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Evaluation of the EGNOS service for topographic profiling in field geosciences

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ABSTRACT

Consumer grade Global Positioning System (GPS) receivers are commonly used as a tool for data collection in many fields, including geosciences. One of the methods for improving the GPS signal is provided by the Wide Area Differential GPS (WADGPS), which uses geostationary satellites to correct errors affecting the signal in real time. This study presents results of three experiments aiming at determining whether the precision of field measurements made by such a receiver (Garmin GPSMAP 62s) operating in either the non-differential and the WADGPS differential mode is suitable for characterizing geomorphological objects or landforms. It assumes in a typical field work situation, when time cannot be devoted in the field to long periods of stationary GPS measurements and the precision of topographic profile is at least as important as, if not more than, positioning of individual points. The results show that with maintaining some rules, the expected precision may meet the nominal precision. The repeatability (coherence) of topographic profiles conducted at low speed (0.5 m s^{-1}) in mountain terrain is good, and vertical precision is improved in the WADGPS mode. Horizontal precision is equivalent in both modes. The GPS receiver should be operating at least 30 min prior to measuring and should not be turned off between measurements that the user like to compare. If the GPS receiver needs to be reset between profiles to be compared, the measurement precision is higher in the non-differential GPS mode. Following these rules may result in improvement of measurement quality by 20% to 80%.

1. Introduction

The success of many geomorphological studies depends on reliable positioning and elevation data. Such information can be provided by non-differential GPS and differential GPS (DGPS) techniques, depending on the required precision. DGPS has been developed to increase accuracy by using two or more receivers at the same time (Haggitt and Warburton, 1999). The idea behind DGPS is to correct errors at one location with measured errors at a known position by a reference station (Kee, 1994). The corrections can be applied to data from the roving receiver in real time in the field using radio signals or by postprocessing after data capture (Chivers, 2003). DGPS has been widely used in geomorphological sciences since the early 1990s (e.g. Morton et al., 1993; O'Regan, 1996), in most cases for monitoring the landform changes with time, for instance shorelines (Khan and Tscherning, 2001; Battiau-Queney et al., 2003; Armaroli et al., 2013; Engel et al., 2015), glacier motion (Zhu et al., 2014; Bosson et al., 2015; Brugger and Pankratz, 2015; Zhang et al., 2015), mass wasting (Messina and Stoffer, 2000; Aucelli et al., 2013), or deformation caused by volcanic activity (Lagios et al., 2005). DGPS enables to retrieve distance changes with an accuracy of centimetres to millimetres when measurements are repeated over years. However in geomorphological works which require positioning accuracy of a few meters, obtaining such a high precision is not mandatory.

DGPS accuracy may also be useful either to describe topography of small objects (1–10s m; scarp, gully, groove, moat, cliff, terrace, landslide features, etc.) or to characterise slope profiles at outcrop scale (pediment, debris slopes, valleys, subglacial stream bed, etc.). Such objects are frequently too large or complex to measure with a tape, and too small to be appropriately depicted by existing topographic maps or DEMs such as those from SRTM (pixel size 30 or 90 m and error typically 5–15 m, Farr et al., 2007) or ASTER stereoscopic processing (ASTER GDEM, pixel size 15 m but frequently very noisy). As an illustration, the present work was motivated by the requirement of quantifying scarp profiles generated by deep-seated gravitational slope deformation

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(DSGSD) in the Tatra Mountains, one of the historic sites of DSGSD studies (e.g., Jahn, 1964; Nemčok, 1972), in order to understand their mechanics (Makowska et al., in press) and compare them with similar scarps observed on Mars (Mège and Bourgeois, 2011; Kromuszczyńska and Mège, 2014). The required vertical precision of scarp profiles, of height between 1 and 20 m, is estimated to be ca. 50 cm, and accuracies higher than 10 cm are estimated to be useless. The required horizontal precision is less critical as long as the same error propagates along each profile.

For such applications, solutions may be provided by consumer grade hand-held GPS receivers, which have become basic field tools, providing adjustment between horizontal and vertical precisions, and the scientific requirements. Modern hand-held GPS receivers can be used in two modes, non-differential, and Wide Area Differential GPS (WADGPS; also called Satellite-Based Augmentation System, SBAS), which uses GEO satellites as reference stations and makes corrections in real time.

Horizontal accuracy is well documented and easy to read on most hand-held GPS devices. It depends on the number of satellites seen by the GPS receiver, the implemented algorithms, and the surveyed area since the accuracy of the GPS frequency for civilians is determined by the US Army. In good satellite viewing conditions (i.e., clear sky and no nearby cliffs, buildings, nor canopy), the GPS horizontal accuracy in the non-differential mode is usually 3–5 m (Chen et al., 2003; Wing et al., 2005; Witte and Wilson, 2005; Skorkowski and Topór-Kamiński, 2012). The GPS specifications claim a horizontal accuracy of 7.8 m at a 95% confidence level (GPS SPS, 2008). Vertical accuracy is more problematic when using a hand-held GPS receiver. It depends on accuracy of the baselines gained from GPS observations, accuracy of the geoid model used in calculating orthometric heights, and the number, accuracy, and geometric location of vertical control points within the network (Meade, 2000). Verbree et al. (2004) reported a vertical accuracy of ~11 m. WADGPS makes use of geostationary satellites to correct various errors affecting the GPS signals, such as ionospheric delay, in order to improve the accuracy of GPS receivers. These satellites form the interoperable EGNOS, GAGAN, MSAS and WAAS networks servicing Europe, southern Asia, North America and eastern Asia, respectively. Most of Poland and Slovakia, where the experiments reported here have been conducted, are currently covered by EGNOS. The first WADGPS concept involved ground-based stations for calculating the corrections and sending them to user in real-time (Kee et al., 1991; Kee, 1994). Today, WADGPS also uses geostationary satellites for broadcasting the information from ground segment to end users. WADGPS consists of three parts: satellite, ground segment, and user segment (Fig. 1; EGNOS, 2014). The space segment comprises geostationary satellites (GEO satellites) responsible for collecting data and sending them to the ground segment. After processing, the correction data are sent back to GEO satellites to be broadcasted to the users' receivers. The ground segment comprises multiple monitor stations and a master station. The ground segment collects observables from GEO and GPS satellites; it receives also tropospheric data. After being collected, the data are processed to determine ionospheric corrections, satellite orbits, satellite corrections, and satellite integrity. Later data verification is provided by using an independent dataset. The corrections are then sent to GEO satellites to allow the user segment to receive them (FAA, 2001). The user segment is simply the WADGPS receiver, which collects the location and time data from GPS satellites as well as the correction data from the space segment.

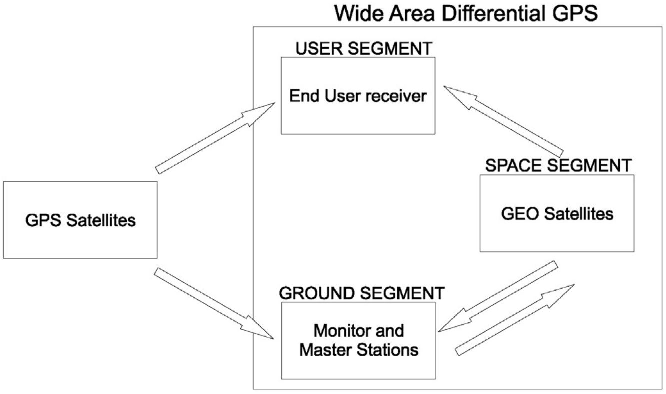

Fig. 1. Relationships among WADGPS segments and directions of data flow.

Several previous studies have shown that WADGPS provides more accurate positioning than non-differential GPS (Verbree et al., 2004; Witte and Wilson, 2005; Skorkowski and Topór-Kamiński, 2012). However, Arnold and Zandbergen (2011), using three different consumer grade GPS devices measuring data points over a time span of 30 min each, noted that WADGPS increases accuracy for one of the devices only, and for longer measurements (27 h), WAAS decreases positional accuracy. They acknowledged, however, that much longer measurement times are required to draw conclusions. Such studies are conducted in conditions that are generally not satisfactory for geomorphological applications. Typically, geomorphologists cover kilometres every day while surveying their study area and collecting scientific information. Measuring each interesting point for 30 min or more, as Arnold and Zandbergen (2011) did, is impossible in most cases. Witte and Wilson (2005) were interested in reliability of speed measurements over ground. Verbree et al. (2004) did water surface elevation profiling as geomorphologists would do on solid ground, but the absence of topographic relief makes their results uncomfortable to extrapolate to steep terrain. The measurement sites and conditions in Skorkowski and Topór-Kamiński (2012) are insufficiently characterised to allow inferences for geomorphological studies.

Conditions of GPS measurements that are convenient in geomorphological field studies for characterizing objects or landscapes include measurements at walking speed, and reliability of the recorded topographic profiles. The latter displays a major difference with previous works whose focus is the accuracy of individual points. In addition, the DSGSD study that inspired the present study (Reference needed) showed that the connection to the GEO satellites may be easily lost in a mountainous region even without canopy, resulting in hybrid profiles partly obtained in the non-differential GPS mode and partly in the WADGPS mode. Therefore, whether hybrid profiles make sense or not is another important issue. The ultimate objective of this work is to identify some rules or “good practices” to precisely quantify topography in the field with a hand-held GPS receiver using or not using WADGPS.

