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Review / Pregledni znanstveni članak

Astrogeodetic Methodology Evaluation for Vertical Deflection Determination in Oil and Gas Exploration: A Case Study in a Ukrainian Deposit

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ABSTRACT. Despite the global efforts to transition towards environmentally friendly energy sources, traditional resources such as oil and gas continue to play a crucial role in meeting energy demands. The features of the following geophysical methods application for mineral exploration are considered: magnetic, electrical, radioactive, seismic, well logging, as well as multispectral aerospace surveys and field spectrometry. Among these methods, the gravity method, specifically its astrogeodetic variant utilizing zenith cameras and GPS positioning, emerges as a highly effective approach for detecting oil and gas deposits. A comprehensive review of literature sources and patent documentation is conducted, focusing on the construction and accuracy characteristics of both analog and digital zenith cameras. The methodology involving a digital zenith camera and GPS receiver for determining the deflections of the vertical in a test site within the Chernihiv region (Ukraine) is examined. The positive results obtained from this exploration not only validate the effectiveness of the approach but also enable the possibility

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of oil-bearing horizons identification. The paper derives formulas for calculating the accuracy of the deflections of the vertical determinations through the astrogeodetic method, specifically tailored for local areas. These formulas empower researchers to conduct a priori accuracy calculations, facilitating the determination of permissible distances between zenith cameras and GPS receivers when installed separately, ranging from 1.05 m to 1.76 m.

Keywords: zenith camera, deflections of the vertical, astrogeodetic method, oil deposits, mineral exploration methods.

1. Introduction

In contemporary times, there is a growing global emphasis on utilizing renewable sources such as wind and solar energy for environmental sustainability. Despite this shift, conventional energy resources like oil and gas remain pivotal in both fuel and raw material aspects, particularly in the chemical industry.

Various methods are employed in the exploration of mineral deposits, with traditional approaches involving drilling wells and excavating pits to gather geological information about rock compositions.

While this method yields objective data, it is associated with substantial costs and time requirements. Blindly conducting pit or well drilling without a prior understanding of rock compositions can lead to non-representative findings (Sokolov and Chernykh 2015).

To address these challenges, indirect methods of mineral exploration, including geophysical techniques, are increasingly employed. The magnetic exploration method, for instance, relies on studying the Earth's surface magnetic field, which varies based on the magnetic properties of minerals and surrounding rocks. This method holds prominence in the search and exploration of magnetic iron ores and less magnetic minerals. Additionally, it finds applications in the geological study of the Earth's crust, deep geology, tectonics, and geological mapping, as evidenced by studies (Maurya et al. 2018, Sokolov and Chernykh 2015).

The electrical exploration method relies on discerning the natural and artificial electric fields emanating from ore bodies or other geological formations. This approach capitalizes on variations in the conductivity of electric current exhibited by ores and the surrounding rocks. Numerous adaptations of the electrical exploration method have proven successful in the search for copper-pyrite and other polymetallic sulfide deposits (Sokolov and Chernykh 2015).

In radioactive exploration, the method centers on measuring the degree of radioactivity in rocks. This technique is instrumental in exploring ores containing radioactive elements and is applied to identify and survey zones of tectonic faults. Additionally, it is partially employed for mapping certain types of rocks, especially those with acidic eruptions (Sokolov and Chernykh 2015).

Seismic exploration utilizes disparities in the propagation speeds of elastic waves within different rocks, induced by artificial explosions. Presently, this method has gained considerable traction in the study of deep geology and tectonics. It is particularly effective in the exploration of oil-bearing and gas-bearing structures, marking a significant advancement in the field (Sokolov and Chernykh 2015).

The gravity exploration method involves assessing the gravity field, which undergoes variations based on the density (specific gravity) of ore bodies or other geological features. Widely employed in deep geology, this method proves instrumental in locating salt domes, oil-bearing and gas-bearing structures, as well as identifying and tracing coal-bearing basins (Essa and Géraud 2020, Sokolov and Chernykh 2015).

Crucial to determining hydrocarbon deposits within the Earth's gravity field are the deflections of the vertical (DOV) (Colic et al. 1996). DOV can be ascertained through gravity field models or astrogeodetic observations. However, gravity field models exhibit a drawback in their low spatial resolution, particularly when searching for hydrocarbon deposits in a localized area. For instance, the widely known EGM2008 model, defined on a 5' angular coordinate grid, provides limited spatial resolution (Pavlis et al. 2012). Conversely, the Word Gravity Map 2012 features a resolution of 2' x 2' (Savchuk and Fedorchuk 2024), while the XGM2019e model, with a maximum degree of 5540, includes topography signals and offers a 2' resolution (Zhang et al. 2023).

To enhance the density of DOV determinations and unveil local variations in the gravity field, the astrogeodetic method for DOV determination is employed. This approach involves the installation of a digital zenith camera and GPS receiver at observation points with sufficient density, allowing for a comprehensive study of the gravity field in the local area.

Geophysical surveys conducted in wells, commonly known as well logging, serve the purpose of refining geological section documentation within wells and assessing the technical condition of these structures. These surveys leverage various rock properties, including electrical conductivity, radioactivity, and magnetic characteristics, to identify and analyze geological formations (Mwenifumbo et al. 2014, Sokolov and Chernykh 2015).

Remote reconnaissance methods involve the registration of electromagnetic radiation emitted from the Earth's surface and interior. These methods encompass multispectral aerospace surveys and field spectrometry, primarily employed in the exploration of hydrocarbons, ores, and non-metallic resources on both terrestrial and sea shelves (Lyalko and Popov 2017).

The integration of geophysical and remote exploration methods, such as magnetic and electromagnetic surveys or satellite imagery, enables researchers to gain a preliminary understanding of the geological structure in research areas. Recognized mineral identification methods include the traditional approaches of well pitting and drilling. Notably, the application of geophysical and remote exploration methods, like magnetic surveys and satellite imagery analyses, proves instrumental in significantly reducing the time and costs associated with drilling and excavation during mineral exploration.

