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Original scientific paper

# Impact of Vial Bubble on the Accuracy of Positions in the GNSS-RTK Mode

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**Abstract:** The use of the GNSS devices in the RTK mode involves taking a vertical position using a circular spirit vial bubble located on the rod. Since the market of geodetic instruments, accessories and software is growing, the authors of this paper performed measurements with the GNSS devices in the RTK mode to determine and demonstrate the impact of the position of the central vial bubble (level) on coordinate accuracy. Measurements were performed on the same rod in the RTK permanent stations network. Instruments of different manufacturers and generations were used in the experiment. Newer generations of the GNSS devices are equipped with special sensors for measuring the inclination of the receiver and eliminating this error. Devices that do not have a sensor give measuring coordinates that are loaded with error. The error is random and cannot be measured. The subject of the analysis of this paper is the magnitude and impact of the error caused by the non-verticality of the rod on which the GNSS-RTK antenna is mounted. The authors experimentally determined that the bubble of the central level has the influence on the accuracy of the position, made conclusions and recommendations for reducing or eliminating the error of non-verticality of the pole.

**Keywords:** GNSS; pole; position accuracy; vial bubble

## 1 INTRODUCTION

Technological advances improve geodetic criteria and introduce new functions and properties. The vial bubble is an integral part of geodetic instruments and accessories. Regardless of the construction and shape of the spirit vial bubble, it is used as a device for bringing planes or straight lines to the desired position.

In geodetic instruments and accessories, horizontal and vertical positions are considered. Vials can be classic and electronic. Classic vials are categorized into circular (bull's-eye) and tubular. Circular spirit vials are used to approximate the desired position.

The tubular spirit vial bubble occupies a definite position, i.e. the position before the start of the measurement activity itself. The role and importance of the central vial bubble in geodetic instruments and accessories have been insufficiently analyzed in the part related to the accuracy of measurements. The reason for that is the fact that the desired position is completely occupied and controlled by the tubular spirit vial bubble.

After the measurement procedure is completed, the measured quantities are processed and the coordinates are calculated. The job of a surveyor is to constantly monitor the equipment and accessories used, improve measurement methods and techniques, and point out possible sources of error to reduce or eliminate them.

In geodetic positioning, it is of the utmost importance to determine the coordinates of points with a high degree of accuracy. This is important for geodetic bases, for monitoring facilities under construction and over the period of exploitation, for monitoring landslides, etc. Under the law of error propagation [9], the accuracy of the coordinates is directly related to the errors of the measured quantities. The errors that are analyzed are random and systematic.

## 2 VIAL BUBBLE

A tubular spirit vial bubble is a processed glass tube with a curved shape and filled with liquid. The liquid is poured into the processed glass tube and a small airless space is left, which represents the bubble of the spirit vial bubble. To protect the glass tube from damage, the spirit vial bubble is placed in a metal frame and fastened to the instrument. To assess the position of the bubble in the spirit vial bubble on the outer side of the glass tube, a marking was made. The marking is expressed in parse, the value of one parse is equal to 2,00 mm. The inner side of the spirit vial bubble is a circular arc of radius *R*. The point in the middle of the circular arc of the spirit vial bubble is called the normal point of the spirit vial bubble (*N*). The radius of the spirit vial bubble, which passes through the normal point, is called the principal radius (*R*). The tangent of a circular arc, which passes through a normal point (standing perpendicular to the principal radius), is called the principal tangent or horizontal axis of the spirit vial bubble.

At the moment when the centre of the bubble of the spirit vial bubble coincides with the normal point, the main tangent-axis of the spirit vial bubble is horizontal, the main radius is vertical and then the bubble of the spirit vial bubble is centered.

The Circular spirit vial bubble is made of a wider cylindrical glass tube whose upper inner part is shaped as a spherical dome. The liquid is poured into the treated tube and a small airless space is left - the bubble of the spirit vial bubble. The circular vial bubble is housed in a cylindrical aluminium or steel housing. A circle of appropriate diameter is engraved around the zero point of the spirit vial bubble. The diameter of the engraved circle is larger than the diameter corresponding to the vial bubble, Fig. 1.

The basic characteristics of the spirit vial bubble are sensitivity and precision [6].

