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PLANNING GPS MEASUREMENTS OF A LINEAR OBJECT FOR A SPECIFIED TIME INTERVAL

ABSTRACT

The previous measurement campaigns planning used in geodesy is conducted exclusively for individual points. For the natural process aimed at the adoption of the introduction of the planning (prediction of constellation state) in navigation, which is characterized by the movement, one should adopt measurement campaigns planning for linear objects. In contrast to the existing planning solutions, focused on point presentation of the state of the constellation of navigation system, the author of this article rearranges the proposal of determination of geometrical factors, and their summation. In the presented simulation, one has specified the route of passing at certain times and it was assumed that the receiver will move with variable motion. One has defined the geometric ratios (PDOP), which allow to distinguish the results corresponding to the adopted criteria for the measurement of linear object to be conducted with the best possible accuracy.

Keywords:
GPS, almanac, position accuracy, GNSS measurements planning.

INTRODUCTION

Fundamental role in the determination of the position is played by the geometry of the satellites of GPS navigation system. Over the years, one can observe an increase in the number of available NAVSTAR GPS satellites and their modernization into newer blocks, which allows to improve the geometric ratio constituting a basis for other supporting navigation systems — using differential or phase corrections on Earth (ground support systems — GBAS) and in space (satellite support systems — SBAS) [C. Specht et al., 2014]. GPS plays a fundamental role in the process of navigation and surveying measurements [ICD-GPS-240, 2010; C. Specht et al., 2015]. For these measurements to be carried out and in order to assess the accuracy of the specified position, prediction of its state is performed in terms of place and specified time. The idea of measurements planning is limited to single points. Available software and applications for measurement campaigns planning are slightly different among themselves, but the terms of their use are virtually the same [M. Skóra, C. Specht, 2009]. Programs used today for measurement campaigns planning do not have useful possibilities of application in dynamic measurements. In order to extend the scope of planning GNSS campaigns to dynamic measurements, it is necessary to develop a new method.

So far, prediction of the state of GNSS constellation was limited only to the point planning. It is required to present the following input data [M. S. Grewal, L. R. Weill, A. P. Andrews, 2007; J. Januszewski, 2004]:

- co ordinates of measurement place;
- specification of the time and time zone;
- determination of the minimum amount of topocentric observation;
- optionally (if necessary), field diaphragms denoting those parts of the celestial sphere, which will be 'covered' by the surrounding objects.

The first surveying and navigation receivers, for technical reasons, had a limited ability to track satellite signals in relation to those which reached it. The problem of minimizing the DOP (Dilution of Precision) from the point of view of importance for GNSS measurements is a key problem which allows to obtain position coordinates with high precision. A few years ago, it was conclusive for the quality of position solution.

In the early nineties of the last century, the receivers, in order to obtain a maximally accurate observed position, performed the satellites selection in such a way so as to minimize the value of the geometric ratio. They did this through the choice of the most optimal 4 satellites (from all visible). Today, this form of tracking and measurement belongs to history. The simplest — manual receivers allow for the parallel tracking of at least 8 satellites with the possibility of simultaneous measurement. Problem of DOP value analysis is still important in precision applications (e.g.: hydrography, geodesy), where there are field obstacles — preventing access to the entire horizon. It is then required to perform pre-planning of measurement campaign aimed at minimizing the DOP value [J. Januszewski, 2004]. The contained in various formats (e.g.: SEM or YUMA) orbital data (almanac) allow the calculation of the DOP value [GICC SMAC, GNSS, Data Collection and Documentation Standards, 2014; M. S. Grewal, L. R. Weill, A. P. Andrews, 2007]. The calculated on the basis of above input data geometric ratios allow for the planning of measurement for the most minimum DOP values.