Three experiments using the non-differential GPS mode and the WADGPS mode were conducted, during which waypoints and trackpoints were recorded. The values of the precision obtained from each experiment, the reliability of topographic profiles, and the influence of walking speed, hybrid profiling, and other practical aspects are discussed.

2. Methodology

2.1. GPS device

The used GPS device is Garmin GPSmap 62s, a popular receiver available since 2010. Considered as a good synthesis of the popular Garmin 60 and 76 series (Owings, 2010a), including the GPSmap 60Cx used by Arnold and Zandbergen (2011) and the GPSmap 76S used by Wing et al. (2005), the chipset of the device, the high-sensitivity STMicroelectronics Cartesio (OpenStreetMap, 2014), has higher performance than the SiRF III chipset of the 60 and 76 series (Owings, 2010b). It is equipped with a quadrifilar helix antenna, a barometric altimeter, and is representative of the most accurate consumer grade GPS receivers currently available on the market. It was run with the firmware version 4.80.

2.2. Study sites

The experiments were performed in two locations: 1) the Lower Tatra Mts. in Slovakia during geomorphology field work, and 2) an esplanade in Wroclaw, Poland, in order to expand the range of experiments to a fully flat terrain, and for easier control of meteorological conditions during measurements. The minimum availability performance expected from EGNOS in the Tatra Mountains is 98%, with a minimum continuity risk performance of 99%; both values are 99% in Wroclaw. The expected vertical and horizontal accuracies are better than 4 m (EGNOS, 2011).

Two series of experiments were conducted on a flat terrain devoid of vegetation, 100 m NNE of the Centennial Hall in Wroclaw. The chosen path for profile measurement was flat and distant from buildings. The nearest construction is a semi-circular, ivy-covered colonnade, located at a minimum distance of 25 m, and a three-storey pavilion, located at a distance of 50 m. As indicated in Fig. 2a, five waypoints were marked for this experiment. The Wrocław 1 experiment was conducted on

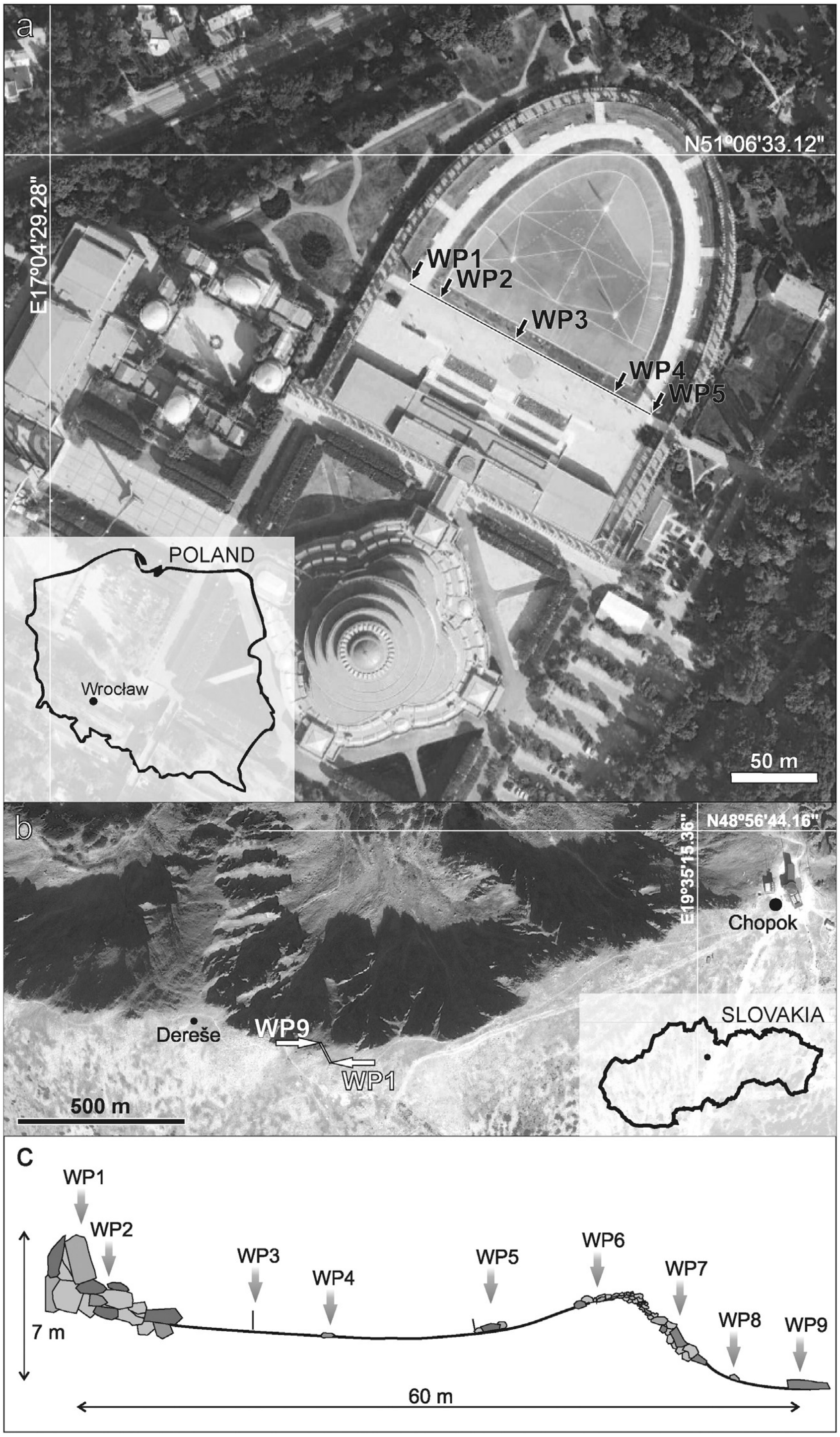

Fig. 2. Locations of experiments. a) Wroclaw experiments site. Source: Google™ Earth; 2015 MGGP Aero. b) Tatra experiment site. Source: Google™ Earth; 2015 CNES/Astrium. c) Sketch of waypoints location for the Tatra experiment; polygones show boulders and gravels.

December 03, 2013, with a clear sky and no wind. The Wrocław 2 experiment was conducted on November 21, 2013; the sky was 100% cloudy and windy. The additional objective of this study was to determine if overcast sky affects the signal of the GPS satellites, and if the high content of water vapor in the troposphere influences the GPS measurements precision.

The Tatra experiment was conducted in the Low Tatra Mts. in Central Slovakia, between Dereše Peak and Chopok Peak (Fig. 2b) on June 9, 2013. The weather was sunny with a few clouds (stratocumulus) and gusty wind. There is no canopy, and the vegetation is mainly grass with isolated shrubs. As indicated in Fig. 2c, the path chosen for the experiment consisted of nine waypoints located at different elevations. The first two waypoints (WP1–2) were marked on a pile of boulders, about 2–3 m high, where the first waypoint was located on the top of the pile, and the second at the bottom. The measurement line was conducted through a slightly depressed area (WP3–5) ending at a rocky scarp (WP6; Supplementary Figs. 1 and 2). The last three waypoints (WP79) were located on the other side of the scarp (Supplementary Fig. 3).

2.3. Data collection

Topographic profiles were collected and afterwards waypoints and trackpoints were analysed. Waypoints were used to evaluate precision, whereas trackpoints were used to investigate profile repeatability using a coherence analysis. During the measurements the GPS receiver was tied to a vertical stick at 78 cm above the ground. The waypoints were marked on the ground along the selected profiles (five waypoints for the Wroclaw experiments, and nine waypoints for the Tatra experiment). The GPS receiver was immobile at each waypoint for about 10 s, and the trackpoints were automatically acquired every 1 s. In each series of experiments, 16 profiles were measured, first from the initial waypoint to the last, and then in the opposite direction (Supplementary Figs. 1–3).

The profiles of the Wroclaw 1 experiment (Table 1) were first made in the non-differential GPS mode (GPS1–4). The GPS receiver was switched off for 13 min. Then, the second group of profiles in the non-differential mode was acquired (GPS5–8). The GPS device was restarted and the first set of the WADGPS mode measurements was acquired (WAD1–4). After a 10 min pause of GPS receiver operation, the second group of WADGPS profiles was obtained (WAD5–8).

In the Wroclaw 2 experiment (Table 2), the first four profiles were obtained in the non-differential mode (GPS1–4); then the device was turned to the WADGPS mode and four profiles were obtained (WAD1–4). The device was turned off for a few minutes and turned on again, and four additional GPS profiles were recorded (GPS5–8). The device was turned on again with the WAD GPS mode, but connection to the EGNOS satellites could not be established. Instead, another four non-differential GPS profiles were acquired (GPS9–12).

The Tatra experiment (Table 3; Supplementary Figs. 1–3) started by acquiring four profiles in the WADGPS mode (WAD1–4). Then the GPS receiver was restarted, and turned into the non-differential mode, and four profiles were measured (GPS1–4). The GPS device was turned off for 13 min and turned on again in the non-differential GPS mode to acquire the next four profiles (GPS5–8). The WADGPS mode was turned on and the last four profiles were obtained (WAD5–8).