The sensitivity of the spirit vial bubble is defined as the central angle corresponding to the arc of one pars, that is, the angular value of one pars, (Fig. 2), expressed in seconds:

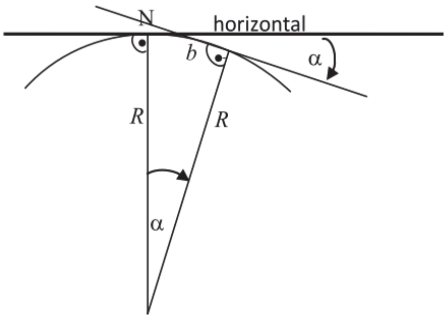
$$\alpha = \frac{b}{R}\ ;\ \alpha'' = \_''\,\frac{b}{R} \tag{1}$$

where:
$R$ - vial bubble radius in m;
$b$ = 2 mm - division grade value;
$\rho''$ = 206265"

**Figure 1** Tubular and circular vials

The sensitivity of the spirit vial bubble determines the purpose of the spirit vial bubble, the larger the radius of the spirit vial bubble, the greater its sensitivity. The dependence of the sensitivity of the spirit vial bubble on the radius can be seen in Fig. 2.

Precision can be defined as the accuracy of the vial bubble. The main difference between tubular and circular vials is in the sensitivity, i.e. the accuracy of the vial bubble. Tubular spirit vials have a higher sensitivity, i.e. a lower angular value so that they achieve greater accuracy in bringing the axis of the spirit level to a horizontal position. This is not the case with circular spirit vials the sensitivity of these spirit vials is measured in minutes and that is why they are used to bring them approximately to the desired position.



| $R$ / m | 20 | 40 | 60 | 80 |
|---|---|---|---|---|
| $\alpha$ / " | 21 | 10 | 7 | 5 |

**Figure 2** The sensitivity of the spirit vial bubble [7]

The Wild T3 theodolite, with horizontal angle measurement accuracy of ±0,5", uses a spirit vial bubble with the sensitivity of 7", while theodolites with horizontal angle accuracy of ±6", use a spirit vial bubble with sensitivity of up to 40".

## 3 GNSS-RTK POSITIONING

Geodetic GNSS-RTK positioning is based on the principle of obtaining real-time coordinates in the Base & Rover system or the permanent stations network [10, 11]. Equipment that supports the RTK provides the ability to directly read coordinates and data for monitoring and control of measurements. Before the start of the measurement, the antenna of the mobile receiver is centred. Centring is done with a rod, maximum height up to 2 m, or optical visor on a tripod. Coordinates are expressed in the Cartesian coordinates ($X$, $Y$, $Z$), the coordinate system on the ellipsoid ($B$, $L$, $h$) [8] and the coordinate system in the projection plane ($y$, $x$) [5]. The positioning accuracy in the RTK mode is defined by the standard deviation for horizontal and vertical positioning by the manufacturer. The GNSS-RTK coordinates are directly related to the position of the electronic phase centre of the antenna, the $\vec{\mathrm{P}}$ vector.

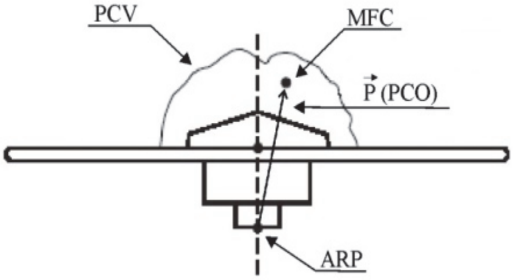


**Figure 3** Position and phase centre variance of the GNSS antenna [2]

"The electronic phase center of an antenna is a virtual point, where all the measurements derived from GNSS signals are referenced. The phase center can be divided into two components, the displacement of the phase center (PCO), which consists of a vector originating on the ARP and Mean phase center extremity (MFC), along with the Phase Center Variation (PCV), which is dependent upon the signal incidence angle. Fig. 3. illustrates the position of the $\vec{\mathrm{P}}$ vector (PCO), MFC, as well as the PCV" [2].