For the exploration of oil and gas deposits, the most effective methods involve seismic studies, remote sensing techniques, and gravity surveys. The advancement of modern digital technologies and positioning tools has notably propelled improvements in the astrogeodetic method of Deflection of Vertical (DOV) determination. This method, in turn, facilitates the implementation of the gravity exploration method for investigating oil-bearing and gas-bearing structures.

This study aims to comprehensively review the instrumentation of the astrogeodetic method for DOV determination and its practical application within a Ukrainian oil deposit. Furthermore, it seeks to develop a formula for calculating the accuracy of DOV determination in a local area and determine the permissible distance between the zenith camera and GPS receiver for their separate installation.

2. Zenith cameras for the deflections of the vertical determination

In the early stages of astro-geodetic Deflection of Vertical (DOV) determinations, observations were conducted through the visual method using specialized tools such as DKM3A, T4, and Astrolabes (Hirt and Bürki 2006). Subsequently, the Institute of Geodesy at the University of Hanover developed photographic zenith cameras TZK 1, 2, and 3 between 1974 and 1981 (Gessler 1975, Wissel 1982). These cameras played a crucial role in determining astronomical and geodetic DOV, studying geoid waviness, and supporting various geophysical applications in countries including Switzerland, Austria, and Germany.

The operation of photographic zenith cameras marked a pivotal moment in survey automation. Capturing images of observed stars eliminated potential observational errors, substantially enhancing the precision of stellar position measurements. However, a notable drawback of photographic zenith cameras was the manual measurement requirement for star coordinates, a process that could be time-consuming and introduce potential inaccuracies into the data. These methods remained prevalent in geodetic astronomy until the 1990s (Hirt and Bürki 2006).

A noteworthy example of this technology is the TZK1 mobile zenith camera, developed at the Hannover Institute of Geodesy, illustrated in Fig. 1 (Hirt et al. 2006).

In recent decades, geodetic astronomy has experienced a transformative shift from analog measurement techniques, primarily reliant on visual and photographic methods, to digital methodologies employing charge-coupled devices (CCD). This transition has significantly enhanced the accuracy of Deflection of Vertical (DOV) observations by approximately an order of magnitude, concurrently reducing observation times (Hirt and Seeber 2008). Moreover, the sensitivity of CCD sensors surpasses that of film by approximately 20–30 times, allowing for the detection of stars with lower magnitudes (Fosu et al. 1998). A noteworthy advancement in this digital era is the development of the Digital Zenith Camera (DZCS) in Hanover and Zurich (Hirt 2006). Functioning as a mobile and fully automated device, the DZCS relies on CCD technology and high-precision star catalogs. CCD sensors, widely utilized in geodesy (Hirt and Seeber 2008) and astronomy (Fosu et al. 1998), serve as efficient image sensors.

In an article (Hirt et al. 2006) a methodology combining satellite and ground-based measurements is outlined to validate the accuracy of the gravimetric model of a quasi-geoid in the German Alps. Utilizing the zenith camera TZK2-D, the authors report DOV measurement accuracy ranging from 0.08” to 0.10”. This approach entails a time-efficient process of approximately 20 minutes per station for astronomical observations and subsequent data processing. Subsequent analyses, considering measurements from the TZK2-D instrument (Hirt and Bürki 2006, Wissel 1982), revealed an improved DOV measurement accuracy of 0.05” – 0.08” since 2005. Achieving an accuracy of 0.05” typically requires one hour of observations per station, highlighting the efficiency of the observation technology outlined in (Hirt 2006, Hirt and Seeber 2008) in comparison to analog instruments used previously in geodetic astronomy.

According to studies by Bürki (1989) and Wissel (1982), the accuracy of DOV determination using traditional analog instruments was limited to 0.3” to 0.5”. Additionally, works (Gladilin et al. 2019, Tereshchuk et al. 2019) provide a comprehensive analysis of GPS positioning accuracy based on the theory of measurement errors.

Over the past decade in Turkey, there has been a pressing need to modernize the vertical datum. The evaluation of existing geoid models and global geopotential models in Turkey has been pivotal, requiring testing through the application of astronomical and geodetic (DOV) methods (Halicioglu et al. 2012). Addressing these challenges, Turkey introduced its first digital zenith camera, known as the Astro-geodetic Camera SYStem (ACSYS), in 2015 (Fig. 2), the ACSYS comprises essential components such as a Schmidt-Cassegrain telescope, a power supply, CCD sensors, and a GPS receiver (Halicioglu et al. 2016). This technological advancement signifies a significant step forward in enhancing precision and efficiency in geodetic observations within the Turkish vertical datum.