2.4. Data analysis

We examined the relative precision of GPS measurements, not absolute accuracy – waypoint analysis was conducted to study the precision of data for points which had been well identified in the field. The waypoints used for this study were located by symbols such as wooden sticks pushed into the ground and pebbles. The analysis of trackpoint, which are defined by time, not location, made possible examination of profile similarity between the waypoints. Trackpoints were recorded every 1 s.

The comparison of waypoint horizontal and vertical locations, and measuring the most distant values for each waypoint gives the horizontal and vertical precisions in meters. Such measurements were conducted for profiles made in both the non-differential GPS and the WADGPS modes. The precisions obtained with both modes were compared.

In order to examine profile similarity, a tool for determining profile coherence was developed. It allows us to compare the profile topographic shapes by applying a transformation of time profiles to distance profiles. The time-scaled trackpoint segments between each pair of consecutive waypoints are aligned with the distance-scaled waypoints, converted to distance segments, and resampled to a common number of trackpoints. The coherence of the segments is compared from profile to profile.

The tool takes the trackpoints and the waypoints in the grid format. The trackpoint data have an array of four columns: the 1st and 2nd

Table 1
Timeline and horizontal accuracy given by the GPS receiver for the Wroclaw 1 experiment (clear sky).

Profile ID	GPS mode	Start point	Start time	End point	End time	Given accuracy	Number of available satellites
GPS1	Non-differential	WP1	09:33:37	WP5	03:36:33	3 m	11
GPS2	Non-differential	WP5	09:37:04	WP1	09:39:59	3–5 m	11
GPS3	Non-differential	WP1	09:40:28	WP5	09:43:18	3–4 m	10
GPS4	Non-differential	WP5	09:43:54	WP1	09:46:44	3–4 m	11
9:47:25 >>>>> GPS receiver switched off <<<<< 10:01:42							
GPS5	Non-differential	WP1	10:04:41	WP5	10:07:46	4–5 m	11
GPS6	Non-differential	WP5	10:08:34	WP1	10:11:38	4–7 m	9
GPS7	Non-differential	WP1	10:12:16	WP5	10:15:09	3–5 m	10
GPS8	Non-differential	WP5	10:15:40	WP1	10:18:54	3–4 m	11
10:19:36 >>>>> GPS receiver switched off <<<<< 10:25:58							
WAD1	Differential	WP1	10:28:27	WP5	10:35:02	3 m	2GEO + 6D
WAD2	Differential	WP5	10:35:33	WP1	10:39:37	3 m	2GEO + 7D
WAD3	Differential	WP1	10:43:19	WP5	10:46:13	2–3 m	2GEO + 8D
WAD4	Differential	WP5	10:46:31	WP1	10:51:39	3–4 m	2GEO + 10D
10:52:08 >>>>> GPS receiver switched off <<<<< 11:01:12							
WAD5	Differential	WP1	11:02:32	WP5	11:05:30	4 m	2GEO + 10D
WAD6	Differential	WP5	11:05:58	WP1	11:11:10	3–5 m	2GEO + 11D
WAD7	Differential	WP1	11:13:54	WP5	11:18:34	3–4 m	2GEO + 7D
WAD8	Differential	WP5	11:19:08	WP1	11:21:46	3–4 m	2GEO + 9D

Table 2
Timeline and horizontal accuracy given by the GPS receiver for the Wroclaw 2 experiment (cloudy weather).

Profile ID	GPS mode	Start point	Start time	End point	End time	Given accuracy	Number of avaliable satellites
GPS1	Non-differential	WP1	09:29:21	WP5	09:32:49	3–4 m	9
GPS2	Non-differential	WP5	09:33:34	WP1	09:37:01	3–5 m	11
GPS3	Non-differential	WP1	09:37:28	WP5	09:40:58	3–4 m	11
GPS4	Non-differential	WP5	09:41:40	WP1	09:45:07	3–4 m	11
WAD1	Differential	WP1	09:48:06	WP5	09:53:25	3 m	1GEO + 5D
WAD2	Differential	WP5	09:53:55	WP1	09:57:03	3–4 m	1GEO + 11D
WAD3	Differential	WP1	10:05:51	WP5	10:09:48	3–4 m	1GEO + 7D
WAD4	Differential	WP5	10:10:07	WP1	10:19:13	3–5 m	1GEO + 3D
10:19:20 >>>>> GPS receiver switched off <<<<< 10:23:46							
GPS5	Non-differential	WP1	10:24:17	WP5	10:27:15	3–4 m	11
GPS6	Non-differential	WP5	10:27:39	WP1	10:30:38	3–4 m	11
GPS7	Non-differential	WP1	10:31:31	WP5	10:34:29	3–4 m	10
GPS8	Non-differential	WP5	10:35:08	WP1	10:38:08	3–6 m	10
10:39:02 >>>>> GPS receiver switched off <<<<< 10:50:34							
GPS9	Differential	WP1	10:56:32	WP5	10:59:24	3–5 m	9
GPS10	Differential	WP5	10:59:53	WP1	11:02:43	3–4 m	9
GPS11	Differential	WP1	11:03:12	WP5	11:05:57	3–4 m	9
GPS12	Differential	WP5	11:06:16	WP1	11:09:12	4–5 m	9

columns are the coordinates (lon, lat) expressed in degrees, the 3rd is the elevation expressed in meters, and the 4th is the acquisition time expressed in the format "year-month-day-hour:minute:second". The waypoint data have an array of five columns; the first four columns have the same structure as the trackpoint array and the last column is the point number. In the Tatra experiment, the number of trackpoints varies between 145 and 443. In the Wroclaw experiments, the number of trackpoints varies from 166 to 210. The method chosen to estimate track similarity (Fig. 3) includes the following steps:

1. The profiles starting from WP9 (or WP5) and ending at WP1 are reversed in order to follow the same direction as the profiles starting from WP1 and ending at WP9 (or WP5).
2. The trackpoints spatially corresponding to the waypoints are identified by comparing their acquisition times:

$$\rho_{\mathrm{p}} = \min(|time_i - time_m|)_{i,\ m=1:N} \tag{1}$$

where ρ_{p} is the position of the resampled point, the subscript m describes the waypoint, and the subscript i the trackpoint. Eq. (1) is used to define which track point corresponds to the waypoint or the nearest waypoint.

3. The succession of trackpoints in time is assumed to be the same as their succession in direction, and none is going backward. The validity of this assumption is tested. If it is not valid, another function reorders the points so that their number increases with the distance from the first point. This function does not compromise the validity of the method because no point is added, and only some of them changed their position. The result is a strictly monotonic increasing function of distance with time:

$$\rho_{\mathrm{p}} = \min(|lat_i - lat_m|,\ \ |lon_i - lon_m|)_{m=1:N} \tag{2}$$

where ρ_p is the position of the resampled point, and *lon* and *lat* represent the coordinates of the points.

4. Each track is divided into subtracks according to the following rule:

$$X_n = \sum_{s=1}^{N} Y_n(s) \tag{3}$$

where X_n is a track, Υ_n a subtrack, n the number of tracks, and s the number of single points belonging to the trackpoints corresponding to the waypoints in the track. The value of s for all the tracks in the

Table 3
Timeline and horizontal accuracy given by the GPS receiver for the Tatra experiment.

Profile ID	GPS mode	Start point	Start time	End point	End time	Given accuracy
WAD1	Differential	WP1	10:02:49	WP9	10:10:10	3 m
WAD2	Differential	WP9	10:11:55	WP1	10:19:17	3 m
WAD3	Differential	WP1	10:20:17	WP9	10:24:27	3 m
WAD4	Differential	WP9	10:24:36	WP1	10:28:34	3–4 m
10:29:25 >>>>> GPS receiver switched off <<<<< 10:31:34						
GPS1	Non-differential	WP1	10:33:03	WP9	10:36:34	3–6 m
GPS2	Non-differential	WP9	10:36:44	WP1	10:39:41	3–4 m
GPS3	Non-differential	WP1	10:39:49	WP9	10:42:40	3–5 m
GPS4	Non-differential	WP9	10:42:53	WP1	10:45:31	3–4 m
10:49:22 >>>>> GPS receiver switched off <<<<< 11:03:00						
GPS5	Non-differential	WP1	11:04:26	WP9	11:07:27	3–4 m
GPS6	Non-differential	WP9	11:07:42	WP1	11:11:20	3–4 m
GPS7	Non-differential	WP1	11:11:31	WP9	11:14:11	3–5 m
GPS8	Non-differential	WP9	11:14:26	WP1	11:18:55	3–4 m
WAD5	Differential	WP1	11:21:06	WP9	11:25:11	3 m
WAD6	Differential	WP9	11:26:44	WP1	11:29:23	3 m
WAD7	Differential	WP1	11:29:35	WP9	11:32:09	2–3 m
WAD8	Differential	WP9	11:32:25	WP1	11:34:49	2–3 m