Measuring at a point means placing the rod in a vertical position. The software that comes with the receiver calculates the height of the rod and the $\vec{\mathrm{P}}$ vector for the GNSS-RTK antenna used for measurement. The GNSS RTK receiver placed on the centering pole is brought to the vertical position using a circular spirit vial bubble. The circular vials on the rod have sensitivity of the order of 15' to 20'. Unfortunately, rod manufacturers rarely provide data on the built-in spirit vial bubble, more precisely the information on the accuracy of the spirit level. The spirit vial bubble limits the productivity, accuracy, and application of the GNSS-RTK in high precision positioning. The use of spirit levels that have not been tested and rectified can cause the receiver to deviate from the vertical and has a direct impact on positioning accuracy.

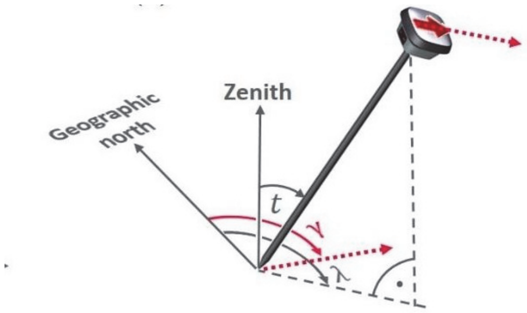


**Figure 4** Compensation of pole tilt based on attitude determination [3]

Also, holding the rod in a vertical position is encumbered by human errors. It is not always possible to hold the rod in vertical positions, for example when measuring the angles of a building. Newer generations of the GNSS-RTK devices are equipped with special sensors for measuring the inclination of the receiver, i.e. deviations from the vertical. The role of the sensor is to determine the slope and eliminate the error by correcting it. Assuming that the length of the rod is known, the position error due to its inclination can be compensated by precisely determining the position of the rod, Fig. 4, where: $t$ - inclination; $\lambda$ - direction of inclination and $\gamma$ - direction of sensor [3].

However, the market is still dominated by the use of receivers that do not have a built-in sensor and when measuring give coordinates that are loaded with the error of non-verticality of the rod. The error is random and cannot be eliminated from the measurement.

## 4 RESEARCH OBJECTIVE AND METHODS

The objective of this research is to examine the impact of using "no-name" spirit vials and the importance of bringing the spirit level to the centre of the marked circle. The research was conducted in two phases.

In the first phase, the GNSS-RTK devices were tested according to the procedure described in the ISO 17123-8: 2014 standard, Clauses 6 "Full test procedure".

In the second phase of the experiment, the impact of the position of the bubble of the circular vial bubble on the accuracy of the coordinates was analyzed.

### 4.1 Testing the GNSS-RTK Device under the Standard Method

Verification of metrological characteristics for horzontal and vertical positioning of the GNSS-RTK was performed in an especially realized test site (Fig. 5)

**Figure 5** Layout of points in the polygon

The realization of the polygon included:

- reconnaissance and stabilization of detail points;
- measurements: zenith angles, length, temperature, pressure, instrument height, and signal height;
- calculation and determination of the standard value of length.

The instructions from the document ISO 17123-8: 2014 were followed during the reconnaissance of the polygon. The site for stabilization of detail points was chosen to simultaneously ensure the durability of the benchmark and the suitability for measurement using GNSS-RTK devices. The durability of the benchmark is ensured by choosing a place that is not subject to significant shifting. Stabilization was performed with geodetic-type bolt rods.

Measurements in the polygon are planned so that for detailed points it is possible to determine the horizontal distance. Before the measurement beginning, the optical pendulums have been tested on the total station and vision prism. Horizontal distance has been determined using the Leica Wild TCA1800 total station (Fig. 5), with a valid calibration certificate. The height of the instrument and the height of the prism were measured with a measuring tape. External temperature and pressure were downloaded from the website https://www.accuweather.com for the day: February 29, 2020. The zenith angles were measured in two positions of the ocular at the same time the lengths were measured. The measurement was performed backward and forward.

For the standard-nominal value of the length, the mean from the backward-and-forward measurements was adopted.

Calibration and testing of metrological characteristics of the GNSS-RTK receivers were performed in the realized polygon (Fig. 6).

