http://dx.doi.org/10.15576/GLL/2014.4.25

GLL

Geomatics, Landmanagement and Landscape No. 4 • 2014, 25–35

THE PROBLEM OF HORIZONTAL REFRACTION IN SETTING OUT TUNNEL CONTROL NETWORKS

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Summary

The paper presents the problem of the influence of non-uniform horizontal refraction field of the measurement environment on the results of determining the astronomical azimuths and transferring the coordinates in the geodetic tunnel network. The concept of a modular network alignment with simultaneous elimination of the effects of horizontal refraction is presented. Automatic TOTAL STATION and the results of precise angles and distances measurements allow currently effective multi stage linear-angular networks adjustment during tunnelling. The results of the innovative group tunnel networks adjustments are the coordinates of the network points and the elimination of existing disruptions in the course of the sight line. The results achieved so far for theoretical studies of horizontal refraction elimination and error ellipses forecasts for long tunnel networks were presented.

Keywords

tunnelling • horizontal tunnel network with traverses • multi stage alignment • azimuth transfer • elimination of horizontal refraction

1. Introduction

Geometry of the sight line and in particular its unilateral deviation – horizontal refraction, is of fundamental importance in determining the astronomical azimuth or direction angle during the setting out of the tunnel. Local conditions in the measuring environment in the tunnel, such as: inhomogeneous field of atmospheric air temperature gradients, humidity and air currents, fumes, dust rock, darkness, shocks, vibrations and others, cause significant disruption in the course of light waves and measurements of angles and distances, and as a result they reduce significantly the accuracy of results of geodetic observations. Significant influence on the accurate determination of direction has the horizontal refraction caused by large gradients of air temperature in the vicinity of the tunnel walls, the value of which can reach up to more than 2° C. The temperature of the Alps rocks is up to 50° C at the depth of 1000 m and at the depth of 300 m to 30° C [Hennes 1998]. For several years a detailed theoretical and experimental studies are conducted to develop alternative strategies to minimize the influence of refraction

[Beluch 1990, Beluch and Bryś 2010, Bryś and Osada 2010, Hennes 1998, Hennes et al. 1998, Heister 1997, Korrittke 1992, Wilhelm 1993]. The problem is particularly important in the case of long (up to more than twenty kilometres), tunnel control network. Currently the longest tunnels in the world are: SEIKAN-TUNEL – 53.850 km (Japan), EUROTUNEL – 49.940 km (the English Channel) and GOTTHARD-BASISTUNNEL – 57.000 km (Switzerland).

Detailed simulation analysis of the influence of the horizontal refraction for established for the entire length of the tunnel, realistic and permanent transverse temperature gradient of 0.1 K · m^{-1} showed for the length of 12 km deviation in the direction of 6.62 m. The accuracy required currently for the breakthrough in the transverse direction is from 1 to 2 cm · km^{-1}. These data clearly confirm the importance and significance of the problem of the negative influence of refraction during the setting up work. In the fundamental publication the author [Korritke 1992] reported about the difference in the sum of the apical angles determined using a theodolite and a gyrotheodolite obtained in the course of Eurotunnel setting up, amounting 47.0 mgon · 2800 m^{-1}, which corresponds to the transverse deviation of 1.11 m in the direction of the tunnel axis. During the measurement campaign in March 1989, in the traverse of "serpentine" course, the author finds that on the length of 6.487 km lateral deviation amounts + 1.052 m. Subsequent control traverse measurements made strictly in the axis of the bored tunnel showed in continuation unexpected linear deviation of + 0.521 m · 13.85 km^{-1} [Korrittke 1997]. As a result, the concept of surveying in the tunnel was changed and additional, time-consuming observations of astronomical azimuths using GYROMAT 3000 were introduced for on average every 6th side of the traverse to define a correction for horizontal directions. Figure 1 shows the results of analysis of the influence of the horizontal refraction on the deviation of the direction for alternative cases of locations of traverses and for different values of temperature gradients in a tunnel with a length of 12.600 km and the theoretical length of the sides of the traverse with a length of 600 m. The lengths of the sides applied in straight tunnels average from 300 to 450 m.

As results from above data, both theoretical analyses and the results of geodetic measurements of long traverse networks confirm the presence of significant systematic influence of refraction on the values of coordinates deviations, significantly exceeding the precision requirements imposed on modern measurements of tunnel (Bryś i Osada 2010).

