Precise Surveying Activities Using Easily Accessible Geodetic Tools and Methods

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Abstract

The publication draws attention to the possibilities of using some generally available geodetic tools and methods - classical and modern, for carrying out precise setting out works, during the construction process. Accordingly, the required accuracy of construction activities and the available geodetic equipment. In this case, a specific type of engineering facilities has been considered, with requirements for precision in fixing the structural elements - in plan, height and orientation of the construction axes. In this regard, the necessary accuracy for carrying out the setting-out work has been investigated. By applying geodetic linear resections and the orthogonal method, in combination with the use of navigation receivers - GNSS /Global Navigation Satellite Systems/, as well as coordinate-oriented satellite images. A method for preliminary assessment of accuracy is presented, when using specific geodetic methods and instruments, regarding construction tolerances. A reasoned conclusion is reached about the appropriateness of the chosen methods in the implementation of similar engineering and geodetic tasks - from the point of view of efficiency, logistical and economic factors. The proposed approach is supported by practical results from geodetic works on completed construction sites from the author's professional practice.

Keywords: *Engineering geodesy, Setting out, GNSS Measurements*

1. Introduction

In accordance with the author's previous publications on the subject [1, 2], a high level of precision in geodetic activities is required during the construction of some engineering facilities. This is achieved by simultaneously implementing the following accuracies [2] in the construction process, presented in Figure **1**.

- The orientation of the main construction axis, (*geodetic azimuth*) - $M_A \leq \pm\ 10'$; (M_A - *orientation's accuracy*);
- The acceptable error M_{dS} of the distances, between the fixed parts of the structure - $M_{dS} \leq \pm 5 \div 10mm$.
- The acceptable error of the levels - $M_H \leq \pm\ 2\text{-}5\ mm$.

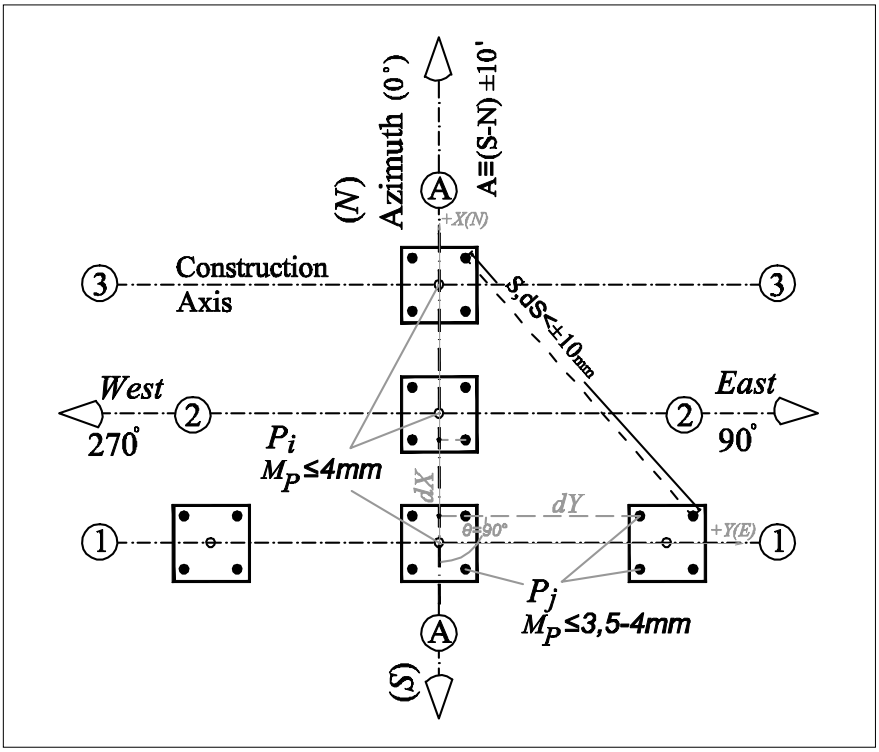

Fig 1. Scheme of the construction parts.

2. Geodetic Setting out Network (GSN)

The Geodetic Setting out Network's points (*GSN*) and the *Geodetic Setting out Activities* (*GSA*) ensure the fulfillment of construction requirements through a specific sequence of actions. The basic steps for completing this task, have already been discussed [2].

