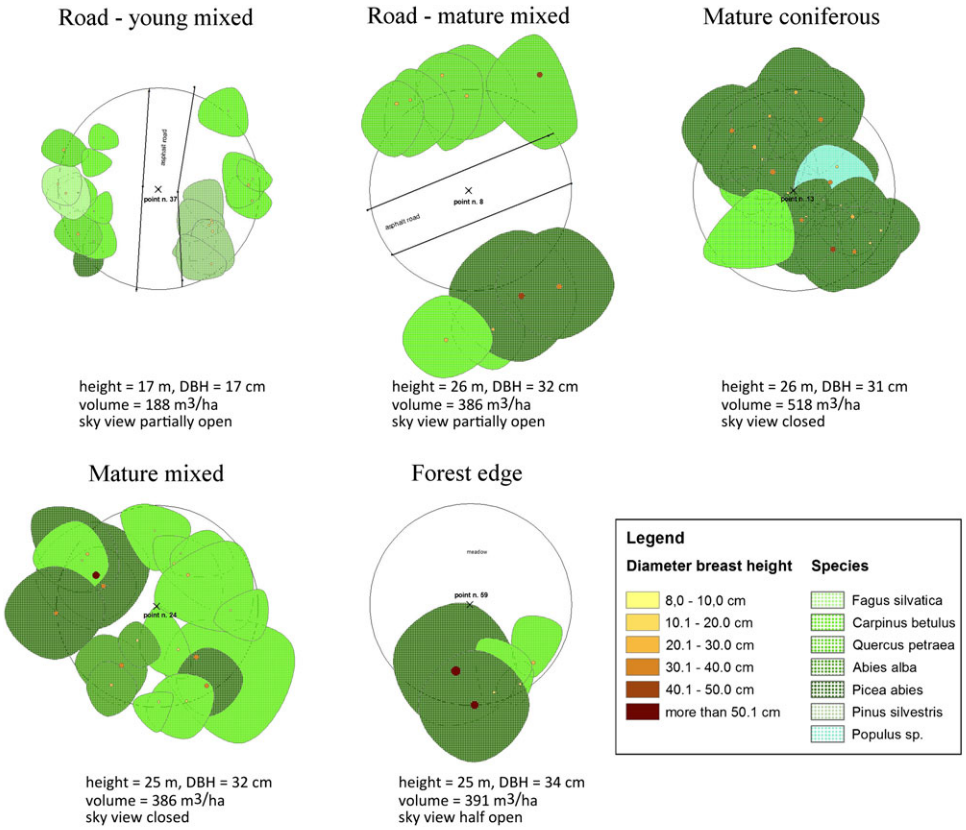

**Figure 2** Examples of forest settings evaluated in the first experiment.

**Table 1** Basic characteristics of devices used in the study

| Device | Type | Operating system | Supported GNSS |
|---|---|---|---|
| ZTE Blade | Cellphone | Android 2.3 | GPS |
| LG G2 | Cellphone | Android 4.4 (5.0) | GPS + GLONASS |
| Sony M4 Aqua | Cellphone | Android 5.0 | GPS + GLONASS |
| Lenovo Yoga 8 | Tablet | Android 4.4 | GPS |
| Trimble Nomad | Mapping-grade receiver | Windows Mobile v6.1 | GPS |
| Topcon HiperGGD | Survey-grade receiver | Windows CE 5.0 | GPS + GLONASS |

### Statistical analysis

The resulting positions were compared to the reference positions using the following measures:

Determination of mean coordinate errors:

$$\mathrm{RMSE}_x = \sqrt{\frac{\sum_{i=1}^{n} \Delta x_i^2}{n}};\ \mathrm{RMSE}_y = \sqrt{\frac{\sum_{i=1}^{n} \Delta y_i^2}{n}}, \tag{1}$$

where $\Delta x_i$, $\Delta y_i$ are differences between the GNSS acquired and reference (true) coordinates, and $n$ is the number of points in the set.

Calculation of the root mean square coordinate error $\mathrm{RMSE}_{xy}$, which is a characteristic of point sets accuracy and is one of the most common accuracy measures in geodesy. $\mathrm{RMSE}_{xy}$ is calculated as follows:

$$\mathrm{RMSE}_{xy} = \sqrt{0.5\,(\mathrm{RMSE}_x{}^2 + \mathrm{RMSE}_y{}^2)}. \tag{2}$$

Šmelko (2007) suggested the use of a 'coefficient of relative efficiency' to compare differences between the mean errors in terms of statistical significance:

$$R_e = \frac{\mathrm{RMSE}_A{}^2}{\mathrm{RMSE}_B{}^2}, \tag{3}$$

where $\mathrm{RMSE}_A$ is the mean error with higher value and $\mathrm{RMSE}_B$ is the mean error with lower value. Since it is a modification of the $F$-test, it is possible to determine the statistical significance of the difference between the tested values, when comparing the coefficient $R_e$ to the upper critical value of the $F$-distribution. This test was used for pair comparisons of the $\mathrm{RMSE}_{xy}$ values. Given the probability level $\alpha = 0.05$, the critical values were $F_{(73,73)} = 1.473$ for the comparison between leaf-on and leaf-off conditions and $F_{(16,73)} = 1.784$ for the leaf-off and open area comparison.

Since the $\mathrm{RMSE}_{xy}$ does not fully describe the within-group variability, a second measure for the positional error of individual points was calculated as follows:

$$\Delta p_i = \sqrt{\Delta x_i{}^2 + \Delta y_i{}^2}. \tag{4}$$

The positional error represents a positional shift of a single point from its position determined using a more accurate device. Minima, maxima, means and standard deviations for individual devices were calculated for this characteristic.

A one-way ANOVA with a *post hoc* Tukey HSD test was used to determine the significance of differences between devices in given conditions. In the case of non-normal distribution of the positional errors, which was present especially under open area conditions where the number of measurements was lower, the Kruskall–Wallis test was applied. The tests were conducted using STATISTICA software (StatSoft, Inc.).

