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ANALYSIS OF THE POSITIONING ACCURACY OF GEOTAGGED PHOTOS TAKEN WITH MOBILE DEVICES IN VARIOUS TERRAIN CONDITIONS

ANNA SZAFARCZYK*, BEATA BAZIAK, MAREK BODZIONY

Cracow University of Technology, Faculty of Environmental Engineering and Energy, Warszawska St. 24, 31-155 Cracow, Poland.

ABSTRACT. Currently, most mobile devices can capture geotagged photos—i.e., images to which the location of capture is assigned. Despite extensive literature on the use of geotagging, there is a limited number of studies addressing the accuracy of the recorded locations. Therefore, this research was undertaken to assess the positional accuracy of geotagged photos, defined, among other metrics, by the mean unit error of the assigned coordinates. This article presents the results of test measurements conducted using various mobile devices to determine situational coordinates within the applicable coordinate system. The study discusses the satellite systems currently in use, as well as the measurement technologies that influence geolocation accuracy in smartphones and cameras equipped with a geotagging feature. Test measurements involved comparing the coordinates embedded in geotagged photos with those obtained using a high-precision GNSS receiver. Depending on the device and technology used, the mean unit location errors ranged from 4.0 metres to nearly 50 metres. These findings highlight the low precision of such devices in determining exact positions. To explore ways of improving accuracy, additional tests were carried out using various features and applications available on different devices, assessing their impact on location determination based on geotagged photos. Notably, the use of the GPS Test application for position stabilisation reduced mean unit errors by nearly 45%. The results of this study led to the development of recommendations aimed at enabling the determination of a mobile device's X and Y coordinates with an accuracy of several metres. This level of precision may be sufficient for many practical applications and presents a cost-effective alternative to expensive GPS receivers, which require specialised geodetic knowledge for professional use.

Análisis de la precisión en el posicionamiento de las fotos geolocalizadas tomadas con dispositivos móviles en diferentes condiciones del terreno

RESUMEN: Actualmente, la mayoría de los dispositivos móviles son capaces de capturar fotografías geolocalizadas, es decir, imágenes a las que se les asigna la ubicación en la que fueron tomadas. A pesar de la abundante literatura sobre el uso del geoetiquetado, existe un número limitado de estudios que aborden la precisión de las ubicaciones registradas. El objetivo de este trabajo es, por lo tanto, evaluar la precisión posicional de las fotografías geolocalizadas, definida, entre otros parámetros, por el error medio unitario de las coordenadas asignadas. Este artículo presenta los resultados de mediciones experimentales realizadas con diversos dispositivos móviles, empleando el sistema de coordenadas correspondiente para la determinación de coordenadas situacionales. El estudio analiza los sistemas satelitales actualmente en uso, así como las tecnologías de medición que influyen en la precisión de la geolocalización en teléfonos inteligentes y cámaras con funcionalidad de geoetiquetado. Las mediciones se realizaron comparando las coordenadas incrustadas en las fotografías geolocalizadas con aquellas obtenidas mediante un receptor GNSS de alta precisión. Según el dispositivo y la tecnología utilizada, los errores medios unitarios de ubicación oscilaron entre 4,0 metros y cerca de 50 metros. Estos resultados evidencian la baja precisión de este tipo de dispositivos para determinar posiciones exactas. Con el fin de explorar posibles mejoras en la precisión, se llevaron a cabo pruebas adicionales utilizando diversas funciones y aplicaciones disponibles en distintos dispositivos, evaluando su impacto en la determinación de la ubicación basada en fotografías geolocalizadas. En particular, el uso de la aplicación GPS Test para la estabilización de la posición permitió reducir los errores medios unitarios en casi un 45 %. Los resultados de este estudio permitieron elaborar una serie de recomendaciones orientadas a posibilitar la determinación de las coordenadas X e Y de un dispositivo móvil con una precisión del orden de varios metros. Este nivel de exactitud puede resultar suficiente para numerosas aplicaciones prácticas y constituye una alternativa económica frente a los receptores GPS de alto costo, cuyo uso profesional requiere conocimientos especializados en el campo de la geodesia.

Keywords: photography, geotagging, GIS, GNSS, mobile device.

Palabras clave: fotografía, geoetiquetado, SIG, GNSS, dispositivo móvil.

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***Correspondence Author:** Anna Szafarczyk, Cracow University of Technology, Faculty of Environmental Engineering and Energy, Warszawska St. 24, 31-155 Cracow, Poland. Email: anna.szafarczyk@pk.edu.pl

1. Introduction

Nowadays, people cannot imagine life without digital technology. One of the inseparable elements of everyday human life is mobile technology. Mobile technologies are used by people in many areas, as evidenced by numerous studies conducted at the beginning of the 21st century (Humphreys and Liao, 2011). With the emergence of mobile technology, there was an increase in human activity on the Internet, which contributed to the creation of numerous social media facilitating interpersonal contact. The widespread popularity of social media led to the development of tools that allow people to access information quickly and easily. This resulted in the advent of various trends in social data processing, which include, among others, tagging, i.e. the ability to mark online materials or digital objects and geospatial tagging, i.e. geotagging (Golder and Huberman, 2006).

Geotagging refers to adding location information, such as latitude and longitude, to digital media files. This process attaches geographic coordinates to media based on where a mobile device is located. Geotags can be applied to photos, videos, websites, text messages, and QR codes, and could also include time stamps or other contextual information.

Thanks to the development of mobile technology and location-based services using, among others, the mobile network and the Global Navigation Satellite Systems (GNSS), geotagging is currently one of the commonly used tools in everyday life. Among its many applications are navigation, social media, photo organisation, and local marketing. Geotagging facilitates the identification of the location of places where a photo was taken or a video was recorded. It is used to locate people, places, and objects for increased interaction, and is increasingly recommended for precise area inventory documentation (Zaragozí *et al.*, 2020). It is often employed in tourism to indicate locations and tourist attractions on maps. It can also serve as a modern technological tool in the cultural sector and the preservation of cultural heritage, as well as for creating maps and visualising data related to various phenomena and processes occurring on Earth. Another instance where geotagging is utilised is in geocaching, which is a growing location-based activity that merges GNSS technology with global exploration (Benson, 2016; Chavez *et al.*, 2004; Ihamäki, 2014; Ihamäki, 2015).

Due to the widespread use of mobile phones, the question arises about the quality of location mapping using mobile devices. One of the studies addressing this topic is the assessment of the accuracy of geolocation obtained using different models of mobile phones conducted by Ryser *et al.* (2024). Merry and Bettinger (2019) analyse the accuracy of horizontal position measurements obtained with the iPhone 6 in urban environments, considering different seasons, times of day, and Wi-Fi usage. The results indicate that the average positioning error ranges from 7 to 13 metred and that Wi-Fi activation and environmental conditions, such as the presence of buildings, have a significant impact on location accuracy, while atmospheric factors have a minimal impact. In the study by Lee *et al.* (2016), detailed statistical analyses were performed on the accuracy and precision of GPS-enabled mobile devices using three different types of measurement errors.

Awareness of the accuracy of positioning using geotagged images is crucial, especially when preparing documentation using this type of technology, which is required by various offices, field research, and education. This paper was inspired by geodetic field measurements and geodetic measurements using mobile geolocation techniques. The aim of this study was to analyse the positioning accuracy when capturing geotagged images in various horizon obscuration conditions (open spaces and built-up areas) and using various mobile devices. The impact of environmental conditions, such as horizon obstructions (e.g., the presence of buildings and trees), on the accuracy of GPS positioning during image capture was also assessed. The effectiveness of using the GPS Test application for position stabilisation and the use of mobile data (GSM) to improve image geotagging accuracy was also verified.

The specific aim of the paper was to formulate practical recommendations for mobile device users on optimising and improving the positioning accuracy of geotagged images. The following hypotheses were formulated in this study:

- The location accuracy of geotagged photos on mobile devices is significantly dependent on terrain conditions and the level of GNSS signal interference.
- Using the GPS Test application to stabilise position and transmit mobile data increases the precision of location determination.
- Different mobile device models and digital cameras exhibit significant variations in the positioning accuracy of geotagged photos, resulting, among other things, from the type of GNSS receiver used.
- User awareness of the factors affecting GNSS signal quality and positioning accuracy translates into varying quality of geotagged photos in practice.

1.1. Examples of the use of geotagged photos

The development of digital technology and mobile devices equipped with digital cameras with geolocation capabilities has resulted in the creation of a huge amount of data that can be used for private use, professional purposes, creating technical documentation, as well as scientific research. The use of photo sharing platforms such as Flickr and Panoramio has contributed to the creation of huge collections of geotagged photos, which constitute digital traces of users. Many sources in world literature discuss the use of these photos. A significant part of the applications of geotagged photos is related to the popularisation of tourist attractions, travel, tracking hiking trails and road transport traffic. An example of the use in tourism is, among others, the work of Xu *et al.* (2015) presenting a method for recommending places to travel in 11 cities in China, based on the thematic distribution of travel history in other locations and the context, such as season and weather. The use of geotagged photos to analyse tourist attractions in different cities (García-Palomares *et al.*, 2015) reveals differences in the distribution of photos taken by tourists and locals and their concentration in different locations. In their 2018 article, Zhang and Zhou analysed publicly available geotagged social media data to quantify and compare the visitation rates of various park types in Beijing. The influence of park attributes, their location, context, and public transportation on the number of visits was analysed using multiple linear regressions. Photos posted on social media by visitors to national parks were used to monitor the activities of visitors to parks and other outdoor recreation areas, especially in remote and unmonitored locations, using four national parks in the USA as an example (Huang, 2023).

The use of such images has also enabled park managers to make rough estimates of population flows along large networks of trails in the Dolomites (Orsi and Geneletti, 2013). Combining geotagged images with machine learning and computer vision algorithms, drawing on current anthropological theories on visuality and heritage tourism, allows for the identification of travel patterns, as was done in Cuzco, Peru (Payntar *et al.*, 2021). Understanding tourist behaviour is crucial for managers planning a sustainable tourism industry. A new approach based on the analysis of geotagged user-generated images, based on the example of inbound tourism in Hong Kong (Vu *et al.*, 2015), can provide practical guidance for destination development and transportation management.

Equally valuable for city planners and transportation analysts is the ability to identify so-called areas of urban interest (AOIs), which attract people's attention and are characterised by a high number of visits. Hu *et al.* (2015) presented a framework for identifying and analysing AOIs from geotagged Flickr photos from six cities in different countries, using the DBSCAN clustering algorithm and analysing the spatiotemporal dynamics of these areas. A major challenge is finding your way in urban space, which can be facilitated by a set of landmarks. Samany (2019) presents a method for automatically extracting landmarks from geotagged social media photos using DBSCAN clustering and deep learning algorithms, which was tested on 48 routes in Tehran. Additionally, GNSS data supports visual recognition of geotagged photos, providing valuable location information. However, current GNSS data only indicates the camera location, which leaves the viewing direction unspecified within 360°. To obtain more precise information about the image location, including the viewing direction, Park *et al.* (2014) additionally used satellite images from Google Earth. Another approach (Foltête *et al.*, 2020) combined geotagged images with information about the direction of the image, allowing the identification of landscape features of the most attractive views.