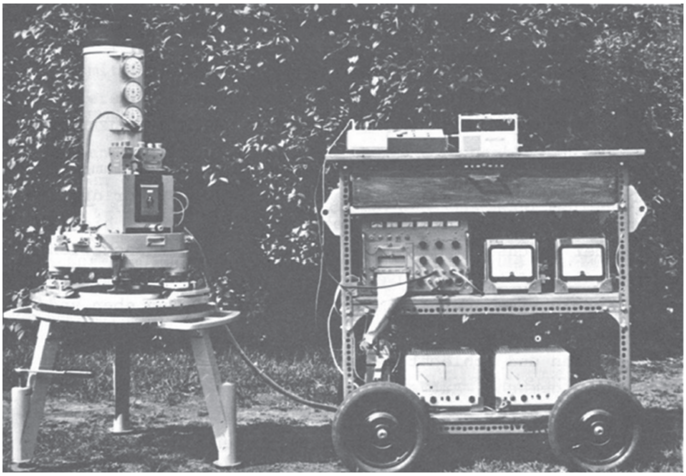

Fig. 1. *Mobile zenith camera TZK1 (Gessler 1975).*

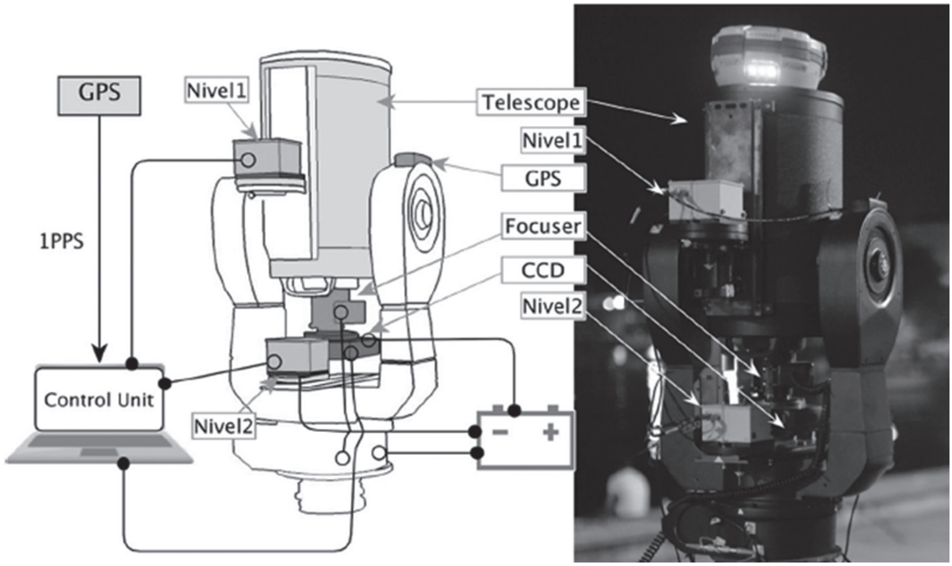

Fig. 2. *Astro-geodetic Camera System developed in Turkey (Halicioglu et al. 2016).*

The determination of (DOV) using the digital zenith camera (DZCS) ACSYS within the test network reveals root mean squared errors (RMSE) of 0.35” in the meridian and 0.37” in the prime vertical direction (Halicioglu et al. 2016). The results obtained from DOV measurements using ACSYS observations demonstrate consistency with those calculated using global geopotential models like EGM08 and GGMplus.

However, limitations in the duration of observations prompted the modernization of ACSYS, leading to the development of ACSYS2 in 2016 (Fig. 3) (Albayrak et al. 2019). Preliminary astronomical and geodetic test observations with ACSYS2 indicate a DOV determination accuracy of approximately 0.3”. The manual leveling process in ACSYS was addressed by automating it in ACSYS2, reducing the setup and leveling time to an average of 20 minutes, compared to 40 minutes for ACSYS.

In another development, the Digital Zenith Camera System (DZCS) designed at the Institute of Geodesy and Geoinformatics of Latvia is presented (Fig. 4) (Zariņš et al. 2016). DZCS features a rotary platform housing a small telescope with a CCD sensor, tilt, level, rotation mechanism, and control equipment. Typically, two full rotations are performed in each direction, and station observations take about an hour. The authors propose a novel approach termed “instrumental” to obtain DOV values based on pattern analysis, connected to determining the projection of the normal to the ellipsoid surface in the CCD coordinate system during device rotation. As described by (Abele et al. 2012) the trajectory of the reference ellipsoid’s normal forms a circle around the plumb line’s projection, and DOV components can be derived from parameters such as its radius and phase.

The results presented in (Zariņš et al. 2016) lack an evaluation of process accuracy. Only a mention is made that, at one observation point, the discrepancy between the DOV component obtained by the described method and the one calculated as the difference between astronomical and geodetic longitude was approximately 0.1”. The figures display the DOV components with RMSE = 0.35”, leading to the general conclusion that the results of the Digital Zenith Camera System (DZCS) tests from Latvia exhibit similar accuracy characteristics to other DZCS.

In another study by (Morozova et al. 2019), the application of Latvia’s DZCS for constructing a quasi-geoid model for the western part of Latvia is explored. The necessity for a new quasi-geoid model arises from the shift to a new physical elevation system. It is demonstrated that astro-geodetic DOV, determined using the DZCS in Latvia, achieves an accuracy of about 0.1”, equivalent to an error of 0.5 mm per 1 km of traverse. This accuracy surpasses leveling to class I in Latvia and proves to be twice as precise.

The quasi-geoid model determination involves the use of parametric modeling with a continuous polynomial surface. Subsequent work (Morozova et al. 2021) delves into the utilization of the same method to determine a precise quasi-geoid model for the entire territory of Latvia and outlines the structure of the DZCS VESTA. The standard deviations for DOV components in the meridian and in the prime vertical direction obtained using DZCS VESTA are 0.055” and 0.046”, respectively.

Additionally, (Murzabekov et al. 2021) introduces the concept of DOV determination through a navigational-geodetic method based on comparing the results of normal heights’ increments and geodetic height determinations. It is highlighted that due to the unknown exact law of mass density distribution within the Earth, astro-geodetic methods, along with GNSS leveling, face challenges in verifying the difference between gravimetric geoid models, particularly in mountainous areas. Contrarily, (Sjoberg 2022) argues that gravimetric models of a quasi-geoid are independent of density distribution and can be determined with precision through the specified methods.