The accuracy of groups of points in several typical forest settings occurring in the experimental area was also calculated. These groups included the outer edge of the forest, an asphalt road in young and mature mixed forest stands, and mature mixed and coniferous forest stands (Figure 2). In order to arrange these groups in terms of accuracy, we used a ranking method. Ranks from 1 (best) to 5 (worst) based on mean coordinate error were assigned to the groups for individual devices. The mean rank of individual groups was used to specify the final order.

Finally, the internal accuracy estimation algorithms that some of the 'smart' devices provided were compared with the true accuracies obtained from the comparison with the total station theodolite measurements. In the Android operating system, the estimated GNSS accuracy is acquired through the *getAccuracy* method which reports the radius of a circle in metres. The radius is calculated so that the probability that the true location is within this circle is 68% (Android Developer, 2016). Therefore, the percentage of real observed errors lower or equal to the estimated accuracy and the Pearson's correlation coefficients were calculated to evaluate a relation between the device's estimated accuracy and the real observed errors. Since the Lenovo Yoga tablet recorded positional dilution of precision (PDOP) instead of estimated accuracy for an unknown reason it was excluded from this analysis. The same applies for the Trimble Nomad and Topcon HiperGGD devices, which did not record estimated accuracy.

### Experiment 2: measurement of disturbed areas size

The second experiment was conducted in July 2014 in the municipal forests of Košice, Slovakia. The aim was to determine the size of contiguous disturbed areas. These disturbed areas were previously evaluated using a visual estimate, which comprised of an inspection of the site and the estimation of the area based on a forestry map and visible landmarks. Two sites with a large amount of damage were selected – 'Potoky' (~48° 44′55″N, 21°10′55″E) and 'Krigrund' (~48°46′50″N, 21°06′40″E) (Figure 1b). Approximate characteristics of the damaged forest stands, derived from forest management plans, are shown in Table 2. Two smartphones, ZTE Blade and LG G2, and the handheld Trimble Nomad receiver were used for the measurement. The measurement of the disturbed areas perimeter was conducted using all three devices simultaneously. The positions were recorded every 3 sec. The resulting boundary of the measured area was not manipulated in any way. Polygons were subsequently processed in QGIS Desktop 2.8.1 and Google Earth Pro software and sizes of individual areas were calculated. At the time of experimental data processing, satellite images of the experimental sites acquired shortly after the storm (September 2014) were already available. Therefore, the areas obtained with GNSS devices were compared to the area determined using satellite imagery in Google Earth Pro software. The differences were expressed as a percentage of the area obtained from satellite images.

Volumes of fallen timber were subsequently calculated by multiplying the determined areas (from both visual assessment and GNSS surveys) with per hectare volumes of individual forest management units (FMUs). The per hectare volumes in Slovak forest management plans are based on the combination of calliper DBH measurements, height measurements, relascope measurements and growth tables for individual species. Real volume of harvested timber was calculated by forest managers using lengths and diameters of individual logs, and volume tables for individual species. The estimated volumes were compared to the real volume only for the 'Potoky' site, because the 'Krigrund' site was struck by a subsequent disturbance in winter 2014, which changed the area and volume of damaged trees.

The measurement of the disturbed areas for the 'Potoky' site was repeated in July 2015 using the same devices to compare the boundaries of these areas before and after clean-up of the disturbance consequences (see the Supplementary data). Differences between polygons collected during the two surveys were computed in the QGIS software after necessary post-processing. The aim was to evaluate the spatial compliance of the repeated measurements and to identify reasons for potential differences. It was not possible to compare these results to actual satellite imagery as it was not yet available for the area of interest.

## Results

### Experiment 1: real-time accuracy under leaf-on, leaf-off and open-sky conditions

The aim of the first experiment was to compare the positions of the points collected using GNSS devices to the measurements conducted using more precise surveying equipment. A few outlying values of positional error were excluded from all

**Table 2** Forest stand characteristics of experimental sites used in second experiment

| Site | Krigrud | | | Potoky | | |
|---|---|---|---|---|---|---|
| Species | *Quercus petrea* | *Fagus silvatica* | *Abies alba* | *Fagus silvatica* | *Abies alba* | *Carpinus betulus* |
| Tree species composition (%) | 45 | 30 | 25 | 65 | 20 | 15 |
| Average diameter breast height (cm) | 36 | 46 | 42 | 36 | 42 | 35 |
| Average height (m) | 26 | 27 | 28 | 28 | 30 | 27 |
| Average age | | 110 | | | 90 | |

subsequent analyses. These individual errors were for leaf-on season: Lenovo Yoga 22.01 m, Topcon HiperGGD 7.85 m; for leaf-off season: ZTE Blade 48.58 m, Sony M4 43.14 m. The basic statistical characteristics for the positional errors Δp of individual points are shown in Figure 3, and the root mean square coordinate errors for the entire set of points are in Table 3. The values of $\mathrm{RMSE}_{xy}$ in the leaf-on season were 4.96–11.45 m for 'smart' devices (median 7.48 m), 10.11 m for handheld and 1.48 m for the survey-grade receiver. $\mathrm{RMSE}_{xy}$ values for the leaf-off season are in most cases lower, ranging from 4.51 to 6.72 m for 'smart' devices (median 5.30 m), 5.94 m for handheld and 1.18 m for the survey-grade receiver. The observed accuracy during leaf-off season is generally higher than in the leaf-on season, but the significance was confirmed only for ZTE Blade, LG G2 (4.4) and Trimble Nomad. The Lenovo Yoga tablet achieved better results in leaf-on than in leaf-off season. The results of the open area measurements are significantly better for all devices when compared to the forest measurements (in both seasons); 'smart' devices' $\mathrm{RMSE}_{xy}$ ranges from 1.90 to 2.26 m (median 2.11 m), while it is 1.63 m for the handheld and 0.06 m for the survey-grade receiver.