Geotagged images are an innovation in the field of agriculture in Ireland (Kenny *et al.*, 2021) and are also a tool for assessing land abandonment in Spain (Zaragozí *et al.*, 2020). Kumaran *et al.* (2024) highlight how integrating geotagging and vegetation indices in crop monitoring with unmanned aerial vehicles (UAVs) provides valuable data, enabling farmers and researchers to make informed decisions and assess crop health using artificial intelligence. The limitations of traditional stationary observations of cherry blossoms, a key indicator of climate change, are difficult to monitor. In the study by Tsutsumida and Funada (2023), a novel semi-automatic cherry blossom observation system was introduced using geotagged street-level images and deep learning models, which enabled efficient mapping of flower presence and flowering time. Land cover maps are key elements in understanding global climate and land use. Geotagged photos on social media can be used to train artificial neural networks to predict image relevance for land cover classification (ElQadi *et al.*, 2020). Geotagged photos have shown the potential of convolutional neural networks (CNNs) in classifying grassland use (Saadeldin *et al.*, 2022).

Tavani *et al.* (2022) demonstrate the application of smartphones equipped with geolocation and orientation sensors as cost-effective and portable instruments for conducting photogrammetric measurements utilising the Structure from Motion/Multiview Stereo (SfM-MVS) methodology. This study concerns the creation of georeferenced 3D SfM-MVS models from smartphone images, using the built-in sensors to register the models during post-processing without the need for ground control points.

Social media platforms have played a key role in collecting and sharing reliable information for disaster assessment and management, using data in the form of geotagged images and text. A new method for extracting geographic location from disaster images using mobile phones and Google Maps API has been shown to be effective in improving situational awareness and crisis management (Sathianarayanan *et al.*, 2024). The use of geotagged images to assess the safety of urban areas, especially large cities, is becoming increasingly popular. In the work of Navarrete-Hernandez *et al.* (2023), a randomised controlled trial was conducted in Santiago de Chile, involving 100 residents of a high-crime neighbourhood. Participants evaluated geotagged images and simulated security interventions. According to the authors, this technique can help understand the spatial distribution of security perceptions.

In addition to the content of geotagged photos, the analysis also includes people's reactions, moods and impressions while taking these photos. Spatial, temporal and thematic information about people's recreation and outdoor activities was the basis of research (Lee *et al.*, 2019; Fan *et al.*, 2024), based on which it was possible to determine the demand for individual cultural ecosystem services.

1.2. Geolocation technology

There are currently several dozen GNSS satellites in orbit (Ai *et al.*, 2021), which are part of the following satellite systems: GPS, GLONASS, Beidou, NavIC, QZSS, created by various countries of the world.

GPS (Global Positioning System) is a global navigation system that uses satellites placed in orbit around the Earth. The GPS was created by the United States Department of Defense and is controlled by the United States Space Force. GPS consists of a network of over 30 satellites that orbit the Earth in a specially designed orbit. These satellites emit radio signals that are received by GPS receivers on Earth. These receivers read the time it takes for the signal to reach the satellite, which allows the receiver's position to be determined with great accuracy (Tsui, 2005; Bogusz. *et al.*, 2019).

GLONASS (*Global'naya Nawigacionnaja Sputnikowaja Sistiema*) is a Russian satellite navigation system covering the entire globe (Zheng *et al.*, 2022). Like GPS, it is a stadiometric system, meaning that the position is determined at the intersection of four spheres with radii calculated based on the signal propagation time and means known from navigation messages sent by satellites. Beidou (Great Bear) is a Chinese satellite navigation system operating worldwide since 2018, with an accuracy of up to 10 metres, and 5 metres in the Asia-Pacific region (Lu *et al.*, 2020).

NavIC (formerly IRNSS) consists of seven satellites, three in geostationary orbit (over the meridians 34°E, 83°E, 132°E) and four in geosynchronous orbit (max. altitude: 24,000 km, inclination: 29°). Its range can cover India and an area within a radius of 1,500 km from the country's borders. The positioning accuracy using IRNSS alone is to be 5 metres in India and 10 metres in the remaining area (Santra *et al.*, 2019). QZSS (Quasi-Zenith Satellite System) consists of 4 navigation satellites. The system is distinguished by the placement of 3 navigation devices in geosynchronous orbit. Its parameters have been selected so that in Japan, at least one satellite is always visible near the zenith. This is to significantly improve the quality of positioning among tall buildings. The fourth satellite is in geostationary orbit. QZSS was designed primarily as a complement to the American GPS. The navigation signals transmitted within this solution are compatible with GPS L1, L1C, L2C and L5 signals (Li *et al.*, 2021).

Mobile devices provide the ability to take photos with assigned locations determined in accordance with the WGS 84 (EPSG:4326) geographic coordinate system. WGS 84 is an Earth-centred, Earth-fixed terrestrial reference system and geodetic datum. WGS 84 is based on a consistent set of constants and model parameters that describe the Earth's size, shape, and gravity and geomagnetic fields. WGS 84 is the standard U.S. Department of Defense definition of a global reference system for geospatial information and is the reference system for the Global Positioning System (GPS). It is compatible with the International Terrestrial Reference System (ITRS) (NGA, 2014).

A-GPS (Assisted GPS) is a technology developed by StanpTrack. The system is a type of GPS that uses mobile operators' base stations to find the position faster. A-GPS helps traditional GPS provide faster initial location results and is mainly used in mobile phones and tablets. This technology significantly shortens the time of loading current GPS data, but it should be remembered that this service must be available from a given mobile operator. Otherwise, the GPS connection will also be successful, but establishing communication with the satellites will take much longer (Lissai, 2006, Kaplan and Hegarty, 2017). The quality of measurements depends on many factors. Measurement errors may result from the GNSS system itself, GNSS signal propagation, measuring equipment and from incorrect geometry of the satellite constellation. When taking photos using smartphones, turning on the location feature alone may not be sufficient to properly map the location. The time between taking subsequent photos may also be significant, as it may be too short for the GNSS signal received by the mobile device to be refreshed.

The accuracy of position determination in GNSS systems depends on many factors, among which the geometric DOP (Dilution of Precision) coefficients, satellite almanacs, and sources of measurement uncertainty are crucial. DOP coefficients such as PDOP, HDOP, and VDOP reflect the impact of satellite distribution on position determination accuracy; the lower their values, the greater the measurement accuracy. Satellite almanacs contain approximate data on orbits and the status of satellites, enabling faster signal acquisition and measurement planning. Measurement uncertainty in GNSS arises from both geometric and technological as well as environmental factors, including clock errors, atmospheric delays, and measurement noise. Understanding these issues is essential for assessing the reliability and precision of GNSS measurements (Hofman-Wellenhof *et al.*, 2008; Kaplan and Hegarty, 2017)

To reduce errors resulting from locating points based on taken photos, additional tools can be used to verify the quality of the GNSS signal. The GPS Test application is one example of a tool that lets users see how many satellites are providing a signal and the strength of each signal. GPS Test is a free app created by Chartcross Limited that lets you check GNSS signal strength at your current location. The application allows the user to check whether their mobile device can receive a GNSS signal. Additionally, it enables device updates utilizing the Assisted GPS feature, which facilitates a more rapid location fix time. It also improves the GNSS and sensor reading of the device. The application works with all standard satellite navigation technologies, such as the BeiDou satellite navigation system, GALILEO, *Global'naya Nawigacionnaja Sputnikowaja Sistiema* (GLONASS), Global Positioning System (GPS), Satellite Augmentation System (SBAS), and Quasi-Zenith Satellite System (QZSS). It contains screens (Fig. 1) with information for navigation with the GPS feature of the device. The GNSS signal (SNR) bar graph of the application shows the signal strength of the satellites supported by this application. It also shows the accuracy and current status of the Global Navigation Satellite System (GNSS) network. The Skyview application locates the positions of satellites in the sky using a rotating compass (barbeau/gpstest,2025; GPS Test,2025).

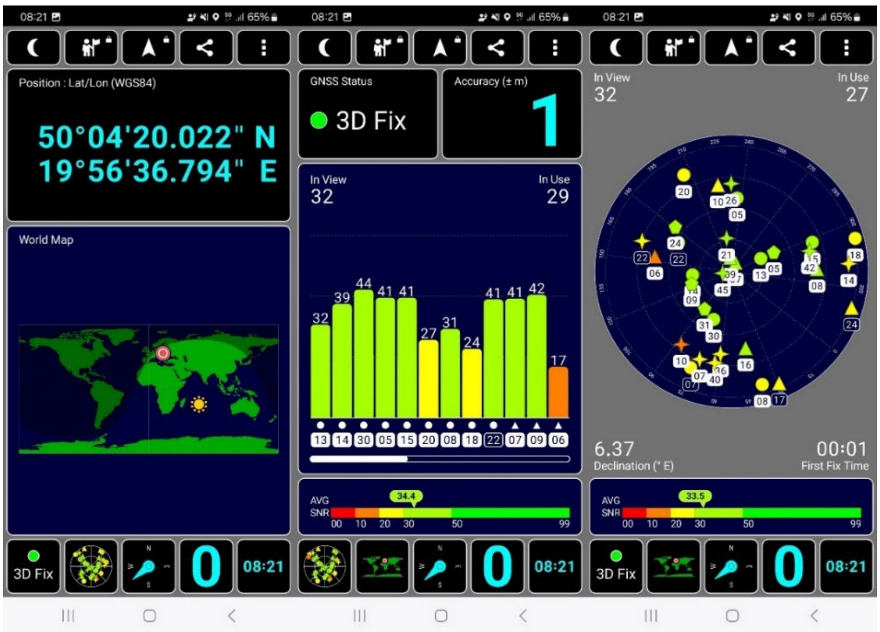

Figure 1 Screenshots of the features used in the GPS Test application for an example measuring point (GPSTest, 2025).

The research consisted of determining coordinates based on geotagged photos, which were entered into the QGIS project using the Import Photos plug-in. The use of this software allowed for visualisation of the obtained results and their development. The verification was carried out in different variants, based on geotagged photography taken using different technologies.

2. Materials and Methods

2.1. Study areas

The study area included two locations in the southern part of Poland. One was an urbanised (urban) area on the campus of the Cracow University of Technology in Cracow, and the other was an open space of a mountainous nature, constituting the area of the Klimkówka reservoir located in two communes: Klimkówka and Uście Gorlickie in the Małopolska province (Poland) (Fig. 2).

Figure 2. Location of the study areas (Geoportal, 2025; OpenStreetMap, 2025).

The first location was the area of the Klimkówka retention reservoir. This is an area devoid of buildings, with a favourable horizon for satellite measurements. In this area, only individual mobile phone stations are present, each situated several kilometres from the measurement locations (see Figure 5a). The research was conducted in two areas (Fig. 3):

I. A narrow valley with a large slope gradient at the reservoir dam (Figure 3 cross-section marked in orange).

II. The reservoir area with a much wider valley than in the case of the dam cross-section. The research in this area was conducted on the water surface, moving by boat (Figure 3 example cross-section marked in blue).