CALCULATION OF VALUES OF DOP GEOMETRIC FACTORS

The process of calculating the geometric coefficients for any moment of observation should begin with the determination of coordinates of GPS satellites and a receiver in a ECEF system (Earth-Centered, Earth-Fixed) for the right moment of time, assuming that the movement of the satellites is described by Kepler's laws and based on the WGS-84 geodetic reference system (World Geodetic System '84) [C. Specht, 2007]. For this purpose, from the almanac files one must obtain the following data for each satellite:

- t_{oa} — GPS time in which almanac file was generated [s],
- e — eccentricity of the orbit [–],
- δ_i — offset of orbit inclination [semicircles], [rad], [°],
- Ω_d — RA update as a function of time [semicircles/s], [rad/s], [°/s],
- $\sqrt{a}$ — square root of large orbit semiaxis [$m^{1/2}$],
- Ω_0 — longitude of the ascending node of orbit at point of the almanac file generation [semicircles], [rad], [°],
- ω — perigee argument [semicircles], [rad], [°],
- M_0 — mean anomaly at point of the almanac file generation [semicircles], [rad], [°].

One must pay special attention to the units in which the almanac data were presented, especially on the [semicircles] unit, which should be converted to radians (1 semicircle = π rad). Other data required for calculation:

- $\mu = 3{,}986005 \cdot 10^{14}\ m^3/s^2$ — gravitational parameter,
- $\Omega_e = 7{,}2921151467 \cdot 10^{-5}$ rad/s — the speed of rotation of the Earth,
- $i_0 = 54°$ — reference value of orbit inclination,

– a_e = 6378137 m — length of large semiaxis of ellipsoid WGS-84,
– b_e = 6356752,3142452 m — length of small semiaxis of ellipsoid WGS-84.

After calculating the coordinates of the satellites in the ECEF system, one should proceed with their transition to ENU (East, North, Up), the designation of their topocentric heights and omission of satellites with its negative value, or with less than the reference value, and for the remaining ones, appointment of the azimuths measured from the receiver position [B. Beesley, 2002]. A matrix of transformation between ENU and ECEF systems [–] in form of:

$$F = \begin{bmatrix} -\sin(L) & -\sin(B)\cdot\cos(L) & \cos(B)\cdot\cos(L) \\ \cos(L) & -\sin(B)\cdot\sin(L) & \cos(B)\cdot\sin(L) \\ 0 & \cos(B) & \sin(B) \end{bmatrix}, \tag{1}$$

allows to specify the satellite coordinates in ENU system[m]:

$$\begin{bmatrix} x_{ENU} \\ y_{ENU} \\ z_{ENU} \end{bmatrix} = F^T \cdot \begin{bmatrix} x_s - x_u \\ y_s - y_u \\ z_s - z_u \end{bmatrix}, \tag{2}$$

and on their basis, the topocentric height of satellites [rad]:

$$el = \operatorname{arctg}\left(\frac{z_{ENU}}{\sqrt{x_{ENU}^2 + y_{ENU}^2}}\right), \tag{3}$$

and its aximuth [rad]:

$$Az = \begin{Bmatrix} 0\ for\ x_{ENU} = 0 \wedge y_{ENU} > 0;\ \operatorname{arctg}\left(\left|\frac{x_{ENU}}{y_{ENU}}\right|\right) for\ x_{ENU} > 0 \wedge y_{ENU} > 0 \\ 0{,}5\pi\ for\ x_{ENU} > 0 \wedge y_{ENU} = 0;\ 0{,}5x + \operatorname{arctg}\left(\left|\frac{y_{ENU}}{x_{ENU}}\right|\right) for\ x_{ENU} > 0 \wedge y_{ENU} < 0 \\ \pi\ for\ x_{ENU} = 0 \wedge y_{ENU} < 0;\ \pi + \operatorname{arctg}\left(\left|\frac{x_{ENU}}{y_{ENU}}\right|\right) for\ x_{ENU} < 0 \wedge y_{ENU} < 0 \\ 1{,}5\pi\ for\ x_{ENU} < 0 \wedge y_{ENU} = 0;\ \operatorname{arctg}\left(\left|\frac{x_{ENU}}{y_{ENU}}\right|\right) for\ x_{ENU} < 0 \wedge y_{ENU} > 0 \end{Bmatrix}, \tag{4}$$

