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# Modern Technologies of Geodetic Support of Planning Works in High-Rise Construction

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*ABSTRACT. The work shows the shortcomings of traditional geodetic technologies in the limited space of a modern construction site on the basis of research and analysis of literature sources, regulatory and production base of geodetic support in the construction of multi-storey buildings. Today, electronic tacheometers are used to perform planning works, which allowed to perform planning of building structures without bringing the building axes of the building to the ground, which, in its turn, had an extremely positive effect on compliance with deadlines of construction. When creating a support base on prefabricated horizons during the construction of buildings up to 150 m, it is suggested to use satellite technology with subsequent planning of building structures directly using electronic tacheometers.*

*Keywords: construction of structural axes, mounting horizon, design work, electronic tacheometers, landmarks, GNSS technology, building construction.*

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# 1. Introduction

In the well-known classical interpretation of geodesy as a science that studies the shape and size of the Earth, its external gravitational field, there is the development of methods of depicting the Earth's surface on maps and methods of measurement in the field (Litynskyj 2001). Over the last few decades, due to the rapid development of digital and information technologies, geodetic methods and tools have undergone radical changes. There was a transition from optical-mechanical geodetic instruments to digital (electronic) ones. Electronic theodolites, levels, tacheometers have appeared, which allow speeding up field measurements and in-house processing of results, reducing subjective errors of the observer and, with the available software, to obtain data for solving various geodetic problems directly at the observation station. Construction of networks of permanent stations of global navigation satellite systems (GNSS) for locating objects, creation of high-resolution aerospace systems for remote sensing of the Earth (ERS), means of laser location of ground and air bases, digital aerial photography and use of unmanned aerial vehicles (UAV), and the use of geographic information technologies to create realistic terrain models, significantly expands the possibilities and horizons of application of geodetic science.

In order to determine the deformations of tunnel walls, a mobile multi-sensor system for monitoring and mapping tunnel walls, a scanning data processing method for estimating displacements on a three-dimensional model and a virtual reality tool that supports data interpretation have been developed (Chmelina et al. 2012).

GNSS is known to be used for monitoring the deflection of bridges (Roberts et al. 2014). Thus, with the help of GPS-receivers attached to the handrails of the bridge and installed along its span, the frequency and amplitude of oscillations of span structures during the movement of vehicles on it was determined.

Geodetic methods of observation were used to determine the vertical deformations of the Ataturk Dam in Turkey, built on the Firat River (Kalkan et al. 2016). For this purpose, deformation marks were placed along the dam, and observations of their vertical position were carried out using GPS-technologies and electronic tacheometers.

Laser scanning techniques have been developed in Romania to monitor the condition of the road surface. The results of scanning in the form of three-dimensional models and construction of profiles on them allow making optimal technical decisions to restore the structure of the pavement (Herban et al. 2017).

Article Jadviščok et al. (2014) describes geodetic works to determine the verticality of the holes of 169 structural components installed in the floor slab between the first floor and the basement of the building for testing building materials. The centres of the openings of the structure components in the basement and on the ground floor were coordinated using an electronic tacheometer and a specially designed centering device.

In Shults and Roshchyn (2016) the free station method, which is one of the modern methods of spatial geodetic monitoring is described. A preliminary calculation of the accuracy of determining the displacements by this method is carried out, and an analysis of errors that affect the accuracy of spatial monitoring is carried out.

In Vrublová et al. (2012) the application of laser scanning methods for removing bucket excavators in order to determine the basic geometric parameters of machines in the dynamic mode of their operation is described. The data will be used to visualize the movement of the excavator and control the process of coal mining in real time. Measurements are carried out at the Doly Nástup coal mine, Tusimice, North Bohemian brown coal deposit, Czech Republic.

The Institute of Geodesy and Mine Surveying of the Technical University of Ostrava monitored and assessed the consequences of the explosions at the Ostrava–Karvina coal basin of the industrial agglomeration in the northeast of the Czech Republic. A pair of professional-grade digital cameras were used to monitor the condition of the buildings and the terrain around the field, and the results of the survey were processed with the help of specialized software and 3-D models of the survey objects were obtained (Kapica and Sládková 2011).

The article Rozenvasser et al. (2014) describes a new multifunctional system for geodetic monitoring, which can be used to monitor complex engineering structures of large sizes. The work of this system for monitoring «Donbass Arena» stadium, Ukraine, which is in extremely unfavorable geotechnical conditions, is described.