Further research was carried out in a built-up area, in the very centre of the city of Cracow. It is a district with dense development, among which there are tall trees over 20 metres high. The development consists of tall, multi-storey buildings of historical character (Kobylarczyk *et al.*, 2024), the height of which reaches up to 30 metres, which causes significant obscuration of the horizon, affecting measurements using satellites (Figure 4). In this location there are dozens of mobile network transmitters of various stations, (Figure 5b), which allow for improving the location determination thanks to the use of A-GPS technology.

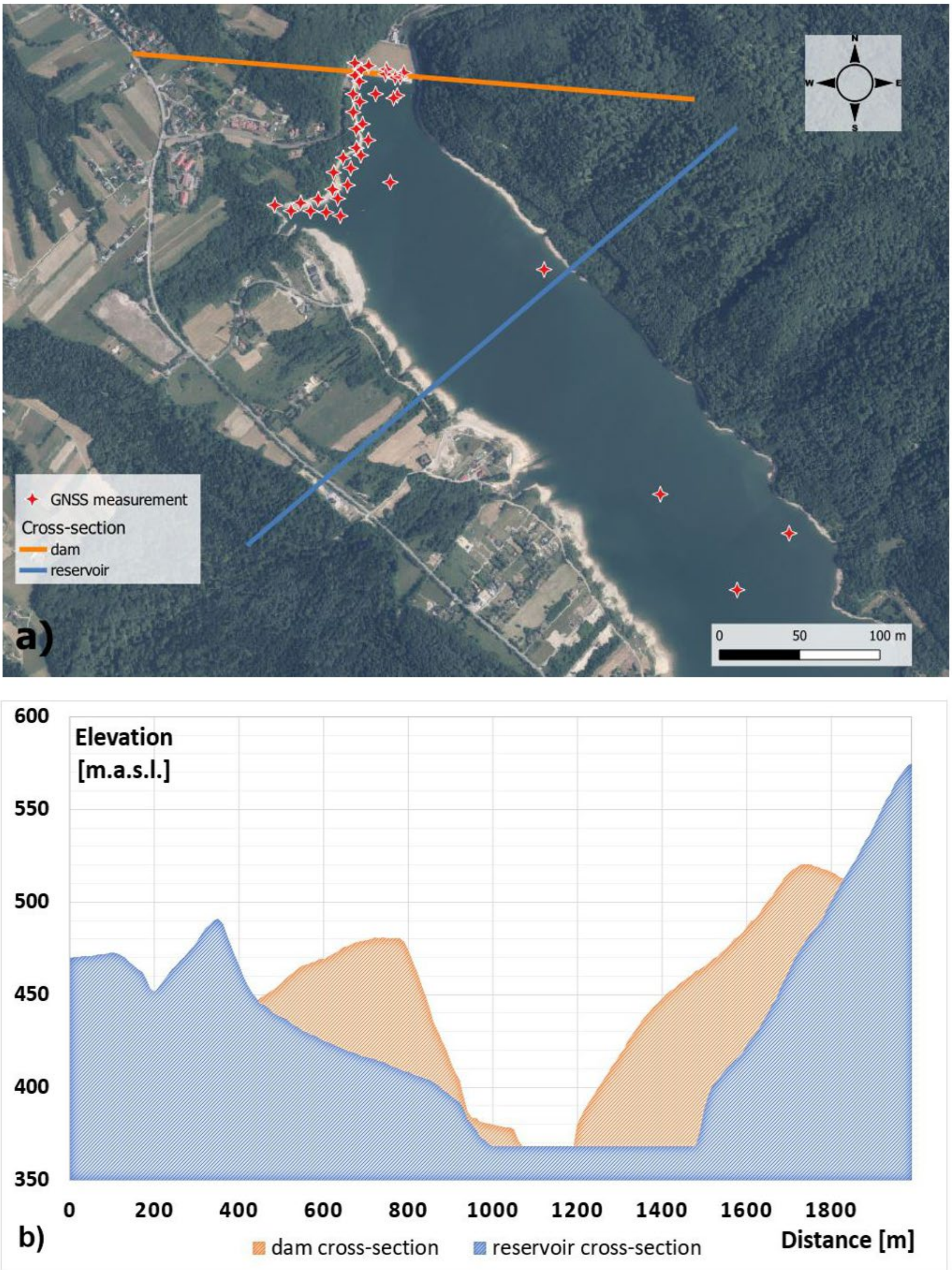

Figure 3. a) The study area in the Klimkówka reservoir showing the GNSS measurements locations (red points) and the cross sections including both a narrow valley (dam, in orange) and a wide valley (reservoir, blue); b) terrain cross-sections by the dam and the reservoir (Geoportal, 2025).

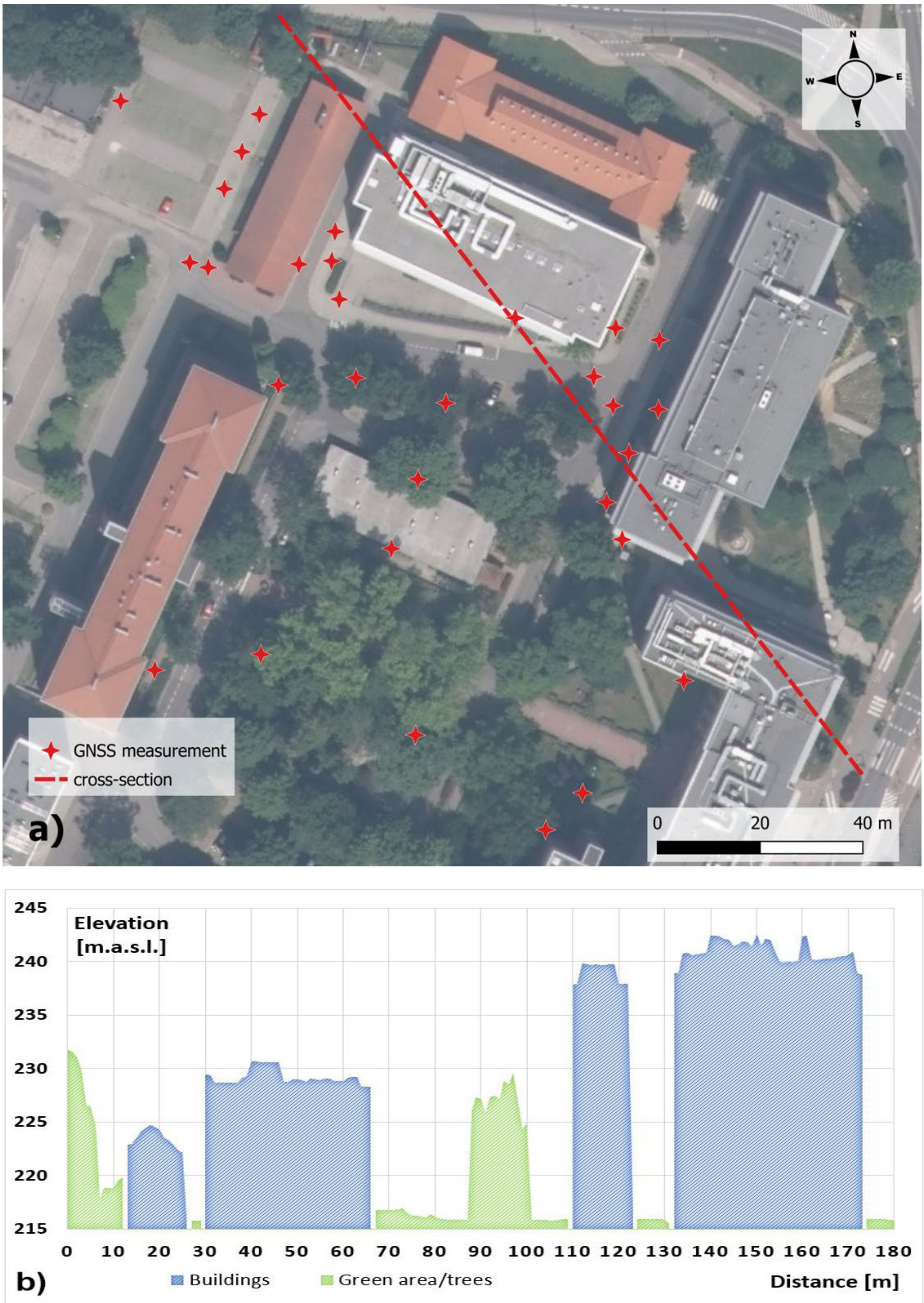

Figure 4. The study area in the campus of the Cracow University of Technology showing the GNSS measurements locations (red points) and the studied cross section (red line); b) cross-section indicating the buildings (blue) and the green areas (green) (Geoportal, 2025).

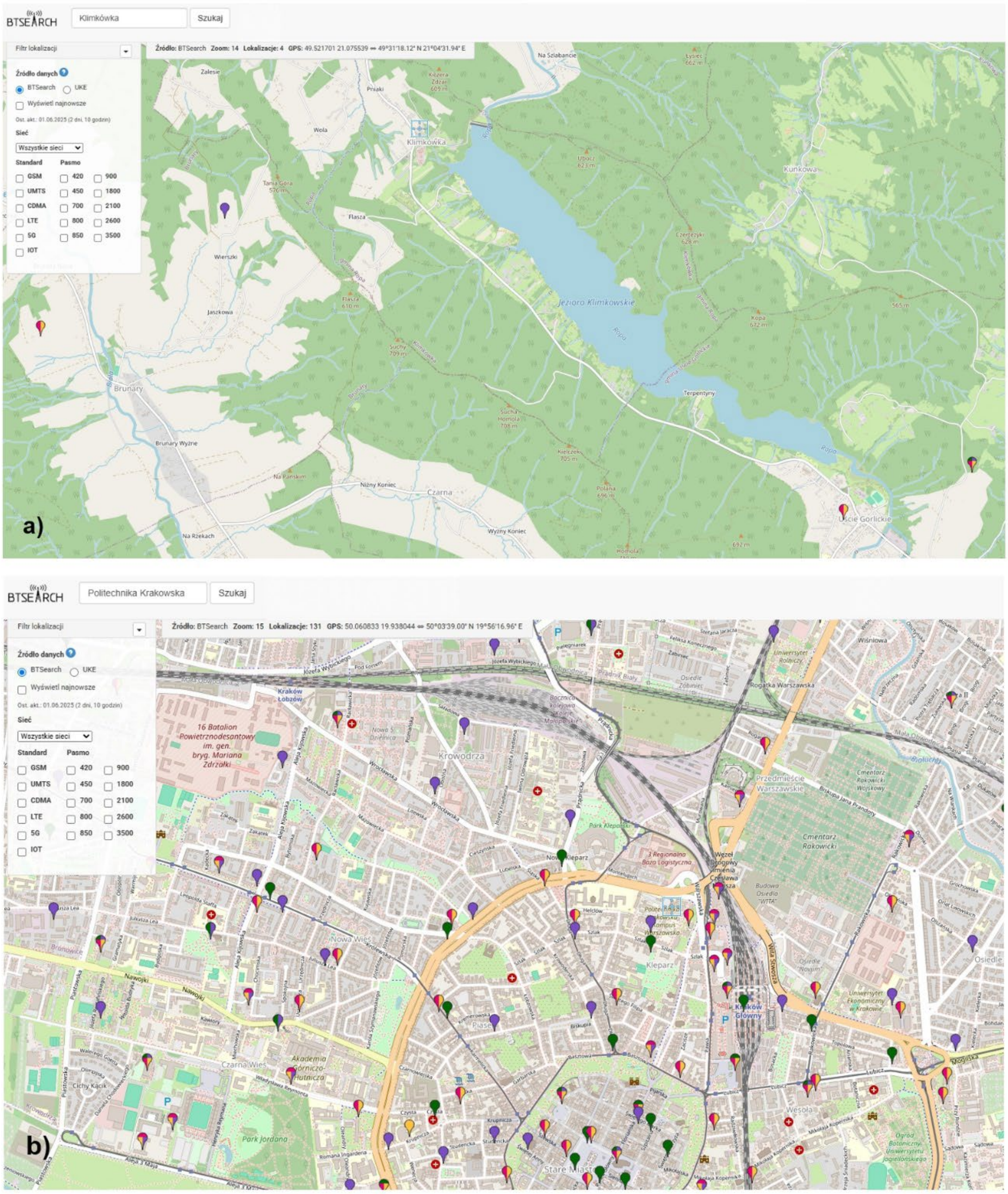

Figure 5. List of mobile network transmitters in a) Klimkówka reservoir and b) Cracow University of Technology campus (BTSearch, 2025).

