ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ
Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
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КАЗАХСТАН
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N E W S

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF
KAZAKHSTAN
Satbayev University

SERIES

OF GEOLOGY AND TECHNICAL SCIENCES

1 (457)

JANUARY – FEBRUARY 2023

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

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«ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).

Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *геология, мұнай және газды өңдеудің химиялық технологиялары, мұнай химиясы, металдарды алу және олардың қосындыларының технологиясы.*

Мерзімділігі: жылына 6 рет.

Тиражы: 300 дана.

Редакцияның мекен-жайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

Типографияның мекен-жайы: «Аруна» ЖК, Алматы қ., Мұратбаев көш., 75.

«Известия НАН РК. Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, химические технологии переработки нефти и газа, нефтехимия, технологии извлечения металлов и их соеденений.*

Периодичность: 6 раз в год.

Тираж: 300 экземпляров.

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, оф. 219, тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75.

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.
Thematic scope: *geology, chemical technologies for oil and gas processing, petrochemistry, technologies for extracting metals and their connections.*
Periodicity: 6 times a year.
Circulation: 300 copies.
Editorial address: 28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19
http://www.geolog-technical.kz/index.php/en/

Address of printing house: ST «Aruna», 75, Muratbayev str, Almaty.

NEWS of the National Academy of Sciences of the Republic of Kazakhstan
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 1, Number 457 (2023), 154-165
https://doi.org/10.32014/2023.2518-170X.266

IRSTI 20.20.19
UDC 528.71+519.7

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MATHEMATICAL MODELING AND DEVELOPMENT OF AN AUTOMATED SYSTEM FOR SEARCHING RING STRUCTURES IN GEOLOGY

Abstract. With the development of satellite technologies, geoinformatics is becoming increasingly widespread. Three-dimensional surfaces are important objects for the study of modern geographic information systems (GIS). In recent years, the number of works on this topic has been growing rapidly due to the deployment of information systems. In works (Brodsky, 2014; Kalyutov, 2015) mathematical models of three-dimensional images are presented. Dissertations (Garanja, 2014; Voloboy, 2012; Kharchenko, 2012; Nguyen, 2011) are devoted to the problem of synthesis of realistic images. A number of works are devoted to the construction of surface models based on the Delaunay triangulation (Kuchunova et al., 2016; Elugachev et al., 2021; Tyukachev, 2010; Khlebnikov et al., 2010). The task of constructing a Delaunay triangulation is one of the basic ones in computational geometry. Many other tasks are reduced to it, it is widely used in computer graphics and geographic information systems for modeling surfaces and solving spatial problems. As practice shows, the choice of a structure for representing a triangulation has a significant impact on the theoretical complexity of the algorithms, as well as on the speed of a specific implementation. In addition, the choice of structure may depend on the purpose of further use of triangulation. In triangulation, three main types of objects can be distinguished: nodes (points, vertices), edges (segments) and triangles. To approximate the relief model to the real one, additional elements are introduced into it, which ensure that its linear and areal structural elements are taken into account and displayed. Such additional elements are structural lines: watersheds, thalwegs, ridges, cliffs, ledges, lakes, ravines, coastlines, boundaries of artificial structures, etc., the totality of which creates the framework of the Delaunay triangulation. These breaklines are introduced into the triangulation as the edges of triangles, which is how the simulation of real relief elements is achieved against the background of general unevenness of the earth's surface. Such edges are called structural (fixed, non-rebuildable), and subsequently do not change. In this regard, there is a need to develop and investigate a mathematical model for displaying the terrain, taking into account its illumination by applying line density. Applying 2D function interpolation techniques allows for smoother surface views. This work is devoted to solving these problems. The developed automated system for searching for ring structures is based on algorithms for the spatial display of the surface relief, taking into account its illumination on raster-type graphic devices. The proposed system can be used in geology to search for hydrocarbons and other minerals.

Key words: automated system, ring structures, illumination, geophysics, minerals.