The technology of monitoring and analysis of deformations of cylindrical tanks for oil storage is given in Beshr (2014). GPS technology was used to create the imaging base, and an electronic tacheometer was used to coordinate points on the tank surface.

To create digital and inexpensive road maps in Easa et al. (2007) use high-resolution satellite images, such as those obtained from the IKONOS satellite.

The article Eschmann and Wundsam (2017) presents the technology of using UAVs to monitor those parts of the bridge that are difficult to access for visual inspection. The bridge structures are inspected with visual cameras or thermal imagers, while the contours of the object are scanned with a LiDAR. The specified equipment is on board of the UAV. The obtained three-dimensional data are integrated into the web platform of the geographic information system developed within the project.

Developments on application of geodetic methods integrating digital, information technologies, possibilities of modern element base for performance of traditional geodetic tasks are carried out. Thus, in Tereshchuk et al. (2021) we proposed a robotic complex, which allows to determine the coverage of the runway of the airport in the mode of remote GIS / GPS control of the complex of mobile levelling robots and to build longitudinal and transverse profiles of the surface. The article Tereshchuk et al. (2019) is devoted to the detection, consideration and minimization of residual systematic errors in the results of GNSS observations.

GNSS is also actively used in geodynamic problems. With the help of GNSS, it was proved that two days before the earthquakes in Zagreb, there was a reduction in the distance between GNSS reference points (crustal compression) (Solarić, N. and Solarić, M. 2021).

The article Zrinjski et al. (2021) considers the use of two independent methods of industrial masonry chimney structural geometrical parameters determination i.e., the unmanned aerial system survey and precise total station, as well as a comparative analysis of the results obtained by these methods. The accuracy of the data set based on the total station survey is about 10 times higher compared to the unmanned aerial system survey (2.6 mm and 25.5 mm, respectively). The results of both methods indicate a deviation of the top of the chimney from its base by almost 15 cm.

In Marjetič (2018) the use of a total station and a terrestrial laser scanner to deformation monitoring of two tall chimneys is described. According to the results of measurements with a total station and a laser scanner, the horizontal offset at the top of the first chimney was about the same (about 8.7 cm), and for the second chimney the difference was about 2 cm. The standard deviation for each of the parameters of the laser scanner is up to ten times smaller than that of the total station (the standard deviation for determining the horizontal offset for each of the chimneys was about 5 mm for the total station and about 1 mm for the laser scanner, respectively).

These examples illustrate the use of modern geodetic technologies to solve applied tasks.

*Aim of the research.* Investigate the usage of modern technologies for geodetic support of planning works during the construction of multi-storey buildings.

## 2. Geodetic data

Geodetic preparation of the project is performed in order to obtain the necessary geodetic data during the execution of planning works on the placing of the construction project to the site. To do this, for example, the coordinates of the two extreme points of the main axis of the designed structure, closest to the geodetic reference points are graphically determined on the master plan. This can be done using AutoCAD, if the topographic basis of the project and the project itself is loaded into this program. According to the coordinates, the directional angle of the axis is calculated and the distance between these points in accordance with the design distance is specified, and considering this, the coordinates of one of these points are recalculated (Kroshka 2018).

Next, having the coordinates of the specified points of the structure and the coordinates of the points of the external planning basis, the planning elements are determined, according to which two points of the main axis are taken out from the geodetic points and fixed on the ground. In the following time, using working construction drawings, according to the corresponding horizontal distances between the axes and angles, the other main axes of the structure are taken out and fixed on the ground (Fig. 1) (Baran 2012, DBN 2010).