2.2. Measurement methods and tools

Around the Klimkówka reservoir, geotagged photographs were taken both in the area near the dam (narrow and steep valley) and in the open area (reservoir surface) using a Samsung Galaxy A25 phone and a Nikon Coolpix P900 camera. The location of these photographs was compared with precise coordinate measurement using a Hi-Target H32 GNSS receiver.

In this area, a total of 165 geotagged photos were taken in 134 locations verified by measurements made with a precise GNSS receiver. Measurements were conducted at sites where the use of a GNSS device was feasible.

In the second location, four measurement tools were used: Samsung A25 5G and Motorola RAZR 40 Ultra mobile phones, a digital camera: Nikon Coolpix P900 and a GNSS receiver. The Samsung A25 5G is equipped with a navigation system: GPS, GLONASS, BeiDou, Galileo, Quasi-Zenith satellite system (QZSS), while the Motorola RAZR 40 Ultra is additionally enriched with the NavIC system. The Nikon Coolpix P900 digital camera has a GPS, GLONASS and Quasi-Zenith satellite system (QZSS).

For the campus area, a total of 231 geotagged photos were taken in 24 locations verified by measurements made with a precise GNSS receiver. In the built-up area, measurements were taken in locations with different GNSS signal availability conditions and places that could be determined based on the orthophotomap.

Coordinate measurements of selected points using a precise GNSS receiver were performed in stable weather conditions, with low PDOP values, obtaining a measurement uncertainty of 10-20 mm, which is sufficient for the needs of this work. Devices such as mobile phones or digital cameras, which are used to take geotagged photos, do not have the ability to control geometric and environmental factors that affect the positioning, as is the case with GNSS receivers.

Due to the greater possibility of using mobile network transmitters in built-up areas (Cracow University of Technology campus), several variants of obtaining geolocation using mobile devices were used to check the accuracy of the measurement point locations:

Variant I. Photos only with the geotagging option.

Variant II. Photos with the geotagging option and position stabilisation using the GPS Test application. Additionally, coordinates were read from the GPS Test application.

Variant III. Photos with the geotagging option, additionally with the mobile data transmission turned on (if possible).

Variant IV. Photos with the geotagging option with position stabilisation using the GPS Test application and the mobile data transmission turned on (if possible). Additionally, coordinates were read from the GPS Test application (GPS Test, 2025).

To verify the locations obtained from mobile technologies, precise measurements were performed using GNSS technology (Hi-Target H32 and Kolida K9X) and measurement points were located based on orthophotomaps (where possible).

In addition, to make the results credible, the measurements were taken by different people with varying degrees of involvement in the research process. For this purpose, field research was conducted on campus with a group of ten students under the supervision of two academic staff members to determine the accuracy of positioning based on geotagged photos using different phone models. Twelve different phone models and a Nikon camera were used to take the photos. Each student and employee took geotagged photos of the same ten easy-to-locate points (manholes) independently. Ultimately, photos from ten phone models and a camera were accepted for analysis due to the lack of meeting the conditions for proper photo taking in all measurements.

2.3. Statistical analysis

In geodetic surveying, measurements are typically taken twice. This is primarily for the purpose of self-checking the correctness of the obtained results. A double, independent measurement practically eliminates the possibility of an error because we always have two measurement results, the value of which should be consistent with each other. A double, independent measurement is also the basis for determining the mean error of such a measurement. In statistical nomenclature, the results of measurements performed in this way create so-called pairs of observations, and the mean unit error m_0 (assigned to a single observation) is calculated using the formula:

$$m_0 = \pm\sqrt{\frac{\sum_1^n d^2}{2n}} \quad \text{(Eq. 1)}$$

where:

d - the difference between two observations, i.e. two measurement results

n - the number of pairs of observations

The measuring devices and applications used to determine the position, as an element of the geotagged photos taken, were verified by precise measurements with a GNSS receiver. Precise measurements were performed using GNSS technology in relation to the ASG-EUPOS system (Uznański, 2017). A Hi-Target H32 GNSS receiver and a Kolida K9X GNSS receiver were used, using NAWGEO_VRS_3_1 corrections. The measurements were performed in the National Geodetic Coordinate System 2000 for zone 7 (EPSG:2178). The National Geodetic Coordinate System 2000 (Dz.U. 2024 poz. 342, 2012) is an accurate rectangular coordinate system using metric units. It covers Poland with four separate zones, each based on the Gauss-Kruger projection, and features some non-uniformity across different areas. The divisions between the zones in the 2000 system were established using county boundaries. This is the coordinate system currently in force in Poland, intended for reproducing maps and recording spatial data with geodetic accuracy (e.g. cadastral maps), at the scales: 1:500, 1:1000, 1:2000, 1:5000. The location of points determined by a precise GNSS receiver was adopted as the reference location.

Then, pairs of observations were created from measurements taken with different devices to assess the accuracy of such measurements expressed by the mean unit error, the value of which indicates the potential possibilities of using geotagged photos taken by a given device or application.

The obtained research results were collected, developed, processed and visualised using the publicly available QGIS software (v.3.34.3). QGIS is an open-source geographic information system (GIS) licensed under the GNU General Public License, which is an official project of the Open Source Geospatial Foundation (OSGeo). Automatic addition of geotagged photos is possible thanks to the QGIS Import Photos plugin (QGIS Python Plugins Repository, 2025). This is a tool that facilitates quick identification of locations based on geotagged photos as points to the QGIS program. As a result of their import, a vector layer is created with points containing descriptive information about the photo. The plugin also allows the use of additional filters.

In the data analysis, standard deviation was employed as a conventional measure of variability to indicate the extent to which the observed values deviate from the mean. The smaller the deviation value, the more the observations are clustered around the mean value.

To compare the results obtained from different devices (Motorola, Samsung, Nikon, and additionally Motorola and Samsung using the GPS Test application), we first checked whether the samples were from a normally distributed population. For this purpose, the Shapiro-Wilk test was used (NIST/SEMATECH, 2025). Due to instances of non-normal distribution among the samples, the nonparametric Kruskal-Wallis test was employed for group mean comparisons, utilising Dunn's (Bonferroni) correction (Dunn, 1964).

All calculations were performed in the GNU R software package. A significance level of α=5% was assumed for all tests.

3. Results

The research consisted of determining coordinates based on geotagged photos, which were entered into the QGIS project using the Import Photos plug-in. The use of this software allowed for visualisation of the obtained results and their development. In accordance with the different variants of determining the position based on mobile devices, the following analyses were carried out.

3.1. Klimkówka reservoir area

For the dam area, locations based on geotagged photographs have significantly larger errors than locations on the reservoir surface. For photographs taken with a Samsung Galaxy A25 (S) phone on the reservoir surface, the average mapping error is about eight times smaller than for photographs near the dam (the maximum error is over ten times smaller). The mean unit error (m_0) of locating the same points near the dam taken with a Nikon digital camera (N) is four times lower than those obtained using a Samsung Galaxy phone. For the open area, significantly smaller m_0 were observed than in the case of the area with the horizon obscured (narrow valley). For the same measurement conditions, much better accuracy of determining the location was achieved with the digital camera than with the mobile phone. The error values for individual devices are listed in Table 1.

Table 1. The value of the location errors of the geotagged photo locations in the Klimkówka reservoir area.

Area	Device	Sample size	Location differences [m]			σ [m]	m_0 [m]
			Minimum	Average	Maximum		
Dam cross-section	***S***	31	1.2	81.8	243.4	96.7	88.7
	N	31	0.7	21.7	59.5	21.5	21.4
Reservoir area	***S***	10	2.1	10.1	21.3	6.4	8.3

Figure 6 shows distances between point coordinates determined based on precise GNSS measurements and the locations of geotagged photos taken with a phone (Samsung Galaxy) or a digital camera (Nikon).

The coordinates of each geotagged photo were compared with the coordinates determined using a precise GNSS device. The comparison involved calculating the difference in coordinates, which is represented by the two-dimensional horizontal error (planimetric error) measured in metres. Computed error is the per-point Euclidean distance in the working CRS (PL-2000 zone 7/EPSG:2178) after transforming WGS 84 EXIF coordinates (Dz.U. 2024 poz. 342, 2012, Spatialreference, 2025). The calculated horizontal errors were grouped into intervals with a fixed distance of one metre. For each of these intervals, the number of coordinate differences was determined. Their share in all intervals expressed as a percentage is presented in Figure 7. The horizontal errors for each of the cases (device/conditions) is marked with different colours: red - Samsung Galaxy A25 dam cross-section, green - Nikon Coolpix P900, orange - Samsung Galaxy reservoir area. The horizontal errors and the areas determined based on these errors are presented in Figure 6. Based on the data presented in Table 1 and Figure 6a and Figure 6b, it was found that in the case of taking photos in an open space (reservoir), the differences in the coordinates of geotagged photos with respect to the nominal coordinates are smaller than in the case of a narrow valley. The errors in determining the dam cross-section area are much smaller when using the Nikon digital camera compared to the Samsung phone (see Figure 6a). The 2D horizontal errors for locations measured with the Samsung Galaxy phone on the reservoir surface range from 2 to 20 metres (Fig. 7). For measurements conducted within a narrow valley (dam cross-section) using the same instrument, approximately half of the error values fall between 1 and 20 metres, comparable to results observed in open space, while the remaining half range from 20 to 240 metres. When the digital camera's view of the horizon is obscured, the maximum difference in coordinates, compared to the reference coordinates, does not exceed 60 metres. For half of the measured points, this difference falls between 0 and 10 metres. Large discrepancies in determining the location may indicate weaker, local access to the GNSS satellite signal because all other measurement conditions were identical.