Then, using the matrix of gradients of position lines [–]:

$$G = \begin{bmatrix} \cos(el_1)\cdot\sin(Az_1) & \cos(el_1)\cdot\cos(Az_1) & \sin(el_1) & 1 \\ \cos(el_2)\cdot\sin(Az_2) & \cos(el_2)\cdot\cos(Az_2) & \sin(el_2) & 1 \\ \vdots & \vdots & \vdots & 1 \\ \cos(el_n)\cdot\sin(Az_n) & \cos(el_n)\cdot\cos(Az_n) & \sin(el_n) & 1 \end{bmatrix}, \tag{5}$$

where:
n — number of satellites with a topocentric height greater than the set value [–], and the covariance matrix [–]:

$$C = (G^T \cdot G)^{-1}. \tag{6}$$

On the basis of the covariance matrix, the geometric factors [–] can be determined according to simple dependencies:

$$GDOP = \sqrt{C_{0,0} + C_{1,1} + C_{2,2} + C_{3,3}}; \tag{7}$$

$$PDOP = \sqrt{C_{0,0} + C_{1,1} + C_{2,2}}; \tag{8}$$

$$HDOP = \sqrt{C_{0,0} + C_{1,1}}; \tag{9}$$

$$VDOP = \sqrt{C_{2,2}}; \tag{10}$$

$$TDOP = \sqrt{C_{3,3}}, \tag{11}$$

where:
1. GDOP (geometric dilution of precision) — the overall ratio of geometric accuracy referring to the 4 variables describing the designated GPS position (x, y, z, t) or (ϕ, λ, h, t). It characterizes the space — 4D. This factor combines the time — spatial essence of navigation describing the object executing the navigation process.
2. PDOP (position dilution of precision) — spatial ratio of geometric accuracy (3D) referring to the three-dimensional position (x, y, z) or (ϕ, λ, h) which is primarily in the interest of air, space, land navigation and precise surveying.
3. HDOP (horizontal dilution of precision) — horizontal ratio of geometric accuracy (2D) referring to the two-dimensional position (x, y) or (ϕ, λ). Important in marine navigation, because there is no need to estimate the height (h).
4. VDOP (vertical dilution of precision) — vertical ratio of geometric accuracy (1D) relating to the accuracy of height measurement of one-dimensional position line (z) or (h). Important in the process of air navigation and space.
5. TDOP (time dilution of precision) — time ratio of geometric accuracy (1D) relating to the time measurement. Its dimension does not, however, refer to the position, but the quality of time estimation.

Considering the above quoted dependencies, one may check the received values of GDOP and PDOP:

$$(GDOP)^2 = (PDOP)^2 + (TDOP)^2; \tag{12}$$

$$(PDOP)^2 = (HDOP)^2 + (VDOP)^2. \tag{13}$$

Determining field aperture becomes an indispensable part of GNSS planning. Apertures in the upper hemisphere constitute an effective obstacle for the reception of direct signal from the satellite to the receiver antenna. It is assumed that the minimum topocentric height for marine navigation should be 10°, and for surveying and hydrographic measurements 15° [C. Specht, 2007]. When measurements are to be carried out in the so called street canyons/urban canyons, it is necessary to identify and take into account the field apertures and objects for the purpose of correct prediction of the state of the constellations at a given place and time — Figure 1 [W. Koc, C. Specht, 2010].

