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THE PROPOSAL OF ADAPTATING THE EXISTING COMPARATIVE BASE OF GLM AGH AS MOVING TEST BASE TO DETERMINE THE ACCURACY OF LASER TELEMETERS IN SCANNING INSTRUMENTS

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Abstract

Determination of the accuracy characteristics of geodetic instruments is – according to the law – the duty of geodetic services doing all the surveying. The certificates are given by the authorized units equipped in special comparative bases. The specifics of modern scanning instruments require much research to get full information about real accuracy of instrument. Wide application of reflectorless measurements in the inventory and monitoring of the natural and anthropogenic objects requires the recognition of accuracy parameters of the definite instrument. This refers both to positioning the head based on reference points, but also the components of the situation error of the point in the cloud. An important component included in the situation error of the point the error of the distance measurement in the option of full automation. Automatism and short time of the measurement of the set of point requires specific approach to the way of determining the characteristic of telemeter. One can use the existing bases for this purpose. In article the algorithm of the use of existing comparative base of the Geodetic Metrological Laboratory of AGH for the needs of testing reflectorless telemeters of scanning total stations of laser scanners within the range of the present length of the base in the online mode.

PROPOZYCJA ADAPTACJI ISTNIEJĄCEJ BAZY KOMPARACYJNEJ GML AGH JAKO RUCHOMEJ BAZY TESTOWEJ DLA POTRZEB WYZNACZANIA DOKŁADNOŚCI DALMIERZY LASEROWYCH INSTRUMENTÓW SKANUJĄCYCH

Słowa kluczowe: kalibracja instrumentów, skaning laserowy, geodezyjne bazy pomiarowe

Abstrakt

Wyznaczanie charakterystyk dokładnościowych instrumentów geodezyjnych stanowi w odniesieniu do wymogów prawnych obowiązek służb geodezyjnych wykonujących wszelkiego rodzaju prace geodezyjne. Świadectwo atestacji wydają upoważnione do tego celu jednostki wyposażone w specjalne bazy komparacyjne. Specyfika nowoczesnych instrumentów skanujących wymaga szerszego zakresu prac badawczych dla uzyskania pełnej informacji o rzeczywistej dokładności instrumentu. Szerokie zastosowanie pomiarów bezzwierciadlanych w pracach inwentaryzacyjnych i monitoringu obiektów naturalnych i pochodzenia antropogenicznego wymaga rozpoznana parametrów dokładnościowych określonego instrumentu. Dotyczy to zarówno pozycjonowania głowicy w oparciu o punkty referencyjne, ale także składowe błędu położenia punktu w chmurze. Istotną składową błędu położenia punktów jest błąd pomiaru odległości w opcji pełnej automatyzacji. Automatyzm i prędkość pomiaru zbioru punktów wymaga specyficznego podejścia do sposobu wyznaczenia charakterystyki dalmierza. Można wykorzystać do tego celu bazy już istniejące. W artykule przedstawiono algorytm wykorzystania istniejącej bazy komparacyjnej Geodezyjnego Laboratorium Metrologicznego AGH dla potrzeb testowania dalmierzy bezzwierciadlanych tachimetrów skanujących i skanerów laserowych w zakresie obecnej długości bazy w trybie ciągłym.

1. INTRODUCTION

According to the content of the Enactment of the Minister of Internal Affairs and Administration of 9th November 2011 *on the technical standards….* [3], measurement works requiring high precision have to be carried out with the application of technologies or instruments meeting accuracy criteria for a specific type of surveying. This means that surveyors, by the proper selection of technologies or instruments, should provide appropriate accuracy of the obtained measurement results. This factor is very important in case of point or areal monitoring (Marcak H., 2001) of natural (natural scarps and slopes) and/or anthropogenic (buildings, artificial scarps, earthworks, spoil tips) elements of environment. The stability of these elements is crucial for the safety of the users. The control and awareness of the real accuracy and repeatability of the applied instruments and conditions limiting their application (Pareja F., et al. 2013), is particularly important in the works connected with the measurement of control lines, geodetic services in investments and the control of subsequent construction stages (the control of the correctness of project implementation), exploitation of individual elements of the industry infrastructure (including mining) and large size engineering objects (Bhatla A., et al. 2012; Golparvar-Fard M., et al. 2011; Bosche F., 2015).

The stage of the selection of the measurement set to determine the changes in the geometry of the examined objects requires metrological control of these instruments. In practice, this stage is carried out in field or laboratory conditions on control bases, specially designed for this purpose. Basic measurement instruments in the surveying inventory and monitoring are total stations with the option of scanning or robot measurements and laser scanners. Regardless the construction of this group of instruments, the positioning of any point in space, towards the points of the control line is carried out by the registration of horizontal and vertical angles as well as skewed distance. The applied now stepper motors, responsible for the angular deviation of the telescope (total stations) or mirrors (scanners) and systems of compensators (Lichti D.D., 2010), guarantee precise angular network (in horizontal and vertical planes), the accuracy of which does not depend on the character of the measured surface (Gawałkiewicz R., 2005). The problem is the measured distance, which has the greatest impact on the value of mean error of the situation of point m_P. In case of scanners making measurements from free stands, an important component, influencing the mean value of the error in the situation of the cloud of points, is positioning based on the resultant directions to special reference shields. The example of such a test base, allowing us to define the influence of a specific configuration of signals and turns of the shields on the size of the error of positioning the instrument was illustrated in figure 1b (example: university base in Calgary (Chow J.C.K., et al. 2010; Rondeel S., et al. 2015).

For many years in various countries special comparative bases have been constructed outdoors (field bases) or indoors – laboratories (Lichti D.D, 2006; Abbas M.A., et al., 2014), the main task of which is the quality control of the measurement instruments (in the framework of legal metrological control of measurement instruments) used by geodetic services to the inventory of natural phenomena and the used engineering constructions and recording of changes in their geometry in the framework of the carried out monitoring. This refers to the control of instruments positioning in the field, based on signals of different type, as well as the accuracy of the measurement of the defined group of details towards the scanning head (Chan T.O., et al. 2015). The duty of the metrological control of total stations and scanners results from the *Law on Measurements* of 11th May 2001 [1] and the regulations required in the European Union, i.e. – Measuring Instruments Directive (MID), announced in the Official Journal of the European Union No. L135 on 30th April 2004 (Polish special issue, chapter 13, volume 34) [2].

A significant number of test principles is based on points permanently stabilized in the ground, usually distributed in different distances, but preserving straight line and constant level of heads to force centring of the tested instruments as well as signals and shields. The example of such a field base is a test base “Wisła” AGH in Krakow, schematically presented in figure 1a.