The variability of errors in the leaf-on season is higher both intra- and between devices when compared to the leaf-off and open area conditions. Maximum errors exceeded 30 m for three 'smart' devices and for the handheld receiver. The range of standard deviations is high – from 3.96 to 10.34 m, excluding the survey-grade receiver, at 1.46 m. The results of the ANOVA *post hoc* test (Table 4) confirmed the statistical significance of differences between certain devices. The difference between LG G2 smartphones with different versions of the operating system is not significant, although the mean error and standard deviation were lower for the device with Android 5.0. The mean errors and standard deviations decreased in the leaf-off season. Maximum errors did not exceed 25 metres. Standard deviation ranges from 2.90 to 6.41 m for 'smart' devices, and is 4.69 m for the mapping- and 1.22 m for the survey-grade receiver. Unlike the results in the leaf-on season, results of the ANOVA test in the leaf-off season did not show any significant difference between devices, with the exception of the survey-grade receiver. Furthermore, the variance of the results decreased. Because the results were significantly different only for the survey-grade receiver also under the open area conditions, the results of the ANOVA under leaf-off and open area conditions are presented in the Supplementary data. As mentioned before, the results of measurements under open area conditions were also significantly better than those under forest conditions in the leaf-off season. The maximum error was 6.21 m; standard deviations were in range of 1.24–1.53 m for 'smart' devices, and 0.94 m for the mapping-grade receiver. The standard deviation for the survey-grade receiver was only 0.02 m.

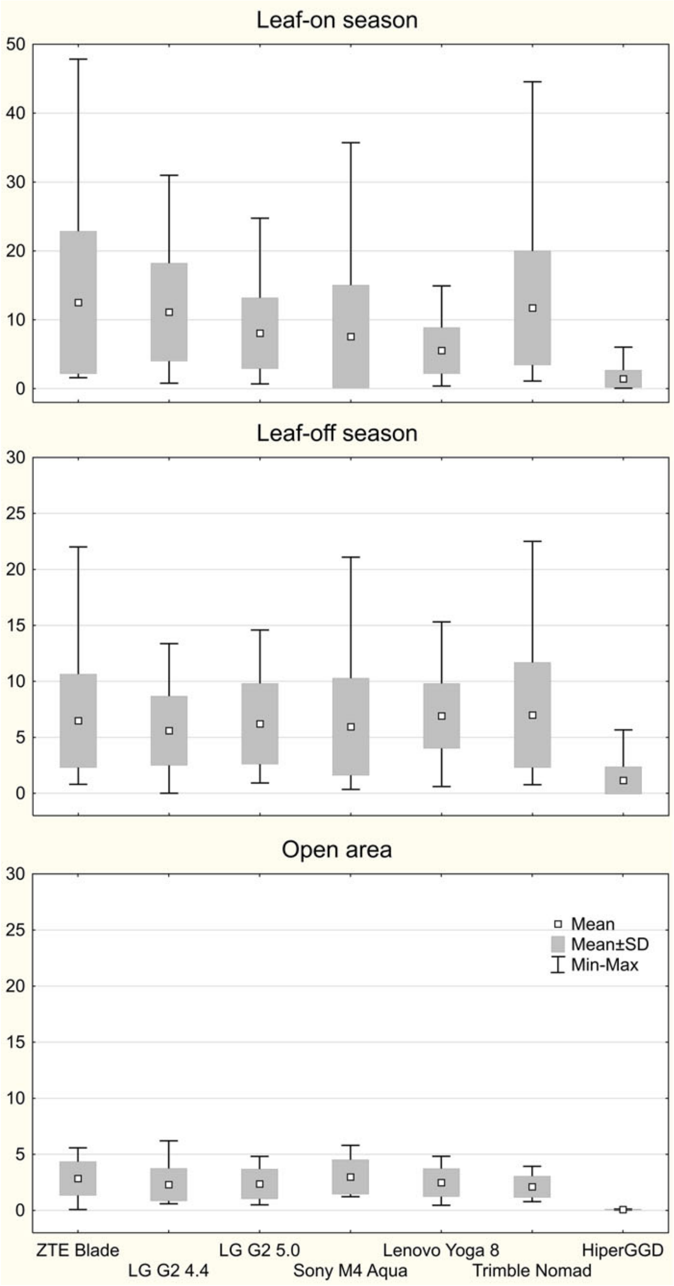

**Figure 3** Means, standard deviations, minima and maxima of positional error (in metres).

**Table 3** Root mean square coordinate errors $\mathrm{RMSE}_{xy}$ (in metres) and coefficients of relative efficiency $R_e$ between errors above and below the $R_e$ value (**bold** indicates significant difference at $\alpha = 0.05$)

| | ZTE Blade | LG G2 4.4 | LG G2 5.0 | Sony M4 Aqua | Lenovo Yoga 8 | Trimble Nomad | Topcon HiperGGD |
|---|---|---|---|---|---|---|---|
| Leaf-on | 11.45 | 9.30 | 6.74 | 7.48 | 4.96 | 10.11 | 1.48 |
| $R_e$ | **1.704** | **2.062** | 1.332 | 1.140 | 1.141 | **1.702** | 1.254 |
| Leaf-off | 6.72 | 4.51 | 5.06 | 6.56 | 5.30 | 5.94 | 1.18 |
| $R_e$ | **2.973** | **2.137** | **2.663** | **2.780** | **2.718** | **3.644** | **19.667** |
| Open area | 2.26 | 2.11 | 1.90 | 2.36 | 1.95 | 1.63 | 0.06 |