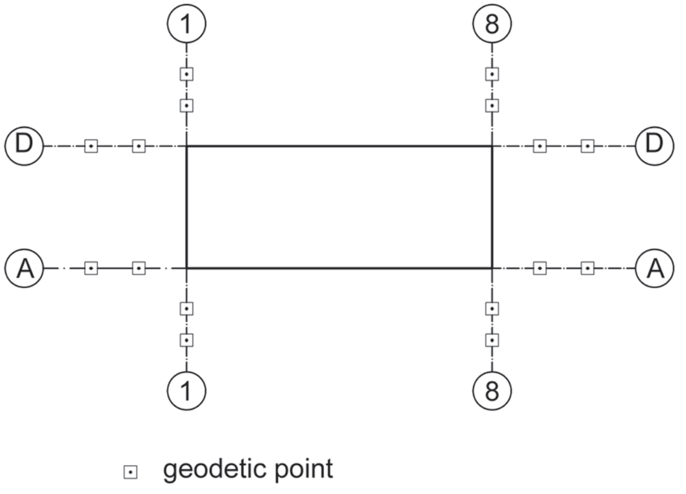


Fig. 1. *Fixing the main axes of the structure with geodetic points.*

From the fixed axes, the contour of the pit and its arrangement, construction of the basement of the structure are planned. Then, there is a transfer of axes of a construction from axial geodetic points (Fig. 2a) on a socle and overlapping of the basement with the use of theodolite.

Transfer of axes to prefabricated horizons in the case of construction of buildings up to 9 floors can be performed by the method of inclined design using a theodolite (Fig. 2b) (DBN 2010). From the main axes on the mounting horizon the planning of the mounting axes is performed, from which the building structures are taken out.

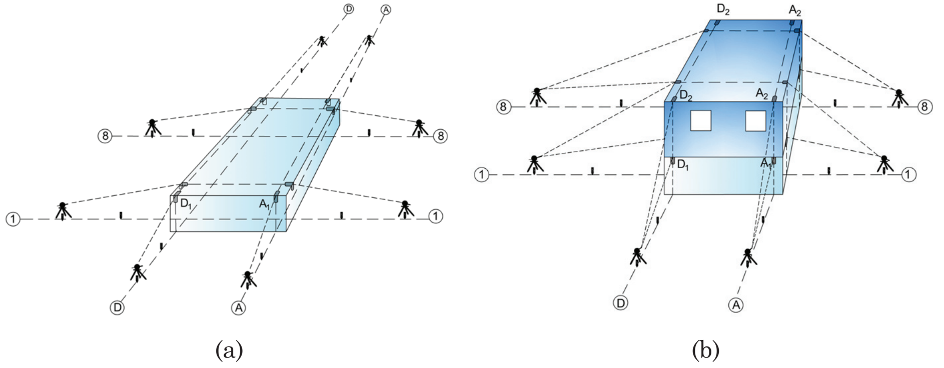


Fig. 2. *Transfer of axes of a construction: (a) on the socle and basement floor, (b) on the mounting horizon.*

If the structure under construction must have more than 9 floors, then the basement floor is equipped with points of the internal planning base, which are tied to the main axes of the structure (Fig. 3) and transferred to the mounting horizons by vertical design devices.

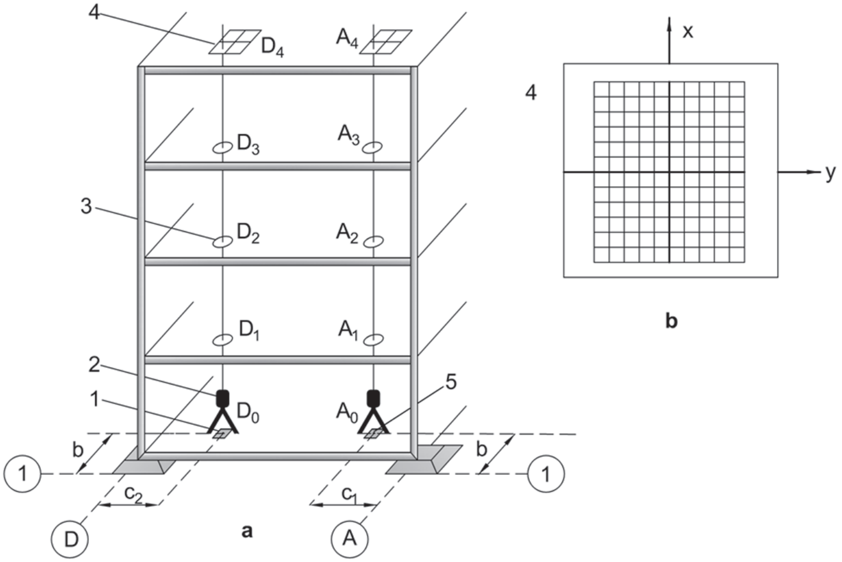


Fig. 3. *Transfer of axes to the mounting horizon by vertical design devices: (a) to the technology of transmission of axes, where: 1,5 – points of the internal planning basis, 2 – vertical design device, 3 – zenith hole in the flooring, 4 – palette; (b) view of the two-coordinate palette.*

The transfer of the planned position of these points on the mounting horizon is performed by the method of vertical design with fixing of their position on the two-coordinate palette. From the received points on the assembly horizon the planning of assembly axes of the building is carried out, and from them – building designs and the equipment (DBN 2010).