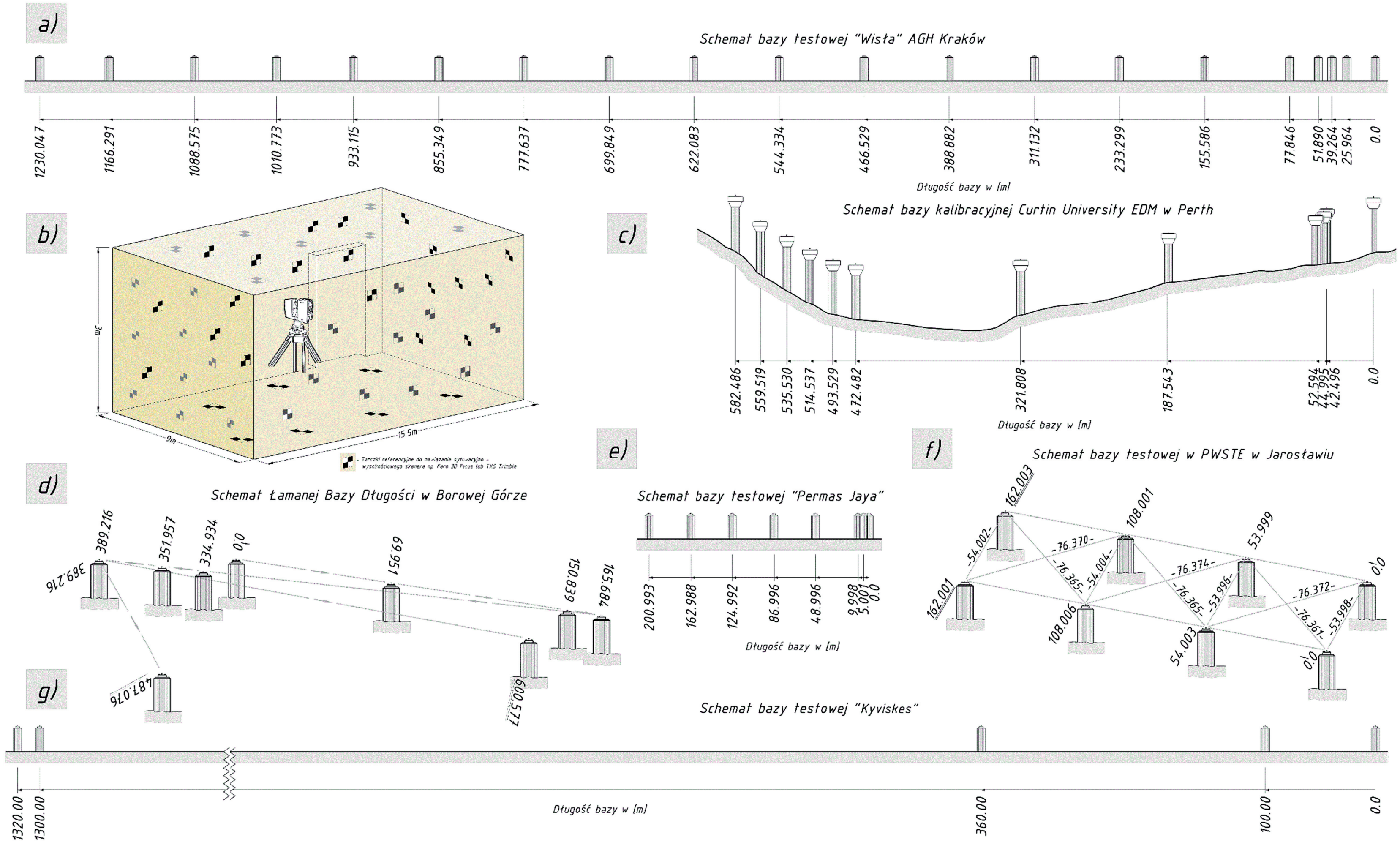

Fig. 1. The example of a test base of telemeters with discrete measurements (based on discrete points)
Rys. 1. Przykładowe bazy testowe dalmierzy o charakterze skokowym pomiaru (w oparciu o punkty dyskretne)

Another straight line base of changeable heights of centring heads is a calibration base Curtin University in Perth (figure 1a). Today, the limitations in the area (property problems) force the construction of "broken bases", which means that the system of forced stands reminds the broken line, while the measurement of longer distances alongside this line is carried out applying the return signals established on the breaking points, as well as in case of the Broken Base of the Length in the Borowa Góra (stands 1 and 2 – figure 1d), or the broken base GLM AGH-UST. Another geometrically atypical base is the academic construction of test stands of the State Technical and Economical University in Jarosław (Banaś M., 2012), consisting of pillar measurements making the network of quadrangles (figure 1f).

Not always the definition of the accuracy characteristics of the telemeter requires long bases. The range of the studies on the accuracy of length measurements can be limited to the range and size of the objects subdued to inventory, thus predicted range of surveying. The drawback of bases based on discrete points presented in figure 1a, c, d, e, f, g is the definition of accuracy only for the selected ranges. Thus practical and very useful in metrology are bases, allowing "flexible" range of the research, i.e. in the way allowing flexibility in shaping base distances of the distance range from HD = 0m to its maximal length HD_{max}. Due to a proper construction based on special linear guides, where a trolley with special handles for return mirrors or target shields and pattern instrument, e.g., linear interferometer (or any other telemeter of increased accuracy), the definition of the accuracy characteristics of any instrument is possible to the measurement of linear values, both to return signals, but first of all the flat surface of the shield. After a proper modification of the tested surface (more complex, but mathematically defined) on the trolley moving on the trail, one can determine the accuracy characteristics of instruments in the situation of more geometrically complicated structures.

A specific way of study refers to the instruments with automatic mode of angular and linear measurement, i.e. scanning total stations and laser scanners. The automation of the reflectorless measurements requires precise definition of reflecting surface in the 3D space. Measurement points are mapped on this surface. The analysis of the distribution of these points making the cloud towards the target shield, precisely positioned in 3D space, makes it possible to define the distribution of the length measurement errors and facilitates obtaining accurate information on possible fluctuations for a very big sample. A high credibility of studies is obtained when the measurements are made referring to the surfaces of different colour, roughness, texture or material the reflecting surface was made of. Such studies also allow the definition of extreme conditions making measurement impossible, caused by the dispersion of the recognition of light impulse on the reflecting surface. The article presents the algorithm of the use of the existing comparative base of Geodetic Metrological Laboratory of AGH-UST for the needs of testing reflectorless telemeters of scanning total stations and laser scanners in the range of the present length of the base in the on-line mode.