Minimization of the effect of the horizontal refraction in determining the azimuthal angle or astronomical azimuth and most probable coordinates values for points of the control network can currently be obtained in the following ways:

- Through the control measurements of astronomical azimuths using gyrotheodolites of latest generation (GIROMAT 5000) with a standard deviation of 0.8 mgon (the so-called "internal") and 1.7 mgon (the standard "external" deviation) and the introduction of appropriate correction to the measured or set out directions. This method is a measuring strategy currently most commonly used in the setting out works fort long tunnels, but effective on sections of the underground network from 1.5 kilometres.

- Introduction of physical amendments to the measured angles / directions. The method practicable for use only during the research in experimental tunnels, it requires extensive work. Impossible during tunnel setting out surveying.
- The use of appropriately designed geodetic networks structures and the strict alignment of measurements and coordinates of control network points. Auxiliary control gyrotheodolite measurements. Optimal and widely used method.
- Measurement of horizontal angles of the network using THEODOLITE-DYSPERSOMETER [Hennes et al. 1998], i.e. electronic total station equipped with two or trichromatic carrier waves. These instruments are currently being used as prototypes in laboratory and experimental measurements in tunnels.
- The simultaneous use of a combination of several ways to minimize the influence of refraction, which often is done in geodetic tunnel measurements.

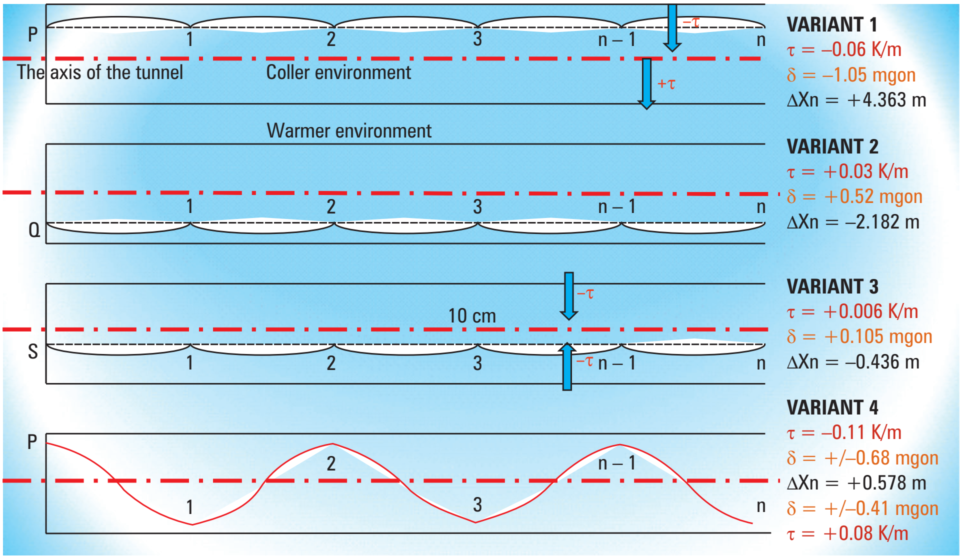

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Fig. 1. The effects of horizontal refraction for 4 variants of the location and the course of traverses in the tunnel for the following data: $L = 12.600$ km – length of the traverse, $D = 600\ m$ – the lengths of the sides, and τ – horizontal air temperature gradient perpendicular to the wall of the tunnel, δ – partial angle of horizontal refraction, ΔX_n – lateral deviation in the direction of the tunnel axis

Implementation of modern tunnel network in the case of bilateral horizontal tunnelling, requires its connection to a superior portal networks (before the entrance to the tunnel) and satellite networks, as shown graphically in Figure 2.