Analysis of the use of traditional geodetic technologies shows that:

- fixing on the ground of each of the axes with a pair of geodetic points on both sides of the building is almost impossible in a modern city due to the limited space of the land provided for construction;
- part of the geodetic points is lost in the construction process due to the movement of various mechanisms on the construction site;
- planning axes on mounting horizons requires additional time, which slows down the pace of construction.

## 3. Experiment design, materials and methods

Currently, a monolithic frame construction method (Fig. 4) is used in the construction. This technology was introduced in order to reduce construction time and save resources. It involves a combination of load-bearing elements (frame) of monolithic reinforced concrete and wall filling of brick or blocks. This technology of buildings or structures construction is possible in conditions of limited urban development. The introduction of this method allows to reduce the pressure on the foundation, as well as to build houses in seismically active areas. In addition, the use of high-quality construction formwork and control over the technology of work allows minimizing the cost of finishing the surfaces of walls, floors and floorings.

Fig. 4. *View of a high-rise building constructed in a monolithic frame way.*

Geodetic support of construction in such conditions has also changed due to the advent of electronic tacheometers – geodetic instruments, which, depending on the model, can measure and set on the ground horizontal and vertical angles with an accuracy of 1” – 5”, distances with an accuracy of 1 mm – 3 mm, which have dual-axis compensator which constantly monitor the inclination of the vertical axis in two directions, with an accuracy of about 1”, which allows the use of electronic tacheometers for high-altitude marking. The built-in processor has memory and software for calculating various geodetic tasks.

Measurements are performed on a portable prism reflector, or on a stationary retro reflective foil target, which is glued on the object, or measurements can also be performed on a laser spot reflected from the building structure (non-reflector mode of operation).

Transfer of the position of the building on the ground can be performed from two mutually perpendicular bases passing through the centre of the building without planning its axes. It is advisable to start the work with the choice of longitudinal and transverse bases that intersect at point $Q$ at the angle of 90° and are parallel to the longitudinal and transverse main axes of the building, but are offset, for example, on 1,000 m, from the axes so as not to intersect in plan future building structures, (Fig. 5). The given technology is described by the authors in Kryachok and Vlasenko (2008).

The point and base directions are plotted on the plan of the structure and the coordinates of point $Q$ and one of the points, such as point 1, are graphically determined, which fixes the direction of the base axis $X$ – in the geodetic coordinate system, the directional angle of the $X$ axis and the coordinates of point 2 are calculated, which fixes the direction of the axis $Y$. According to these coordinates, the planning elements of the specified points and point $Q$ are calculated and taken out to the area from the geodetic reference points and are fixed on it. Next, with the use of an electronic tacheometer the distances on the ground from point $Q$ to points 1 and 2 and the angle between them are measured, and, if necessary, the position of a point, for example, 2 is reduced so that the angle between fixed axes $X$ and $Y$ was 90°00'00".

Calculations of the coordinates of items 1 and 2 are performed, as well as the known design distances and angles between the axes of the structure and the dimensions of building structures, the coordinates of the angles of constructions $\Delta X_i$, $\Delta Y_j$ are determined (for example, the angle 4 of columns $\Delta X_4$, $\Delta Y_4$) already in the coordinate system with the centre at the point $Q$ and the coordinate axes $X$ and $Y$ as necessary for the layout of these building structures by rectangular coordinates.

To plan the building elements by the method of polar coordinates, it is necessary to calculate the values of angles $a_i$ and horizontal distances $d_i$, using the coordinates $\Delta X_i$, $\Delta Y_j$ (see Fig. 5). From the nearest reference point of the basic geodetic network by the method of geometric levelling the mark is transferred to point $Q$ and its height is recalculated to the construction one. The coordinates of the corners of building structures and points 1 and 2 are stored in the memory of the electronic tacheometer and personal computer.