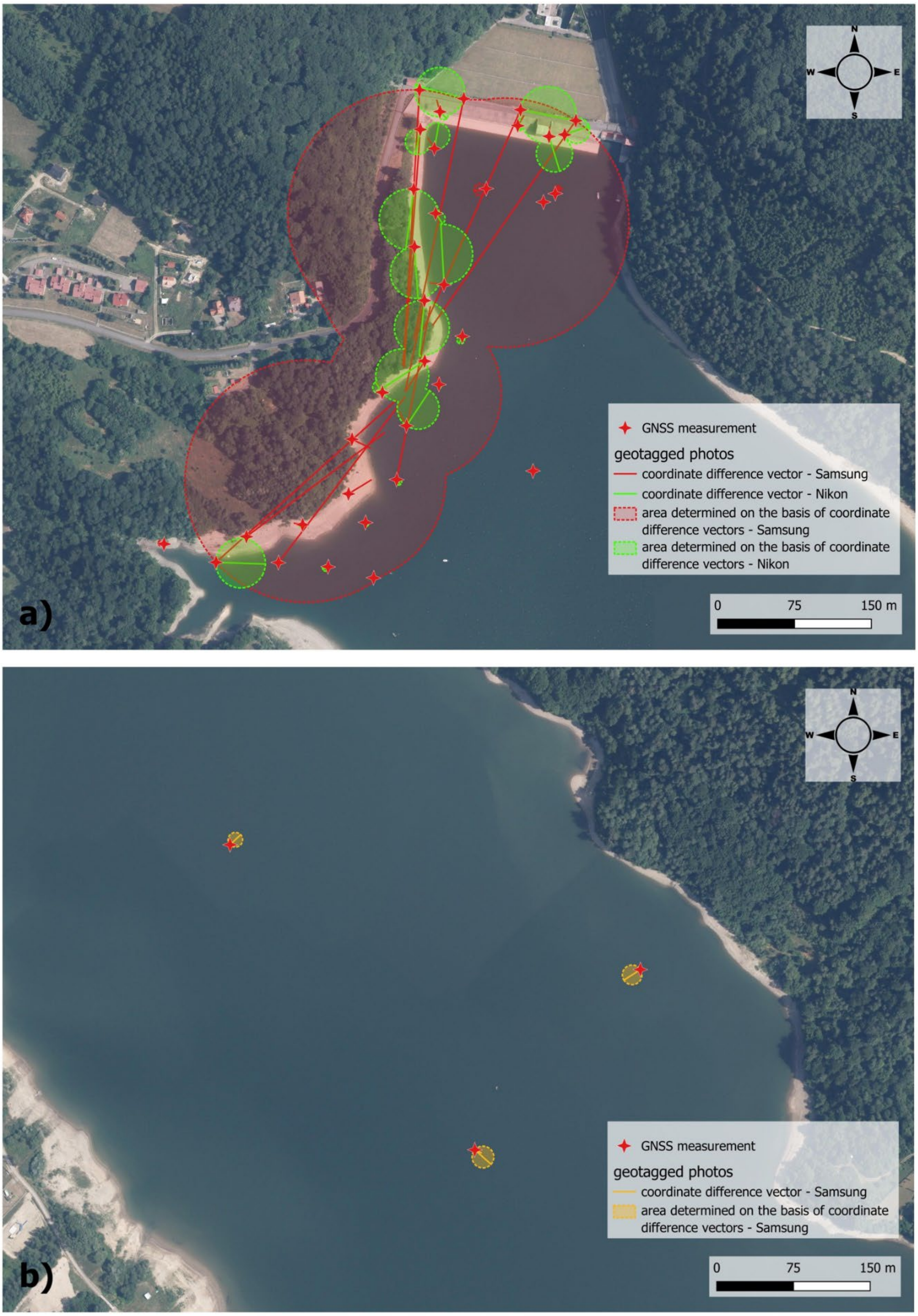

Figure 6. Differences between the location of the geotagged photos and the precise GNSS measurement taken at the Klimkówka reservoir, including a) dam area and b) reservoir area.

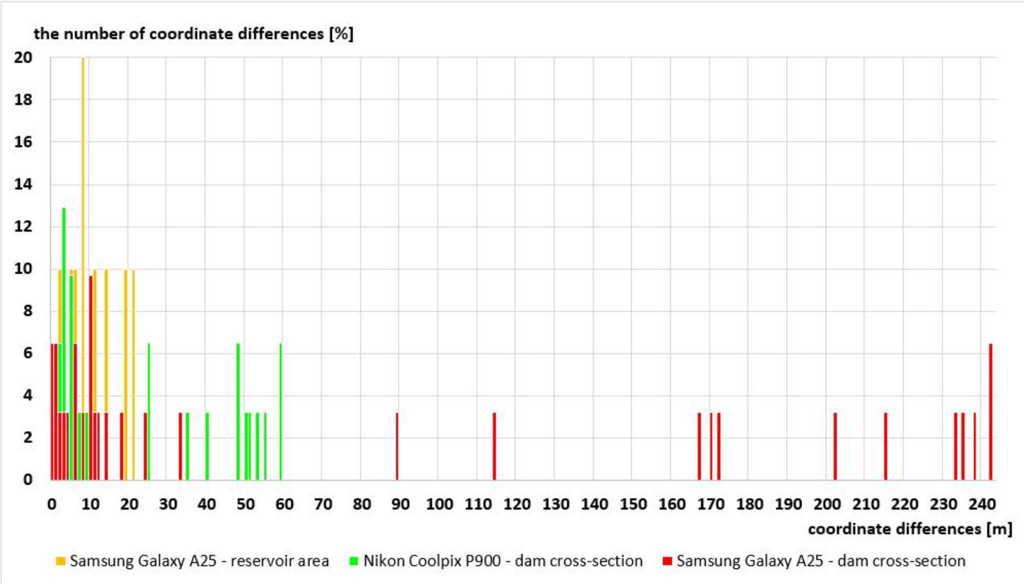

Figure 7. The percentage share of 2D horizontal errors in 1-metre intervals for geotagged photos taken at the Klimkówka reservoir.

3.2. Campus of the Cracow University of Technology in Cracow

Independently, a series of measurements was performed in an urban area with dense development located in Cracow, on the campus of the Cracow University of Technology (Fig. 4). Measurements were performed for 30 points. The locations at which the geotagged photographs were captured were determined through direct measurement using GNSS receivers, specifically the Hi-Target H32 and Kolida K9X models.

The parameters characterising the accuracy of geotagged photos taken with Samsung and Motorola phones and a Nikon digital camera, taking into account four measurement configurations on the campus of the Cracow University of Technology are presented in Table 2.

Table 2. Comparison of geolocation error values of geotagged photos taken with Samsung Galaxy A25 (S), Motorola RAZR 40 Ultra (M) and Nikon (N) digital camera, taking into account all considered measurement configurations (Variant I to IV) and reading coordinates from the GPS Test application used on the phones: Samsung Galaxy A25 (App GPS Test S) and Motorola RAZR 40 Ultra (App GPS Test M) along with standard deviations (σ) and mean unit errors (m_0) on the campus of the Cracow University of Technology.

Variant	**Device**	**Sample size**	**2D horizontal error [m]**			**σ [m]**	**m_0 [m]**
			Minimum	**Average**	**Maximum**		
I	***S***	86	1.2	16.2	41.9	9.5	13.3
	M	89	0.2	44.3	247.5	54.8	49.7
	N	34	0.9	11.4	44.1	9.1	10.3
II	**S**	34	0.4	10.9	67.0	12.6	11.7
	M	35	0.5	5.4	20.4	4.9	5.1
	App GPS Test S	10	1.4	7.2	23.8	6.4	6.7
	App GPS Test M	10	1.4	4.2	15.4	4.0	4.0
III	***S***	10	3.7	10.6	21.5	5.7	8.4
	M	10	2.2	36.5	84.8	31.8	33.5
IV	***S***	10	1.4	9.9	19.0	6.7	8.3
	M	10	2.6	19.6	77.8	25.8	22.2
	App GPS Test S	8	1.5	6.4	17.8	5.0	5.6
	App GPS Test M	10	0.4	6.3	22.8	7.0	6.4

3.2.1. Variant I - Photos only with the geotagging option

Photos were captured at designated locations on the Cracow University of Technology campus using mobile devices that had only their location features activated. Photos with geotags were taken three times with an interval of several days. To determine the accuracy of the location, the differences in coordinates were calculated in relation to the coordinates measured with a precise GNSS device. Similarly to the Klimkówka reservoir area, the differences in coordinates, obtained on the Cracow University of Technology campus using different devices, were grouped into intervals with a fixed distance of one metre. Figure 8a shows the percentage of coordinate differences in 1-metre intervals for the Motorola phone (blue), the Samsung phone (red) and the Nikon camera (green). Figure 8a and Table 2 show that the Motorola phone's coordinate differences from GNSS measurements are much larger (up to 247.5 m) than those of the Samsung phone (41.9 m) and Nikon digital camera (44.1 m). The obtained error values may be related to the obscuration of the horizon at some points, especially near buildings and trees. Since all measurement conditions were identical, the reason for such large differences in the obtained measurement errors may be the refresh time of the GNSS signal used for geolocation of photos, as well as the type of GNSS receiver that the phone is equipped with (single- or dual-frequency).

In the case of the described studies, the photos were taken in a rather limited area of the PK campus and in short intervals. Using only the location feature on the phone meant that in many cases the location of the photos was not updated. This is especially visible in the case of the Motorola RAZR 40 Ultra phone.

3.2.2. Variant II - Photos with the geotagging option and position stabilisation using the GPS Test application. Additionally, coordinates were read from the GPS Test application

Using mobile devices with location enabled and using the GPS Test application enabling the determination of a stable position, photos were taken at the same measurement points. The GPS Test application was used to check the signal strength, number of available satellites, position accuracy expressed as the mean position error specified in metres and the stability of the determined coordinates with an accuracy of hundredths of an arc second (Fig. 1). Additionally, screenshots of the coordinates determined using the GPS Test application were taken, based on which the read coordinates were compared with the coordinates determined using the GNSS receiver. In Figure 8b, a solid fill was used for photos geotagged with the GPS Test application, a dotted fill for coordinate values read from the GPS Test application obtained with the Motorola phone (blue) and the Samsung phone (red). In this variant, the location determined with the Motorola phone is characterised by an error m_0 that is more than twice smaller (5.1 m) than the Samsung phone (11.7 m). In the case of the Motorola phone, the maximum coordinate differences decreased to 20.4 m compared to Variant I. However, in the case of the Samsung phone, the maximum coordinate differences increased to 67 m. Analysing the m_0 value (Table 2) for both phones in Variant I and Variant II, the use of position stabilisation using the GPS Test application reduces measurement errors.

3.2.3. Variant III - Photos with the geotagging option, additionally with the mobile data transmission (GSM) turned on (if possible).

At the chosen measurement points used in Variant I and Variant II, photos were taken using mobile devices with enabled location and mobile data transmission (GSM). The obtained results are shown in Figure 8c for the Motorola phone (blue) and the Samsung phone (red). In the case of both phone models, the maximum coordinate differences are smaller than in Variant I (Table 2). In the case of the Motorola phone, the maximum distance differences decreased from 247.5 m (Variant I) to 84.8 m, and for the Samsung phone from 41.9 m (Variant I) to 21.5 m. The use of mobile data transmission reduces the mean unit error m_0 compared to Variant I and II in the case of the Samsung phone and compared to Variant I for the Motorola phone.