The Geodetic Setting out Activities (*GSA*) begin with a preliminary assessment of accuracy [6]. The construction tolerances in ***Azimuth*** (*orientation*), ***Position*** and ***Elevation*** are leading. This assessment has been extensively discussed in another publication of the author on the subject [1], and therefore only the main considerations and final conclusions will be given here.

First circumstance - the tolerance in the distance between two setting out points (P_J), must be observed – *DRMS (Distance Root-Mean-Square),* $M_{dS} \leq \pm 5$ *mm - averaged lower limit*

Second circumstance - the tolerance ($M_A \leq \pm\ 10''$) in the orientation of the main construction axis - *A-A* (**Fig. 1**), depends on the mutual position of the already fixed points [1, 2].

Based on the above considerations and using the data from the mentioned sources [1],
for **the acceptable error (*RMSE*) in the plan position** of a fixed point, it can be written:
→ $M_p \leq 3.5\text{- }4$ *mm* – the acceptable *RMSE* in the plan position.

Considering that this is an error, functionally dependent on the setting out operations and the *RMSE* of the geodetic, basic points (*GSN*), for the required accuracies, one can write (*equation 1*)

$$M_p = \sqrt{M_{GSN} + m_{\Sigma}} \rightarrow M_{GSN} = m_{\Sigma} \leq \frac{M_p}{\sqrt{2}} \leq 3mm \tag{1}$$

Under these circumstances, applying *the principle of equal influences*, for the value of the total error from the setting out operations ($\boldsymbol{m_{\Sigma}}$) and *RMSE* of the points from geodetic network ($\boldsymbol{M_{GSN}}$), one can write:

→ $M_{GSN} \leq 3mm$ - the acceptable *RMSE* in the absolute position of the points of the *GSN* in the projection plane.
→ $M_{\Sigma} \leq 3mm$ - the total, acceptable *RMSE* when performing planned, setting out operations.

3. Geodetic Setting out Activities (GSA) through precise GNSS determinations in combination with Orthogonal method

The method is suitable for the *GSA* for small-area objects localized in a compact area. In this particular case, the setting out in the planned position of building elements - *structural axes, steps of structural elements and centers of anchor bolts* have been studied. Attention will be paid to the permissible accuracies when performing the *GSA* - calculation and measurement of the setting-out elements.

In a previous publication of the author [2], an approach using *GNSS* and a polar-orthogonal method for setting-out was considered. Below, another variant of the setting-out method used by the author in practice will be presented, namely: an *orthogonal method with reduction of the abscissa axis*.

3.1 Geodetic Setting out Network - Precise GNSS measurements

After selecting suitable locations for the *GSN's* points and their stabilization, we move on to the main geodetic activity in this stage, namely:

- **Determination of the geodetic ellipsoidal coordinates (*B, L*) of the *GSN*'s points by *GNSS static* measurements and subsequent transformation to an appropriately selected projection's plane.**

In this approach, the emphasis is on implementing a transformation from geodetic ellipsoidal coordinates (*B, L*) obtained by direct GNSS, static measurements, to orthogonal coordinates in the plane projection (*x, y*). For this purpose, it is necessary to choose a suitable plane projection (*map projection*). Respectively, transition from a geographic (geodetic) Azimuth (*A*) to a Direction angle in the plane projection (*T*), with minimal loss of accuracy [4], (2).

$$c = A\text{-}T \tag{2}$$

In this case, the *meridian convergence* value - *C* is essential, which can be determined following [4].

According to the author's research [1], in order to maintain equality in the transformation of the angles, it is best to use a *Conformal projection*. As a result of the conformity of the image, the meridian convergence on the ellipsoid is equal to the meridian convergence in the plane ($A=A'$), ($T=T'$), where A', T' are the corresponding images of *A* and *T* in the projection's plane.

To set-out the structural elements in the height, it needs selecting the appropriate places for the base GNS benchmarks. The selection of these benchmarks complies with the geodetic project under the "*Grading Plan*" part. Attention should also be paid to proper *drainage* and the corresponding removal of the surface water [5].

3.2 Orthogonal method with reduction of the abscissa

This method is performed in two stages.