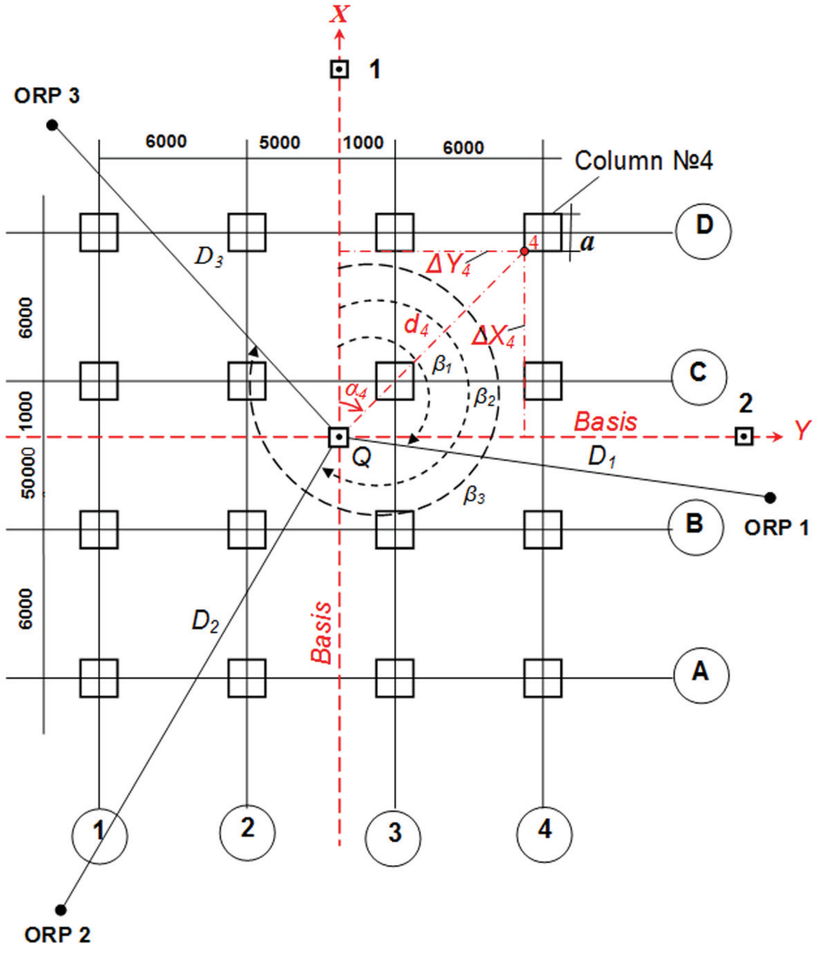


Fig. 5. *The planning of building structures in the coordinate system of the building (source: Kryachok and Vlasenko 2008).*

Since points 1 and 2 and the point fixing the point $Q$ can be destroyed during excavation work on the construction site, prismatic reflectors detached from the bar are installed outside the construction site on the surrounding structures, or retro reflective foil targets are glued, forming reference points (RPs) (Fig. 6). ORPs are located in a sector that should not exceed 150° (Mukovskii and Riabova 2019).

Coordination of the ORPs in performed using an electronic tacheometer installed at point $Q$ and oriented relative to the direction to point 1 using the measured horizontal angles $\beta_i$ and horizontal distances $D_i$ in the coordinate system of the structure (see Fig. 6). Neighboring ORPs are located in sectors that should not exceed 150° (Mukovskii and Riabova 2019).

Using the coordinates and marks of the ORPs as a starting point, if necessary, the planned and altitude position of auxiliary observation points is set by the method of spatial linear notation (Baran et al. 1986), which is convenient during the implementation of geodetic planning works at zero level and the arrangement of the pit (Nikonov 2013).

The planned position of the $Q$ point on the mounting horizons is determined by the method of vertical design through the zenith holes in the floors. Particularly effective is the use of laser devices for vertical design. Immediately after installing the device on the source horizon above the $Q$ point and turning it on, the visible projection of the $Q$ point is illuminated on a transparent plate on the mounting horizon.

To control the transmission of the planned point $Q$ over the laser spot, an electronic tacheometer is set to the operating position and a linear notch is performed on the ORPs, and its coordinates are determined. After that, the planning of the directly planned position of the building structures is performed according to the planning elements taken from the memory of the electronic tacheometer.