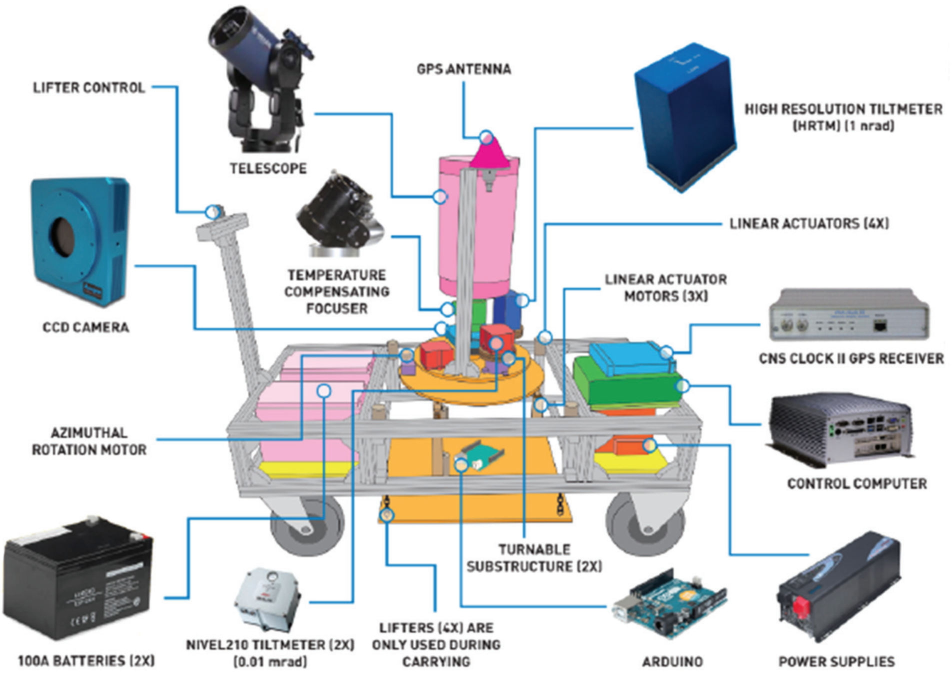

Fig. 3. *ACSYS2 (Albayrak et al. 2019).*

Fig. 4. *DZCS (Zariņš et al. 2016).*

Varna et al. (2023) conducted a study utilizing CODIAC and VESTA digital zenith cameras, engaging in simultaneous parallel observations to ensure the mutual consistency of both devices. The comparison of results revealed an average difference in Deflection of Vertical (DOV) of 0.08" for the North-South component and –0.06" for the East-West component.

3. Materials and Methods

3.1. A Novel Technical Approach for a Two-Channel Digital Zenith Camera Design

Over the past decade, substantial efforts have been directed towards enhancing the design of digital zenith cameras. In earlier works (Burachek et al. 2014, Burachek et al. 2017), a pioneering technical solution was proposed – the two-channel digital zenith camera (see Fig. 5), for which a Ukrainian patent for invention was successfully obtained.

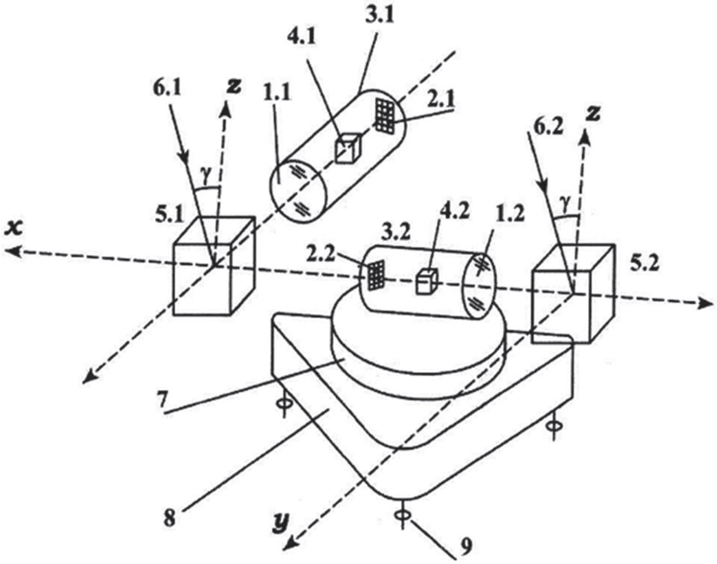

Fig. 5. *Design of a two-channel digital zenith camera: 1 – channel lenses (1.1 – longitude channel, 1.2 – latitude); 2 – CCD-sensors (2.1 – longitude and 2.2 – latitude, respectively); 3 – telescopes of channels (3.1 – channel of longitude and 3.2 – channel of latitude); 4 – horizon compensators (4.1 – channel of longitude and 4.2 – channel of latitude); 5 – optical deflecting blocks (5.1 – channel of longitude and 5.2 – channel of latitude); 6 – luminous flux from the working star, which falls on the lenses 1.1 and 1.2 of the optoelectronic device; 6.1 and 6.2 vizier lines; 7 – electromechanical block of the device 1 alidad rotation by 180°; 8 – tribach; 9 – lifting screws.*

The entire apparatus is housed within a unified casing, comprising a sighting device for orientation, a power supply unit, and an automated control unit. The opto-electronic channels are rigidly interconnected, with their sight axes positioned in the horizontal plane perpendicular to each other. Before commencing measurements, the geodetic latitude and longitude of the observation point are determined through GPS positioning. The device, along with all its components, is positioned with its vertical axis on a tribach, situated on a tripod directly above the observation point. Through the segregation of measurements into two channels (latitude and longitude), the incorporation of high-precision opto-mechanical compensators within the optical channel systems, and the strategic distribution of time for measuring and stabilizing the compensator pendulum, the calculated accuracy DOV determination ranges between ±0.35" and ±0.4". The device seamlessly conducts astronomical measurements in an automated mode. Continuing the trajectory of technical enhancement, the development of a schematic solution for an automated system for determining astronomical coordinates and DOV has been pursued. This innovative system relies on the optoelectronic method of sighting near-zenith stars, employing a scheme that segregates the optoelectronic channels by latitude and longitude. The system encompasses multiple two-channel vizier astroblocks, each constructed according to the aforementioned scheme (see Fig. 5), all integrated into a unified automated system. The quest for heightened precision in determining astronomical coordinates and DOV involves calculating average values derived from the observations collected by several two-channel astroblocks (Burachek et al. 2014, Burachek et al. 2017).

3.2. Investigation of astrogeodetic method use for the oil and natural gas deposits exploration

Utilizing a zenith camera, the astronomical coordinates of a specific point on the Earth's surface, namely the latitude (φ) and longitude (λ), are determined through star observations (Fig. 6).