In the first stage, an operational axis "*abscissa*" has materialized, in a general position and near the site, by fixing two geodetic points, using two approaches:

A) by static GNSS determinations, in the coordinate system established above.

B) by Linear Intersections or orthogonal setting-out, from the geodetic points of GSN.

The reduction distances to one of the main construction axes (*in this case - oriented in the "North-South" direction*) are calculated – **Fig.1**. By setting out these distances (*Orthogonal method or Linear Intersections*), the desired construction axis is established on the terrain - *A≡(S-N).*

In the second stage – *Length-alignment method* the *orthogonal setting out* consist of measuring the *abscissa* (***∂X***), raising a right angle (***θ=90°***) and measuring the *ordinate* (***∂Y***) until reaching the design point ($\boldsymbol{P_i}$, $\boldsymbol{P_j}$).

- Initially, all project points that are located on this main construction axis (*A-A*) are fixed, using the determined abscissa distances - ***∂X*** .
- From this main (*abscissa*) axis and from the already fixed points along it, all other project points are fixed, using *orthogonal methods* or by *Linear Intersections*.
  If necessary, a new operational axis (*abscissa line*) has materialized, using offset (parallel) transfer.

When using this approach, there is no need to use a high-precision angle measuring instrument!

Due to the small distances in the *ordinates*, right angles (***θ***) can also be erected with a horizontal circle, which most levels are equipped with (with an accuracy *of ≈0.2 degrees)*. Or they can be erected with *construction right angles tools*, directly on the underlying concrete, when the *ordinates* are up to *2m*.

The preliminary assessment of the accuracy and tolerances for the different measurements is presented below.

It should be kept in mind that the accuracy for fixing the points (P_i , Pj) on the terrain also depends on the accuracy of the points from the *GSN and from the* accuracy of the two stages of setting out activities:

1st stage – *the total error* off the *linear Intersections* $(m^1{}_\Sigma)$ - for points (P_i)

2nd stage – *the total error* off the *orthogonal setting out activities* $(m^2{}_\Sigma)$ - for points (P_j)

The accuracy (*RMSE*) of the points (***M$_p$***), fixing in the plan position the ground, can be deduced from the following dependence

$$M_p = \sqrt{(M_{GSN})^2 + (m^1{}_\Sigma)^2 + (m^2{}_\Sigma)^2} \tag{3}$$

Under this circumstance (3), and applying *the principle of equal influences*, for the value of the total error from the setting out operations (***m***$_\Sigma$), one can write:

$$\rightarrow m^1{}_\Sigma = m^2{}_\Sigma = \frac{M_p}{\sqrt{3}} = \frac{4}{\sqrt{3}} \leq\approx 2.8mm \tag{4}$$

In the first stage - the acceptable *RMSE* (***m$_D$***) of the *linear Intersections distances* can be calculated by (5) , [2].

$$(m^1{}_\Sigma) = \sqrt{\left[\frac{m_{D1}^2 + m_{D2}^2}{(\sin\gamma)^2}\right]} \quad \rightarrow \quad m_D = \frac{m^1{}_\Sigma}{\sqrt{2}} \leq\approx 2mm \tag{5}$$

*To determine the RMSE (**m$_D$**) of the measured horizontal distances (D_1 , D_2), it is assumed that the linear Intersection is performed under the best possible geometrical conditions. An angle at the Intersection point $\gamma\approx 90^o$, respectively → $\sin\gamma \approx 1$, as well as the distances $D_1 \approx D_2$.*

In the second stage – the *orthogonal setting out activities* consist of measuring the *abscissa* (***∂X***), raising a right angle (***θ=90^o***) and measuring the *ordinate* (***∂Y***) until reaching the design point (***P$_i$***).

$$(m^2{}_\Sigma)^2 = \left[m_{dY}^2 + \left(\frac{m_\theta}{\rho} dX\right)^2 + m_{dX}^2\right] \leq 2.8mm \tag{6}$$

After applying the appropriate mathematical transformations developed in other publications on the subject [1, 2, 3] regarding the acceptable values of the surveying quantities, one can write **the conclusion**.