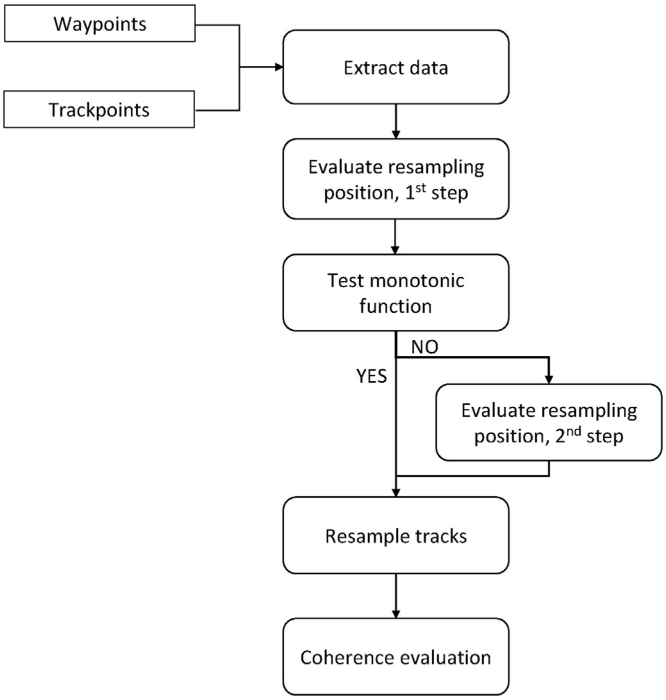

Fig. 3. Routine of track coherence evaluation.

Wroclaw experiment is 5, and that for all the profiles in the Tarta experiment is 9.

5. Each subtrack is resampled according to the homologue subtrack on the profile having the highest number of points. Resampling is done by linear interpolation to the value at the nearest point.
6. The coherence γ between tracks is calculated:

$$\gamma = 1 - \frac{\sum_{m=1}^{M} E\left[X_{track(i)} - X_{track(m)}\right]}{maxE\left[X_{track(i)} - X_{track(m)}\right]_{m=1:N}} \quad (4)$$

where E is a weighted mean, and X_{track} can be either the height extracted from the trackpoints array, or the coordinates obtained after converting the (lat[deg]/lon[deg]) vectors into UTM coordinates transformed into the horizontal vector of distances.

7. The global coherence from the average of the two arrays of coherence obtained from the height and coordinates is calculated.

Coherence can vary from 0 to 1; 1 means that the two compared profiles are exactly the same, whereas 0 means that they are the most different among all the profiles. Therefore, the significance of the coherence value of 0.8 depends on the range of differences of all profiles in the experiment.

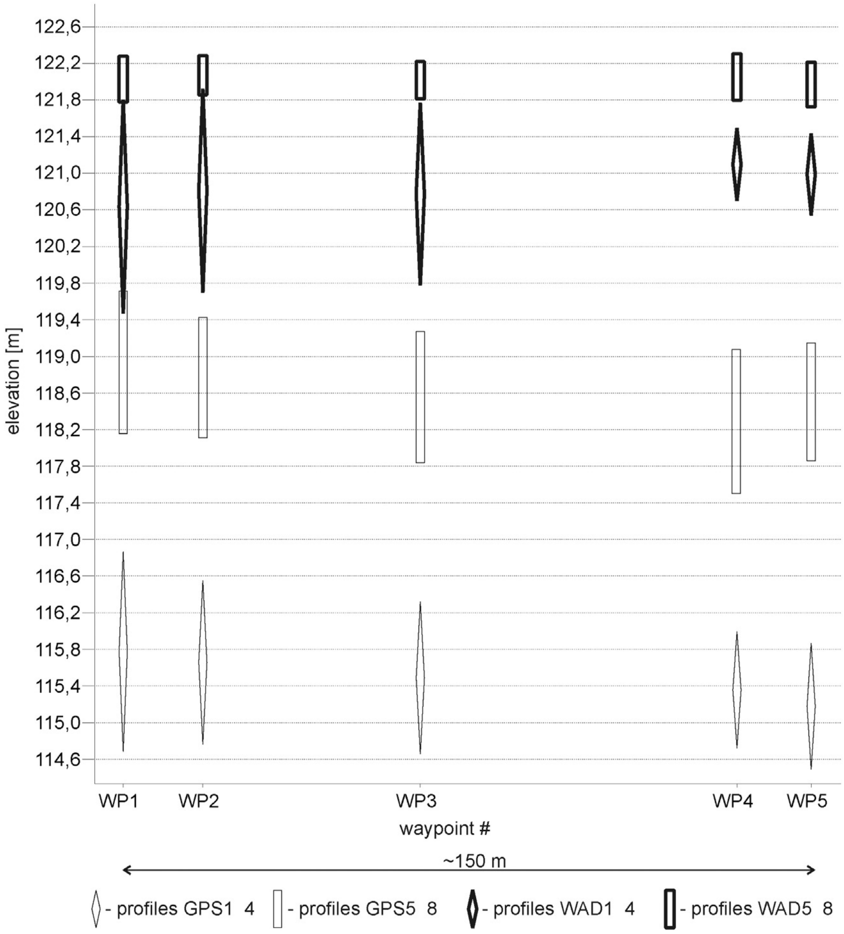

Fig. 4. Records of waypoint elevation for the eight profiles measured in the non-differential GPS and WADGPS modes during the Wroclaw 1 experiment.

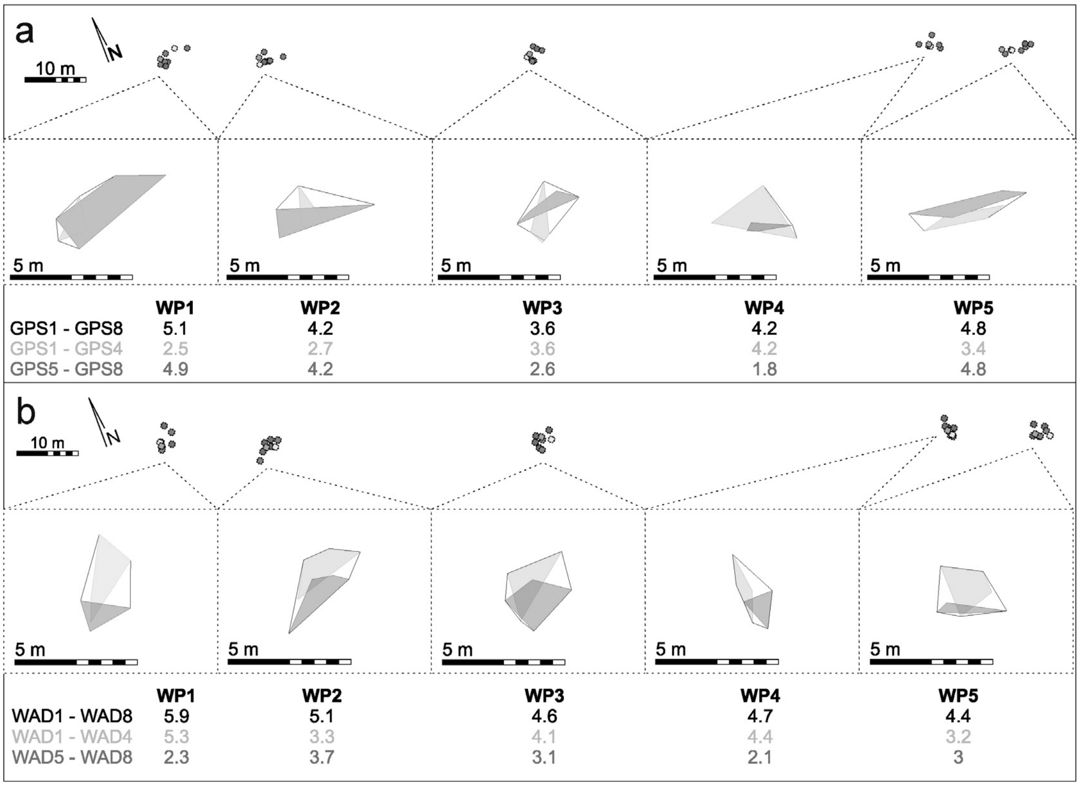

Fig. 5. Map view of location variability of waypoints measured during the Wroclaw 1 experiment. a) Non-differential GPS mode. b) WADGPS mode.

3. Results

The minimum vertical shift between adjacent trackpoints was nearly 40 cm, which appears to be the vertical resolution of the GPSmap 62s receiver.

3.1. Wroclaw 1

The highest elevation discrepancy for individual waypoints measured in the non-differential GPS mode (profiles GPS1–8) is between 4.3 m (WP4) and 5 m (WP1). The vertical precision is improved for profiles between which the GPS receiver was not switched off: 1.3 m (WP4) to 2.2 m (WP1) for profiles GPS1–4, and 1.3 m (WP5) to 1.6 m (WP4) for profiles GPS5–8 (Fig. 4). The overall horizontal precision (Fig. 5a, profiles GPS1–8) varies from 3.6 m (WP3) to 5.1 m (WP4). Switching off and on of the GPS receiver also affects the horizontal precision, but not as significantly as the vertical precision, i.e. for profiles GPS1–4: 2.5 m (WP1) to 4.2 m (WP4), for profiles GPS5–8: 1.8 m (WP4) to 4.9 m (WP1).