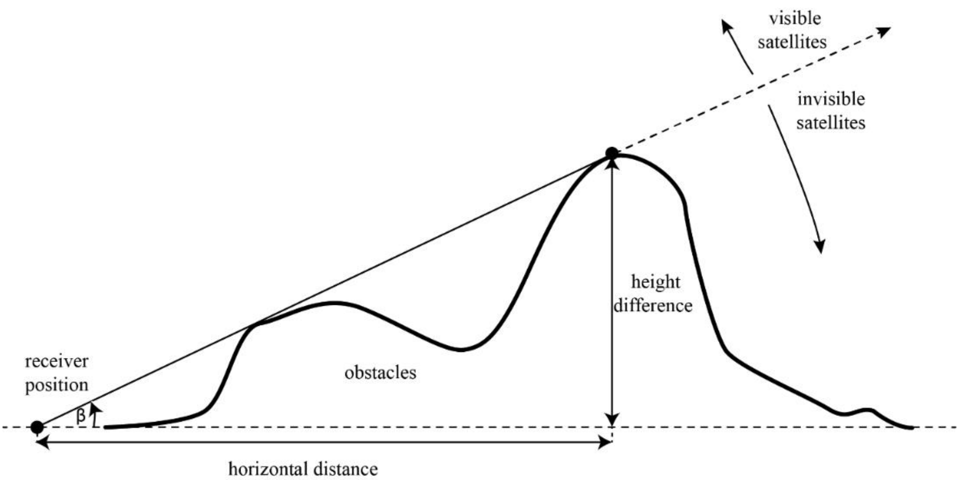

Fig. 1. Determination of β angle with consideration of field obstacles

For each angle between the northern part of the meridian and the given horizontal direction, one should determine the maximum angle at which satellites are obstructed by obstacles (buildings, trees, etc.). This equation has the form:

$$\beta\,[°] = \tan^{-1}\left(\frac{Heigh\ difference\ [m]}{Horizontal\ distance\ [m]}\right) \cdot \left(\frac{180}{\pi}\right). \tag{14}$$

Bearing to the obstacle point is determined on the basis of the following dependence:

$$Na = \begin{Bmatrix} \left(\frac{180}{\pi}\right) \cdot arctg\left(\frac{b}{a}\right) + \pi \; dla \; a < 0 \wedge b \geq 0 \\ \left(\frac{180}{\pi}\right) \cdot arctg\left(\frac{b}{a}\right) - \pi \; dla \; a < \wedge b < 0 \\ \left(\frac{180}{\pi}\right) \cdot \frac{\pi}{2} \; dla \; a = 0 \; \wedge b > 0 \\ \left(\frac{180}{\pi}\right) \cdot -\frac{\pi}{2} \; dla \; a = 0 \; \wedge b < 0 \\ \left(\frac{180}{\pi}\right) \cdot arctg\left(\frac{b}{a}\right) \; dla \; a > 0 \end{Bmatrix}, \qquad (15)$$

where:

a = x coordinate of the measured point — x position of the receiver; (16)

b = x coordinate of the measured point — x position of the receiver. (17)

In order to obtain the actual value of the bearing in the scope from 0–360° one must improve the received values by the following dependencies

$$Bearing = \begin{Bmatrix} 90 \; for \; Na = 0 \\ 90 - Na \; for \; Na > 0 \wedge Na < 90 \\ 0 \; for \; Na = 90 \\ |90 - Na + 360| \; for \; Na > 90 \wedge Na < 180 \\ 270 for \; Na = 180 \\ 90 - Na \; for \; Na < 0 \; \wedge Na > -90 \\ 180 \; for \; Na = \; -90 \\ |90 - Na| \; for \; Na < -90 \end{Bmatrix}. \qquad (18)$$

The value of β can take a maximum value of 90°, when the upper hemisphere of the antenna will be entiraly covered and the measurement will not be possible. The β value generated for specific values of the azimuth angle value allows for the graphical representation in the polar coordinates system of field diaphragms. Figure 2 was presented with indication of the topocentric height (elevation — E).