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ГЕОЛОГИЯДА САҚИНАЛЫ ҚҰРЫЛЫМДАРДЫ ІЗДЕУДІҢ АВТОМАТТАНДЫРЫЛҒАН ЖҮЙЕСІН МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ ЖӘНЕ ӘЗІРЛЕУ

Аннотация. Спутниктік технологиялардың дамуымен геоинформатика кеңінен таралуда. Үш өлшемді беттер қазіргі заманғы географиялық ақпараттық жүйелерді (ГАЖ) зерттеу үшін маңызды объектілер болып табылады. Соңғы жылдары ақпараттық жүйелердің енгізілуіне байланысты осы тақырыптағы жұмыстардың саны қарқынды өсуде. (Brodsky, 2014; Kalyutov, 2015) мақалалар үш өлшемді кескіндердің математикалық модельдерін ұсынады. (Garanja, 2014; Voloboy, 2012; Kharchenko, 2012; Nguyen, 2011) диссертациялар реалистік бейнелерді синтездеу мәселесіне арналған. Бірқатар жұмыстар Делоне триангуляциясы негізінде беттік модельдерді құруға арналған (Kuchunova et al., 2016; Elugachev et al., 2021; Tyukachev, 2010; Khlebnikov et al., 2010). Делоне триангуляциясын құру міндеті есептеу геометриясындағы негізгі тапсырмалардың бірі болып табылады. Оған көптеген басқа міндеттер қосылады, ол компьютерлік графикада және беттерді модельдеу және кеңістіктік есептерді шешу үшін географиялық ақпараттық жүйелерде кеңінен қолданылады. Тәжірибе көрсеткендей, триангуляцияны көрсету үшін құрылымды таңдау алгоритмдердің теориялық күрделілігіне, сондай-ақ нақты іске асыру жылдамдығына айтарлықтай әсер етеді. Сонымен қатар, құрылымды таңдау триангуляцияны одан әрі пайдалану мақсатына байланысты болуы мүмкін. Триангуляцияда объектілердің үш негізгі түрін ажыратуға

болады: түйіндер (нүктелер, шыңдар), жиектер (сегменттер) және үшбұрыштар. Рельефтік модельді нақтыға жақындату үшін оған қосымша элементтер енгізіледі, олар оның сызықтық және аумақтық құрылымдық элементтерін есепке алуды және бейнелеуді қамтамасыз етеді. Мұндай қосымша элементтер құрылымдық сызықтар болып табылады: су айрықтары, талвегтер, жоталар, жартастар, қырлар, көлдер, жыралар, жағалау сызығы, жасанды құрылыстардың шекаралары және т.б., олардың жиынтығы Делоне триангуляциясының негізін жасайды. Бұл үзік сызықтар триангуляцияға үшбұрыштардың жиектері ретінде енгізіледі, жер бетінің жалпы біркелкі еместігі фонында нақты рельеф элементтерін модельдеу осылайша жүзеге асырылады. Мұндай жиектер құрылымдық (бекітілген, қалпына келмейтін) деп аталады және кейіннен өзгермейді. Осыған байланысты, сызықтық тығыздықты қолдану арқылы оның жарықтандыруын ескере отырып, жер бедерін бейнелеудің математикалық моделін әзірлеу және зерттеу қажет. 2D функциясының интерполяция әдістерін пайдалану беттердің тегіс кескіндерін алуға мүмкіндік береді. Бұл жұмыс осы мәселелерді шешуге арналған. Сақиналы құрылымдарды іздеудің әзірленген автоматтандырылған жүйесі растрлық типтегі графикалық құрылғыларда оның жарықтандыруын ескере отырып, беттік рельефті кеңістікте көрсету алгоритмдеріне негізделген. Ұсынылған жүйе геологияда көмірсутектер мен басқа да пайдалы қазбаларды іздеуде қолданылуы мүмкін.

Түйінді сөздер: автоматтандырылған жүйе, сақиналы құрылымдар, жарықтандыру, геофизика, пайдалы қазбалар.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ И РАЗРАБОТКА АВТОМАТИЗИРОВАННОЙ СИСТЕМЫ ПОИСКА КОЛЬЦЕВЫХ СТРУКТУР В ГЕОЛОГИИ