The difference of elevation for individual waypoints measured in the WADGPS mode (profiles WAD1–8) is between 1.8 m (WP5) and 2.8 m (WP1). The vertical precision is improved for the groups of profiles both before and after switching off the GPS receiver. It is 0.7 m (WP4) to 2.3 m (WP1) for profiles WAD1–4, and 0.4 m (WP3) to 0.5 m (WP4; Fig. 4) for profiles WAD5–8. The horizontal precision (Fig. 5b) for profiles WAD1–8 varies from 4.4 m (WP5) to 5.9 m (WP1). The horizontal precision is better when profiles are compared in two separated groups, before and after switching off the GPS receiver, i.e. it is 3.2 m (WP5) to 5.3 (WP1) for profiles WAD1–4, and 2.1 m (WP4) to 3.7 m (WP2) for profiles WAD5–8.

The results of trackpoint profile coherence analysis (Fig. 6c–e) show that each group of four profiles represents a coherent series in terms of height. The two WADGPS groups are more coherent than the two GPS groups. In the vertical coherence graph, a gradual shift from high coherence to low coherence is observed from the beginning to the end of the experiment. This corresponds to a drift in the GPS base level with time. The analysis of the successive GPS profiles shows shift of 8 m in elevation for all 16 profiles. We do not correlate that drift with the degradation of the GPS signal because the number of satellites seen by the receiver and the quality of their signal were constant during all the measurements. For the horizontal coherence, the diagram shows no shift. The eight non-differential GPS profiles are more coherent set than the WADGPS profiles. However, the similarity of each group of the WADGPS profiles is not high. Especially the first set of WADGPS profiles (WAD1–4) is incoherent. Some WADGPS profiles (WAD2 and WAD3) are more similar with the GPS profiles than with the other WADGPS. The global coherence (Fig. 6e, right), an average value of vertical and horizontal coherence, shows that the first group of the non-differential GPS profiles (GPS1–4) and the second group of WADGPS profiles (WAD5–8) are the most homogeneous.

3.2. Wroclaw 2

For all the twelve profiles (GPS1–12) measured in the non-differential GPS mode, the vertical precision for individual waypoints is in the range from 44.0 m (WP5) to 50.6 m (WP1; Fig. 7).

In the first group of profiles (GPS1–4), before switching off the GPS receiver, the highest elevation discrepancy is from 10.5 m (WP5) to 18.6 m (WP1). It may show that with full overcast sky, the GPS device needs more time to start proper measurements. The second group of profiles (GPS5–8), between switching the GPS device on and off again, has a vertical precision from 0.3 m (WP5) to 1.7 m (WP1). Among the third group of profiles (GPS9–12), the values of vertical precision are even smaller: from 0.2 m (WP5) to 1 m (WP1).

The horizontal precision for the whole series of the profiles measured in the non-differential GPS mode (Fig. 8a) is from 4.6 m (WP1) to 6.1 m (WP4). The results of horizontal measurements do not show a great discrepancy, especially at the beginning of measurements, as in the case of vertical measurements. The horizontal precision is affected by the switching off and on of the GPS receiver; for each

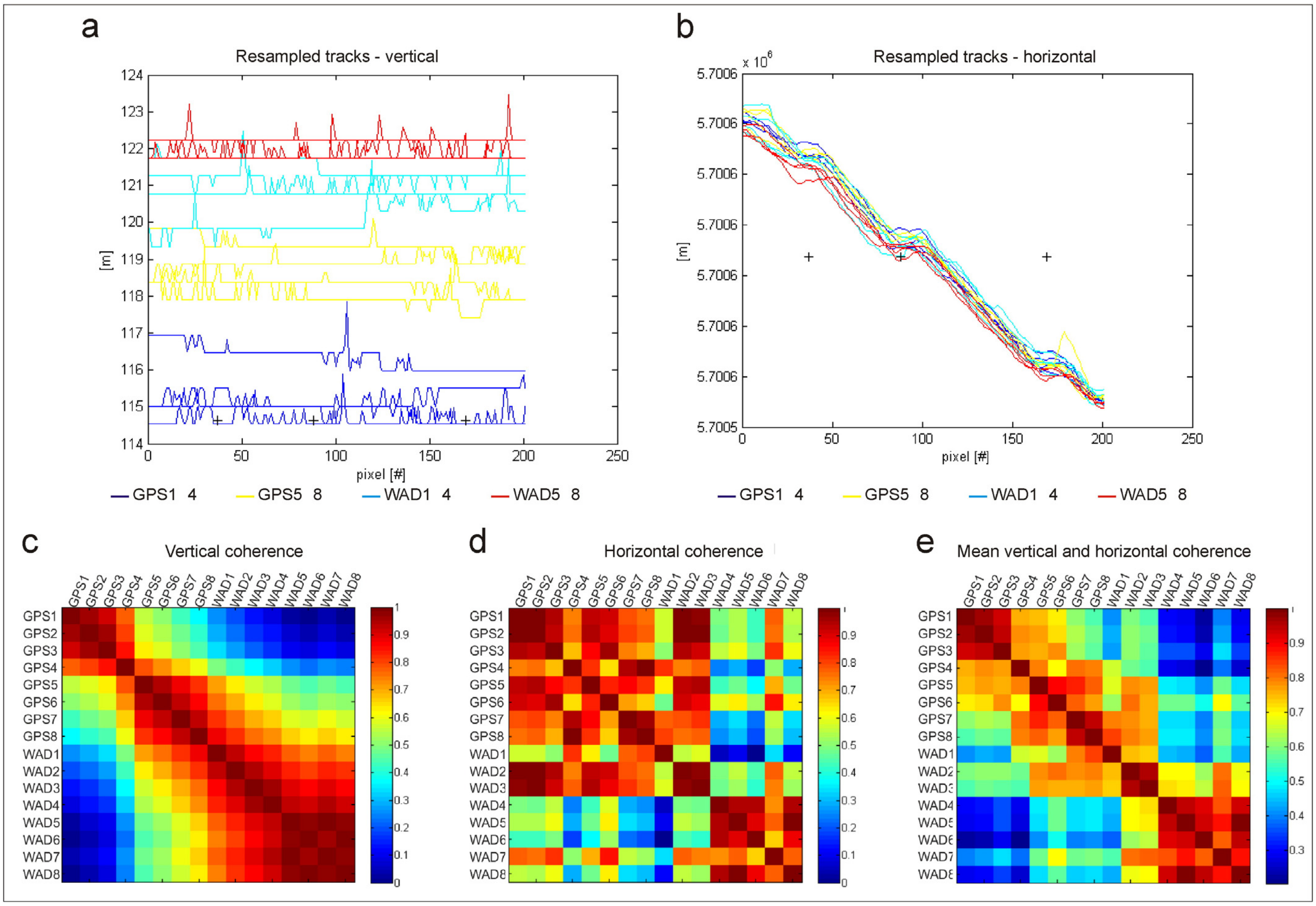

Fig. 6. Results of coherence analysis for the Wroclaw 1 experiment. a) Resampled topographic (vertical) profiles. b) Profile traces in the map view. c) Vertical profile coherence. d) Horizontal profile coherence. e) Global profile coherence (1: identical profiles, 0: most different profiles in the experiment).

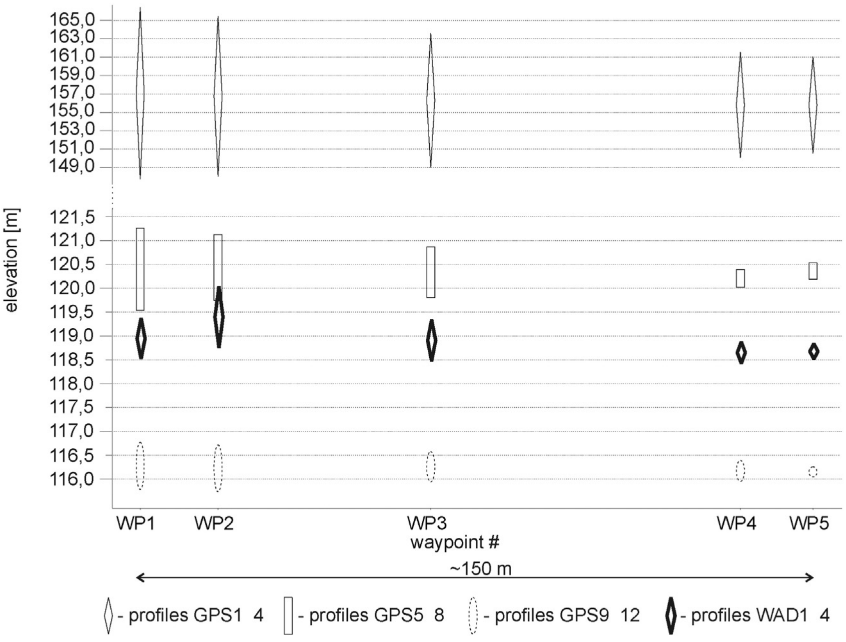

Fig. 7. Records of waypoint elevation for the eight profiles measured in the non-differential GPS and WADGPS modes during the Wroclaw 2 experiment.