**Table 4** *P*-values of Tukey HSD test between devices in leaf-on season (**bold** values are significant at $\alpha = 0.05$)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| (1) ZTE Blade | | 0.87985 | **0.00451** | **0.00092** | **0.00003** | 0.99235 | **0.00003** |
| (2) LG G2 4.4 | 0.87985 | | 0.15269 | 0.05427 | **0.00012** | 0.99838 | **0.00003** |
| (3) LG G2 5.0 | **0.00451** | 0.15269 | | 0.99977 | 0.45202 | **0.04124** | **0.00003** |
| (4) Sony M4 Aqua | **0.00092** | 0.05427 | 0.99977 | | 0.70410 | **0.01136** | **0.00003** |
| (5) Lenovo Yoga 8 | **0.00003** | **0.00012** | 0.45202 | 0.70410 | | **0.00003** | **0.01431** |
| (6) Trimble Nomad | 0.99235 | 0.99839 | **0.04124** | **0.01136** | **0.00003** | | **0.00003** |
| (7) Topcon HiperGGD | **0.00003** | **0.00003** | **0.00003** | **0.00003** | **0.01431** | **0.00003** | |

Mean errors of groups in the specific forest settings are shown in Figure 4. We used a simple ranking method described in the methodology to order these groups in terms of accuracy. The order of groups in the leaf-on season was: forest edge (mean rank (m.r.) 1.00), road in young mixed stand (m.r. 3.00), road in mature mixed stand (m.r. 3.29), mature mixed stand (m. r. 3.57), and mature coniferous stand (m.r. 4.14). In the leaf-off season, the order was: forest edge (m.r. 1.29), road in mature mixed stand (m.r. 2.57), road in young mixed stand (m.r. 3.29), and mature mixed and coniferous stands shared the same mean rank of 3.86. The forest edge was the highest ranked in almost all cases. The difference between the $\mathrm{RMSE}_{xy}$ of the whole forest environment and the forest edge was 22–63% in leaf-on season and 10–56% in leaf-off season for the 'smart' devices. The differences for the survey-grade receiver were 79% and 88%, respectively. The differences between groups inside the forest environment were much lower, but the groups in partially open conditions were ranked higher than those under closed canopy.

The real positional errors and the values of estimated accuracy recorded by the 'smart' devices for every point were used to evaluate the reliability of the accuracy estimation algorithms of the tested devices. Percentages of errors equal to or lower than the estimated accuracy, Pearson's correlation coefficients and *P*-values are shown in Table 5. The reliability of the estimated accuracy was variable especially at the forest plots. Two of four devices achieved percentages higher or very close to 68% in the forest. Three of four devices achieved percentages higher than the defined criterion under the open area conditions. The correlation between estimated and observed accuracy was weak. The maximum correlation coefficient was 0.52 and, according to the *P*-value, many correlations cannot be considered significant. This problem is very noticeable under the open area conditions, where none of the correlations was significant, some of them actually negative.

## Measurement of disturbed areas size

The areas resulting from GNSS measurements were compared to the data obtained using visual estimation and consequently to the areas obtained from satellite images using Google Earth Pro software (Figure 5). The differences expressed as a percentage of the area obtained from satellite images are reported in Table 6. Visual estimation in most cases underestimated the areas compared to the satellite derived data. Exceptions are the FMUs 374a and 392 I. FMU 392 I was the smallest of the measured areas, where it was difficult to determine the area even on satellite images. The differences vary according to individual plots and devices, but in large areas of disturbance the errors are obvious: In the 'Krigrund' locality, the largest area formed by parts of FMUs 373 a and 373 I with an area of ~4.4 ha was underestimated by 1.1 ha using visual estimation. In the locality 'Potoky', the largest area formed by parts of FMU 309 and 310 with a total area of ~6.7 ha was underestimated by up to 4.6 ha with the visual method.

The determination of the volume of fallen trees closely followed the determination of the disturbed area size. According to the initial visual estimation conducted by the forest manager, the wind-thrown volume in the 'Potoky' locality should have been ~2525 $\mathrm{m}^3$. In comparison, the estimation based on the area determined using GNSS suggested volumes of 4599 $\mathrm{m}^3$ (LG G2), 4844 $\mathrm{m}^3$ (Trimble Nomad) and 5163 $\mathrm{m}^3$ (ZTE Blade). The estimation based on the satellite images was 4495 $\mathrm{m}^3$. The total volume of processed timber at the site was 4802 $\mathrm{m}^3$ according to the forest managers' records. This figure

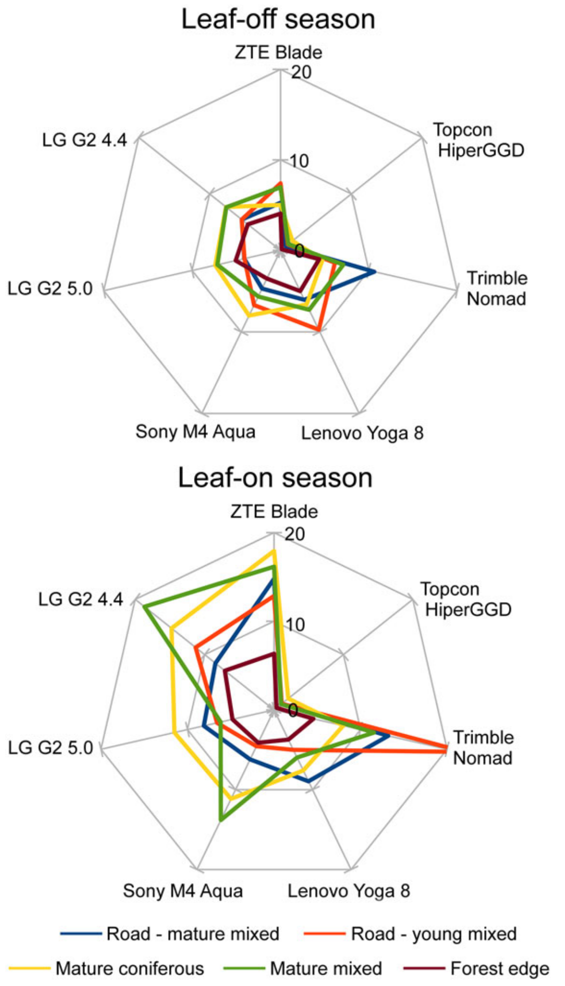

**Figure 4** Mean positional errors in various forest settings (in metres).

also included timber volume from scattered accidental felling, as it was not separately registered; this timber represented ~10–15% of the total volume of processed timber according to rough estimations. The visual estimation underestimated the wind-thrown timber volume by up to 47% in this particular case.