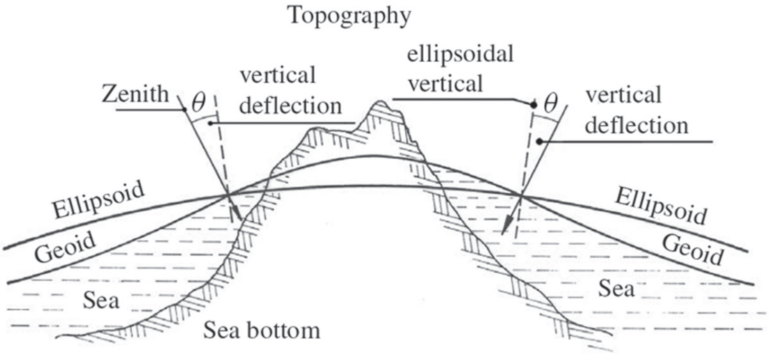

Fig. 6. *Deflections of the vertical θ (Seeber 2003).*

Using a zenith camera, the observations of stars determine the astronomical coordinates of the point of the earth's surface: φ – latitude, λ – longitude. Using GPS positioning, the geodetic coordinates of the same point are determined: B – latitude, L – longitude. According to these data, the components of the astronomical and geodetic DOV are calculated, namely: ξ – in the meridian direction (north–south), η – in the prime vertical direction (east–west) (Fig. 7) and azimuth A of DOV direction relative to the geodetic meridian (Hofmann-Wellenhof and Moritz 2006):

$$\xi = \varphi - B \,, \tag{1}$$

$$\eta = (\lambda - L)\cos\varphi \,, \tag{2}$$

$$\theta = \sqrt{\xi^2 + \eta^2} \,, \tag{3}$$

$$tgA = \frac{\eta}{\xi} \,. \tag{4}$$

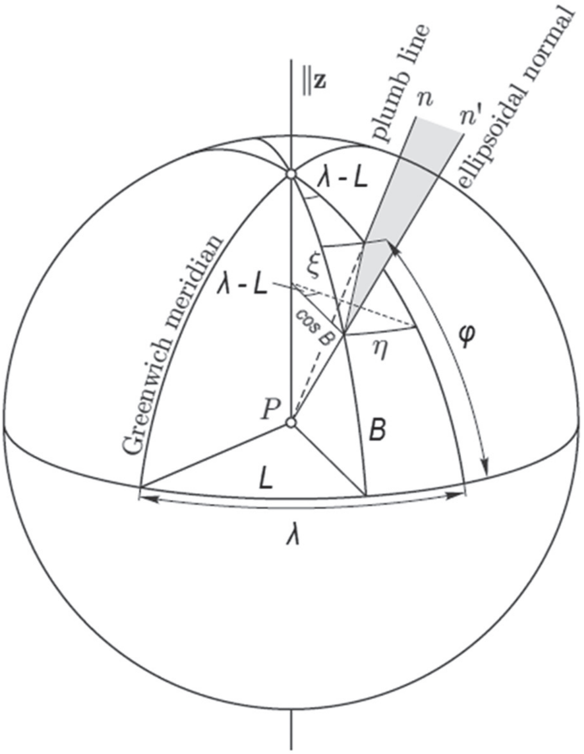

Fig. 7. *Components of the deflections of the vertical on a sphere of a unit radius centered at a point P (Hofmann-Wellenhof and Moritz 2006).*

Deflections of Vertical hold a significant role in various fields such as geodesy, gravimetry, and other earth sciences. Understanding DOV at all measurement points is essential for transforming measurements conducted in the coordinate system linked to the actual gravity field of the Earth into a geodetic or spatial rectangular coordinate system (Torge and Müller 2012). DOV also serve a crucial purpose in validating global geopotential models or altitude transfers using GPS and astronomical leveling (refer to Fig. 8). Moreover, they offer insights into the Earth's gravity field structure, proving sensitive to local mass distribution and finding applications in geophysical studies (Hirt and Wildermann 2018). In the paper (Gladilin et al. 2015) authors present information on the technology of utilizing digital zenith cameras (DZC) for DOV determination, specifically in the vicinity of oil and gas deposits.

The calibration of the digital zenith camera took place at a point within the astro-geodetic network of the 1st class, featuring known astronomical and geodetic coordinates. Star observations were conducted in four repetitions, and the orientation of the DZC in the meridian plane was achieved with an accuracy of ±15". The true meridian's direction was predetermined using the gyrotheodolite Gi-B2. The results indicated RMSE as $m_{\phi} = 0.23"$ and $m_{\lambda} = 0.27"$ for determining astronomical coordinates.