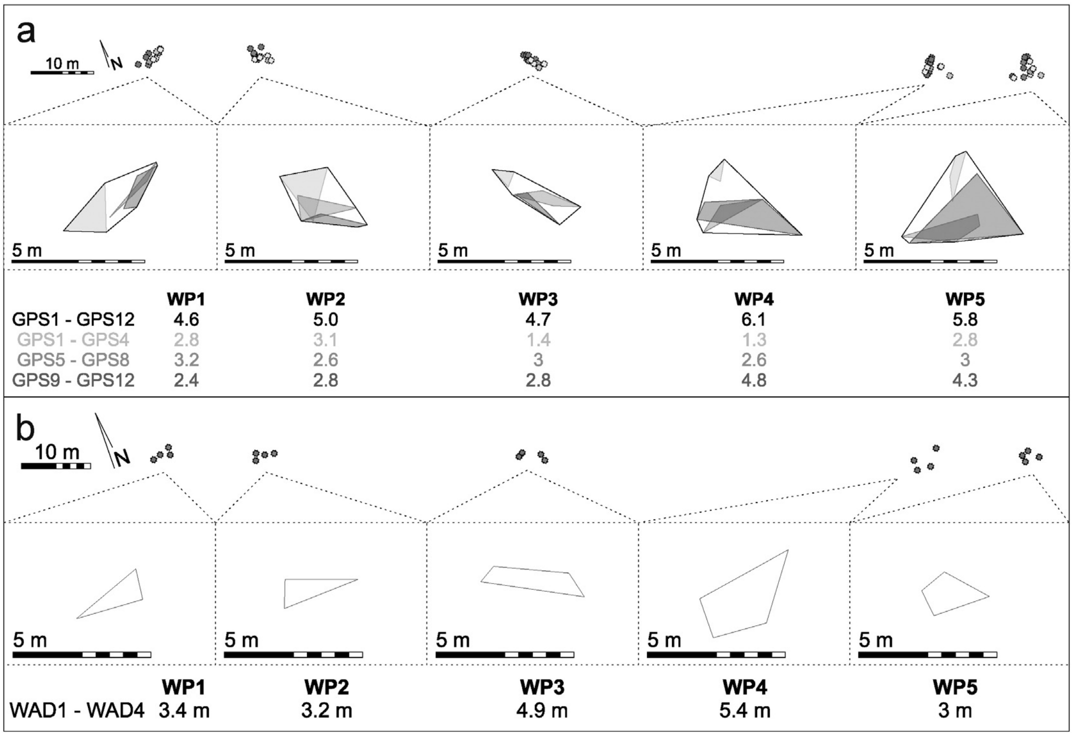

Fig. 8. Map view of location variability of waypoints measured during the Wroclaw 2 experiment. a) Non-differential GPS mode. b) WADGPS mode.

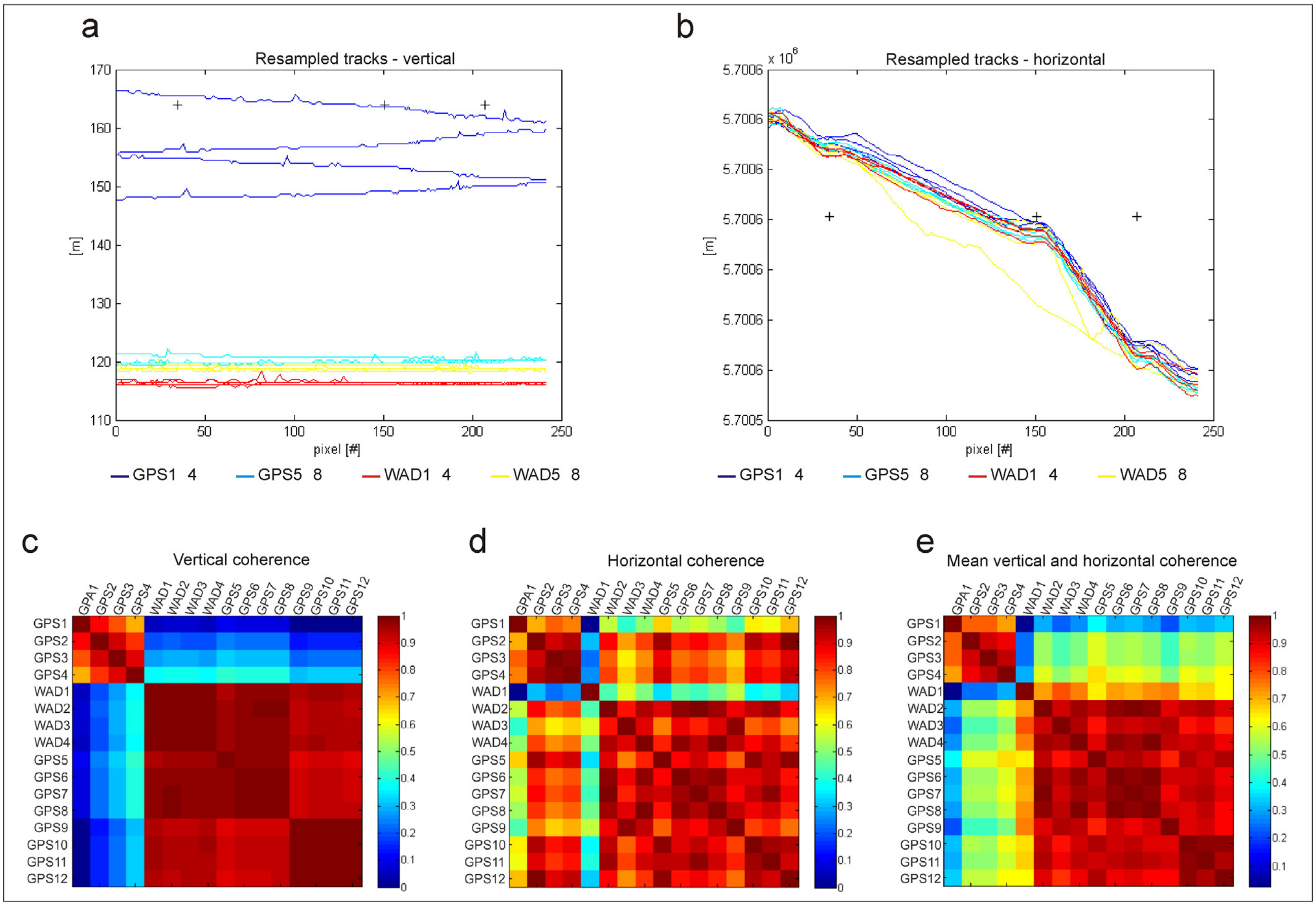

Fig. 9. Results of coherence analysis for the Wroclaw 1 experiment. a) Resampled topographic (vertical) profiles. b) Resampled profile traces in the map view. c) Vertical profile coherence. d) Horizontal profile coherence. e) Global profile coherence (1: identical profiles, 0: most different profiles in the experiment).

group of profiles between resets, the precision is slightly better. Compared to the overall 4.6–6.1 m precision, between the turning off and on of the receiver (Table 2), horizontal precision improves: for profiles GPS1–4 by 1.3 m (WP4) to 3.1 m (WP2), for profiles GPS5–8 by 2.6 m (WP4) to 3.2 m (WP1), and for profiles GPS9–12 by 2.4 m (WP1) to 4.8 m (WP4).

The four WADGPS profiles that were possible to record (WAD1–4, Fig. 7) display a vertical precision in the range of 0.3 m (WP5) to 1.3 m (WP2; Fig. 7). The horizontal precision (Fig. 8b) varies from 3 m (WP5) to 5.4 m (WP4).

The coherence analysis results in Fig. 9c–e show that the first group of GPS profiles (GPS1–4) is vertically different from all the other profiles. In the first group of the non-differential GPS profiles, a drift in elevation is visible. From the beginning of GPS1 to the end of GPS4, the elevation decreased by about 20 m. Changing mode to WADGPS removes the drift, and the four WAD1–4 profiles have high vertical coherence. Resetting the GPS receiver and changing the mode again shows signs of an elevation drift, but not as clear as at the beginning of the experiment. The GPS5–8 group of profiles is internally coherent except for GPS5, which deviates from the others in terms of elevation; the group is vertically different from the last set of profiles (GPS9–12) measured in the non-differential GPS mode by 4–5 m. The horizontal coherence diagram shows that all the profiles are similar irrespective of the mode, except WAD1, which is noticeably different and may be horizontally erroneous. The highest combined horizontal and vertical coherence is obtained in the second group of GPS profiles (GPS5–8).

3.3. Tatra Mountains

The highest elevation discrepancy for individual waypoints measured in the non-differential GPS mode (profiles GPS1–8; Fig. 10) is between 1.9 m (WP6) and 3.9 m (WP1). The vertical precision is improved if the GPS receiver was not switched off: 0.1 m (WP6) to 1.5 m (WP5) for profiles GPS1–4, and 0.7 (WP8) to 3.7 m (WP2) for profiles GPS5–8. The horizontal precision of the non-differential GPS measurements is presented in Fig. 11a. The overall waypoint precision is from 2.5 m (WP8) to 4.3 m (WP3). Similar to vertical precision, the switching off and on of the GPS receiver affects horizontal precision, although weaker, with discrepancies ranging from 1.2 m (WP8) to 4.3 m (WP3) for profiles GPS1–4, and 1.1 m (WP4) to 3 m (WP1) for profiles GPS5–8.