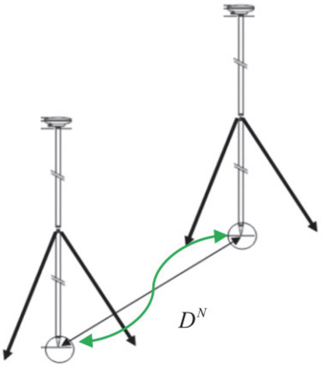


**Figure 6** Polygon

The equipment for calibrating GNSS-RTK receivers according to the standard method consists of: a mobile bipod (Thumb Release Bipod for Surveying) and a carbon rod for GNSS with a circular spirit level (Carbon Fiber GNSS Rover Rod). Before the beginning of the measurement, the GNSS receiver is being centred using a mobile bipod on a 2 m high pole. Measurements are performed at different time intervals and are used to estimate measurement uncertainty and perform statistical testing.

The series of measurements consists of five measurements at points 1 and 2 which are performed at intervals of five minutes. It takes about 30 minutes to realize one series of measurements, i.e. to determine the rectangular coordinates of points 1 and 2. The complete test procedure in the "Full test procedure" consists of 3 series and lasts about 90 min. From certain rectangular coordinates for each set of GNSS-RTK measurements ($j$ = 1, ..., 5) in the series ($i$ = 1, ..., 3) the length is calculated:

$$D_{i,j}^{GNSS}=\sqrt{\left(x_{i,j,2}-x_{i,j,1}\right)^{2}+\left(y_{i,j,2}-y_{i,j,1}\right)^{2}} \tag{2}$$

Statistical testing involves the formation of mean value:

$$\bar{D}^{GNSS} = \frac{1}{15}\sum_{i=1}^{3}\sum_{j=1}^{5} D_{i,j}^{GNSS} \tag{3}$$

and calculating deviations from the nominal value and standard deviations as follows:

$$\Delta_{i,j}^{GNSS} = D_{i,j}^{GNSS} - D^{N} \tag{4}$$

$$\sigma_{D^{GNSS}} = \sqrt{\frac{\sum\left(\bar{D}^{GNSS} - D_{i,j}^{GNSS}\right)}{n\cdot\left(n-1\right)}},\ n = 15 \tag{5}$$

### 4.2 Impact of Circular Spirit Vial Bubble Position on Coordinate Accuracy

When the calibration of the GNSS-RTK was completed according to the procedure described in the ISO 17123-8: 2014 standard and thus confirmed the metrological characteristics of the receiver for the RTK positioning, we proceeded to determine the impact of the vial bubble on coordinate accuracy.

The measuring equipment consists of: a mobile bipod (Thumb Release Bipod for Surveying) and a carbon rod, for GNSS with a circular spirit vial bubble of 20' (Carbon Fiber GNSS Rover Rod). The measurement is performed in the same polygon (Fig. 6) at a single point.

Before the start of the measurement, the GNSS receiver with a movable bipod is centred on a 2 m high rod. Centring involves bringing the centre of the spirit vial bubble to the centre of the circle "position *c*", Fig. 6. In this position, the first series of observations is realized. Afterward, the rod is tilted and the compass is used to shift the vial bubble towards the North, "position *N*" and the second series of observations is being realized. Then the rod is being tilted to the other side and the spirit vial bubble to tangent the second point, to the South, "Position *S*". The third position is "Position *E*" to the East and the fourth to the West, "Position *W*" (Fig. 7).

Observations were made in 10 series with a registration period of 30 s and an interval of 1 s.

For each receiver, the "position *c*" was repeated after the "position *W*", as a control and to determine whether the change in satellite constellation affected the coordinates.

Measurements using the GNSS receivers were performed without prior planning but following the available time. The whole experiment was realized over a period of 5 months. Five receivers participated in the experiment, some of which had a built-in verticality sensor, but it was turned off at the time of measurement.


"Position *c*" "Position *N*" "Position *S*" "Position *E*" "Position *W*"

**Figure 7** Positions used for registering coordinates

For each boundary position of the spirit vial bubblebubble, i.e. when the spirit vial bubble touches the spirit level circle, differences are calculated concerning the position when the spirit level peaks, i.e. when it is in the centre of the circle - "Position *c*". The differences are calculated for the coordinates in the projection in the direction and by the formula:

$$\begin{aligned}\Delta_i\left(x\right) &= x_i - x_c\\ \Delta_i\left(y\right) &= y_i - y_c\end{aligned} \tag{6}$$

where:
$i = N, S, E, W$ - measurement series;
$(x_c\ ,\ y_c)$ - position in the center of vial bubble;
$(x_i\ ,\ y_i)$ - positions per series.