2. THE DESCRIPTION OF TEST BASE

Worldwide, in technical literature referring to metrological issues in the range of geodetic testing of laser telemeters, many configurations of the elements of test bases could be found (e.g., different relations of distances between the measurement pillars). The majority of traditional study lines in the range of several hundred metres of distances is located within free spaces and consists of the measurement pillars (discrete points) situated alongside straight-line sections. The longest objects of this type are, among others, straight-line baselines (Lechner J. et al., 2008; Hazelton N.W.J., 2009):

- Koštice Baseline – Czechy (1450.011m);
- Taylor Baseline – in the county of Marion, State Missouri – USA (1300m);
- Wisła AGH in Krakow – Poland (1230. 047m – figure 1a);
- Breaside Baseline and Hamilton Baseline in State Victoria – Australia (1160m);
- Aarau Baseline in Aarau, canton Argovia – Switzerland (1080m);

and curved line baselines:

- Hobart Baseline in Hobart in Tasmania – Australia (1160m);
- Heerbrugg Baseline in canton Sankt Gallen – Switzerland (1021.45m);
- Bathurst Baseline in New South Wales – Australia (888m – base of changeable height of the stands in the arch revised in the vertical plane);

Many of them are used as test objects in the widely spread now technology of laser scanning (Hazelton N.W.J., 2009). The selection of the type of the calibration base is determined by factors such as: the characteristics of the base (on-line measurements or discrete points), the measurement range of the examined scanner, configuration of pillars (test distances). Usually, for this purpose bases of length of 200÷300m are applied (average length of the range of the measurement by laser scanners). The documented example of test bases applied to define the accuracy characteristics of scanners are:

- Permas Jaya (Johor Bahru District) – Malaysia (200.993m – straight line base – figure 1e – Abbas M.A., et al. 2013);
- Curtin University in Perth – Australia (582.486m – straight line base of changeable height of stands in the vertical plane – figure 1c).
- *Kyviskes Calibration baseline* at the Gediminas Technical University – Lithuania (1320m – straight line base – figure 1g – Buga A., et al. 2008; Antanavičiūtė U., et al. 2013);
- HAV baseline in Hamburg – Ohlsdorfie (120m – academic base at the Hamburg Univeristy of Appied Sciences – Kersten Th., et al. 2004).

The possibility of smooth regulation of distance is guaranteed by the interference comparative base located in Geodetic Metrological Laboratory (Geodezyjne Laboratorium Metrologiczne – GLM AGH) of the Faculty of Mining Surveying and Environmental Engineering of the AGH University of Science and Technology in Krakow. It makes the equivalent of the University base in Zurich in the Institute of Geodesy and Photogrammetry, of 52m length, which is also used in determining the accuracy characteristic of laser scanners (Schulz Th., 2007). The universal bases are also straight line bases (Salo P., et al. 2008; Kutalmis G., Halil E., 2013):

- Leica Geosystems w Heerburgg – Switzerland (120m – called “railway” – source: *www.leica-geosystems.de/de/Reporter63 MAG 201009 en.pl*);
- Helsinki University of Technology – Finland (80m);
- Yildiz Technical University – Turkey (20m).

Another important advantage of both comparative bases is the possibility of the application of laser interferometer of Hewlett Packard HP 5529A with double-frequency helium – neon laser HeNe of maximal power 1.0mW, to determine pattern length. The device applying the phenomenon of light interference, allows the definition of the section length with accuracy ±1.7ppm (in the air) [1]. Such a device guarantees preserving high degree of confidence to the measured base length, not only because of the construction, but also due to stable atmospheric conditions taking place in the room of the Faculty comparative laboratory. The presence of the set of ventilators in the laboratory GLM AGH makes sure that the atmospheric parameters are constant during the experiments, i.e.: constant temperature, pressure and air humidity. Making stable conditions in the closed room of GLM AGH eliminates the errors of laser interferometer HP 5529A, otherwise caused by external factors. In the interference method of measurement, the carrier of the data of the measured length is the length of the light radiation λ, while the calculated number of bands is proportional to the difference of optical waves of the rays (Frukacz M., Markiewicz M., 2000). In the measurements, the important role is played by the linear retro-reflector HP 10767A, which makes the source of information of the pattern distance, defined by interferometer and the geometric centre of the prism, which makes the base of the accuracy analysis of the measurement distance of the tested surveying instruments (total stations, scanners) (Janusz J., et al. 2003). The disadvantage of the described system is a limited length of the base, i.e. a small range of the measurement. Until recently, GLM AGH base made it possible to determine the accuracy characteristics of the length measurement of tested instruments in the range distance 0 ÷ 34.2m (today up to 17m). Shortening the base in GLM AGH narrowed down the distance range of the studied instruments. It is, however still possible to define the accuracy of tested telemeters of reflectorless instruments applied in the processes is usually connected with the construction and architecture inventory of the objects (architectural monuments, industrial buildings, including mining, etc.) and the monitoring of objects or their selected parts in terms of pod structural deformations.

Apart from the limited examining range of the comparator’s trajectory, another limitation is the construction of interferometer and the lack of centering sign on its body, which does not allow the realization of test tasks with the use of stands with forced centering, and consequently, direct comparison of values measured with the pattern value. Thus drawing conclusions on the accuracy of tested telemeters is carried out based on the analysis of differential measurements based on the records of laser interferometer and tested telemeter, according to the scheme illustrated in figure 2. Horizontal situation of the comparator's rail the trolley with the attached retro-reflector is moving provides high accuracy of the determination of pattern values on the whole length of the base. Such a system allows the definition of the accuracy characteristics of any telemeter in the form of the errors of the length differences m_{Dd} based on repeatable manual point measurements to the retro-reflector HP 10767A. In case of determining the pattern values it is important to apply a high class of retro-reflectors. The precision of making prism can decide on the distribution of length measurement errors in the considered range of studies, and, referring to the problem of the analysed base to the differences of the determined length (Gawałkiewicz R., 2006).