The WADGPS mode measurements (profiles WAD1–8) show that the highest elevation discrepancy for individual waypoints is between 4.3 m (WP7) and 7.1 m (WP5). The groups of profiles measured before and after switching off the GPS receiver are characterized by an elevation discrepancy of 0.7 m (WP4) to 2.7 m (WP5) for profiles WAD1–4, and 1 m (WP7) to 2.5 m (WP1) for profiles WAD5–8 (Fig. 10). The overall horizontal waypoint precision (Fig. 11b) is from 3.7 m (WP8) to 6 m (WP5). The horizontal precision is improved for the profiles before which the GPS receiver was turned off (profiles WAD1–4): 1.7 m (WP6) to 4 m (WP1). For profiles WAD5–8 the horizontal precision is similar to the mean horizontal and vertical coherence: 3.4 m (WP2) to 6 m (WP5).

The coherence diagrams of resampled tracks (Fig. 12c–e) show that the first series of WADGPS profiles (WAD1–4) and the two series of non-differential GPS profiles (GPS1–8) have the similarly high vertical coherence. The WADGPS mode does not improve coherence, which is already very high in the non-differential mode. The profiles GPS1–4 and GPS7–8 with the WAD1–4 profiles are more coherent than GPS5–6 profiles, illustrating that the GPS mode is not a discriminating factor for vertical precision. The second WADGPS series of profiles (WAD5–8) is internally coherent, but not coherent with the other profiles. The reason for this could be the reset of the GPS receiver between measuring profiles GPS4 and GPS5. The receiver needs more time to get back to the elevation level that prevailed before the reset. The horizontal coherence of the profiles made in the non-differential mode is higher. Coherence is not significantly affected by the reset of the GPS receiver. The combined vertical and horizontal diagram shows that the second group of non-differential GPS profiles (GPS5–8) has the highest global coherence.

4. Discussion

4.1. Positioning precision and topographic profile repeatability

The profile precision obtained from the waypoint analysis is summarized in Table 4. In both Wroclaw experiments, the WADGPS mode improved the vertical measurement precision, which agrees with the results obtained by Skorkowski and Topór-Kamiński (2012). However, Skorkowski and Topór-Kamiński (2012) as well as Witte and Wilson (2005) show that the WADGPS technology also provides more accurate

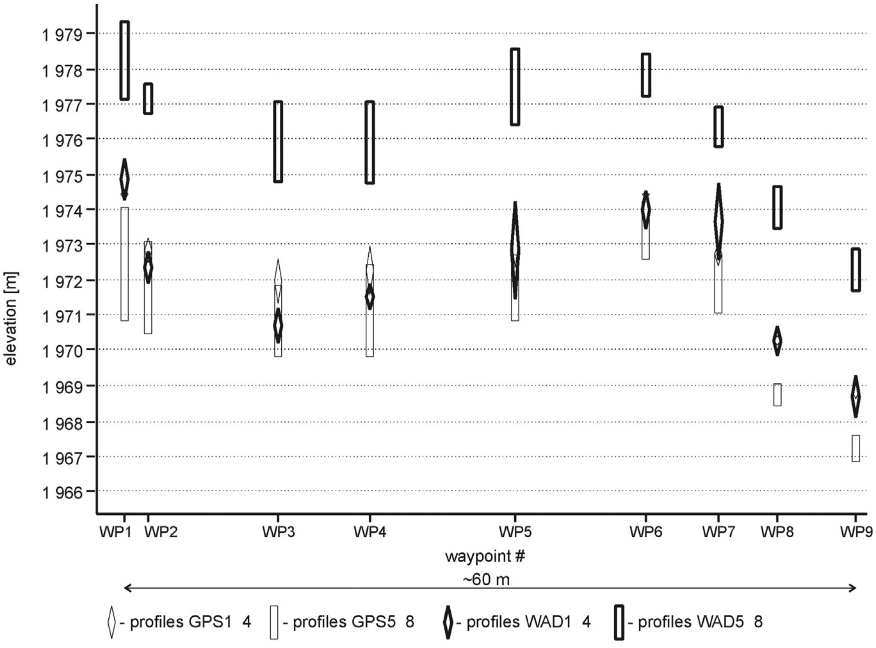

Fig. 10. Records of waypoint elevation for the eight profiles measured in the non-differential GPS and WADGPS modes during the Tatra experiment.

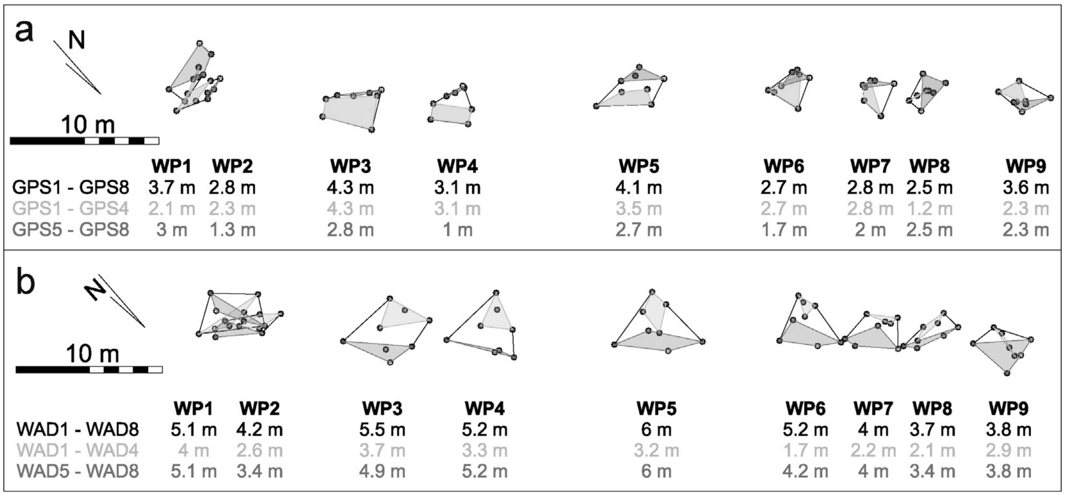

Fig. 11. Map view of location variability of waypoints measured during the Tatra experiment. a) Non-differential GPS mode. b) WADGPS mode.

horizontal positioning. This is not unambiguous in our study. The range of horizontal precision for the non-differential GPS and WADGPS does not differ significantly. In the Wroclaw experiments, measurements resulted in a drift in vertical measurements only ca. 10 min after turning on the GPS receiver, even though a comparison with other sources suggests that the indicated elevation was correct. Base level stabilization occurred only after 30 min. This observation requires further investigations to be generalised. On the basis of the waypoint and coherence analyses of the profiles, we conclude that it is an effect of a shift in the GPS base level with time. This shift is more visible in the experiment conducted under a cloudy weather. The cloud cover may also affect the availability of the EGNOS satellites. Tables 1 and 2 show that GEO satellites are more difficult to connect under a full cloud cover (Table 2, last column, WAD1–4) than under a clear sky (Table 1,