3.2.4. Variant IV - Photos with the geotagging option with position stabilisation using the GPS Test application and the mobile data transmission (GSM) turned on (if possible). Additionally, coordinates were read from the GPS Test application.

In this variant, photos were using mobile phones with enabled location and mobile data transmission and with coordinate stabilisation using the GPS Test application. As in variant 2, in addition to using the GPS Test application, coordinates read from the GPS Test application were used to determine the position stabilisation. In Figure 8d, a solid fill was used for photos geotagged with the GPS Test application, a dotted fill for coordinate values read from the GPS Test application obtained with the Motorola phone (blue) and the Samsung phone (red). The values of the maximum coordinate differences for both phone models are slightly lower than in the case of Variant III and significantly lower than in the case of Variant I (Table 2). In the case of Variant II, this value also decreased for the Samsung phone (from 67 m to 19 m) but increased for the Motorola phone (from 20.4 m to 77.8 m). For the Samsung phone, the mean unit error m_0 (8.3 m) is also the lowest among all variants. In the case of the Motorola phone, the use of mobile data transmission did not reduce the m_0 error value when using coordinate stabilisation with the GPS Test (Variant II) application.

Based on the accuracy characteristics obtained in the four variants, two extreme cases were selected: the least accurate – Variant I (Figure 9a) and the most accurate – Variant II (Figure 9b). For all devices used, horizontal error in relation to the GNSS receiver and areas designated on the basis of these errors were determined: Motorola – blue, Samsung – red, Nikon – green (Figure 9a), Motorola with GPS Test application stabilisation – violet and Samsung with GPS Test application stabilisation – orange (Figure 9b).

The impact of technologies on geotagged photo capture, evaluated across four variants, demonstrates observable differences based on the device employed. As shown in Figure 8, Figure 9, and Table 2, using only geolocation provides the least accurate coordinates for both phones among all options analysed. It is difficult to clearly identify the option that is best for obtaining the most accurate coordinates, as this depends on the device used. The smallest mean unit error value were obtained for the Motorola phone using the GPS Test application and amounted to 4.0 m (Variant II). For the Samsung phone, the best results were obtained using the GPS Test application with mobile data transmission (GSM) enabled (Variant IV), m_0=5.6 m. The Nikon camera (Variant I) delivered surprisingly good results, especially given that there was no way to enable extra features to enhance measurement quality. For a sample size of 34, the mean unit error value m_0=10.3 m was obtained with the smallest standard deviation (σ=9.1 m) among all devices. Based on the conducted research, using the GPS Test application to stabilise the position had the greatest impact on the accuracy of determining the location.

Statistical analysis of the error data sequences obtained from the measurements (Motorola, Samsung, Nikon, Motorola, and Samsung with GPS Test stabilisation) was performed using the nonparametric Kruskal-Wallis test, since most of the studied samples did not come from a normally distributed population. The Kruskal-Wallis test was: chi-squared = 152.4144, df = 4, p-value = 0.

The p-value of the Kruskal-Wallis test was less than the assumed significance level of α = 5%, indicating that the results obtained from at least one device differed from the results from the other devices. To determine which groups differ, post-hoc tests were performed using a Dunn test for each pair of devices, with a Bonferroni correction for multiple hypothesis testing (Table 3).

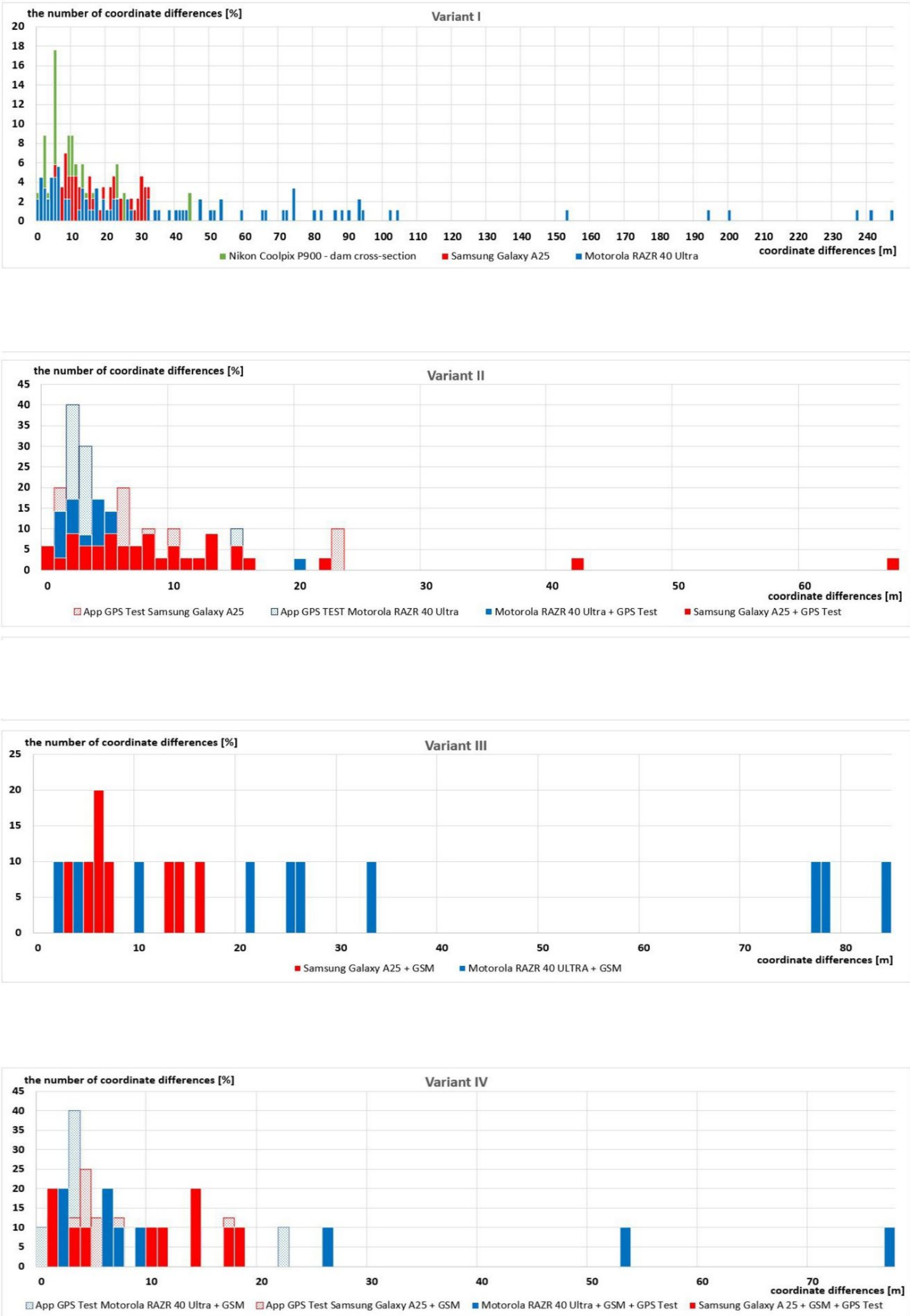

Figure 8. Difference in percentage in 1-metre intervals for geotagged photos taken for all variants on the campus of the Cracow University of Technology.

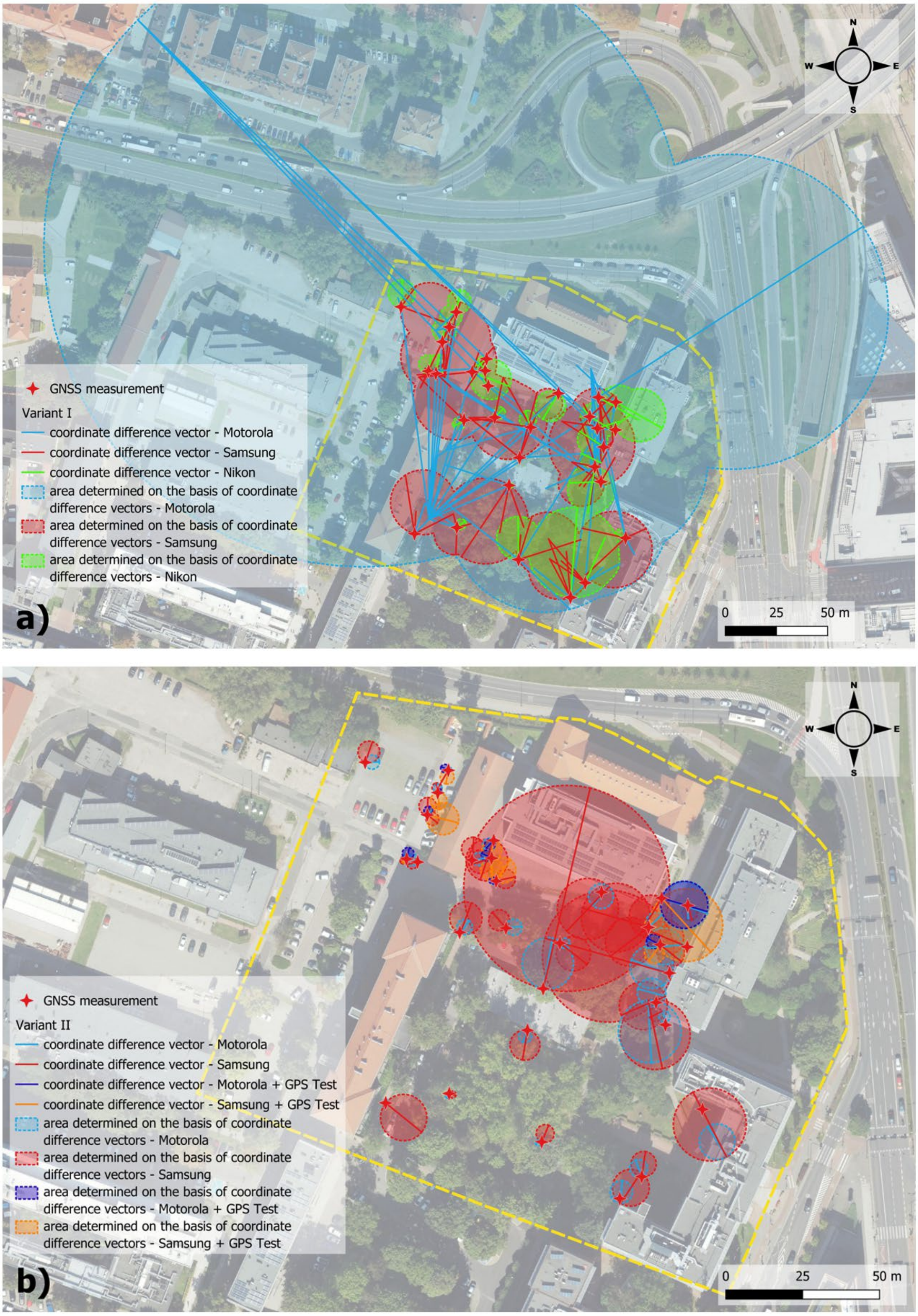

Figure 9. Differences between the locations of the geotagged photos and the precise GNSS measurement taken in the campus of the Cracow University of Technology in Cracow with a) only geotagged photos case – Variant I, b) geotagged photos with GPS Test stabilisation – Variant II.