In case of GLM AGH calibration base, it is possible to make a study model allowing the obtaining of any distance of the tested instrument – base purpose (shield, sphere, cylinder, etc.) in the range of the full length base. GLM AGH base consists of the aluminium rail (channel section) supported by several openwork supports, which allow spatial regulation of the straight line in both planes, i.e. horizontal XY and vertical XH. The verges of the beam of the channel section make a kind of rails on which the wheels of the trolley with the attached retroreflector HP10767A. Additionally the trolley has a winder, which should protect from accidental move during the test measurement for the given distance (linkage between the rail and rolls of the trolley). Equipping the trolley with additional target shield makes a test field to check and mark mean errors of distances and their distributions with the application of reflectorless instruments, first of all scanning instruments. Placing pattern instruments and tested pattern on the axis of the trajectory, towards initial trajectory towards the initial and ending situation of the trolley with the retro-reflector, guarantees obtaining optimal test system with a small number of necessary reductions. This also makes it possible to mark the deviations of the curvature of the trajectory horizontal and vertical planes (in the points where the trolley stops) based on the analysis of the measured horizontal and zenith angles and the

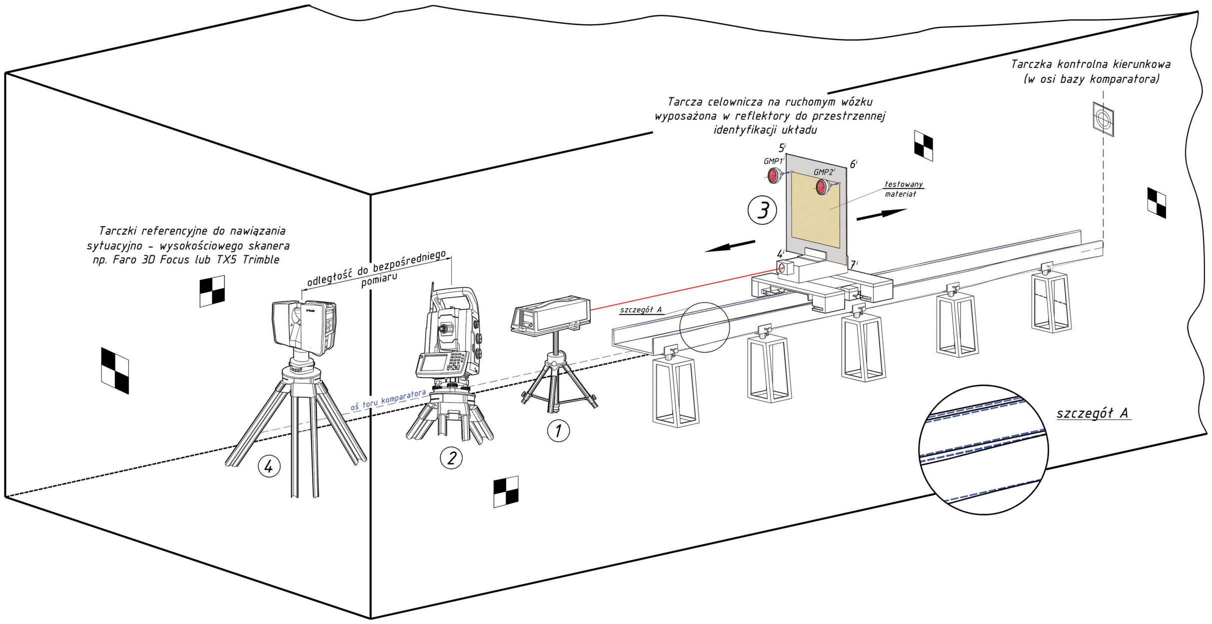

Fig. 2. The scheme of the test base of the horizontal comparator with the application of the measurement set: ① – laser interferometer Hewlett Packard HP 5529A, ② – precise total station TCA 2003 Leica or S6 Trimble, ③ – trolley equipped with retroreflector HP 10767A, mini prisms Leica GMP101 and target shield, ④ – tested instrument, e.g., scanning total station of scanner

Rys. 2. Schemat bazy testowej komparatora poziomego z wykorzystaniem zestawu pomiarowego: ① – interferometr laserowy Hewlett Packard HP 5529A , ② – tachimetr precyzyjny TCA 2003 Leica lub S6 Trimble, ③ – wózek wyposażony w retroreflektor HP 10767A, mini pryzmaty Leica GMP101 oraz tarczę celowniczą, ④ – instrument testowany, np. tachimetr skanujący lub skaner lengths to the retro-reflector in a full range of the length base. The scheme of the base was illustrated in figure 2.

Despite of the application of the aluminium T-bean of a significant stiffness, playing the role of the trajectory for the moving trolley, supported by many points on the whole its length, the ideal straight line of the trail verges cannot be achieved. The twist of the trajectory can also result from the quality of making the T-beam (tolerance). This system resembles a train rail or crane track, on which the wheels of the trolleys move. Every deviation from the trajectory in any plane is transferred into geometric deviation of the moving trolleys. Thus the system of horizontal comparator GLM AGH forces to introduce corrections to the length due to lack of the straight line of its axis (trajectory) and leeway between the rail of the comparator, and the rolls of the trolley causing its local horizontal twist, and this way – the target shield attached to it. The combination of the influence of the twist of the verge of the rail and the factor connected with the leeway between the edges of the rails and the wheels of the trolley forces to look at the pattern plane of the target shield in any of its situation, as a result of its twist in the space. Thus it requires making a definite algorithm of the measurement and calculation to obtain high credibility of the base system in every place the base shield stops.

3. THE PROPOSED ALGORITHM OF SPATIAL ANALYSIS OF THE ACCURACY OF TESTED SCANNING INSTRUMENTS BASED ON THE HORIZONTAL COMPARATOR EQUIPPED IN A TARGET SHIELD

To determine the accuracy characteristics of total stations and laser scanners in close range measurements (up to several meters) with the application of horizontal comparator of GLM AGH, a practical test tool is a target shield moved on the rail of the comparator with the help of the trolley. The twist of the trajectory influences the changes of the system of the trolley and shield in the relation to the initial (zero) state, which causes that the base planes (the areas of the shield being a target) are not parallel in subsequent states towards the initial system. Thus testing total stations and laser scanners requires the application of not only interferometer, as base to determine the corrections of the base length, but also precise total station used to determine the position of additional two signals attached to the target shield located on the trolley to create a system that could be mathematically solved.

Based on the spatial model presented in figure 3, every time, it is possible to determine coordinates of the prisms of the shield, which define the equation of the plane of the shield surface in its every situation. Moreover, linear measurements to retroreflector allow the adjustment of the distance measured with base instrument (precise total station). The twist of the trajectory on which the trolley with prism and shield disturbs the system, compared to the initial situation. Thus, apart from a natural translation of the trolley system also its special twist occurs. Consequently, each position of prism and shield corresponds to other coordinates, adequate to the values of the distortion of the trajectory and transverse dislocations of the trolley. Treating system as a fully rigid model (distance between the measured elements are constant) the definition of new coordinates of the shield in ith situation, based on the angular and linear observations (in two situations of the telescope). The determination of coordinates of the shield corners was carried out using the triple product of three vectors. Owing to them, the determination of the shield corners was carried out from the given below system of coordinates, assuming that the distance between three points (prisms) and their sought co-ordinates do not change (are constant). The discussed model reflecting the presented situation in the initial state is presented in figure 3.