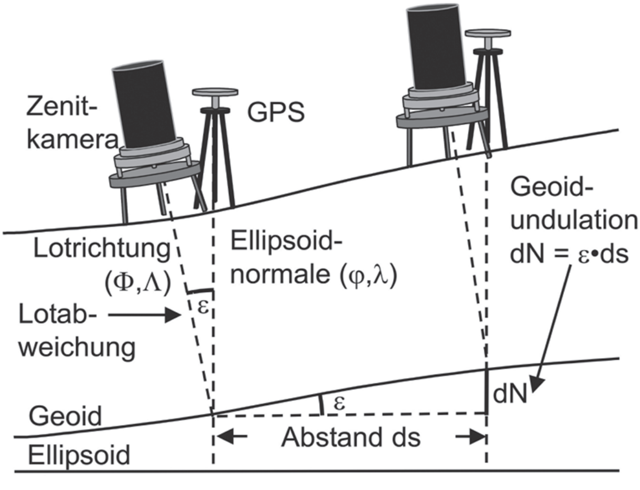

Fig. 8. *Building a geoid profile (Hirt and Bürki 2006).*

To investigate the DOV behavior at an oil deposit in the Chernihiv region of Ukraine, measurements were conducted along a profile extending from West to East. The central observation point, No. 8, was strategically positioned near drilling well No. 18, extracting oil from depths of 2341 m. Considering geological diversity, observations were conducted both outside the deposit and within the extraction area. The ProMark-2 GPS receiver from Ashtech Solutions Inc. facilitated these measurements in static mode, with session durations ranging from 40 to 60 minutes. Simultaneous determination of astronomical and global coordinates, utilizing a unified setup comprising a Digital Zenith Camera (DZC) and GPS receiver, posed a challenge in centering the GPS antenna precisely over the measurement point. The inability to center the GPS antenna either above or below the DZC lens led to issues in fixing star positions or obstructing signals from Earth's artificial satellites, resulting in suboptimal Position Dilution of Precision (PDOP). To address this, the GPS antenna was fixed at a specific distance from the vertical axis of the zenith camera's monoblock. Aligning the physical center of the GPS antenna with the zenith camera's installation center during its rotation by 180° around the zenith camera's axis ensured consistent geometric distances. Average values were calculated from geodetic coordinates of diametrically opposite observation points, corresponding to the axis of DZC rotation. Based on the observation results and calculations using relevant formulas (1) – (4), the components, absolute values, and azimuths of DOV were determined. It's essential to note that the value of ξ is specified based on the observation points' geodetic height H namely

$$\xi'' = (\varphi - B)'' - 0{,}171'' H \sin 2B \,, \tag{5}$$

H taken in kilometers (Hofmann-Wellenhof and Moritz 2006).

As a result of the study, a graphical representation depicting the distribution of absolute DOV values at various observation points was compiled and is presented in Fig. 9.

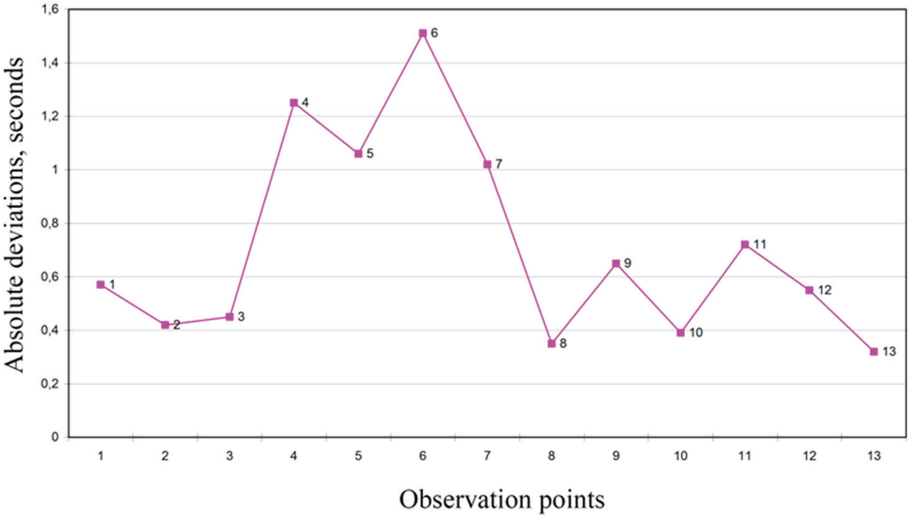

Fig. 9. *Profile of absolute DOV determination at observation points (Gladilin et al. 2015).*

The observation points are uniformly spaced at a distance of 1 km from each other.

To further analyze the geological characteristics, a vector profile of horizontal gravity gradients was constructed at these points, as illustrated in Fig. 10. The determination of gradient azimuth directions was carried out using Formula (4). The application of these gradients in vector form allows us to discern the direction where the force of gravity experiences the most rapid increase, aiding in predicting the location of attracting masses.

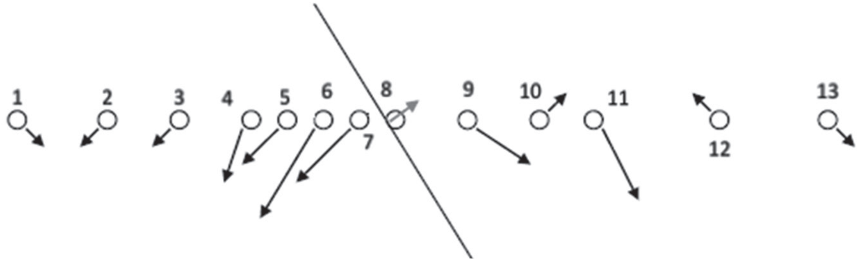

Fig. 10. *Horizontal gravity gradients vectors at the observation points (Gladilin et al. 2015).*

In instances where the vectors diverge in a specific area, it indicates the presence of substances with a density lower than that of the surrounding regions of the Earth's crust. Notably, between points #7 and #8 in Fig. 10, gradient vectors diverge in opposite directions, suggesting a high probability of oil deposits, which aligns with real-world findings (Gladilin et al. 2015). The visual interpretation of DOV results can be correlated with features such as the oil horizon profile illustrated in Fig. 11 (Pulkina and Zimina 2011).

Fig. 11. *Oil horizon profile (Pulkina and Zimina 2011).*

For subsequent analysis, it is imperative to ascertain the precision involved in computing the DOV utilizing a zenith camera and a GPS receiver. This involves the determination of partial differentials from the given expression

$$\theta = \left[(\varphi - B)^2 + (\lambda - L)^2 \cos^2 B \right]^{\frac{1}{2}}, \tag{6}$$

obtained on the basis of formulas (1) – (3) and go to RMSE. As a result, the RMSE formula for determining the DOV was obtained, subject to the independence of the definition of astronomical and geodetic coordinates, in the form of

$$m_\theta = \frac{1}{\theta}\left[\xi^2 m_\varphi^2 + (\xi + \eta^2 tgB)^2 m_B^2 \ + \eta^2 \cos^2 B(m_\lambda^2 + m_L^2)\right]^{\frac{1}{2}}, \tag{7}$$

where m_ϕ, m_λ, m_B, m_L – RMSE of astronomical and geodetic coordinates determination, respectively.