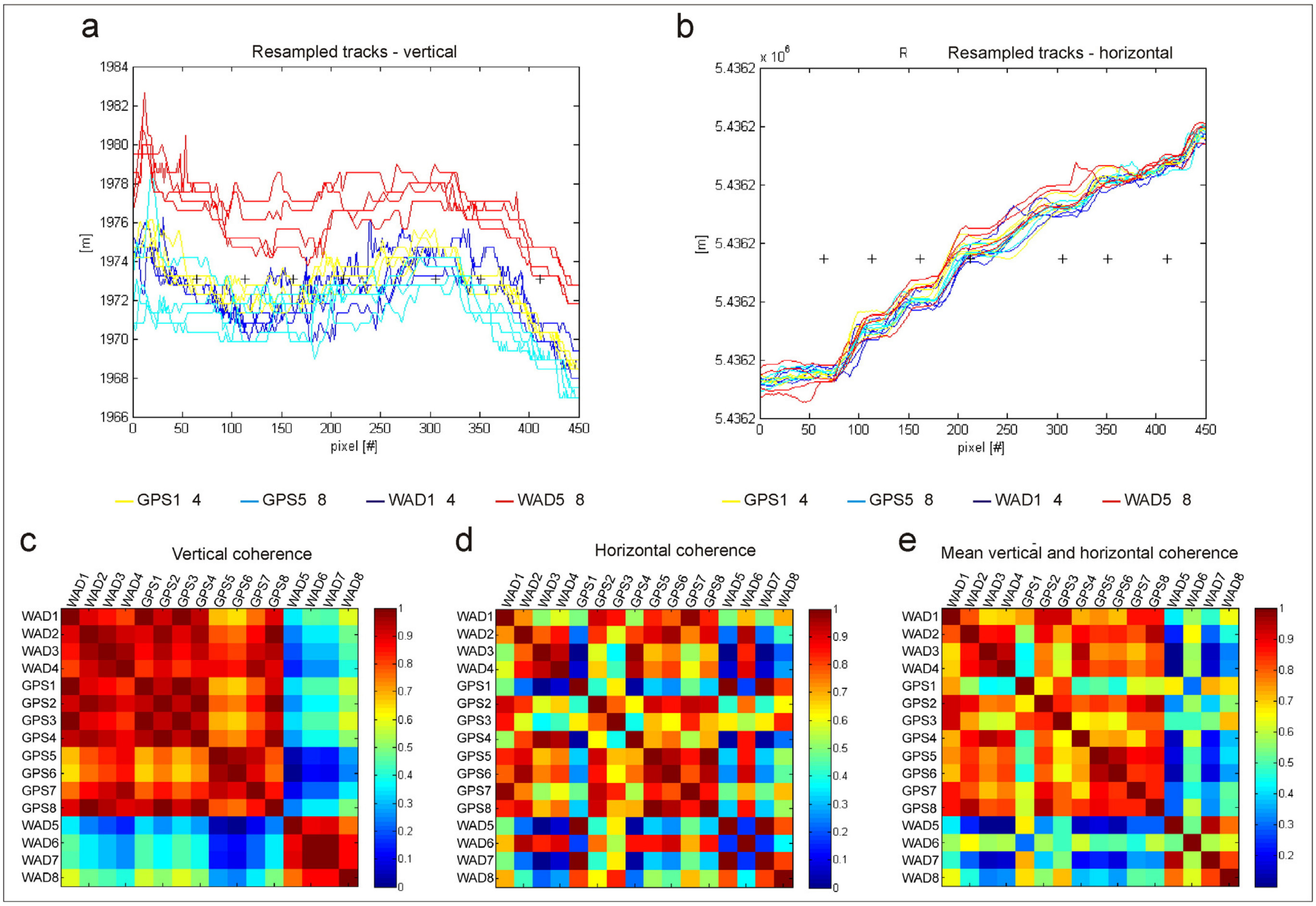

Fig. 12. Results of coherence analysis for the Tatra experiment. a) Resampled topographic (vertical) profiles. b) Resampled profile traces in the map view. c) Vertical profile coherence. d) Horizontal profile coherence. e) Global profile coherence (1: identical profiles, 0: most different profiles in the experiment).

Table 4
Summarized results of precision measurements.

		Wroclaw 1 Experiment		Wroclaw 2 Experiment		Tatra Experiment	
	Profile #	GPS	WAD	GPS	WAD	GPS	WAD
Vertical precision [m]	All	4.3–5	1.8–2.8	44–50.6	–	1.9–3.9	4.3–7.1
	1 to 4	1.3–2.2	0.7–2.3	10.5–18.6	0.3–1.3	0.1–1.5	0.7–2.7
	5 to 8	1.3–1.6	0.4–0.5	0.3–1.7	–	0.7–3.7	1–2.5
	9 to 12	–	–	0.2–1	–	–	–
Horizontal precision [m]	All	3.6–5.1	4.4–5.9	4.6–6.1	–	2.5–4.3	3.7–6
	1 to 4	2.5–4.2	3.2–5.3	1.3–3.1	3–5.4	1.2–4.3	1.7–4
	5 to 8	1.8–4.9	2.1–3.7	2.6–3.2	–	1.1–3	3.4–6
	9 to 12	–	–	2.4–4.8	–	–	–

last column, WAD1–8), and the connection was sometimes impossible (WAD5–8 had to be replaced by GPS5–8). In the GPS mode, cloud coverage does not decrease the coherence between profiles (Fig. 9c–e).

The Tatra Mountains experiment does not confirm the precision improvement by the employment of WADGPS mode. The precision of waypoint positioning, both vertical and horizontal, is similar for the GPS and WADGPS profiles; it is occasionally slightly better for the non-differential GPS profiles (Table 4). Arnold and Zandbergen (2011) used a Garmin GPSmap 60Cx receiver instead of the Garmin GPSmap62s which we used, and the WAAS network instead of EGNOS. They had found, just as we did, no significant difference between horizontal and vertical accuracies. Our horizontal and vertical precisions are also similar to those obtained by Arnold and Zandbergen (2011), especially when the groups of four profiles are considered. However, Arnold and Zandbergen (2011) obtained their results with 30-minute measurements, while in this study similar field work led to the same precision level. This result may suggest the higher sensitivity of chipset in the GPSmap 62s. Further experiments of simultaneous data acquisition with the GPSmap 60 and 62 devices are required to confirm this hypothesis.

The basic device feature necessary for geomorphological application is a good repeatability of profile measurements. It is indicated by the high coherence values (usually higher than 0.8 in the two GPS modes), when the GPS receiver is not reset at any moment. The measurements were done at the slow walking speed of ~0.5 m s^{-1}. Results obtained at higher speed may not display similar quality, although this work does not allow us to determine the maximum acceptable speed.

A less favourable situation occurs if the GPS device in the WADGPS mode loses connection to GEO satellites during measuring a profile. In this case the best results are obtained if the differential mode is turned off, and the entire profile is measured again.

4.2. Reasons for precision loss

Several factors degrade the EGNOS signal and decrease measurement accuracy (EGNOS, 2011). Broadcasting delay did not affect the Tatra experiment because the GPS receiver had been turned on long before the first measurement. The EGNOS signal blockage could have affected the results, because part of the profile line was shadowed by the rock slope. It is unlikely that local interference affected the EGNOS signal in the Tatra Mountains, because EGNOS uses the frequency band protected by the International Telecommunication Union, and national agencies are in charge of detecting and enforcing the lawful use of spectrum within their boundaries. Ionospheric disturbance is not thought to degrade the signal significantly because this factor is important only at boreal and subtropical latitudes. Two EGNOS satellites were constantly available during the WADGPS mode measurements, and at least eight GPS satellites were working in the differential mode. Therefore, the GPS core constellation and GEO satellite orbit inclination were not degraded during the measurements.

Tables 1–3 show data obtained when the GPS device was turned off. The comparison of this information with the shift of coherence in Figs. 7b, 10b and 13b indicates that restarting the GPS receiver system strongly affects its performance. In all experiments, regardless of the acquisition mode, vertical and horizontal precisions are higher for the profiles not interrupted by turning off the receiver than for profiles belonging to different groups (Table 4). Vertical precision improvement is more significant than horizontal improvement.

The mean horizontal accuracy of non-differential consumer-grade GPS receivers for open sky is ~5 m (e.g., Wing et al., 2005). Our results are in agreement with this conclusion, and show even better precision for profiles made by GPS receiver which is not switched off.

The vertical accuracy obtained with the EGNOS network reported in several studies has been improving since 2006, from 12.4 m (Męsikowski et al., 2006) to 1.7 m (Specht and Felski, 2010), then to 1.5 m (Felski et al., 2011), and to several tens of centimetres (Hesselbarth and Wanninger, 2013). Our results show precision values corresponding to the pervious results for the last 5 years.

5. Conclusions

The EGNOS technology has been improved by decreasing uncertainties and errors (Lechner and Baumann, 2000; Specht and Felski, 2010), which encourages its use for precise and low-cost topographic profiling in geomorphological studies. The previous accuracy assessment of non-differential GPS and WADGPS data did not meet the needs of geomorphologists; in particular, they were not intended to characterise landforms at the outcrop scale, measure locations while walking in mountains, and address the loss of GEO satellite connection during continuous data acquisition.

Getting good GPS accuracy is reputed to require long measurement times, based on studies aiming at determining what is the maximum accuracy that can be obtained with GPS devices. However, in geomorphology, when landform topographic profiling is concerned, the issue is different as the variation of error between the profile trackpoints is at least as important as, if not more than, the accuracy of a given data point. Our coherence analysis has shown that high quality topographic profiles can be obtained with a widely used GPS device and meet the nominal GPS and EGNOS accuracy specifications in either GPS or WADGPS mode. The maximum 40 cm vertical resolution that seems inherent to this device is also good enough for a wide range of application, such as the measurement of scarps affected by mass wasting (Kromuszczyńska and Mège, 2014; Makowska et al., in press). For a maximum speed of ~0.5 m s^{-1}, fully cloudy weather did not affect profile repeatability in any mode, but affected connectivity to GEO satellites. The following rules are proposed for successful scientific surveys:

1. Turn on the GPS receiver long before measurement.
2. If the vertical precision is important, use the WADGPS mode. If the WADGPS connectivity to the GEO satellites is unstable, record the profile without using the non-differential mode. If the connexion is lost while recording, measure the whole profile again.
3. Before successive measurements of topographic profiles, check that the receiver batteries are charged enough. If the GPS receiver needs to be reset, use non-differential GPS.

This work has been conducted with a Garmin GPSmap 62 series. Similar results are expected with consumer grade GPS devices having a similar chipset, including the Garmin Oregon series and the Earthmate DeLorme PN series devices, although accuracy also depends on other components such as the antenna and firmware. The recently released Garmin GPSmap 64 series with both GLONASS compatibility and WADGPS capability, is also expected to yield similar results because the accuracy of GLONASS is comparable with that of the GPS system (Afanasyev and Vorontsov, 2010).

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