Having data coordinates of thee geodetic prisms attached to the trolley moving on the rail of the comparative base of the trolley and also coordinates of the corners, the target shields, marked based on the orthogonal measurements method in the initial state (lower edge of the shield perpendicular to the trajectory axis of the base), the distances between them were determined, i.e.: d_1, d_2, d_3 (figure 3). The twist of the trajectory base, on which the trolley and shield with the prism is moving, changes the situation of the whole system towards the initial situation, i.e. “zero” situation (figure 4). The lack of straight line in the trajectory, transverse dislocations of the trolley during the move, apart of moving the model, also causes its twist in space. The degree of trajectory deformation and local movements of the trolley towards the edge of the rail perfectly describe measured prism and changes of their coordinates defined in the polar measurement with the application of a precise total station. The knowledge of new coordinates of prisms in subsequent situa-

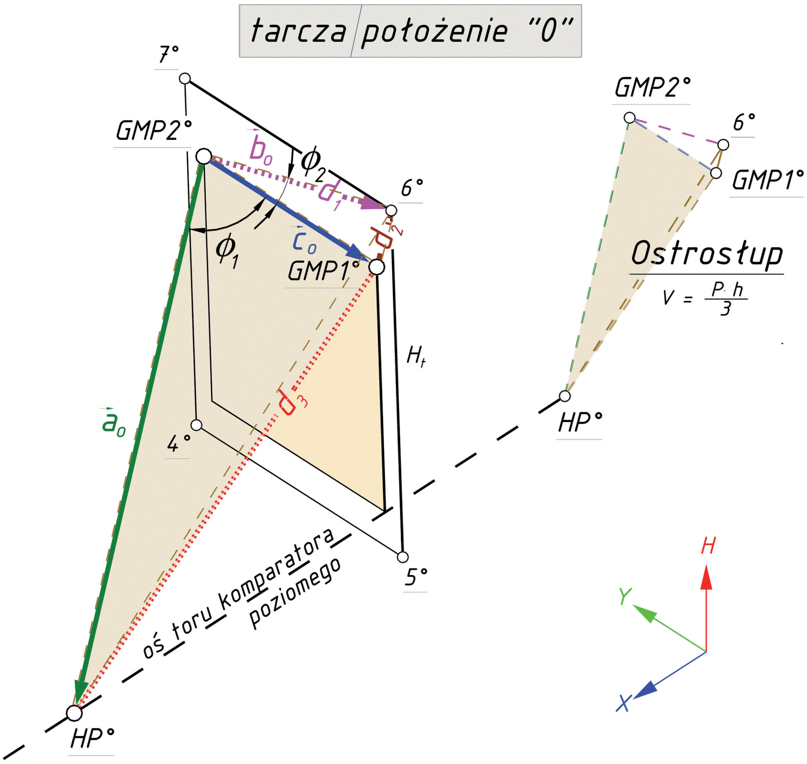

Fig. 3. Graphical illustration of the study model in the initial state "0". HP° – retro-reflector HP; GMP1° and GMP2° – precise mini prisms Leica; ϕ_1 and ϕ_2 – spatial angles between vectors a_o, b_o and c_o

Rys. 3. Graficzna ilustracja modelu badawczego w stanie początkowym „0". HP° – retroreflektor HP; GMP1° i GMP2° – precyzyjne mini pryzmaty Leica; ϕ_1 i ϕ_2 – kąty przestrzenne między wektorami a_o, b_o i c_o

tions of the trolley, assuming that the presented system is rigid, allows determination of new coordinates of the aluminium target shield making reference for scanning measurements, i.e. tests focused on the determination of the accuracy characteristics to make the distance measurement, based on the system of three equations:

$$\begin{cases}\cos\phi_1 = \dfrac{a^i_x b^i_x + a^i_y b^i_y + a^i_h b^i_h}{\sqrt{a_{0x}^2 + a_{0y}^2 + a_{0h}^2}\cdot\sqrt{b_{0x}^2 + b_{0y}^2 + b_{0h}^2}} \\ \cos\phi_2 = \dfrac{c^i_x b^i_x + c^i_y b^i_y + c^i_h b^i_h}{\sqrt{c_{0x}^2 + c_{0y}^2 + c_{0h}^2}\cdot\sqrt{b_{0x}^2 + b_{0y}^2 + b_{0h}^2}} \\ V = \dfrac{1}{6}\cdot\left|\vec{a}^i \times \vec{c}^i\right|\cdot\vec{b}^i \end{cases} \qquad (1)$$

where:

V – the volume of pyramids of the base in points HP°, MP1°, GMP2° and vertices in points: 6°, 7°, 5° i 4°.

ϕ_1, ϕ_2 – angles between two non-zero vectors in space;

$\left[a^i_x, a^i_y, a^i_h\right]$ – coordinates of vector $\vec{a}^i$, defined based on geodetic coordinates of the classically measured prisms in i^{th} situation of the analysed model;

$\left[c^i_x, c^i_y, c^i_h\right]$ – coordinates of vector $\vec{c}^i$ defined based on geodetic coordinates of the classically measured prisms in i^{th} situation of the analysed model;

$\left[a_{0x}, a_{0y}, a_{0h}\right], \left[b_{0x}, b_{0y}, b_{0h}\right], \left[c_{0x}, c_{0y}, c_{0h}\right]$ – coordinates of vectors $\vec{a}_0, \vec{b}_0, \vec{c}_0$ defined based on geodetic coordinates of the classically measured prisms in the initial situation of the analysed model;

$\vec{b}^i$ – sought vector anchored between the defined prism, and the determined point of the target shield of coordinates $\left[b^i_x, b^i_y, b^i_h\right]$.