An important change in the planning of existing GNSS is the introduction of a linear object as a route on which the receiver is to move, including apertures in the upper hemisphere of the antenna. Linear object is defined in the construction law — Act of 7 July 1994, Journal of Laws of 1994, No. 89, item 414.

Art. 3. Whenever the Act mentions:
'[…]
3a) linear object — it should be understood as construction building which characteristic parameter is length, in particular the road with exits, railway line, water pipe, canal, gas line, heat line, pipeline, electric power line and traction, ground cable line and line placed directly in the ground, underground, flood embankment and cable ducting, while the cables installed in it do not constitute a building or part thereof or construction equipment'.

Tab. 1. Received values of β angle [°] for the simulated height differences and the horizontal distance from the obstacle

Horizontal distance [m]	Height difference [m]									
	5	15	30	50	75	100	125	150	175	200
5	45,0°	71,6°	80,5°	84,3°	86,2°	87,1°	87,7°	88,1°	88,4°	88,6°
10	26,6°	56,3°	71,6°	78,7°	82,4°	84,3°	85,4°	86,2°	86,7°	87,1°
15	18,4°	45,0°	63,4°	73,3°	78,7°	81,5°	83,2°	84,3°	85,1°	85,7°
20	14,0°	36,9°	56,3°	68,2°	75,1°	78,7°	80,9°	82,4°	83,5°	84,3°
25	11,3°	31,0°	50,2°	63,4°	71,6°	76,0°	78,7°	80,5°	81,9°	82,9°
30	9,5°	26,6°	45,0°	59,0°	68,2°	73,3°	76,5°	78,7°	80,3°	81,5°
35	8,1°	23,2°	40,6°	55,0°	65,0°	70,7°	74,4°	76,9°	78,7°	80,1°
40	7,1°	20,6°	36,9°	51,3°	61,9°	68,2°	72,3°	75,1°	77,1°	78,7°
45	6,3°	18,4°	33,7°	48,0°	59,0°	65,8°	70,2°	73,3°	75,6°	77,3°

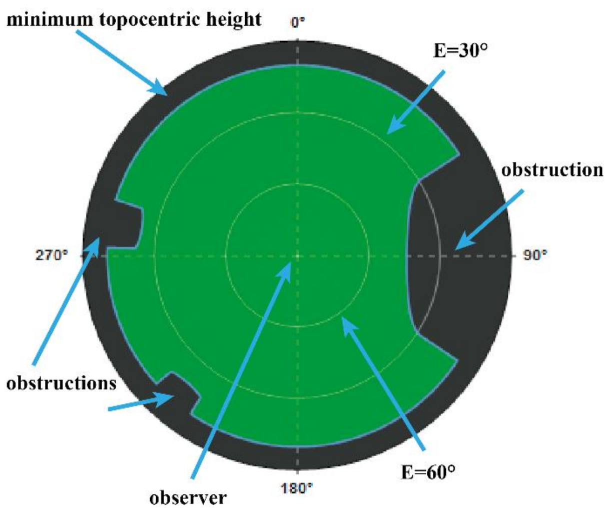

Fig. 2. Description of the generated polar diagram with field apertures

The receiver moving with uniform motion covers in the same time interval the same sections of the road (whether it is straight or curved movement):

$$v = \frac{ds}{dt} = const. \tag{19}$$

The once established and introduced apertures can be treated as an unchanging element, but the space segment of the navigation system is to be determined each time for the period of measurements. Presentation of the next steps in the algorithm of planning GNSS measurement campaigns for dynamic measurements of linear objects is presented in Figure 3.