According to DBN (2010) for houses higher than 15 m, buildings and structures from 73.5 m to 100 m high the root mean square error (RMSE) transfer of points of the axes of the vertical must not exceed $(2+3\cdot H)$ mm, where $H$ is the difference in height of any two installation horizons expressed in hundreds of meters. For transfer of the planned position of point $Q$ to the assembly horizon 100 m relative to the output horizon, the specified RMSE is equal to 5 mm. To transfer the plan position of point $Q$ to the assembly horizon in this case, the vertical projection optical instrument PZL-100 can be used. The RMSE of transferring plan coordinates by this device is (in millimeters):

$$m_P = 0.27 + 0.0141 \cdot H\,, \tag{1}$$

where $H$ is the height of the vertical projection in meters. For $H = 100\,\mathrm{m}$ we have $m_P = 1.7\,\mathrm{mm}$.

According to Provorov's formula, RMSE of the point position for which the planned coordinates are determined by a linear intersection, can be determined as follows (Kryachok and Vlasenko 2008):

$$m_{LI} = m_S \sqrt{\frac{n}{\sum_{i=1}^{n} \sin^2 \gamma_i}} \tag{2}$$

where $\gamma_i$ is the central angle at a point $Q$ between the directions on the ORPs;

$n$ is number of a linear intersection directions, $n = 3$;

$m_S$ is RMSE of distance measurement.

For example, for distances to the ORPs 300 m, the RMSE of distance measurement by electronic tacheometers $m_S = 2\ \text{mm} + 2 \cdot 10^{-6} \cdot S = 2.6\ \text{mm}$, linear intersection angles $\gamma_1 = 145°12'53''$, $\gamma_2 = 101°58'43''$, $\gamma_3 = 112°48'24''$ we get the value $m_{LI} = 3.1\ \text{mm}$ according to formula (2). The values obtained by the formulas (1) and (2) do not exceed the specified standard value of 5 mm.

To transfer construction marks from the source to the mounting horizons, it is advisable to use a laser tape measure, which allows measuring the distance up to 100 m with an accuracy of 1 mm – 2 mm without a reflector.


Fig. 6. *Location of ORP 1 in the form of a retro reflective foil target on the facade of a high-rise building.*

To do this, in the vertical line of the zenith openings of the floorings at a relative mark of ±0.000 m of the initial horizon, it is necessary to equip a horizontal shelf, install a laser tape measure and measure the distance to the transparent plate installed above the zenith hole of the mounting horizon. A levelling rail is installed on the plate and with the help of a level, after determining the horizon of the device, either its position is applied to the building structure and the distance corresponding to the design mark of the structure is set down, or a levelling rail is used.

Construction of the horizontal plane of the floor slab, taking into account the size of the device is better to perform with a laser rotary level. Control of the transfer of elevations between the mounting horizons is carried out by an electronic tacheometer by trigonometric levelling with two face observations. Planning work must be performed in the morning, before the appearance of shock and vibration loads from mechanical means that are present on the construction site and while there are no temperature deformations of buildings (Kryachok and Vlasenko 2008, Mukovskii and Riabova 2019).

According to DBN (2010) for houses above 15 m, buildings and structures from 73.5 m to 100 m high the average RMSE of the transfer of marks by trigonometric leveling with an electronic tacheometer or handheld laser distance meter (also called electronic distance measurer or tape measure) should not exceed $(4+15\cdot H)$ mm, where $H$ is the difference of marks of any two installation horizons, expressed in hundreds of meter. For $H=100\,\text{m}$ the specified RMSE is 19 mm. The electronic tacheometer in this case must have a vertical angle measurement RMSE of 5", the distance measurement RMSE of both the electronic tacheometer and the laser distance meter is $m_S = 2\,\text{mm} + 2\cdot 10^{-6}\cdot S$, and the number of measurement receptions is 2 (DBN 2010).

Today, satellite technologies are widely used to create a geodetic basis on the prefabricated horizon in high-rise construction (Shults and Medvedskyi 2009). The basis for attracting satellite technologies was the fact that on January 1, 2020 in Ukraine new building codes came into force (DBN 2019), which apply to the design and construction of high-rise residential buildings up to 100 m and public buildings up to 150 m. It is clear that the implementation of the above-mentioned technologies using electronic tacheometers and landmarks in these cases becomes impossible due to the lack of a suitable structure on which to install ORPs, which are visible from the last installation horizons of the high-rise building.

The application of step-by-step transfer of planned coordinates to the upper mounting horizons using vertical design requires additional time for the transfer process and the planning of axes on the mounting horizon. The essence of the use of satellite technologies in general is reduced to the location of several GPS-receivers at the points of the external planning basis of the construction site (Fig. 7).