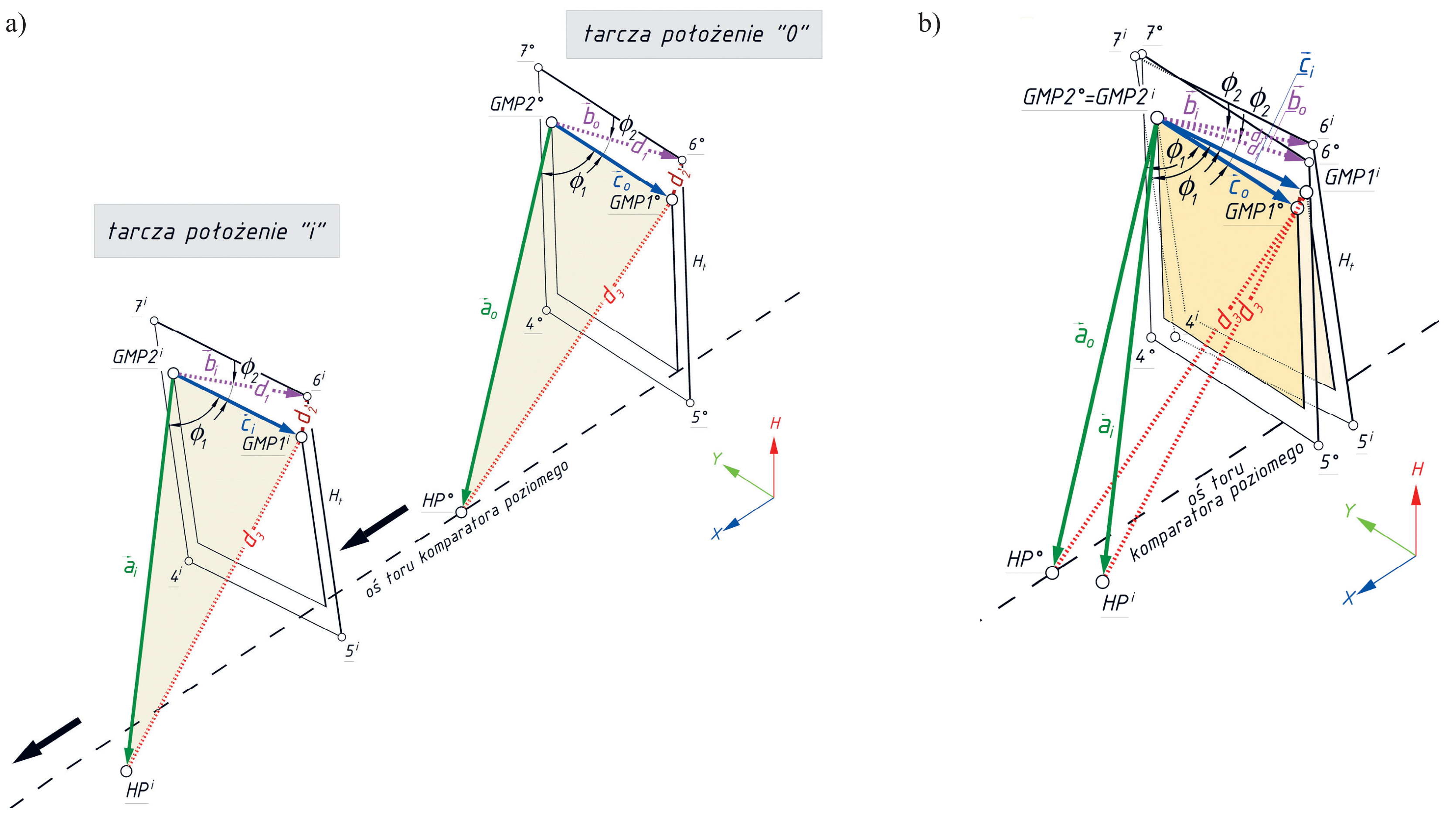

Fig. 4. Grafic interpretation of the behaviour of the system: a – in subsequent situations of the trolley (ith) in the respect to the initial situation (°) with the analysed values influencing the situation of the target shield; b – combining two systems in ith and zero situation. Explanations to figure: **HP^{i}, GMP1^{i}, GMP2^{i}** – geodetic mini prisms GMP101 in ith situation trolley in the accepted system coordinates; **4^{i}, 5^{i}, 6^{i}, 7^{i}** – corners of the shield in subsequent states

Rys. 4. Graficzna interpretacja zachowania układu: a – w kolejnych położeniach wózka (i-tych) względem położenia początkowego (°) wraz z wielkościami analizowanymi wpływającymi na zachowanie (położenie) tarczy celowniczej; b – złożenie dwóch układów w i-tym i zerowym położeniu. Objaśnienia do rysunku: **HP^{i}, GMP1^{i}, GMP2^{i}** – mini pryzmaty geodezyjne GMP101 w i-tym położeniu wózka w przyjętym układzie współrzędnych; **4^{i}, 5^{i}, 6^{i}, 7^{i}** – naroża tarczy w kolejnych stanach

Triple product of vectors $\left|\vec{a}^i \times \vec{c}^i\right| \cdot \vec{b}^i$ can be written in the form of matrix:

$$\left|\overrightarrow{a^i} \times \overrightarrow{c^i}\right| \cdot \vec{b}^i = \begin{vmatrix} a^i{}_x & a^i{}_y & a^i{}_h \\ c^i{}_x & c^i{}_y & c^i{}_h \\ b^i{}_x & b^i{}_y & b^i{}_h \end{vmatrix} = W^i \tag{2}$$

Having the constructed system of linear equations of 3 unknowns (formula 1) and making its transformations into the form:

$$\begin{cases} \cos\phi_1 \cdot \sqrt{a_{0x}{}^2 + a_{0y}{}^2 + a_{0h}{}^2} \cdot \sqrt{b_{0x}{}^2 + b_{0y}{}^2 + b_{0h}{}^2} = \\ \quad = a^i{}_x b^i{}_x + a^i{}_y b^i{}_y + a^i{}_h b^i{}_h \\ \cos\phi_2 \cdot \sqrt{c_{0x}{}^2 + c_{0y}{}^2 + c_{0h}{}^2} \cdot \sqrt{b_{0x}{}^2 + b_{0y}{}^2 + b_{0h}{}^2} = \\ \quad = c^i{}_x b^i{}_x + c^i{}_y b^i{}_y + c^i{}_h b^i{}_h \\ 6V = (a^i{}_y c^i{}_h - a^i{}_h c^i{}_y) \cdot b^i{}_x + (a^i{}_h c^i{}_x - a^i{}_x c^i{}_h) \cdot b^i{}_y + \\ \quad + (a^i{}_x c^i{}_y - a^i{}_y c^i{}_x) \cdot b^i{}_h \end{cases} \tag{3}$$

then the application of Cramer's formulae is possible. They take the form:

$$b^i{}_x = \frac{W^i{}_x}{W^i}, \quad b^i{}_y = \frac{W^i{}_y}{W^i}, \quad b^i{}_h = \frac{W^i{}_h}{W^i} \tag{4–6}$$

where:

W^i – main indicator of system made of coefficients with unknowns b^i_x, b^i_y, b^i_h;

W^i_x, W^i_y, W^i_h – indicators made of matrix W^i replacing subsequently first, second and its last column of absolute terms (constant – left side of the system – formula 3), due to which the coordinates of the sought vector $\vec{b}$ were found.