The conclusion: when using *Linear Intersections* with combination with *Orthogonal setting out* the errors for the measured elements, and *RMSE* of the *GSN* points (***M$_{GSN}$***), should not exceed the following values:

$M_{GSN} \leq\cong 3mm$ - *RMSE* of the position of *GSN* points.

$m_D \leq 2mm \rightarrow D \leq 30m$ - *D* are the horizontal distances to the Intersection point, measured by a ***Tape***;

$m_\theta \leq\approx 5' \rightarrow \partial Y \leq 5m$ - where, ***∂Y*** is the length of the ordinate.

$m_{dX} = m_{dY} \leq 1.5mm$ - *RMSE* of the measured lengths - the abscissa and the ordinate.

4. GSA using GNSS with navigational accuracy, in combination with Linear Intersections and Orthogonal method

The method is similar to the one described above, *with some significant differences in the first part of the Geodetic Setting-out Activities (GSA)*, namely - creating a *GSN / Geodetic Setting-out Activities /*.

A case for planned *Setting-out* of compactly located structural elements is considered, with the implementation of two options for the orientation of the *GSN* coordinate system:

- Orientation of the *GSN*, using coordinate geo-referenced, satellite images.

- Orientation of the *GSN*, using a GNSS receiver with navigational accuracy.

The *GSN* usually consists of a minimum of two permanently stabilized points located near the site. It is appropriate that at least two of them are selected in an axis that is approximately parallel to the main construction axis of the site. The definition and orientation of the *GSN* in a suitably chosen coordinate projection system, as mentioned above, can be done in two ways:

4.1 Orientation of the GSN, using situational elements near the site with coordinated geo-referenced satellite images.

If a satellite image is available in the area of the site (*e.g. Google Earth*), clearly visible situational elements are used to geo-reference the image in an appropriate coordinate system. The necessary and sufficient accuracy for determining the coordinates of the points used for image transformation is in the order of *1m ÷ 3m*, depending on the distance between them. For plan transformation, at least *2/two/* clearly visible points from the image are required, for example, corners of a building or curbs/axis lines of a street/road or alley network in the area of the site. It is most appropriate to use such situational elements that will subsequently be easily deciphered on the site. Since they will be the reference lines for stabilizing the points from the GSN.

A. Defining a coordinating system

In the image below (**Figure 2**) a clearly visible axis line from a street was used for transformation – *1 ÷ 5* (N_i) - *points at the beginning, middle (bend in the axis) and end of the axis*. The distances between the points are $S_{1\text{-}2} \approx 250m$ and $S_{3\text{-}5} \approx 500m$, respectively. Their geographical coordinates are known, extracted from *Google Earth*, with absolute position accuracy up to *~0.02''* (*corresponding to* $M_i \approx < \pm$ *0.5-7m in metric measure*). With these initial data, the *RMSE* in the mutual position of the points - M_S *(dS)* will be within ≈ *±1m*, (*7*).

$$M_S \equiv \sqrt{(M_i)^2 + (M_{i+1})^2} = \sqrt{2(M_i)^2} \rightarrow M_S = \sqrt{2} M_P \cong \pm 1m \qquad (7)$$

Accordingly, the *RMSE* in the orientation (*azimuth*) of the axis between points *3-5* ($A_{3\text{-}5}$) will be equal to *±5-7 min,* according to the dependence below (8), which in the specific case of technical specifications ($M_A \leq \pm$ *10'*) is sufficient accuracy for the orientation of the main construction axis of the design facility.

In the case of an error in the mutual position between N_i and N_{i+1} → $dS \equiv M_S \approx \pm$ *1m* and distances $S \equiv S_{i,\,i+1} \approx 500m$ the error in the *Direction angle* (M_T) will be calculated according to the lower dependence (8) , [1] .

$$dA \equiv dT'' = \frac{dS}{S}\rho'' \quad , \qquad \rho'' = \frac{180^o}{\pi} \rightarrow \rho'' = 206265'' \qquad (8)$$

According to *formula (8)*, it follows → $dT \equiv M_T < 7'$, which is practically a small value of the error in *T* (*A*), given the set tolerance of $M_A \leq \pm 10'$ in section 1.