### *Repeated area determination*

Data of the repeated measurement from July 2015 at the 'Potoky' site were evaluated visually and numerically in terms of area changes. Figure 6 illustrates the visual evaluation of these measurements using the LG G2 smartphone measurements. Areas were computed for individual disturbance plots and were not divided into separate FMUs. The corresponding results are shown in Table 7. The differences in area have a wide range, but for plots formed by FMUs 309, 310 and 315 I the total difference is up to ± 10% of the original area.

The reason for these differences in area before and after the clean-up of the storm damage are mainly be explained by: (1) additional interventions of forest managers (one example can be seen in the southwest corner of 309–310 area (Figure 6)); (2) the inability of the surveyors to follow the original track; and (3) accuracy limits of the applied devices. The differences for the area formed by FMUs 307a and 311 are much higher than for the aforementioned units. This area has an oblong shape and is surrounded by mature forest stand, as opposed to the 315 I area that has similar shape, but is surrounded by young forest and clearings. The area of this plot was also enlarged because of the processing of damaged trees in peripheral areas, what can be seen in positive differences in area of the repeated surveys using LG G2 and Trimble Nomad (Figure 6 and Table 7). The results of the measurement using the ZTE Blade smartphone showed a negative difference, as opposed to the positive differences obtained by the other two devices. This contrast was most probably caused by the lower accuracy of the older device, which was also a result from the first experiment under leaf-on conditions.

## Discussion

### *Experiment 1*

Most other authors working on the comparison of GNSS devices (e.g. Ransom *et al.*, 2010; Wing and Frank, 2011) differentiate between consumer (recreational)-, mapping- and survey-grade GNSS receivers. Smartphones can be classified as consumer-grade receivers, according to the achieved accuracy. This category already includes a wide range of devices and it would be beneficial to establish a separate subcategory for positioning-enabled mobile phones to differentiate them from dedicated recreation-grade receivers. In the present study, the comparison of GNSS devices showed differences in accuracy between the survey-grade receiver and all other devices in both seasons (i.e. with and without foliage). These differences are partly caused by the grade differences between GNSS receivers, but probably to a higher degree by the application of differential GNSS (DGNSS) in the Topcon HiperGGD survey-grade receiver. On the contrary, only minimal or no positional accuracy differences were observed between the 'smart' devices and the mapping-grade receiver. This can be explained mainly with the hardware of the mapping-grade receiver examined here, which uses a SiRFstarIII chip as basic GNSS module. This module is currently mostly used in consumer-grade receivers. Therefore, this mapping-grade receiver cannot be considered representative of the current generation of mapping-grade receivers, as many of the recent models already offer some type of DGNSS solution.

The experiments confirmed that the forest environment substantially affects GNSS measurements, as has also been reported by other authors (e.g. Rodríguez-Pérez *et al.*, 2007; Trajkovski *et al.*, 2010). The root mean square coordinate errors ($\mathrm{RMSE}_{xy}$) of the survey-grade receiver in the forest were 20 (leaf-off) and 25 (leaf-on) times higher compared to the open area conditions with smooth signal reception. The values of $\mathrm{RMSE}_{xy}$ in forest are also significantly higher when evaluating other tested devices. The openness of forest canopy for the signal reception, for example due to gaps resulting from the disturbance events, has an important role as well. A relatively high positional accuracy can be obtained in large openings in forests, which have conditions comparable to the outside edge of a forest. In contrary, a transition of the examined devices to the interior of a forest caused a rapid decline in accuracy. This has a direct

**Table 5** Relation between estimated accuracy and observed error. Percentage of observed errors better than estimated accuracy (%), correlation coefficient (*R*) and *P*-level (*P*)

| | ZTE Blade | | | G2 4.4 | | | G2 5.0 | | | M4 Aqua | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | *R* | *P* | % | *R* | *P* | % | *R* | *P* | % | *R* | *P* |
| Leaf-on | 42 | 0.52 | 0.00 | 51 | 0.45 | 0.00 | 84 | 0.38 | 0.00 | 70 | 0.35 | 0.01 |
| Leaf-off | 47 | 0.41 | 0.00 | 54 | 0.25 | 0.03 | 67 | 0.08 | 0.55 | 77 | 0.22 | 0.10 |
| Open area | 94 | −0.30 | 0.24 | 82 | −0.09 | 0.73 | 100 | 0.28 | 0.27 | 53 | 0.41 | 0.10 |

Lenovo Yoga 8 tablet recorded PDOP instead of estimated accuracy, while Trimble Nomad and Topcon HiperGGD did not record estimated accuracy at all.