The obtained coordinates vector $\vec{b}^i = \left[b^i{}_x, b^i{}_y, b^i{}_h\right]$ allow the determination of spatial coordinates of the sought point (corners of the shield) in ith situation. I tak, e.g., dla point 6 coordinates defined from the relation:

$$X^i{}_6 = [b^i{}_x + X^i{}_{GMP2}], \tag{7}$$

$$Y^i{}_6 = [b^i{}_y + Y^i{}_{GMP2}], \tag{8}$$

$$H^i{}_6 = [b^i{}_h + H^i{}_{GMP2}], \tag{9}$$

Using the described algorithm, is caused by coordinates of the remaining points characteristic for the target shield (corners), i.e., points 5^i, 6^i, 7^i for ith situation of the trolley – figure 6.

The knowledge of the spatial coordinates of the corners of the shield (4^i, 5^i, 6^i, 7^i), defined based on the mentioned above parameters, allows determining the equation of the plane for each stand of the shield in the full range of the base.

The equation of the plane of the shield with the test material (varying in colour, texture, roughness), serves as a fundament of formulating length measurement errors based on the mapped within the shield points of test measurement of the scanning instrument. A typical, very simple tool to check the accuracy of reflectorless telemeters is the target shield fixed on classical tribrachs (also in the calibration of the systems of airborne laser scanning of flat objects – Skaloud J., Lichti D., 2006). The introduction of additional horizontal angular scale (Gawałkiewicz R., 2006), allows its twist towards the light beams emitted by the tested instrument. Such a study model allows us to additionally examine the influence of twisting the area under the inventory on the accuracy of the distance measurement.

In case of the application of the horizontal comparative base GLM AGH, determining base distance to retro-reflector HP is applied with the application of laser interferometer HP. It allows precise definition of the distance do one of the signals of the spatial system and determination the values of the dislocation of the trolley with the target shield in the differential measurement. The application of precise angular–telemeter instrument (S6 Trimble, TCA 2003 Leica), allowed the spatial coordinates of three prisms put on the trolley and indirectly defining 3D coordinates of moving alongside the axis of the trajectory of target shield. Due to the application of the base instruments of higher accuracy than test telemeters, determination of the accuracy characteristics of the distance measurement can be based on the theory of real errors. The development of traditional 2D system of interpretation errors in distance measurements with the application of scanning total stations and laser scanners, into 3D system, allows the determination of spatial distribution of real errors. In the analysis of distribution errors one can accept local system of coordinates that start in the middle of the scanning head (point P_1 of coordinates

$X_1 = 0.0$; $Y_1 = 0.0$; $H_1 = 0.0$) and axis X located alongside the axis of the comparative base. For a larger number of points mapped within the shield (P^i_2), accepted for the analysis, it is necessary to determine their theoretical situations on shield $P^{i''}_2$.

Coordinates of spatial points:

- scanning head of the scanning total station of scanner (X_1; Y_1; H_1);
- measurement points mapped in the light of the target shield P^i_2 (X^i_2; Y^i_2; H^i_2),

allow the determination of linear equations of the pencil of lines going trough the centre of the scanning head.

Thus the equation of the line is defined by the parametric form $\boldsymbol{l}_{P1P^i_2}$:

$$l_{P_1P^i_2} : \left\{ \begin{array}{l} x = x_1 + t(x^i_2 - x_1) \\ y = y_1 + t(y^i_2 - y_1) \\ h = h_1 + t(h^i_2 - h_1) \end{array} \right\},\ t \in \Re^3 \tag{10}$$

Moreover, the knowledge of spatial coordinates of selected 3 corners of shield (points P_5, P_6, P_7 – figure 5), allows the determination of parametric equation of plane, based on two independent vectors $\vec{u}, \vec{v}$. Thus the parametric equation takes form:

$$\prod_{P_5P_6P_7} : \left\{ \begin{array}{l} x = x_5 + \alpha(x_6 - x_5) + \beta(x_7 - x_5) \\ y = y_5 + \alpha(y_6 - y_5) + \beta(y_7 - y_5) \\ h = h_5 + \alpha(h_6 - h_5) + \beta(h_7 - h_5) \end{array} \right\} \tag{11}$$

In case, when straight line *l* passes the beginning of the system of coordinates (scanning head), the equation of line takes the form:

$$l_{P_1P^i_2} : \left\{ \begin{array}{l} x = t \cdot x^i_2 \\ y = t \cdot y^i_2 \\ h = t \cdot h^i_2 \end{array} \right. \tag{12}$$

Puncture point of line $\boldsymbol{l}_{P1P^i_2}$ with plane $\Pi_{P5,P6,P7}$ is expressed by the relationship:

$$\begin{aligned} \Pi_{P5,P6,P7} \cap l_{P1P^i_2} &: Ax^i_2 \cdot t + \\ &+ By^i_2 \cdot t + Ch^i_2 \cdot t + D = 0 \end{aligned} \tag{13}$$

Thus parameter *t* for any measurement point mapped on the target shield is defined by the formula:

$$t^i = \frac{-D}{Ax^i_2 + By^i_2 + Ch^i_2} \tag{14}$$

The definition of direction co-efficients A, B, C of the equation of plane *Π* in space is possible through the use of the definition of vector products. In case of independent vectors (non-zero) $\vec{u}, \vec{v}$:

$$\begin{aligned} \vec{N} = \vec{u} \times \vec{v} = &\left(\overbrace{\begin{vmatrix} y_6 - y_5; h_6 - h_5 \\ y_7 - y_5; h_7 - h_5 \end{vmatrix}}^{\text{A}} - \right. \\ &\left. - \overbrace{\begin{vmatrix} x_6 - x_5; h_6 - h_5 \\ x_7 - x_5; h_7 - h_5 \end{vmatrix}}^{\text{B}} + \overbrace{\begin{vmatrix} x_6 - x_5; y_6 - y_5 \\ x_7 - x_5; y_6 - y_5 \end{vmatrix}}^{\text{C}} \right) \end{aligned} \tag{15}$$