Table 3 Pairwise comparisons between mobile devices using Dunn test

device	App GPS Test S	S	App GPS Test M	M
S	-7.6612			
	0.0000*			
App GPS Test M	0.6545	8.7152		
	1.0000	0.0000*		
M	-6.5768	1.6002	-7.5993	
	0.0000*	0.5478	0.0000*	
N	-0.0238	7.6318	-0.6787	6.5474
	1.0000	0.0000*	1.0000	0.0000*

The upper values in each row of Table 3 represent the Dunn test statistics, while the lower values represent the p-value. If the p-value is less than 5%, the groups differ significantly and are marked with an asterisk symbol. Significant differences were found between the following device pairs: Samsung vs. Samsung with GPS Test stabilisation; Motorola with GPS Test stabilisation vs. Samsung; Motorola vs. Samsung with GPS Test stabilisation; Motorola vs. Motorola with GPS Test stabilisation; Nikon vs. Samsung; and Nikon vs. Motorola. No significant differences were observed among Motorola, Samsung, Nikon (with or without GPS Test stabilisation), or between any of these groups when GPS Test stabilisation was applied.

Table 4 presents statistics for the Dunn test with Bonferroni correction.

Table 4 Statistics for the Dunn test with Bonferroni correction.

Device	Minimum	Mean	Median	Maximum	IQR
S	13.81	47.23	44.15	84.13	19.27
M	23.80	41.12	40.47	57.37	5.30
N	0.72	8.93	8.96	24.90	7.10
App GPS Test S	0.35	8.54	7.82	22.78	6.78
App GPS Test M	0.49	5.85	4.57	20.40	4.23

To check the influence of the different phone models on the quality of determining geolocation, additional studies were conducted, in which a group of students at the Cracow University of Technology participated. Ten points were analysed using geotagged photos, taken both with standard photo geolocation and the GPS Test app. The precise coordinates of these points were determined in the same way as in the case of previous studies on the campus of the Cracow University of Technology. Several phones were used in the studies, however, not all students provided complete data, which did not allow for the assessment of the quality of determining the location on all devices used. Finally, in the analysis of the accuracy of geolocation based on photographs, the results from the following models were adopted: Motorola RAZR 40 Ultra, Samsung Galaxy A25 5G, Samsung SM-A202F, Samsung SM-G998B, Pixel 8 Pro, OPPO Reno6 Pro 5G, Xiaomi M2102J20SG. The polar graphs in Figure 10 show the values of geolocation errors obtained by different devices under the same conditions and at the same time. Figure 10a shows the maximum, and Figure 10b the average values of geolocation errors. In both cases, the values of geolocation errors of geotagged photos with position stabilisation (dark blue – Figure 10a and orange – Figure 10b) were compared with the values of errors without position stabilisation (light blue – Figure 10a and yellow – Figure 10b).

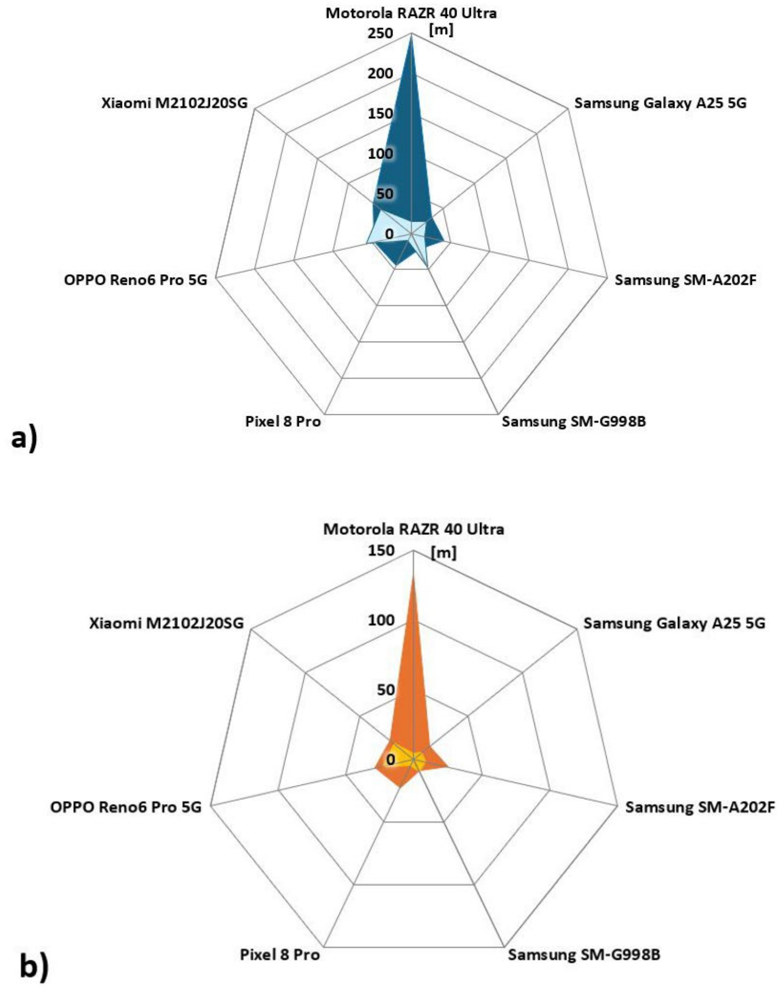

Figure 10. Polar plots showing geolocation error values for different mobile devices: a). Maximum coordinate differences, b) Average coordinate differences.

Due to position stabilisation using GPS Test application, a significant reduction in both maximum and average coordinate differences can be observed in most devices (maximum: 15-fold, average: 30-fold - Motorola). There are also situations where the size of maximum coordinate differences increases despite the use of position stabilisation (OPPO Reno and Samsung SM-G998B phones), which may result from too short period of time spent on determining the position. After analysing how the time spent determining position affects geolocation error using six mobile phones, no clear impact can be identified (see Fig. 11).

Circles with radius equal to the calculated mean unit errors were designated for all measurement points. Areas for which m_0≥25 m were aggregated into one area (red) and for m_0<25 m into another area (grey) (Fig. 12). The most significant errors are observed at locations in proximity to tall structures, such as buildings equipped with telecommunications transmitters and antennas, as well as in areas situated among trees that obstruct a clear view of the horizon. This can affect the attenuation and interference of the signal reaching the measuring devices. Compared to open terrain (Klimkówka reservoir), the m_0 errors obtained are significantly larger.

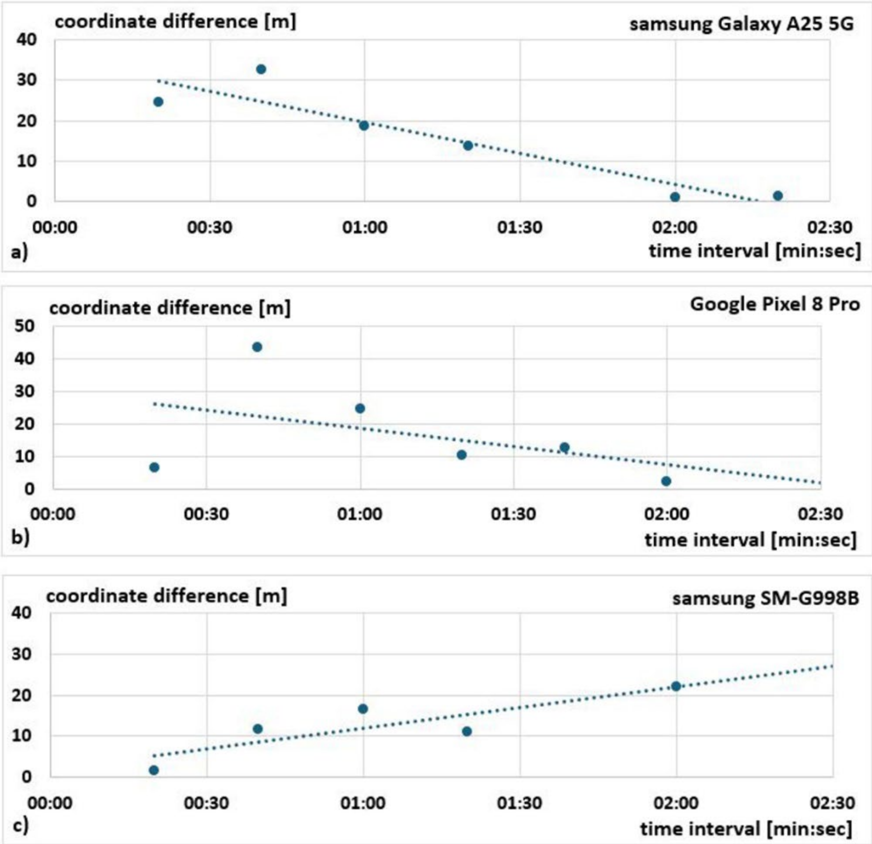

Figure 11. Relationships between the time spent on the measurement and the values of geolocation errors for a). Samsung Galaxy A25, b) Google Pixel 8 Pro, c) Samsung SM_G998B.

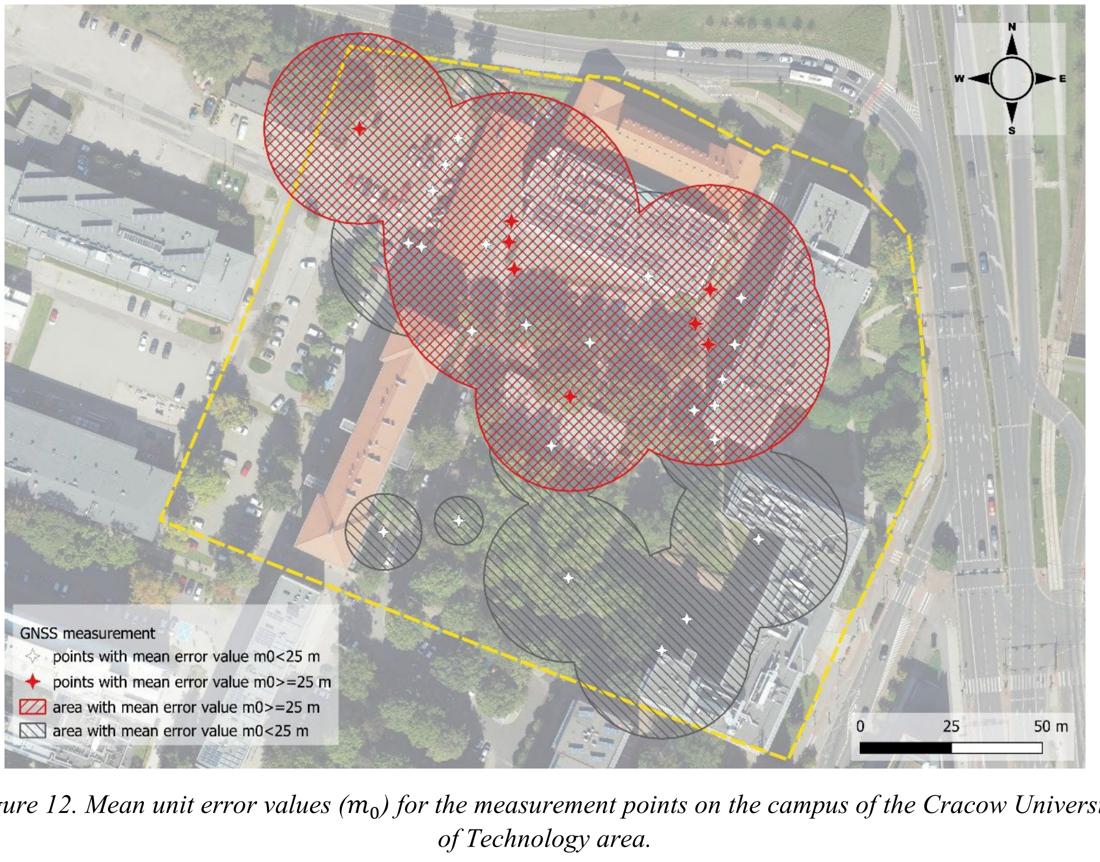

Figure 12. Mean unit error values (m_0) for the measurement points on the campus of the Cracow University of Technology area.