RMSE associated with the determination of astronomical coordinates are documented in the article by Gladilin et al. (2015), while the RMSE for geodetic coordinates determination requires further calculation. In the course of GPS observations conducted within the Chernihiv region, the base GNSS station CNIV was employed. In Fig. 12, it is depicted as point A with coordinates L_A = 32°18’49”, B_A = 52°31’08”. Point B in Fig. 12 denotes the midpoint of the astronomical and geodetic traverse conducted for DOV determination, with coordinates L_B = 33°13’56”, B_B = 51°33’07”. It is important to emphasize that the coordinates of these points have been uniformly shifted by a constant value to enhance security in presenting this information.

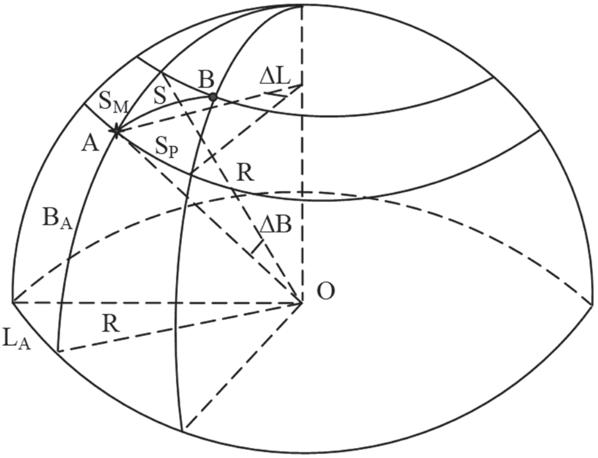

Fig. 12. *To the accuracy of the geodetic coordinates of the research area determination: A – base GNSS station CNIV; B – midpoint of the research area.*

From Fig. 12 it is clear that

$$B_B = B_A + \Delta B\ , \tag{8}$$

$$L_B = L_A + \Delta L\ . \tag{9}$$

So, the RMSE of point *B* coordinates determination will be equal to

$$m_{B_B} = \left[m_{B_A}^2 + m_{\Delta B}^2 \right]^{\frac{1}{2}}, \tag{10}$$

$$m_{L_B} = \left[m_{L_A}^2 + m_{\Delta L}^2 \right]^{\frac{1}{2}}. \tag{11}$$

where m_{B_A}, m_{L_A} – RMSE of CNIV GNSS-station coordinates determination, $m_{\Delta B}$ and $m_{\Delta L}$ – RMSE of coordinate increment determination by latitude and longitude of point *B* relative to point *A*.

The CNIV GNSS station holds an accuracy classification of 'A' due to its stable position, making it a reliable reference station for network sealing within the EUREF framework (Tereshchuk and Nistoriak 2015). From (Legrand et al. 2021) it is known that stations categorized as 'A' are expected to exhibit horizontal position observation errors not exceeding 1 cm in all epochs. We will consider the CNIV GNSS station, where the horizontal position accuracy is uniform in both latitude and longitude. Taking into account the radius of the Earth (R = 6378 km), it can be established that 1 cm on its surface corresponds to:

$$m_{B_A} = m_{L_A} = (0,01\,m / 6378000\,m \cdot 206265'' = 0,000323''.$$

A parallel and a meridian length is determined by the formulas (Torge and Müller 2012)

$$S_P = R \cos B_A \frac{\Delta L}{\rho}, \tag{12}$$

$$S_M = R \frac{\Delta B}{\rho}, \tag{13}$$

where $\rho = 206265''$. The calculations using the formulas (12) and (13) for the above values of the arguments are: S_P = 62.22 km, S_M = 107.64 km. To assess accuracy, we make the assumption that segments of parallels and meridians, at relatively small distances, are mutually perpendicular and planar. Hence, the distance between points A and B on the surface of the globe is considered equal (refer to Fig. 12)

$$S = \left[S_P^2 + S_M^2 \right]^{\frac{1}{2}}. \tag{14}$$

Numerically, the distance between points A and B on the surface of the globe is S = 124.33 km. Upon transitioning to partial differentials and RMSE components in longitude m_{S_P} and latitude m_{S_M} as expressed in equation (14), the determination of RMSE for distance is

$$m_S = \left[\left(\frac{S_P}{S} m_{S_P} \right)^2 + \left(\frac{S_M}{S} m_{S_M} \right)^2 \right]^{\frac{1}{2}}. \tag{15}$$

We will assume that the accuracy of determining the components along the meridian and parallel is the same – $m_{S_P} = m_{S_M}$. Substituting this data into (15) allows us to obtain

$$m_{S_P} = m_{S_M} = m_S. \tag{16}$$

The accuracy of points horizontal position determining using the ProMark 2 GPS receiver is $m_S = 5\,mm + 1\,mm/km$ (Legrand et al. 2021), that allows to calculate m_S = 129.3 mm. Further, from (13) follows

$$m_{\Delta B} = \frac{m_{S_M}}{R} \rho, \tag{17}$$

what's for $m_{S_M} = 0.1293$ m allows one to get $m_{\Delta B} = 0.00418"$ and $m_{B_A} = 0.000323"$ from (10) get the value $m_{B_B} = 0.00419"$.

Formula (12) can be used to determine Δ*L*, and after differentiation, we can switch to RMSE,

$$m_{\Delta L} = \left[\left(\frac{m_{S_P}}{S_P} \Delta L \right)^2 + (tgB_A \cdot m_{B_A} \Delta L)^2 \right]^{\frac{1}{2}} \tag{18}$$

by substitution of values: $m_{S_P} = 0.1293$ m; $\Delta L = 3307"$; $S_P = 62220$ m; B_A = 52°31'08"; $m_{B_A} = 0.000323"$; it becomes clear that the second term is an order of magnitude smaller than the first. Therefore

$$m_{\Delta L} = \frac{m_{S_P}}{S_P} \Delta L. \tag{19}$$

This finally allows one to get out from (19) $m_{\Delta L} = 0.00687"$. Substitution of this value and $m_{L_A} = 0.000323"$ allows you to get from (11) $m_{L_B} = 0.00688"$.