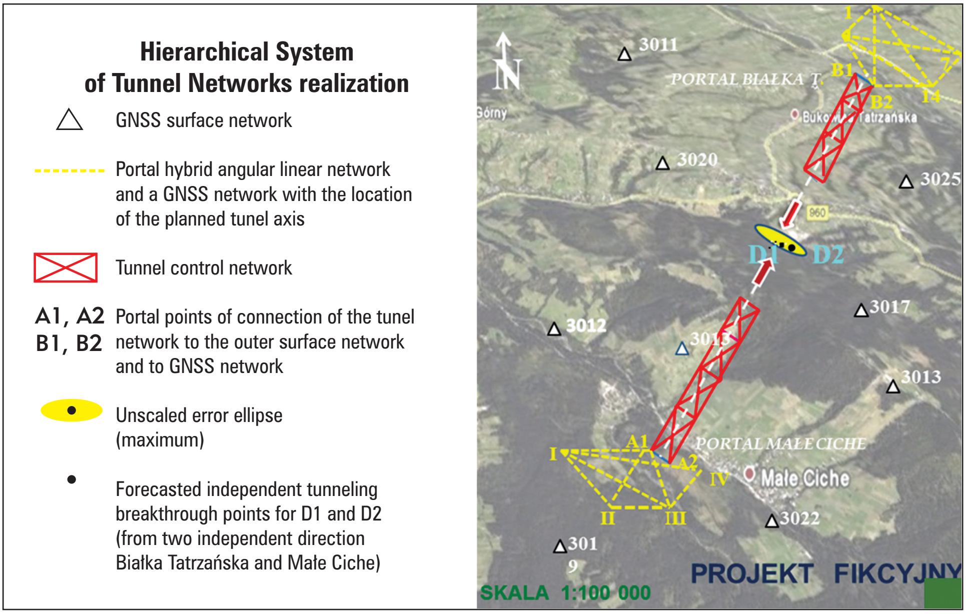

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Fig. 2. The structure of geodetic networks for the tunneling of long tunnels

The author present the results of theoretical research work on the innovative multi stage method of adjustment of a symmetrical control network with traverses assuming lack of knowledge asymmetrically occurring partial angles of horizontal refraction during the measurement process. The aim of adjustments of the network coordinates based on simulated data of horizontal angles and length of sides, was to demonstrate that the elimination of the systematic influence of side refraction in the horizontal control networks is possible and fully realistic.

2. Line-angle modular tunnel network with traverses

Traditional, single and double, open traverses – straight and serpentine, has always been critically evaluated horizontal networks for the carrying out of the tunnel measurements in the absence of any controls of the sum of the apical angles closure. They are the simplest, but now exceptionally used tunnel networks. Currently, the most commonly used control networks structures are different combinations of linear-angular networks [Beluch 1991, Beluch and Bryś 2000]. The author present a hybrid-modular model of a special network constructed of intersecting traverses with additional segments – traverses and the traverse networks along the side walls (the walls of the excavation) of the tunnel. As shown by the results of the model adjustments, presented variant of the optimized linear-angular network is a structure of the network characterized by an almost total elimination of the partial angles of the horizontal refraction. The principle of strict alignment of coordinates of simulation network consists in the group, successive step adjustments, from the portal to the front of the driven tunnel. Alignment is performed by ReTuNetz autor's computer program based on the program MATHCAD 14. The entire section of being gradually extended tunnel network is divided into n equal parts (in presented calculation example of 1800 m), adjusted in sequence together with the progress of drilling works.

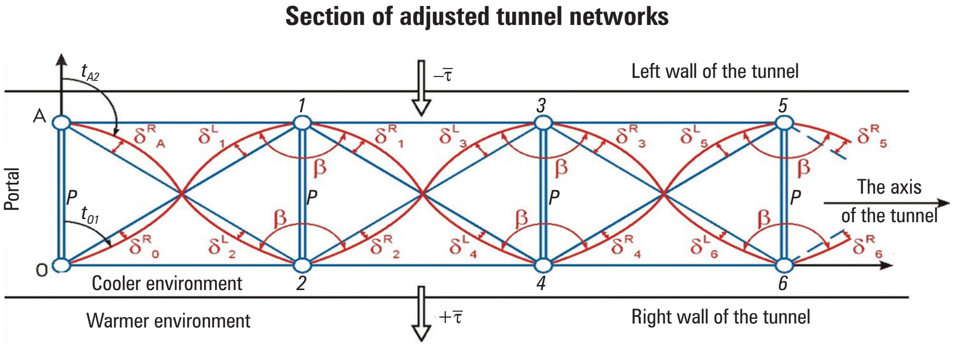

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Fig. 3. Part of a horizontal tunnel hybrid network with the course of the deformed lines of sight in a heterogeneous field of refraction

After every stage adjustment are obtained the coordinates of the points of cross-beams network being the basis for the further carrying out of the surveying tasks, i.e. setting out working points of the network as free positions using motorized instruments of TOTAL STATION type. From this positions the fixed positioning of the direction is performed on the monitor of the control system of the drilling machine TBM (Tunnel-Bohring-Machine) and control of the geometric parameters of the proper drilling of the excavation of the tunnel – horizontally and vertically.