4. Discussion

The study confirmed that the positioning accuracy of geotagged photos is strongly dependent on terrain conditions and the type of device used, which aligns with the stated goals and hypotheses. In open areas like the Klimkówka reservoir region, the variations in geotag positions were much smaller, with average location differences of just a few metres. In conditions with a limited horizon view, such as in a narrow ravine or in a densely built-up urban area, location deviations were significantly larger, reaching up to several dozen metres, indicating a significant impact of GNSS signal obscuration by terrain obstacles such as buildings or trees.

Differences in the susceptibility of devices to horizon obscuration are primarily due to the properties of their GNSS receivers. Using the GPS Test application and enabling mobile data transmission (GSM) positively affected position stabilisation, reducing the maximum and average location differences. The tested configurations confirm that the use of additional tools (GPS Test, GSM) yields better results, supporting the hypothesis that technologies supporting position stabilisation positively impact geotagging accuracy. For example, a Motorola phone's geotagging error dropped from nearly 250 metres to about 4 metres after applying stabilisation and data transmission.

The accuracy of positioning using smartphones may vary and depend on many factors. Merry and Bettinger (2019) assessed the horizontal positioning error of an iPhone 6 in an urban environment, considering seasonality, time of day, and Wi-Fi activity. The results indicated that the average positioning error was in the range of 7–13 m, comparable to the accuracy of recreation-grade GPS receivers in environments with high levels of multipath interference. Importantly, the time of year did not significantly impact the error, but better accuracy was observed in the afternoon during the leafless period and during periods of high Wi-Fi activity. Field studies conducted on the University of Georgia campus, however, showed a clear correlation between positional error and the presence of multi-story buildings, which cause reflections of satellite and Wi-Fi signals, although Wi-Fi activity itself seemed to have a moderate impact on accuracy. Similar observations regarding the impact of the environment on geolocation accuracy were confirmed in the research conducted as part of this article, which assessed the accuracy of geotagged photos taken with various smartphone models and a Nikon digital camera in both field and urban environments, including the Cracow University of Technology campus and the natural areas around the Klimkówka reservoir. Research conducted on campus shows that location accuracy varies greatly, from just a few metres to several dozen metres, with the largest errors occurring in places where the horizon is obstructed, such as urban areas with tall buildings. In addition, using dedicated applications like GPS Test for position stabilisation and enabling mobile data transmission (GSM) greatly enhanced geolocation accuracy. Both the maximum and average errors were reduced, with this improvement being especially evident in Motorola and Samsung devices. Unlike the above studies, the article by Tavani *et al.*, 2020, focuses on the use of smartphone sensors (GNSS, magnetometer, accelerometer/gyroscope) for full georeferencing of 3D models created using the SfM-MVS method, without the need for ground control points (GCPs). Although the precision of the built-in sensors is insufficient for direct 3D reconstruction, postprocessing using acquired positional and orientation data can achieve a satisfactory level of model georeferencing, which is sufficient for many geological and geoengineering applications. In this context, localisation accuracy of several metres is acceptable, especially for large-scale scenes, such as a 400-metre-wide abyss photographically documented with a Xiaomi MiA1 smartphone (Tavani *et al.*, 2020).

The statistically significant effect of device type and measurement location presented in the study by Lee *et al.* (2016) is confirmed by the results obtained in this paper. Analyses conducted by the authors, as well as those by Merry and Bettinger (2019), Tavani *et al.* (2020), and Lee *et al.* (2016), confirm that the accuracy of GNSS measurements in smartphones is closely related to environmental conditions, device characteristics, and additional features supporting position stabilisation (Wi-Fi, GSM, apps). Significant factors include multi-story buildings and forestation, which cause multipath phenomena, reducing accuracy. However, the impact of atmospheric factors was found to be negligible

(Merry and Bettinger, 2019). The tests conducted in this study suggest that professional GNSS receivers remain indispensable in field measurements requiring high precision. However, smartphones can be successfully used in situations requiring moderate accuracy, especially in the context of geotagged images, population movement studies, or georeferencing large 3D models (Tavani *et al.*, 2020; Merry and Bettinger, 2019).

The study used a limited number of samples for each case, which may affect the representativeness of the results. Each field point was measured multiple times, but the number of device models tested was limited to selected phones and a single digital camera, which may not reflect the full diversity of available mobile technologies and their geotagging capabilities. Furthermore, some environmental variables, such as GNSS signal interference related to the measurement site (e.g., the presence of telecommunications antennas, buildings, vegetation), cloud cover variations, and time of day, were not fully controlled and could impact positioning accuracy. These atmospheric and terrain factors can cause local fluctuations in signal quality, which were difficult to standardise during field testing. Consequently, the results should be interpreted with these limitations in mind, and further research could expand the testing scope to include a larger number of devices and more controlled measurement conditions to more precisely assess the impact of individual variables on geotagging accuracy. To expand knowledge about the accuracy of geotagged images, it is worth extending the scope of future research to include a larger number of mobile device models, considering different operating systems (e.g. Android, iOS) and devices with varying technical parameters, including the latest smartphones with advanced GNSS receivers. The analysis should also encompass broader and more diverse urban contexts, encompassing areas with varying degrees of development, building heights, and the deployment of telecommunications antennas, which will allow for a better understanding of the impact of the environment on measurement quality.

A valuable direction would be to investigate the possibility of correcting GPS location errors during image post-production, particularly using algorithms and statistical methods that improve the precision of coordinates determined from geotagged images. It is recommended to evaluate the effectiveness of different correction techniques, particularly under conditions involving considerable horizon obscuration and signal interference. Furthermore, future research could include longer and more systematic measurements, considering variability in atmospheric conditions and time of day, which would allow for the identification of the impact of seasonal and weather factors on geolocation accuracy. Broadening the scope of this research will enhance comprehension of the factors influencing the accuracy of positioning using geotagged photographs, enabling the development of more precise guidelines for users and developers of geotagging software.

5. Conclusions

Unlike navigation and geodesy specialists, most mobile technology users do not know what factors influence the accuracy of position determination when using the geotagging feature. Additionally, the mobile devices that most people around the world use do not provide data typical of precise GNSS receivers, which makes it impossible to rely on PDOP values or almanac while taking geotagged photos. The authors' intention was to determine the accuracy of geotagged photos taken by users lacking specialised technical knowledge. As a result of the research, recommendations were formulated to improve the accuracy of determining the position of geotagged photos. These recommendations allow determining the position of geotagged photos with the highest possible precision by any user using a typical mobile device, which does not provide the ability to assess the conditions affecting the quality of the GNSS signal and optimise the measurement. To draw the attention of mobile device users to the influence of environmental conditions on the accuracy of positioning, the authors carried out research in two areas differing in terms of terrain and its development as well as access to and quality of the GNSS signal.

Both cases (Klimkówka reservoir and Cracow University of Technology campus) required the preparation of photographic documentation with geotagging. Analysis of such documentation showed low precision of the location related to the research area, especially when photos were taken without awareness and without paying attention to the stability of the measuring device. The conducted research indicated that the methods and techniques of taking photos have a decisive impact on the quality of the measurement. This is directly related to the awareness of the possibility of making an error due to: the research area (built-up area, open area), limited access to the satellite signal (obscuration of the horizon and signal interference), techniques for taking geotagged photos (location option, access to mobile data transfer, stabilisation time of the device's position), technical parameters of the mobile device. In open areas and urban areas with limited or disrupted satellite signal, the values of geolocation errors obtained from geotagged photos can reach up to several hundred metres (Table 1, Table 2).

Stabilising the device's position for a longer measurement time (position stability can be verified, for example, in the GPS Test application) results in much smaller geolocation error values (this value can be even several times smaller), which significantly affects the accuracy of determining the location. In regions with limited or disrupted signal access, it is important to recognise that measurement errors may range from several metres to several dozen metres, depending on the device used. However, if the measurement is performed in accordance with the principles of correctness given in this manuscript, the error values are on average several metres and sometimes even several dozen centimetres. This type of geolocation accuracy allows the use of geotagged photos to perform, among others, reports using photographic documentation with geotagging, object maps, conducting surveys using mobile technology, documentation of the location of field research, markings of objects of interest, destination points, viewpoints, places of danger (e.g. occurrence of floods, illegal waste dumps, landslides, related to atmospheric phenomena, documentation of accident sites, related to the sense of security, comfort), which fits into the wide scope of use of geotagged photos in various areas of life. Photographic documentation with geotagging is increasingly an element required by offices due to both the common use of mobile technologies by citizens and the progressive digitisation of society.

This research has shown that there are factors that have a significant impact on the accuracy of positioning using mobile devices. When taking geotagged photos, based on their own studies, the authors recommend using the following good practices that may be useful for researchers, practitioners and even during the educational process:

1. Before taking a photo with geotagging, check the phone settings:
    - Turn on the phone's location mode.
    - Turn on the photo location mode in the camera settings.
    - Turn on mobile data transmission, if possible.
2. Stabilise the device's position:
    - To achieve this, wait a few minutes without changing position.
    - The stability of the position can be checked using appropriate applications, e.g. GPS Test (position stability is understood as the invariability of the coordinate reading).

Additional notes when creating documentation:

1. In addition to taking a photo of the actual object, additional photos of characteristic places or objects should be taken, which will allow for verification of the coordinates based on maps, e.g. orthophotomaps.
2. If possible, add a comment about the location of the place where the geotagged photo was taken, e.g. the exact address or a brief description of the characteristics of the place.

Based on the conducted research, the authors would like to draw special attention to the fact that measurements with mobile devices cannot replace measurements using precise GNSS receivers, especially for geodetic purposes. However, these methods may be appropriate for applications where determining locations with extremely high precision, such as in the range of millimetres or centimetres, is not necessary.

This paper can serve as a guide for teaching spatial data quality, encouraging students to actively engage in real-world data collection, error analysis, and critical literature reading. The use of this type of information may prove particularly valuable in courses on GIS, geoinformatics, digital geography, or citizen science.

Acknowledgements

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- Geoprtal.gov.pl - all content published on the website is available under the Creative Commons Attribution-NonCommercial-NoDerivatives 3.0 license.
- GPSTest - screenshot of the free app developed by Chartcross Limited installed on a smartphone.

Data supporting the results of this study can be made available upon request.

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