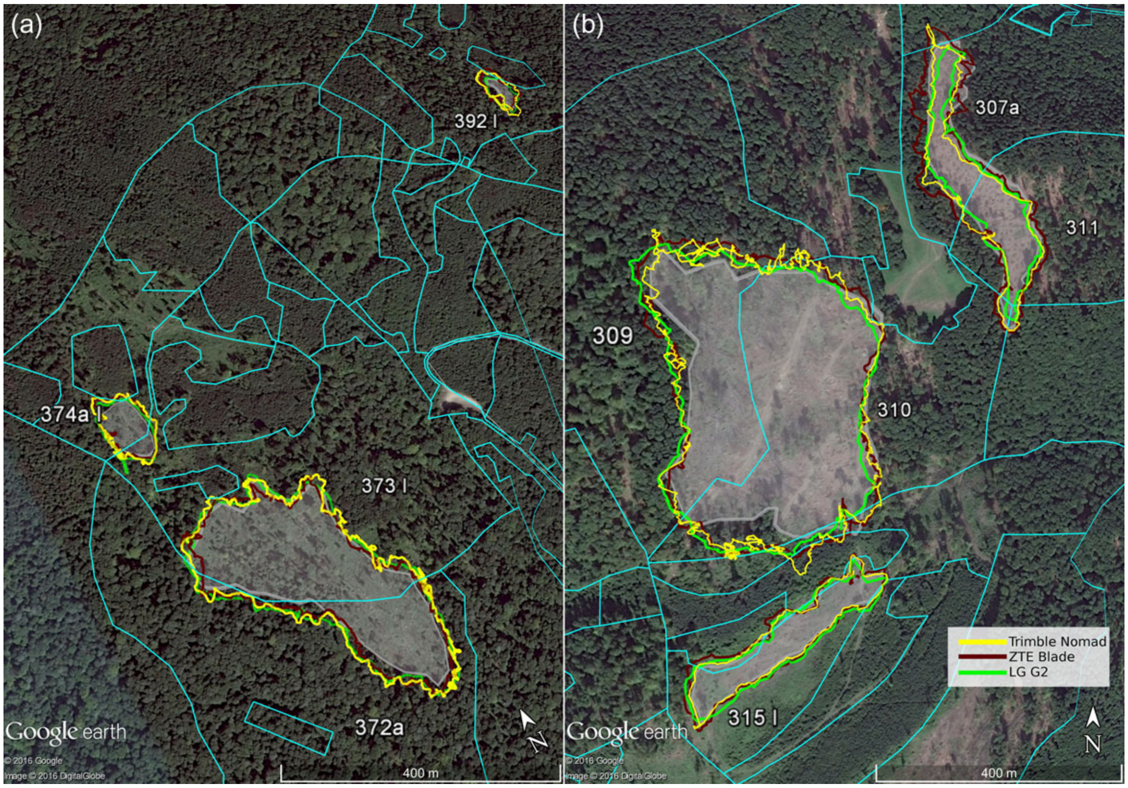

**Figure 5** Perimeters of disturbed areas, determined using examined devices and satellite images (a) ‘Krigrund’ site, (b) ‘Potoky’ site.

impact on the suitability of the examined devices for mapping of disturbed areas within a forest. The results of the second experiment suggest that the accuracy of the current state-of-art devices is not sufficient to map small open areas (below ~0.5 ha) where the edge effects of the remaining canopy are too strong. In accordance to this finding, Ucar *et al.* (2014) reported that the relative errors of the area determination, related to GNSS accuracy, decrease with increasing size. Furthermore, the results for groups situated on the skid-road in the first experiment showed that gaps in the canopy can improve the positional accuracy obtained with GNSS measurements.

Earlier studies have reported variable results of the GNSS measurements under a closed canopy. Some studies also tried to explain the obtained positional accuracies based on forest stand and environmental characteristics. For example, Frank and Wing (2014) took the basal area, horizontal dilution of precision, weather, terrain slope and GNSS receiver setting into account, but the best model explained only 14% of the variation in positional accuracy for a mapping-grade receiver. Wing *et al.* (2008) reported a decrease of horizontal error as canopy was reduced. For the correlation between positional accuracy and different characteristics of forest stands, Deckert and Bolstad (1996) reported an $R^2$ value of 0.106 for canopy, while Naesset (2001) reported $R^2$ values of 0.227 for basal area and 0.190 for tree height when using survey-grade receivers. Andersen *et al.* (2009) suggested that the size class and density of the stand do not affect the accuracy of under-canopy GNSS coordinates. Measurements of the multipath effect caused by multiple reflections of the GNSS signal in the complex forest canopy is

**Table 6** Areas (in hectares) according to locality, FMU and device. The percentage difference is given compared to the areas determined using satellite images

| Locality | Krigrund | | | | Potoky | | | | |
|---|---|---|---|---|---|---|---|---|---|
| FMU | 372a | 373 I | 374a I | 392 I | 309 | 310 | 315 I | 307a | 311 |
| Trimble Nomad | 1.9 | 3.2 | 0.36 | 0.27 | 2.43 | 5.03 | 1.08 | 0.79 | 0.86 |
| | +20% | +14% | +29% | +108% | +20% | +7% | +7% | −24% | −9% |
| ZTE Blade | 1.66 | 2.96 | 0.34 | 0.25 | 2.6 | 5.11 | 1.19 | 1.34 | 0.99 |
| | +5% | +5% | +21% | +92% | +29% | +8% | +18% | +29% | +5% |
| LG G2 | 1.88 | 3.15 | 0.33 | 0.22 | 2.54 | 4.8 | 1.17 | 0.7 | 0.79 |
| | +19% | +12% | +18% | +69% | +26% | +2% | +16% | −33% | −16% |
| Estimation | 0.8 | 2.5 | 0.6 | 0.2 | 0.55 | 1.5 | 1 | 0.8 | 0.6 |
| | −49% | −11% | +114% | +54% | −73% | −68% | −1% | −23% | −36% |
| Satellite images | 1.58 | 2.81 | 0.28 | 0.13 | 2.02 | 4.72 | 1.01 | 1.04 | 0.94 |