3. Algorithm of a hybrid tunnel network alignment and example of calculations

Functional model of a stage alignment of the presented tunnel network with effective elimination of partial refraction angles according to the Least Squares Method rules designed on the basis of the following algorithm in matrix notation:

$v = Ax + l$ – vector of measurements correction (1)

$N = A^T PA$ – matrix of normal equations (2)

$Q = N^{-1}$ – matrix of weights reverses (3)

$n = A^T Pl$ – vector of constant terms in the normal equations system (4)

(P = weight matrix)

$x = (A^T PA)^{-1} A^T Pl$ – vector of unknowns – adjusted results (5)

$C_X = (A^T PA)^{-1}$ $i = 1, 2$ – covariance matrix of adjusted coordinates (6)

Network points and refraction angles

$A^T Pv$ – adjustment control (7)

where:

- $\boldsymbol{A}$ – matrix of coefficients (partial derivatives),
- $\boldsymbol{l}$ – matrix of shortened constant terms.

$$S_0 = \sqrt{\frac{v^T Pv}{w-u}} \quad \text{– standard deviation of an observation with weight } p = 1 \tag{8}$$

$$S_{l_i} = S_0 \cdot \sqrt{Q_{l_i l_i}} \quad \text{– standard deviation of an observation after adjustment} \tag{9}$$

where:

$Q_{l_i l_i} = AQA^T$
w – number of observations,
u – number of unknowns,
$w - u = r$ – number of redundant observations.

$$|v_i| \le k \cdot S_0 \quad \text{– test of standardized corrections} \tag{10}$$

$$S(t)^2 = S_{X_i}^2 \cdot \cos(t)^2 + S_{X_i Y_i} \cdot \sin(2t) + S_{Y_i}^2 \cdot \sin(t)^2 \tag{11}$$

Equation (11) describes the curve of the position error of a point of the relative error ellipse with semiaxes A and B in either direction angle or azimuth t.

This equation enables user to determine deviations of the measurement dependent of the direction. For the direction angles $t_A = 0^g.0000$ and $t_B = 100^g.0000$, we obtain for the semiaxes A and B of the relative unscaled error ellipse (Figure 4):

$$A = S(t)_A = S_Q \quad \text{and} \quad B = S(t)_B = S_L$$

where: S_Q i S_L are radial vectors of the relative error curve (11).

Results of staged adjustments are believed to be correct, if they met the condition: $S_0 \cong 1.0$, with the possible tolerance not exceeding 10%.

For test adjustments of consecutive parts of the tunnel network, the following realistic measurement data, standard deviations and the partial horizontal refraction the angles were assumed:

$L = 1800.00$ m – length of the part of the simulated network,

$D = 600.00$ m – length of the sides of the network,

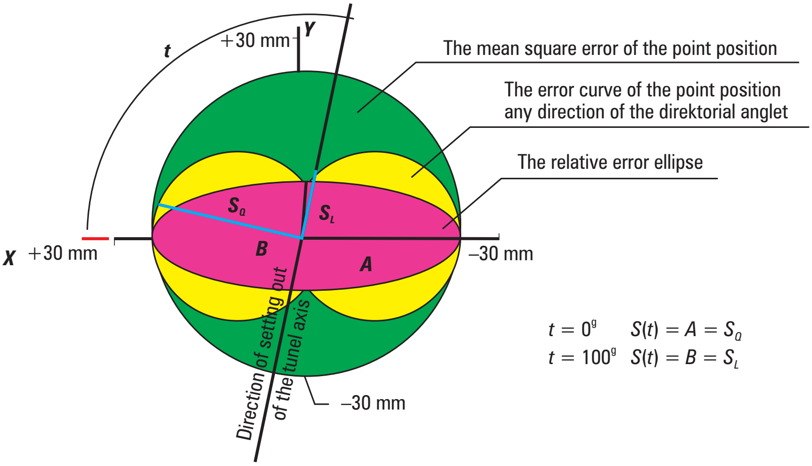
$p = 5.00$ m – crossbeams lengths,

$\beta = 198^g.9380$ – the bend angles (apical),

$t_{A_2} = 100^g.5305$ – initial directional angle of tunnel network connection,

$S_{tA2} = 0.2$ mgon, $S_\beta = 0.2$ mgon, $S_D = 1.0$ mm, $S_p = 1.0$ mm,

$\delta =$ from 0.2 mgon to 0.8 mgon – partial angles of horizontal refraction.