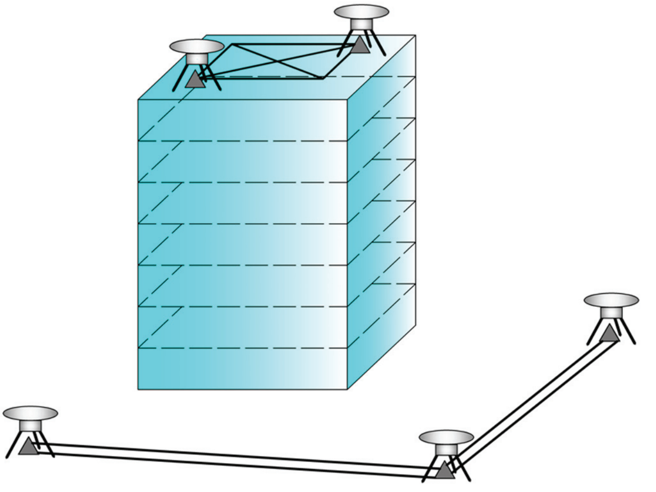

Fig. 7. *Before the transfer of coordinates to the mounting horizon using satellite technology (source: Shults and Medvedskyi 2009).*

In the differential mode, the coordinates of these points in the WGS-84 coordinate system are determined by the static method. Having these values and coordinates of points in the coordinate system of the site, the keys for the mutual transition of the coordinate systems are calculated. GPS receivers are installed both on the mounting horizon and the coordinates of reference points are determined in the mode of statics or fast statics (under favourable conditions) and achieve a plan accuracy of 5 mm, which meets the requirements of construction regulations (Shults and Medvedskyi 2009).

Next, an electronic tacheometer is installed above one of them, and a reflector is installed on the other, and the construction of buildings is planned according to their coordinates. It is possible to use an electronic tacheometer with a GPS receiver that is mounted directly to the tacheometer.

To improve the reception of signals from satellites, it is necessary to place GPS receivers on the roofs of surrounding high-rise buildings above the points whose coordinates are determined, for example, by the method of inverse angular notch from the points of the external planning basis (Shults and Medvedskyi 2009).

## 4. Conclusions and consequences of the research

The development of digital and information technologies, the elemental base of geodetic instruments contributes to the improvement of geodetic technologies and significantly expands the possibilities and horizons of application of geodetic science, especially for solving applied tasks.

Analysis of literature sources, production and regulatory framework of geodetic support for the construction of multi-storey buildings in Ukraine shows that the use of traditional geodetic technologies in modern conditions has certain disadvantages, namely:

- fixing on the ground of each of the axes with a pair of geodetic points on both sides of the building is almost impossible in a modern city, due to the limited space of the land provided for construction;
- part of the geodetic points is lost in the construction process due to the movement of various mechanisms on the construction site;
- planning of axes on assembly horizons requires additional time, which slows down the pace of construction work, in which modern technologies are used.

Electronic tacheometers are used to perform planning works. Thankfully to these high-tech devices it is possible to carry out planning of building designs without transferring axes of a construction on the site, thereby reducing the time for the performance of geodetic works, and consequently on the construction of objects.

To create a supporting base on the prefabricated horizons during the construction of buildings up to 150 m, it is proposed to use satellite technology with subsequent planning of building structures using electronic tacheometers.

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# Suvremene tehnologije geodetske podrške u planiranju radova u visokogradnji

*SAŽETAK. U radu se prikazuju nedostaci tradicionalnih tehnologija u ograničenom prostoru suvremenoga gradilišta na temelju istraživanja i analize literature, regulatorne i proizvodne osnove geodetske podrške u izgradnji višekatnih zgrada. Danas se elektronički tahimetri primjenjuju za provedbu radova u planiranju, što je omogućilo izvođenje planiranja građevinskih konstrukcija bez spuštanja građevnih osi objekta na tlo što je imalo pozitivan učinak na poštivanje rokova izgradnje. Prilikom uspostave potporne osnove na montažnim horizontima tijekom izgradnje zgrada visine do 150 m predlaže se primjena satelitske tehnologije s naknadnim planiranjem građevinskih konstrukcija primjenom elektroničkih tahimetara.*

*Ključne riječi: izvođenje osi građevine, montažni horizont, radovi u planiranju, elektronički tahimetar, orijentiri, GNSS tehnologija, visokogradnja.*

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