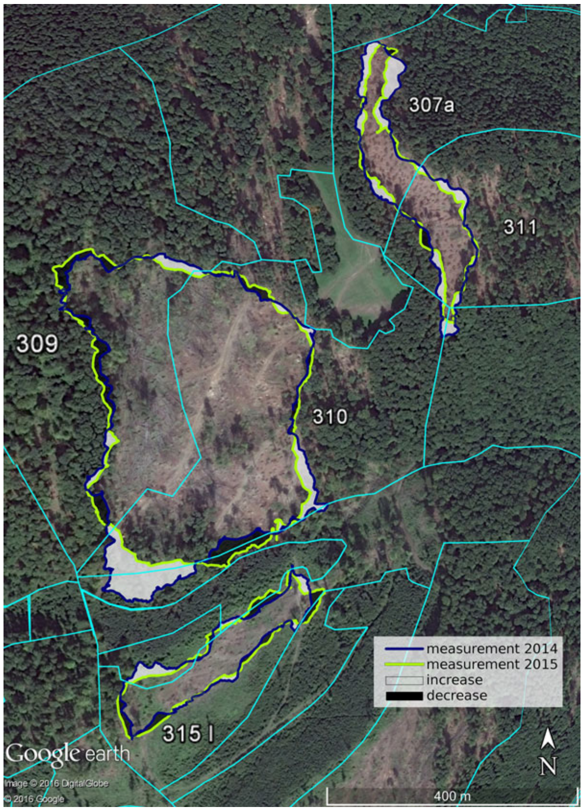

**Figure 6** Comparison of disturbed area perimeters acquired using LG G2 smartphone before and after clearing of disturbance consequences.

still complicated, although there are already methods addressing this problem (e.g. Xie and Petovello, 2015).

Further investigations on the multipath effect caused by forest canopies are desirable as it currently is – together with direct signal blocking – the main reason of the decrease of GNSS accuracy in forest. Another reason for signal blocking is topography. Topography is typically more rugged in forested areas (in Slovakia) and can therefore affect GNSS measurements, although some studies suggest that the importance of slope is low compared to the variable forest settings (Frank and Wing, 2014). In particular, the simple patch antennas and single-frequency L1 chips used in mobile phones and recreation-grade receivers have difficulties when dealing with the deterioration of the GNSS signal. This explains better accuracies (differences between 12% and 52%) observed for all smartphones during the leaf-off season. Surprisingly, the Lenovo Yoga 8 tablet achieved better results in the leaf-on season. No sound explanation was found for this. The proportion of the coniferous trees in the forests surrounding the point network used in the first experiment was ~30%. The impact of the vegetation period will possibly change with the relative proportion of coniferous and deciduous trees in the stand composition.

Furthermore, GNSS accuracy varies not only with regard to (canopy) conditions of an individual surveyed point, but also with respect to the time of measurement (Hofmann-Wellenhof *et al.*, 2008). To minimize the influence of the time of data acquisition the measurements in the first experiment were taken from all devices within a short time window, typically under 2 min on a single point. The measurements in the second experiment were conducted simultaneously and therefore excluded the time factor completely for any comparison between devices.

One important finding of this study is that the accuracy of smartphones used in the first experiment was significantly different only during the leaf-on season, with slightly better results for newer hardware and software. The results for the open area and the leaf-off season measurements, showed no significant difference even between mobile phones using the GNSS technology of 2015 and 2010. This could suggest that the current state-of-the-art smartphones are reaching technological accuracy limits. Hence, a technological change, for example the introduction of the differential GNSS in smartphones, is needed to improve positional accuracies for real-time measurements.

Although the number of types of smartphones in the market is very large, there is only a limited number of technological solutions used for the reception of GNSS signals. This study only includes devices with Android operating systems. The worldwide smartphone OS market share of the Android devices was 82.8% in 2015 Q2 (IDC, 2016). The iOS operating system with 13.9% was the second-most common. Zandbergen (2009) reported an average RMSE value of 9.0 m for iPhone 3G A-GPS measurements. Schaefer and Woodyer (2015) reported mean

**Table 7** Positive, negative, total and relative differences between areas determined before and after clearing of areas disturbed in the storm (in hectares)

| | | Disturbance area | | | | | |
|---|---|---|---|---|---|---|---|
| | Difference | 309–310 | | 315 I | | 307a–311 | |
| ZTE Blade | +/– | 0.43 | –0.93 | 0.17 | –0.19 | 0.12 | –0.43 |
| | Total/relative | –0.5 | –6.2% | –0.02 | –1.5% | –0.31 | –12.3% |
| LG G2 | +/– | 0.68 | –0.44 | 0.2 | –0.14 | 0.53 | –0.07 |
| | Total/relative | 0.24 | 3.3% | 0.06 | 5.1% | 0.46 | 30.9% |
| Trimble Nomad | +/– | 0.63 | –1.05 | 0.22 | –0.13 | 0.48 | –0.2 |
| | Total/relative | –0.42 | –5.6% | 0.09 | 8.3% | 0.28 | 17.0% |

errors of 2.65 and 4.19 m for iPhone 4 and iPhone 5, respectively. They also tested mobile phones manufactured by Samsung and reported a mean error of 2.75 m. Dabove and Petovello (2014) tested the iPhone 4 and Samsung Galaxy S5, and achieved an accuracy of ~2 m. These results were obtained under open-sky conditions and are similar to our results in most cases. However, excluding the hardware components, accuracy can be influenced also by the operating system and the application used for the data acquisition (von Watzdorf and Michahelles, 2010; Bauer 2013). The accuracy of smartphones with different versions of the operating system tested in this study was not significantly different, but the accuracy is not the only thing that can be influenced by OS version. The experience of the authors suggests that in terms of GNSS positioning the OS version can influence the time to lock, signal stability, acquirement of A-GPS data and other factors. Although some limits of the smartphone GNSS accuracy overall could already be evident, it is hard to generalize the results in terms of absolute numbers. The reason is a very high variability of hardware and software settings. Moreover, the technology of the 'smart' devices is more complicated compared for example to the dedicated consumer-grade receivers. Failure or even non-optimal function of one part of the complex system of a 'smart' device can influence other parts; including GNSS measurement.