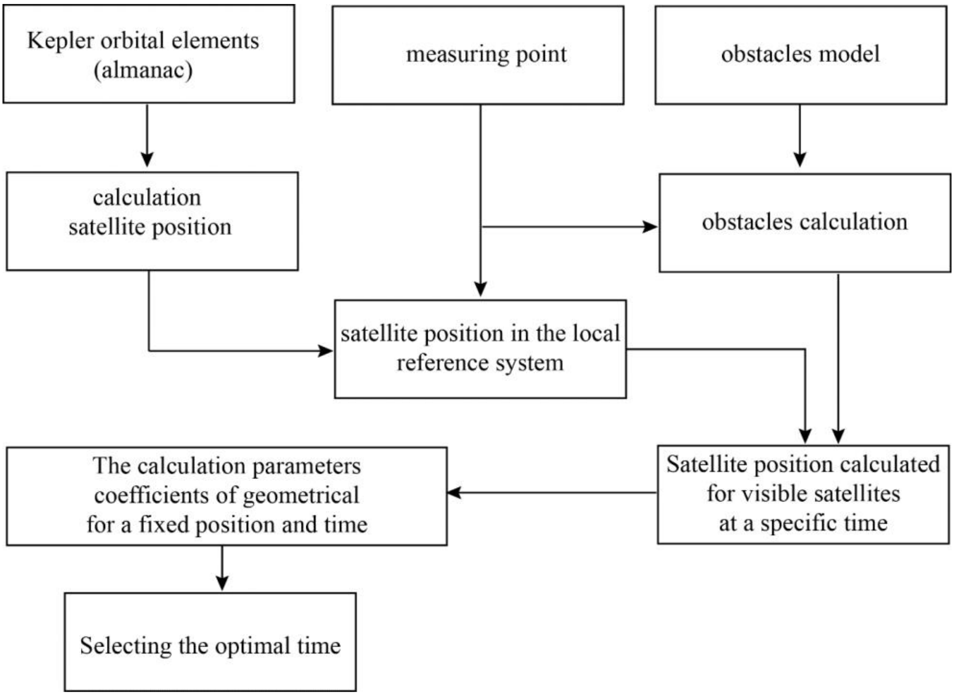

Fig. 3. Block diagram of dynamic GNSS measurements

THE ADOPTED ASSUMPTIONS

For both types of predictions of static and dynamic measurements, there are common difficulties in determining the values affecting the assessment measures, determining the final result. An innovative approach to prediction of the state of the constellations for a limited time and route points obliges to identify additional findings. Thus, this paper was submitted, subject to certain assumptions and limitations which include:

- take into account the planning of measurement of a linear object only with NAVSTAR GPS, the choice of which is dictated by the full constellation, operational readiness and availability of the almanac;
- the date and exact time of the start and end of measurements;
- not taking into consideration the multipath character of signal reflected individually and repeatedly to the receiver antenna, which is not additionally protected against this unfavorable phenomenon;
- taking into account only the field apertures is treated as prevention of reaching the direct microwaves from the satellite to the receiver in the line of sight without examining the impact of devices emitting electromagnetic waves of high intensity (e.g. power lines, radars, broadcasting stations);
- not taking into consideration the factors of the medium (for propagation of radio signal), including forecasts of models of the ionosphere and the troposphere;
- prediction does not take into account the technical and operational parameters of receivers (apparatus);
- the calculated geometrical ratios do not include the time required for the acquisition of the satellite in the case of occurrence on the previously planned route;
- omission of errors occurring as a result of conscious distortion of satellite signal, for example the switched off in the night from 1 to 2 May 2000 S/A disturbance (Selective Availability) or in the form of intentional interference, such as jamming, spoofing, disturbing and meaconing the signal;
- change of position of the receiver is planned and executed only one way (no return), or re-passing;
- the aim is not to re-define the route (the demarcation of the route of linear object), but covering it with the best possible to achieve result of measurement accuracy.