Thus the plane equation takes form (16):

$$\Pi_{P5,P6,P7} : A(x - x_5) + B(y - y_5) + C(h - h_5) = 0$$

$$\Pi_{P5,P6,P7} : Ax + By + Ch + (-Ax_5 - By_5 - Ch_5) = 0$$

Coordinates of the point of shield puncture with line P^i_2, i.e. the point equivalent to errorless situation of the mapped point $P^{i'}_2$ are:

$$\begin{aligned} P''^i_2 : (&\frac{-x^i_2 \cdot D}{Ax^i_2 + By^i_2 + Ch^i_2}; \\ &\frac{-y^i_2 \cdot D}{Ax^i_2 + By^i_2 + Ch^i_2}; \\ &\frac{-h^i_2 \cdot D}{Ax^i_2 + By^i_2 + Ch^i_2}) \end{aligned} \tag{16}$$

Real error of distance measurement m_{dC} is defined by the relationship:

$$\begin{aligned} m_d &= \left| \overline{P^i_2 P''^i_2} \right| = \\ &= \sqrt{(x''^i_2 - x^i_2)^2 + (y''^i_2 - y^i_2)^2 + (h''^i_2 - h^i_2)^2} \end{aligned} \tag{17}$$

A graphical interpretation of error in length measurement m_d is presented in figure 5.

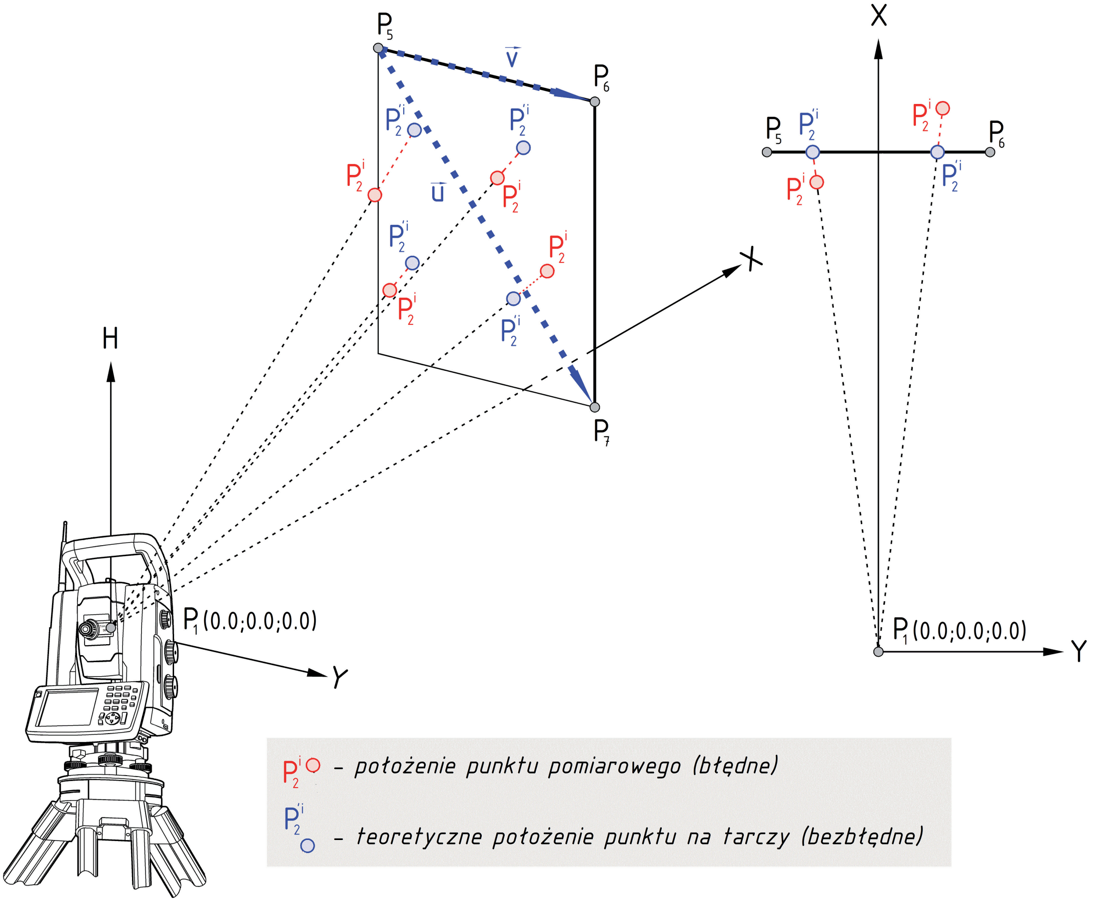

Fig. 5. Graphical interpretation of the model of the analyses of distance measurement errors: a – graphical interpretation of errors in perspective; b – view of the target shield with the mapped points (view from above)

Rys. 5. Graficzna interpretacja modelu analiz błędów pomiaru odległości: a – graficzna interpretacja błędów w perspektywie; b – widok tarczy celowniczej wraz z punktami odwzorowanymi (widok z góry)

4. CONCLUSIONS

The horizontal comparative base of Geodetic Metrological Laboratory AGH, is a practical tool of the accuracy control of measurement instruments based on fully automatic reflectorless angular–linear measurement in the scanning mode. Due to the application of laser interferometer Hewlett Packard of accuracy ±1.7ppm, the control of distance differences determined to the retro-reflector HP with the help of precise total station, used to determine coordinates of all the return signals included in the rigid trolley and shield system moving alongside the trajectory. The determination of coordinates of prisms and the target shield linked with them, giving the possibility of mathematical definition of the measurement system in space. Made in such a way geometryc system based on the measurement of the angles of horizontal and vertical skewed distances to reference points (return signals attached to the trolley) at the application of laser interferometer HP and precise total station, allows spatial analysis of the shield. Apart from this, the combination of these data with the set of points projected in the scanning measurement of the tested scanning instrument on the shield surface in the calculation sheet Excel, by Microsoft, fully allows us to make conclusions about the distribution of errors m_d and allows its visualization in the form of the chart of the mean values or export of these data to the programmes of 3D graphics and their 3D presentation e.g., in program Surfer by Golden Software.

In case of the application of scanning total stations and scanners in works connected with documenting architecture details and post-exploitation mining excavations, in the close range distances, the range of the comparative base GLM AGH seems to be a sufficient interval of the telemeters' control. The advantage of the base is "flexibility" in the distribution of shield alongside the trajectory of the comparator, which enabled us to check the accuracy of tested instruments for any distance within the length range of the base. This allows the definition of the trend in the parameter of length measurement accuracy (mean error distance m_d), which has a significant influence on the results of the modelling of the objects under the inventory. Thus, often in case of the application of different scanning instruments, obtaining a high accuracy of point models depends not only on the size of laser spot, the kind of telemeter, but also on a proper selection of measurement check-points for the scanned element (distance: instrument – object).

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