As mentioned before, the averaging of a higher number of observations is one of the ways to improve GNSS accuracy for point measurements. The objective of the present experiments was to determine real-time accuracy, where the positional measurements are neither averaged nor post-processed. Such measurements can be easier applied to line and polygon measurements, but are very prone to higher errors and extremes. Therefore, the measurements of multiple point locations in the field were used to determine the mean characteristics of occurring errors. Besides averaging, there are also other options that could be applicable to improve the GNSS accuracy of smartphones. The application of the differential GNSS in GNSS-enabled mobile phones is probably just a matter of time, since the communication with DGNSS reference stations is technically already possible with most smartphones using a mobile data connection. The availability of raw data from a cellphone GNSS receiver is limiting in this case, because the current generation of smartphones does not provide such data (Chen *et al.*, 2014). In general, the raw data consist of primary determined data (pseudoranges, satellite ephemeris, clock and orbit details) that are used to calculate the position of the receiver. Smartphones and most consumer-grade receivers provide only the results of this calculation. The other possibility could be the integration of satellite-based augmentation systems. These regional systems can provide additional information about clock drift, ephemeris, ionospheric delay or direct information about signal errors in the past, which are broadcasted using geostationary satellites and used to eliminate some sources of GNSS error. Again, the raw GNSS data are necessary for this technology. Therefore, the only current option is the use of an external GNSS receiver with a Bluetooth connection (EGNOS, 2016). Various smartphone sensors (e.g. digital compass, accelerometer) providing partial information about the movement of the device could also be used to enhance the accuracy of smartphone positioning after integration with GNSS measurements (Hwang and Yu, 2012; Li *et al.*, 2013).

Information on the accuracy of positional measurements is crucial for certain tasks. Often, the estimated positional accuracy provided by the device is the only measure of accuracy available for the user. In this study, the relationship between estimated accuracy and observed errors was poor, as has also been reported by other authors (e.g. Zandbergen and Barbeau, 2011). The experience of the authors is that most of the smartphones tend to use a relatively small number of rough estimated accuracy values. For example, 100% of observed errors for the LG G2 5.0 under open-sky conditions were lower than the estimated accuracy, but a value of 10 m was estimated in half of the cases. Values of 3, 5 and 10 m were very frequent across all examined devices (as can be seen in the Supplementary data). Such a behaviour limits the use of estimated values. The reason for this problem is most likely connected to technical limitations of the receiver-hardware as this problem has also been documented for recreational-grade receivers (Andersen *et al.*, 2009).

### *Experiment 2*

The use of the Google Earth imagery as a reference in the second experiment is less reliable compared to the total station theodolite measurements in the first experiment. Therefore, it was not considered to be the 'truth', but the base for comparison. The reason for this was that a survey using a total station or even GNSS is very complicated, if not impossible, under conditions just after the disturbance. Remote sensing is the only convenient source of data in such a case. The aim of the second experiment was to compare areas; therefore, even a constant systematic shift of positions may not be problematic. However, the trajectories surveyed using GNSS devices did not show any apparent shift.

The result of the second experiment can lead to several practical suggestions. A mismatch between the course of a boundary in a forestry map and in terrain was detected in the case of FMU 374a. A damaged area that should have been wholly included in the FMU 374a according to a boundary marked in the forest, is divided between the FMU 374a and the adjacent FMU according to the forestry map (Figure 5a). This was caused by the presence of two forest roads, where the course of the boundary in the forestry map was created according to the first one, while the marked boundary in terrain according to the other. Such knowledge, coincidentally resulting from more precise determination of spatial data, can help a user to facilitate the renewal of forestry maps. The visual area estimation in situations where it is nearly impossible to use even basic landmarks is very difficult and highly dependent on the experience of forest managers. The highest area errors related to the visual estimation resulted from the non-transparent situation just after the storm, in conjunction with rugged terrain (altitudinal differences higher than 100 m) at the 'Potoky' site. Under such conditions where the visual estimation is complicated, GNSS measurement can be a viable solution, especially because it also benefits from the higher openness of the canopy. The results of the experiment showed that in contrast to the visual estimation, the delineations obtained with smartphones and the handheld receiver in most cases slightly overestimated the size of damaged areas compared to the remote sensing data. The overestimations were mainly caused by the need to circumnavigate parts that were impassable due to a high concentration of lying trees during the field survey. This is also evident from Figure 5, where the most significant differences between the areas identified using satellite imagery and those designated using the GNSS devices are on the southern and western edges of the disturbed areas. This corresponds to the wind direction and thus to the direction of fallen trees. This could be avoided by measuring well-accessible break points only, but it would require further processing that could cause complications for the average user. Also, most of the GNSS equipment allow to save separate points of interest during the line or polygon measurements, which could subsequently be used to refine the determined elements. However, such a correction was not used in this study, as a prevention of the introduction of possible subjectivity. Although the devices used for GNSS measurements cannot be considered as absolutely accurate, they were found useful to notably improve the estimates of damaged forest areas and the corresponding wood volume.

## Conclusion

The real-time horizontal accuracy of several 'smart' mobile devices was evaluated and compared to the results of a handheld and a survey-grade GNSS receiver under forest conditions in central Europe. According to the results, the current generation of smartphones could successfully compete with some consumer-grade and older mapping-grade receivers in terms of accuracy. The accuracy for point measurements under open area conditions was 2–6 times better compared to point measurements under forest conditions, depending on the vegetation period and the tested device. Positional accuracy differences between the examined 'smart' devices used in the study were significant only in the leaf-on season. The variability of the positional errors for 'smart' devices was high; therefore, in practice it is desirable to conduct at least occasional accuracy tests using, e.g., landmarks with known location and comparisons with maps.

The application of 'smart' devices to map larger damaged forest areas briefly after a storm event was found to notably improve area estimates in comparison to visual assessment. For mapping of smaller patches of damaged forest (less than 0.5 ha), the 'smart' devices were found to be less useful.

The results indicate that 'smart' devices can be a low-cost alternative for forestry tasks with lower accuracy demands, e.g. under-canopy navigation, preliminary detection of points of interest, mapping of linear and polygonal objects of interest. Further benefits of smartphones, like the possibility of logging the data to central databases in real time, can make them competitive with other GNSS devices.

## Supplementary data

Supplementary data is available at *Forestry* online.

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## Conflict of interest statement

None declared.

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