SIMULATION TESTS ON SPECIFIC ROUTE

In order to present the impact of obstacles on the formation of geometrical factors and estimation of the lowest possible summary PDOP coefficient, an algorithm was developed in the Wolfram Mathematica program in 10.4 version. On the tested route (Fig. 4) one determined 9 tested intermediate points, so that the segments are of equal length — 1 113 m (total length of the linear object is 8905 m). As obstacles constituting an effective obstacle for the reception of the direct signal from the satellite to the receiver antenna, one added solids — cylinders. In order to explain the change of constellations and geometrical factors formation, it was decided to carry out a simulation from 10:00 to 12:00 o'clock for the time interval of 6 minutes. The lower limit of the topocentric height was set at 10°. All the tested items were at the same height — 0 m. It was decided to choose the PDOP coefficient for accuracy test. The simulation was performed on 16th September 2016. The SEM almanac is from 7th of September (almanac.sem.week0889.319488.txt) and covers only the NAVSTAR GPS satellite system.

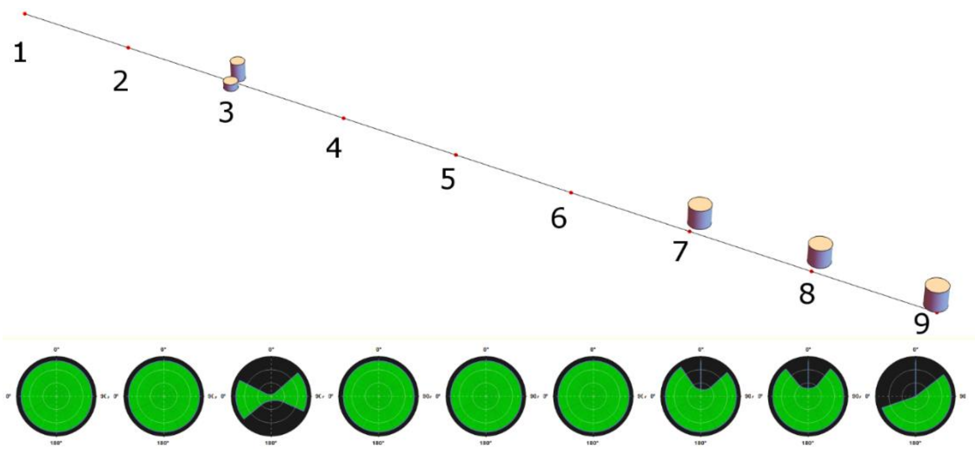

Fig. 4. Sketch of the simulations carried out with the numbers of tested positions and proper pole diagrams

The numbers of positions and their coordinates are as follows:

Position number	**Latitude**	**Longitude**
1	54°31.8' N	18°30' E
2	54°32.4' N	18°30' E
3	54°33.0' N	18°30' E
4	54°33.6' N	18°30' E
5	54°34.2' N	18°30' E
6	54°34.8' N	18°30' E
7	54°35.4' N	18°30' E
8	54°36.0' N	18°30' E
9	54°36.6' N	18°30' E

The defined PDOP coeficcients were presented in the table 2 with marking.