Source: author's study

Fig. 4. Graphic image of curves characterizing the deviations of points coordinates of tunnel network after simulation adjustment

Separate analysis of the systematic deviations and random errors of the tunnel network allows to estimate the influence of refraction on directional angles and coordinates X for the whole adjusted hybrid network and the network in the form of "serpentine" traverses (O, 1, 4, 5, … *n* and A, 2, 3, 6, … *n*). The lateral deviation of the *X* coordinate of the end for "serpentine" running traverse without adjustment can be calculated according to the following formula in the arc angle measure [Beluch and Bryś 2000]:

$$Q_{Pn} = \Delta Y_{An} \cdot \left|\delta_A^R\right| - \Delta Y_{2n} \cdot \left|\delta_2^L + \delta_2^R\right| + \Delta Y_{3n} \cdot \left|\delta_3^L + \delta_3^R\right| - \Delta Y_{6n} \cdot \left|\delta_6^L + \delta_6^R\right| + \ldots \pm \Delta Y_{(n-1)n} \cdot \left|\delta_{(n-1)n}^L + \delta_{(n-1)n}^R\right| \quad (12)$$

where:

δ_i^R, δ_i^L – partial angles of horizontal refraction (Figure 3).

To evaluate minimization of systematic refraction influence in implemented modular tunnel network the author propose that the following criterion of external reliability should be used:

Table 1. Summary of the results of the simulation adjustments, calculation of deviation of the tunnel hybrid network model and breakthrough forecasts

Section of network	Lengths: of network section/ Network side [m]	Simulated angles of refraction [mgon]		Network point number	Adjusted *X* coordinates Mean deviation Average *X* of crossbeams The outer reliability factor *Zi*	Standard deviation S_X S_O forecasts for S_X S_O [mm]	Lateral deviation without adjustment of refraction [mm]
		Left wall of the tunnel	Right wall of the tunnel				
1	2	3	4	5	6	7	8
A	1 800/600	0.4	0.2	8 7	+5.001 +0.001 +2.500 0.4403	7.6 1.0 7.5 1.1	+11.3 +5.5
A + B	3 600/600	0.4 0.6	0.2 0.4	13 14	+5.011 +0.011 +2.511 0.4467	17.4 1.01 17.4 1.5	+32.1 +35.8
A + B + C	5 400/600	0.4 0.8 0.8	0.2 0.4 0.6	20 19	+5.025 +0.001 +2.525 0.6160	29.3 1.07 29.3 1.8	+81.1 +71.5
A + B + C + D	7 200/600	0.4 0.8 0.6 0.8	0.2 0.4 0.6 0.6	25 26	+5.015 +0.014 +2.514 0.6819	43.1 1.07 43.1 2.1	+133.9 +137.1
A + B + C + D + E	9 000/600	0.4 0.8 0.6 0.8 0.8	0.2 0.6 0.4 0.6 0.6	32 31	+5.011 +0.011 +2.510 0.7238	58.6 1.04 58.6 2.4	+216.7 +207.6

A + B + C + D + E + F	10 080/600	0.4 0.6 0.8	0.8 0.8 0.8	0.2 0.4 0.6	0.6 0.6 0.6	37 38	+5.004 +0.004 +2.504 0.7575	75.5 1.09 75.5 2.6	+312.6 +310.2
A + B + C + D + E + F + G	12 600/600	0.4 0.6 0.8 0.8	0.8 0.8 0.8	0.2 0.4 0.6 0.6	0.6 0.6 0.6	43 44	+5.003 +0.004 +2.504 0.7782	94.1 1.05 94.0 2.8	+435.6 +411.9

Source: Bryś and Osada 2010

$$Z_i = 1 - \frac{Sx^2}{Q_{PM}^2} \tag{13}$$

where:

S_X – the standard deviation of the X coordinate for the stepwise adjustment,

Q_{PM} – average deviation of the X coordinate of the point from two traverses.