→ *respectively for* $dS \equiv M_S \approx \pm$ *3m* → $S \equiv S_{i,\,i+1} \approx$ *1 000m it follows* → $dT \equiv M_T \equiv M_A < 10'$

Fig 2. Scheme of the orientation points.

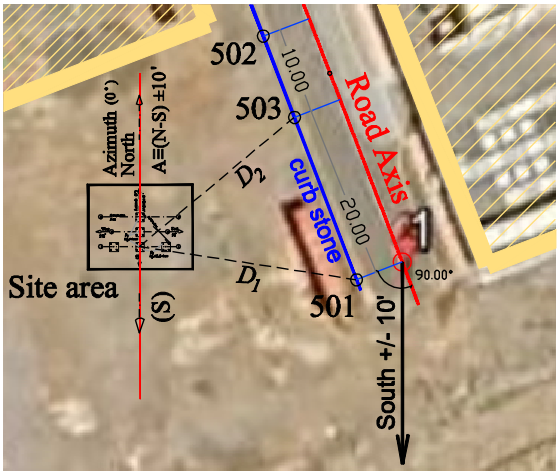

Fig. 3. Scheme of the site and *GSN* points.

As mentioned above (section 3.1), to eliminate the value of the meridian convergence, it is necessary to transform the geodetic, ellipsoidal coordinates of the points into a pre-selected projection plane, *e.g. UTM* with a local (*prime*) Meridian near the object - L_0. In this case, the direction angles (*T*) in the projection plane will be equal to the geodetic azimuth (*A*) , [1].

In this way, an orthogonal coordinate system is defined, with the orientation of the axes (*X-Y*) parallel to the geographic directions (*N–E*), with an accuracy of *±7 minutes* in the specific example.

B. Stabilization of the points of GSN, in the defined coordinate system

In order to materialize the *GSN* of the site area in the same coordinate system, it is necessary to stabilize at least two geodetic points, according to the principal diagram shown below (Fig. 3). In the example shown - one of the points (*501*) is stabilized in the middle of the curb line, clearly visible on the satellite image, and parallel to the axis (*1-2*) perpendicular to the axis along which the coordinate system (*3-5*) is defined.

The second point (*502*) is stabilized in the same curb line, at a pre-selected distance from *501* (*for example 20m or 30m*). The distance should be fixed up to *30 meters*, so that it can be measured easily and quickly, even with a tape measure, and with an accuracy of *±1-2 mm*.

The coordinates (*X,Y*) of point *501* can be selected in multiples of *100* or *1000 meters*, thus translating the origin of the already defined independent (*local*) coordinate system for the site. Accordingly, the coordinates of the points on this line (*502, 503*, ….) are calculated by the first basic geodetic task, with the measured distance $S_{501\text{-}2,3}$ and the *Direction angle* $A_{1\text{-}2}$ - a function of the angle enclosed by the positive direction of the *X(N)* axis and the axis/border line of the satellite image, in the above-defined orthogonal coordinate system.

This angle ($A_{1\text{-}2}$) can be calculated or directly measured in the drawing model of the geo-referenced image (**Fig. 3**). The calculated coordinates of points *502, 503* from the GSN with this approach will have an absolute *RMSE* in the position $M_{Pi} \leq \pm 3\ mm$, (9).

$$M_{503} = \sqrt{\left[m_{501}^2 + \left(\frac{m_R}{\rho} S_{501\text{–}503} \right)^2 + m_S^2 \right]} \leq 3мм \qquad (9)$$

- where $m_{501} \equiv 0mm$, $m_R \approx 0^{''}$; $S_{501\text{–}503} = 20m$; $m_S = 2mm$; $\rho^{''} = 206265^{''}$

To coordinate additional points outside this line, a polar method can be used, by measuring the angle and distance in the direction of this point, with acceptable values for the measured quantities as shown below:

- where $m_\beta \leq 10^{''} = \approx 30^{cc}$ $\rightarrow$ $m_R \leq 7^{''} = \approx 20^{cc}$; $S_{P1,i} \leq 30m$; $m_S \leq 2mm$;

According to the scheme described above, we already have two or more points from the *GSN*, stabilized on the ground, near the site and defining a coordinate system, oriented in the *North (N/X)-East (E/Y)* direction, with an accuracy of $M_A \leq \pm\ 7'$ *(±7 minutes).*

4.2 Orientation of the GSN, by using a GNSS receiver with navigational accuracy.

In this case, the principle of operation is the same as in the previous article (*4.1*), but in reverse order.