To test the significance of coordinate differences, standard errors of means in the individual series were calculated according to the formula:

$$\begin{aligned}\sigma_{x_i} &= \sqrt{\frac{\sum\left(\bar{x} - x_j\right)}{n\cdot\left(n-1\right)}};\ j = 1,\ ...,\ 5;\ n = 10\\ \sigma_{y_i} &= \sqrt{\frac{\sum\left(\bar{y} - y_j\right)}{n\cdot\left(n-1\right)}};\ j = 1,\ ...,\ 5;\ n = 10\end{aligned} \tag{7}$$

where:
$\bar{x}, \bar{y}$ - means of coordinates from all series in the appropriate position, and
$x_j, y_j$ - measured value in the individual measurement series.

Based on these mean errors, the standard errors of the direction differences were calculated according to the formula:

$$\begin{aligned}\sigma_{\Delta_x} &= \sqrt{\sigma_{x_i}^2 + \sigma_{x_c}^2}\\ \sigma_{\Delta_y} &= \sqrt{\sigma_{y_i}^2 + \sigma_{y_c}^2}\end{aligned} \tag{8}$$

and for the limit of the difference its double value is adopted:

$$\Delta_{\text{gran}} = 2\cdot\sigma_{\Delta} \tag{9}$$

The total linear deviation of each position was calculated using the formula:

$$f_{d_i} = \sqrt{\left(\Delta_i\left(x\right)\right)^2 + \left(\Delta_i\left(y\right)\right)^2},\ i = N, S, E, W \tag{10}$$

## 5 RESEARCH RESULTS

The receivers used are of the geodetic type and have all the necessary characteristics to be used in the permanent stations network. For the research, 5 GNSS-RTK receivers were used, whose declared accuracy for the horizontal position in the RTK mode is shown in Tab. 1. For all receivers, calibration was previously performed according to the procedure provided by the [4] chapter 4.1 and as a result, the deviation of the length from the reference value was determined Tab. 1.

**Table 1** Equipment used

| Receiver/ Software | Horizontal / vertical | ( $\Delta_{i,j}^{GNSS} \pm \sigma_{D^{GNSS}}$ ) |
|---|---|---|
| Trimble R8s<br>TrimbleAccess | (10+1ppm) mm<br>(20+1ppm) mm | (−0,15 ± 0,95) mm |
| Topcon HiPer SR<br>TopSutv | (10+1ppm) mm<br>(15+1ppm) mm | (0,90 ± 1,30) mm |
| Ruide R93i<br>Carlson SurvCE | (8+1ppm) mm<br>(15+1ppm) mm | (1,93 ± 1,54) mm |
| Topcon HiPer Pro - 2<br>Magnet Fild | (10+1ppm) mm<br>(15+1ppm) mm | (−0,98 ± 1,10) mm |
| Topcon HiPer SR<br>Magnet Fild | (10+1ppm) mm<br>(15+1ppm) mm | (−2,00 ± 2,61) mm |

Tab. 1 implies that the GNSS receivers meet the accuracy of horizontal positioning, which is prescribed by the manufacturer.

After the completion of the verification of metrological characteristics in the system of the permanent stations network of the Republic of Serbia, AGROS-RTK service [1], the measurement of coordinates was started according to the procedure described in section 4.2. The characteristic values of the differences in the projection coordinates for the series of measurements, as well as their limits $\Delta_{granx}$, $\Delta_{grany}$, are shown in Tab. 2.