Tab. 2. Value of PDOP for specific times

Hour	Position number								
	1	2	3	4	5	6	7	8	9
10:00	2.01	2.01	Lack	2.01	2.01	2.01	2.22	2.01	2.85
10:06	2.10	2.10	Lack	2.10	2.10	2.10	2.37	2.10	2.93
10:12	1.81	1.81	Lack	1.81	1.81	1.81	1.93	1.81	3.00
10:18	2.04	2.04	Lack	2.04	2.04	2.04	2.04	2.04	3.06
10:24	2.13	2.13	3.74	2.13	2.13	2.13	2.13	2.13	3.09
10:30	2.20	2.20	3.80	2.20	2.20	2.20	2.20	2.20	3.06
10:36	2.24	2.24	3.82	2.24	2.24	2.24	2.24	2.24	2.99
10:42	2.24	2.24	3.81	2.24	2.24	2.24	2.24	2.24	2.88
10:48	2.19	2.19	Lack	2.19	2.19	2.19	2.19	2.19	2.75
10:54	2.12	2.12	Lack	2.12	2.12	2.12	2.12	2.12	2.60
11:00	2.04	2.04	Lack	2.04	2.04	2.04	2.04	2.04	4.04
11:06	1.95	1.95	6.83	1.95	1.95	1.95	1.95	1.95	4.03
11:12	1.78	1.78	Lack	1.78	1.78	1.78	2.29	1.78	3.88
11:18	1.51	1.51	6.51	1.51	1.51	1.51	1.90	1.51	3.79
11:24	1.60	1.60	8.83	1.60	1.60	1.60	2.02	1.60	3.81
11:30	1.58	1.58	16.93	1.58	1.58	1.58	2.04	1.58	3.70
11:36	1.56	1.56	229.2	1.56	1.56	1.56	2.28	2.04	3.40
11:42	1.86	1.86	14.3	1.86	1.86	1.86	2.33	2.28	6.22
11:48	1.92	1.92	3.91	1.92	1.92	1.92	2.33	2.33	6.45
11:54	1.98	1.98	3.61	1.98	1.98	1.98	2.37	2.37	6.50
12:00	2.04	2.04	5.75	2.04	2.04	2.04	2.42	2.42	6.35
Lack — the inability to determine the DOP coefficient due to the insufficient number of visible satellites									

The data presented in the above table allow for the presentation of optimal value when it comes to the specified time interval. Although the time interval in the simulation was defined between 10:00 and 12:00 o'clock, the movement on linear object between 10:12 and 11:36 o'clock would be more appropriate. The total value of the PDOP coefficients is then the smallest. In the third position, is in some periods it is impossible to determine the position because of the apertures. The inability to determine the position significantly influenced the planned passage time.

CONCLUSIONS

The presented results of the experiment show that the field apertures significantly affect the development of the geometric factor. Very small changes in the size of the coefficient result from a short distance between the tested points. Significant differences between the values of the PDOP coefficient during the occurrence of field apertures change noticeably over time. Some apertures do not hinder the visibility of the satellite when it is above the topocentric horizon of the observer. The sum of obtained values of the coefficient should not be the only indicator when choosing the lowest possible position error, but one should also determine the standard deviation, which can change the measurement time due to the expected accuracy and the smaller variation. The presented simulation of the experiment does not exhaust the issue of planning a measurement campaign for a linear object. One can expand it even further with other satellite navigation systems.

Another group of opportunities for further research are certain limitations which include the lack of taking into consideration the single, multipath reflection or diffraction of an electromagnetic wave sent from the satellite. The used in the simulation primitive solids (cylinders) as obstacles are only a small representation of the apertures, the best solution is now a digital terrain model (DTM). One also has not taken into account forecasts of the state of the ionosphere and troposphere, which can be modeled. At the end, it should be noted that the almanac file as a predictor is the approximate state of the system, the usefulness of which is estimated to be 60 days from the date of measurement and as a result of intended or unintended actions, the state of constellation of the system may be different than anticipated.

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STRESZCZENIE

Dotychczasowe planowanie kampanii pomiarowych w geodezji odbywa się wyłącznie dla pojedynczych punktów. Za naturalny proces ukierunkowany na wprowadzenie planowania (predykcji stanu konstelacji) w nawigacji, którą cechuje ruch, należy przyjąć planowanie kampanii pomiarowych dla obiektów liniowych. W przeciwieństwie do dotychczasowych rozwiązań, skupionych na punktowym przedstawieniu stanu konstelacji systemu nawigacyjnego, autorzy przestawiają propozycję określania współczynników geometrycznych, a następnie ich sumowania. W symulacji określono trasę przejazdu w konkretnych godzinach i przyjęto, że odbiornik będzie poruszać się ruchem zmiennym. Określono też współczynniki geometryczne (PDOP), które pozwalają wyróżnić odpowiadające przyjętym kryteriom wyniki, by pomiar obiektu liniowego odbył się z jak największą dokładnością.