A. Stabilization of the GSN points of the site area

First, two points of the *GSN* (*points 1, 2*) are stabilized near the site - usually in a line approximately parallel to one of the main construction axes of the project facility. The distance between the points is recommended to be ≈*500-600 m*. The coordinates are measured by a *GNSS* receiver with a navigational accuracy of ±*0.03''*(*0.03 seconds ≈ 1m along the meridian*).
In this hypothesis, the *RMSE* in the orientation will be up to ±*10'* (±*10 minutes*), according to (8).

B. Defining a coordinate system

The geodetic ellipsoid coordinates are transformed into orthogonal (*planar coordinate system*), with the selection of a prime meridian near the site, as mentioned above.

The approach is then like that described in the previous case – along the line *1-2*, a point (3) is selected at a distance of up to *30 meters* from point *1*. The distance ($S_{1\text{-}3}$) is measured with an accuracy of ±*2 mm*. The coordinates of point *3* are calculated according to the first basic geodetic task, with the measured distance $S_{1\text{-}3}$ and the indicated angle - $A_{1\text{-}2.}$ Point *1* gives the origin, and the direction *1-2* defines the orientation of the coordinate system thus determined. The calculated coordinates of point *3* and all additional points of the *GSN* in this approach will be with the *RMSE* in the position $M_P \leq \pm 3\ mm$, in the coordinate system thus created and in accordance with the preliminary accuracy assessment - 4.1.B, (9).

After defining the coordinate system of the *GSN*, the following setting-out operations are performed by combining *Linear Intersections* and the *Orthogonal method*, according to the scheme described above (section 3.2).

5. Conclusion

Through the approaches presented above, a reasoned conclusion is reached that in certain cases of construction practice it is expedient to use accessible and easy-to-apply classical, geodetic methods. In combination with some widely known modern technologies and tools, a result can be reached that fully satisfies the technical specifications for precise fixing of the building elements. The proposed methods are supported theoretically, by the preliminary assessment of accuracy, as well as by practical research.

A comparison was made between a method involving the application of precise and expensive *GNSS* equipment (*case 1*), discussed in another publication by the author [2] and used as a reference (comparative). And the method performed according to the methodology described in this article – *without precise GNSS* measurements, but by orientation of the coordinate system using satellite images (*case 2*).

In both methods, no precise geodetic equipment for measuring angles and distances (*e.g., a total station*) was used. Only inexpensive and easily accessible instruments were used, such as - *a tape measure, an optical geodetic level with technical accuracy, and construction right angles*.

The methods described in the publication theoretically provide the necessary accuracy for the setting out works. This is also confirmed by practical results achieved by the author on real sites.

The practically achieved accuracy levels are presented below:

(First case)

1. **Setting out in plan** - *GNSS* in combination with *Orthogonal method* and *Linear intersections*:
   Setting-out of the levels - *Geometric leveling*
   Practically achieved accuracy from control measurements after execution of rough construction (*setting out the centers of anchor bolts - 2 /two/ sites in different geographical locations*):
   - $M_A \approx \pm\ 4'\ 30''$; $M_{dS} \leq \pm\ 5\ mm$; $M_{dH} \leq \pm\ 2\ mm$ [2]

(Second case)

2. **Setting out in plan** – Satellite images for azimuth orientation (4.1)
   in combination with *Orthogonal method*/*Length-alignment method*
   and *Linear intersections*

   Setting-out of the levels - *Geometric leveling*

   Practically achieved accuracy from control measurements after execution of rough construction (*setting out the centers of anchor bolts - 2 /two/ sites in different geographical locations*):

   - $M_A \approx \pm 7'$; $M_{dS} \leq \pm 5$ *mm* ; $M_{dH} \leq \pm 2$ *mm*

From the theoretical research and the practical results achieved, it can be concluded that both presented methods (*cases 1 and 2*), provide the necessary accuracy of execution. At the same time, the combination of methods described in Example/Case 2 is much easier and more accessible to implement in terms of the necessary geodetic instruments.

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