In the formula (7), the calculation of DOV contains the value θ in denominator. Therefore, it is advisable to use this formula for the maximum and minimum DOV values calculations. According to the data (Gladilin et al. 2015) and formula (3) $\theta_{\max} = 0.218"$ – for values $\xi = +0.06"$ and $\eta = -0.21"$ and $\theta_{\min} = 0.058"$ – for values $\xi = +0.03"$ and $\eta = -0.05"$. So, using the parameter values calculated above in the formula (7), $m_{\phi} = 0.23"$ values and $m_{\lambda} = 0.27"$ (Gladilin et al. 2015) and maximum and minimum θ values, the formula for DOV RMSE calculation is simplified to the expression

$$m_{\theta} = \frac{1}{\theta}\left[\xi^2 \cdot m_{\phi}^2 + \cos^2 B \cdot \eta^2 \cdot m_{\lambda}^2\right]^{\frac{1}{2}}. \tag{20}$$

This is made possible by neglecting two orders of magnitude, which have a significantly lesser impact on the accuracy of determining geodetic coordinates compared to geographical ones. Therefore, based on formula (20), we obtain values $m_{\theta\max} = 0.17"$ and $m_{\theta\min} = 0.16"$. It is evident from these results that the calculation of RMSE for Deflections of the Vertical using formula (20) is independent of the actual DOV value. The observed difference of 0.01" occurs due to the rounding of intermediate calculation results. Subsequently, if we substitute $\xi = 0"$ and $\eta = 1"$ we get $\theta = 1"$ from equation (3), and from formula (20) for $B_A = 52°31'08"$ we get $m_{\theta} = 0.17"$. Thus, formula (20) can be simplified to the form:

$$m_{\theta} = \cos B_B \cdot m_{\lambda}. \tag{21}$$

As seen from formula (21), if the accuracy of determining astronomical longitude of the observation point by the zenith camera and the geodetic latitude of the area of DOV determination are known, it is possible to calculate the expected accuracy of DOV determination. This can be crucial in ensuring that the DOV is calculated with the required precision. It is important to note that in the case of locating traverse points along the parallel, having the latitude of one of the points or the middle points of these blocks is sufficient. Otherwise, you can dismember the traverse project into several blocks and get the latitudes of the middle points of these blocks.

Applying formula (21) when designing a traverse to determine the DOV allows the determination of, for example, the allowable distance between the rotation axes of the zenith camera and GPS receiver. During RMSE calculation, one of its components, which is a third to a fifth of the second component, can be neglected. For this case, the range of neglectable shares are from $0{,}17''/5 = 0{,}034''$ to $0{,}17''/3 = 0{,}057''$, allowing the setting of the GPS receiver's rotation axis relative to the zenith camera's rotation axis at distances from $(0{,}034''/206265'')6378000\ m = 1{,}05\ m$ to $(0{,}057''/206265'')6378000\,m = 1{,}76\,m$. In the specific measurements mentioned in (Gladilin et al. 2015), it would have been possible not to design a monoblock DZC together with a GPS receiver and use them separately at distances ranging from 1.05 m to 1.76 m from each other.

4. Conclusions and consequences of the research

The gravity method, rooted in astronomical and geodetic determination of Deflections of the Vertical (DOV), is widely acknowledged in the literature as an effective geophysical approach for locating oil and gas deposits. This study delves into a comprehensive review of relevant literary sources and patent documentation, focusing on the designs and accuracy characteristics of both analog and digital zenith cameras.

The research specifically explores the application of a digital zenith camera and a GPS receiver for DOV determination at a designated test site in the Chernihiv region of Ukraine. The method yielded promising results, successfully identifying an oil-bearing horizon within the geological structure.

Furthermore, this study contributes by deriving formulas for calculating the accuracy of DOV determination using the astrogeodetic method, particularly tailored for local areas. These formulas serve as valuable tools for performing a priori assessments of accuracy levels, aiding in the determination of permissible distances between the zenith camera and GPS receiver when installed separately. This approach not only enhances the accuracy of DOV calculations but also simplifies the design of digital zenith cameras by incorporating standard GPS receivers. The integration of these methods offers a streamlined and effective solution for astrogeodetic applications in the exploration of natural resources.

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Procjena astro-geodetskih metoda za određivanje otklona vertikale u istraživanju nafte i plina: Studija slučaja u ukrajinskom ležištu

SAŽETAK. Unatoč globalnim naporima da se prijeđe na ekološki prihvatljive izvore energije, tradicionalni resursi poput nafte i plina i dalje igraju ključnu ulogu u ispunjavanju energetskih zahtjeva. Razmatraju se značajke primjene sljedećih geofizičkih metoda za istraživanje minerala: magnetska, električna, radioaktivna, seizmička, karotažna mjerenja u bušotinama, kao i multispektralna mjerenja u zračnom prostoru i terenska spektrometrija. Među tim metodama, gravimetrijska metoda, posebno njezina astro-geodetska varijanta koja primjenjuje zenit-kamere i GPS pozicioniranje, pojavljuje se kao vrlo učinkovit pristup za otkrivanje nalazišta nafte i plina. Proveden je opsežan pregled izvora literature i patentne dokumentacije, s naglaskom na karakteristike konstrukcije i točnosti analognih i digitalnih zenit-kamera. Ispituje se metodologija koja uključuje digitalnu zenit-kameru i GPS prijamnik za određivanje otklona vertikale na mjestu ispitivanja u regiji Chernihiv (Ukrajina). Pozitivni rezultati dobiveni ovim istraživanjem ne samo da potvrđuju učinkovitost pristupa, već također omogućuju mogućnost identifikacije naftonosnih horizonata. U radu su izvedene formule za izračunavanje točnosti određivanja otklona vertikale astro-geodetskom metodom, posebno prilagođene lokalnim područjima. Te formule omogućuju istraživačima da provode a priori izračune točnosti, olakšavajući određivanje dopuštenih udaljenosti između zenit-kamera i GPS prijamnika kada su instalirani odvojeno, u rasponu od 1,05 m do 1,76 m.

Ključne riječi: *zenit-kamera, otkloni vertikale, astro-geodetska metoda, ležišta nafte, metode istraživanja minerala.*

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