The increase in the value of Z together with the length of the network part means an increase in its reliability, as well as the degree of efficiency in minimizing the impact of refraction on the determined X coordinates. Detailed results of the simulated stepwise adjustments based on realistic angles of horizontal refraction are presented in Table 1.

Analysis of the results of the strict adjustment of the optimized tunnel network (Figure 3) showed unequivocally that it is possible to eliminate effectively asymmetrical horizontal refraction caused by non-uniform temperature field. The deviation of the last X coordinate of the network (Table 1, column 6, D = 12.600 km) amounts to 4 mm, and is insignificantly small in relation to the predicted value of the semiaxis A of the relative error ellipse SQ = 94 mm. While the average lateral deviation of the end points of nonadjustable, "serpentine" traverses is equal 43 cm (Table 1, column 8) and significantly exceeds the precision requirements imposed on forecast values of the tunnel breakthrough using techniques and technologies of the latest generation (automated TOTAL STATION).

4. Conclusions

- Non-homogeneous field of refraction in measurement environment occurring in close proximity to the tunnel walls (approx. 30 cm), produces systematic deviation of direction, which can be up to 10 mgon/400 m.
- Measurement errors analysis showed that the greatest impact on the lateral deviation of the X coordinate of the end points of the network are induced by the effects of refraction on the first horizontal directions of the sides of the network, just behind the portal. This fact is of fundamental importance in planning, design and modification of the geometry of the network and in strategies of minimizing the impact of the horizontal refraction phenomenon in the performance of precise angular measurements and transmission of directional angle or azimuth.
- The proposed variant of the modular tunnel network with the crossbeams, thanks to the large number of redundant elements, is characterized by a higher internal reliability.
- Setting out precise direction angle or azimuth and the X coordinate with a submillimeter accuracy is currently obtained with the use of motorized total stations with automatic tracking of the prisms on the points of the network, and specialized software such as: *SmartWorx* – standard software*: RoadRunner Tunnel – LEICA GEOSYSTEMS*.

- Presented in the work, modular network alignment method with effective elimination of the phenomenon of refraction is an alternative to traditional methods of realization of tunnel control networks of special purpose.
- If the results of investigations of model modular networks in geodesic practice are confirmed then carrying out time-consuming measurements of astronomical azimuths using precision gyrotheodolites with an "external" standard deviation of 1.7 mgon and introducing the necessary directions corrections, would become unnecessary.

References

Beluch J. 1991. Chains of elongated figures as control networks in mines and tunnels. Applications of Geodesy to Engineering, Symposium No 108, Springer Verlag, Stuttgart.

Beluch J., Bryś H. 2000. Minimisation of the effect of horizontal refraction on the accuracy of breaking through in underground drivages. 11th International Congress of the International Society of Mining Surveying, Kraków, September, vol. 1.

Bryś H., Osada E. 2010. Zur Problematik der Minimierung des Einflusses der Horizontalrefraktion in Tunneln-Vortriebs-Lagenetzen, Allgemeine Vermessungs-Nachrichten, 2.

Hennes M. 1998. Zum Einfluss inhomogener Brechungsindexfelder auf die Verschwenkung offener Polygonzüge am Beispiel des Tunnelvortriebs. Institut für Geodäsie und Photogrammetrie an der Eidgenössischen Technischen Hochschule Zürich, Mitteilungen, 65.

Hennes M., Böckem B., Flach P. 1998. Recent developments for refraction free optical measurements. Paper to FIG, XXI International Congress, Brighton, 19–26 July.

Heister H. 1997. Experimentelle Untersuchungen zur Horizontalrefraktion im Tunnelbau. IX. Int. Geodätische Woche, Obergurgl. Institutmitteilungen, 17, Fachvorträge, Universität Innsbruck, Institut für Geodäsie.

Korittke N. 1992. Horizontalrefraktion in langen Tunneln. XI. Int. Kurs für Ingenieurvermessung, Zürich, 2, IV/4, Dümmler Verlag, Bonn.

Korittke N. 1997. Zur Anwendung hochpräziser Kreiselmessungen im Bergbau und Tunnelbau. DMT-Berichte aus Forschung und Entwicklung, 65, Essen.

Wilhelm W. 1993. Empirische Bestimmung der Seitenrefraktion an 10 Objekten der Praxis. Bericht 219, IGP, Eidgenössische Technische Hochschule, Zürich.

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