**Table 2** Deviation of coordinates against the vial bubble centre in mm

| Value | *N-c* | *S-c* | *E-c* | *W-c* |
|---|---|---|---|---|
| Trimble R8s | | | | |
| *x-axis* | −11,80 | 9,40 | 10,20 | −8,60 |
| $\Delta_{granx}$ | 0,75 | 1,39 | 1,83 | 0,85 |
| *y-axis* | −5,20 | 6,20 | −13,80 | 7,80 |
| $\Delta_{grany}$ | 0,98 | 1,60 | 0,75 | 0,98 |
| Topcon HiPer SR | | | | |
| *x-axis* | −3,80 | 9,80 | 10,80 | 4,10 |
| $\Delta_{granx}$ | 1,92 | 3,16 | 2,68 | 1,98 |
| *y-axis* | −7,00 | 1,80 | −8,00 | 5,30 |
| $\Delta_{grany}$ | 0,85 | 0,98 | 1,06 | 1,25 |
| Ruide R93i | | | | |
| *x-axis* | −13,72 | 8,96 | 8,86 | −4,04 |
| $\Delta_{granx}$ | 1,47 | 1,33 | 1,25 | 1,24 |
| *y-axis* | −7,42 | 1,82 | −15,38 | 4,98 |
| $\Delta_{grany}$ | 0,61 | 1,36 | 0,72 | 0,59 |
| Topcon HiPer Pro - 2 | | | | |
| *x-axis* | −4,58 | 6,26 | 4,29 | 5,35 |
| $\Delta_{granx}$ | 2,23 | 1,63 | 2,06 | 2,28 |
| *y-axis* | −7,15 | −2,78 | **−18,38** | −10,33 |
| $\Delta_{grany}$ | 2,03 | 1,53 | 1,98 | 1,53 |
| Topcon HiPer SR | | | | |
| *x-axis* | −5,60 | 11,96 | **16,56** | 11,24 |
| $\Delta_{granx}$ | 3,44 | 4,25 | 4,07 | 3,80 |
| *y-axis* | 4,97 | 11,61 | −2,97 | 18,12 |
| $\Delta_{grany}$ | 3,28 | 4,52 | 2,94 | 3,27 |

## 6 DISCUSSION AND CONCLUSIONS

The experiment was realized after calibration of GNSS receivers over a period of 5 months (due to the use of different types of receivers). Tab. 1, which provides data from calibration, yields the conclusion that the differences in measured lengths between points 1 and 2 are less than their double errors of determination and are much less than the declared accuracy. The reason is that the receivers are re-centred at each measurement (the spirit vial bubble is brought to the peak position). The centring error is a random variable and therefore the errors of the length are random.

Measurements for the experiment in each position lasted up to 10 minutes. All required measurements per receiver were completed within 60 minutes. The measurements were carried out according to the manufacturer's instructions and the rules prescribed by the Republic Geodetic Authority for Connection and Use of the Active Geodetic Basis of the Republic of Serbia.

**Table 3** Linear deviation for each position in mm

| Value | $N-c$ | $S-c$ | $E-c$ | $W-c$ |
|---|---|---|---|---|
| Trimble R8s | | | | |
| $f_{d_i}$ | 12,9 | 11,3 | 17,2 | 11,6 |
| Topcon HiPer SR | | | | |
| $f_{d_i}$ | 8,0 | 10,0 | 13,4 | 6,7 |
| Ruide R93i | | | | |
| $f_{d_i}$ | 15,6 | 9,1 | 17,7 | 6,4 |
| Topcon HiPer Pro - 2 | | | | |
| $f_{d_i}$ | 8,5 | 6,8 | 18,9 | 11,6 |
| Topcon HiPer SR | | | | |
| $f_{d_i}$ | 7,5 | 16,7 | 16,8 | **21,3** |

After processing the measurement results and calculating the definite coordinates for each bubble position, the differences of the coordinates in the projection in the directions $x, y$ were calculated, Tab. 2. Analyzing the results has determined that the coordinates between the epochs differ significantly. The maximum deviation in the *x*-axis direction is 16,56 mm. The maximum deviation in the *y*-axis direction is 18,38 mm. These maximum values are outside the declared accuracy limits. The total linear deviation was calculated for each position, Tab. 3. The maximum linear deviation is 21,3 mm. A review of the values from Tab. 3 yields the conclusion that the position of the vial bubble bubble has a dominant role.

Some further analysis should be planned for the GNSS-RTK receivers that contain a sensor for measuring the inclination of the receiver, i.e. deviations from the vertical. The sensors can determine the inclination of the receiver and eliminate the error [3]. The use of "no-name" vials that have not been tested and rectified has a direct impact on the accuracy of horizontal positioning.

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