Аннотация. С развитием спутниковых технологий все большее распространение получает геоинформатика. Трехмерные поверхности являются важными объектами для изучения современных геоинформационных систем (ГИС). В последние годы количество работ по этой теме стремительно растёт в связи с внедрением информационных систем. В работах (Brodsky, 2014; Kalyutov, 2015) представлены математические модели трёхмерных изображений. Диссертации (Garanja, 2014; Voloboy, 2012; Kharchenko, 2012; Nguyen, 2011) посвящены проблеме синтеза реалистических изображений. Ряд работ посвящен построению моделей поверхности на основе триангуляции Делоне (Kuchunova et al., 2016; Elugachev et al., 2021; Tyukachev, 2010; Khlebnikov et al., 2010). Задача построения триангуляции Делоне является одной из базовых в вычислительной геометрии. К ней сводятся многие другие задачи, она широко используется в машинной графике и геоинформационных системах для моделирования поверхностей и решения пространственных задач. Как показывает практика, выбор структуры для представления триангуляции оказывает существенное влияние на теоретическую трудоёмкость алгоритмов, а также на скорость конкретной реализации. Кроме того, выбор структуры может зависеть от цели дальнейшего использования триангуляции. В триангуляции можно выделить 3 основных вида объектов: узлы (точки, вершины), рёбра (отрезки) и треугольники. Для приближения модели рельефа к реальной в нее внедряются дополнительные элементы, обеспечивающие учет и отображение ее линейных и площадных структурных элементов. Такими дополнительными элементами являются структурные линии: водоразделы, тальвеги, хребты, обрывы, уступы, озера, овраги, береговые линии, границы искусственных сооружений и др., совокупность которых создает каркас триангуляции Делоне. Эти структурные линии внедряются в триангуляцию в качестве ребер треугольников, чем и достигается моделирование реальных элементов рельефа на фоне общих неровностей земной поверхности. Такие ребра называются структурными (фиксированными, неперестраиваемыми), и в последующем не изменяются. В связи с этим возникает необходимость разработки и исследования математической модели отображения местности с учётом её освещённости путём применения линейной плотности. Применение методов интерполяции 2D-функций позволяет получить более гладкие изображения поверхностей. Решению этих задач посвящена данная работа. В основе разработанной автоматизированной системы поиска кольцевых структур лежат алгоритмы пространственного отображения рельефа поверхности с учётом его освещённости на графических устройствах растрового типа. Предлагаемая система может быть использована в геологии для поиска углеводородов и других полезных ископаемых.

Ключевые слова: автоматизированная система, кольцевые структуры, освещение, геофизика, полезные ископаемые.

Introduction. Ring structures – geological formations in terms of a ring, round or oval shape in the stone shell of the Earth and other planetary bodies. They are established mainly by geological interpretation of space and air-altitude images of the earth's surface. Interest in ring structures especially increased in the late 1970s and early 80s due to the widespread use of satellite imagery materials in the practice of geological research (Livinsky et al., 2017; Miroshnikova et al., 2022).

The study of ring structures is associated with the identification of previously unknown patterns in the distribution of minerals, incl. focal nature over undiscovered intrusive arrays, low-temperature mineralization associated with volcano-tectonic ring structures of mineralization zonality in relation to ring structures of a nuclear nature. Large ring structures (or concentres) can play an important role in the localization of oil and gas accumulation zones and individual oil and gas fields. Tectonic ring structures often serve as indicators of low-amplitude uplifts in platform areas that are promising in terms of oil and gas (Gubin, 2014; Sheshukov et al., 2014). According to the latest results of processing high-quality space images, it was found that ring structures larger than 100 km across are naturally associated with all known giant deposits (Tengiz, Romashkinskoye, Chikontepeg in the USA, etc.).

A number of scientific papers (Miroshnikova et al., 2022; Kocharyan et al., 2020) are devoted to the problem of automated detection and analysis of ring structures.

A real leap in the study of ring formations on Earth, and even on other planetary bodies of the solar system, occurred in connection with the beginning of the space age. With the help of satellite imagery, similar forms were found on the surface of some planets - Mercury, Mars, the Moon, where they form the main background; on Venus, where they are developed to a somewhat lesser extent, as well as on most satellites of Jupiter.

At present, in connection with the intensive development of remote sensing of the Earth and other planets, much attention is paid to the detection and analysis of ring structures based on satellite imagery. The study of ring structures is of great importance for the search for new mineral deposits. According to available data, up to 70% of known deposits of ore minerals and many hydrocarbon deposits are associated with ring structures (Zeylik et al., 2012; Zeylik et al., 2013).

At the same time, aerospace images do not always make it possible to identify ring structures associated with the location of the object of study itself, sources of illumination, and observation (photography) points.

At the same time, mathematical modeling makes it much cheaper to obtain a graphical representation of the terrain by arbitrarily placing light sources and an observation point. In particular, it is possible to place the light source on the north side, which is never possible with aerial surveys.

The aim of the work is to develop technology and software for automated search for ring structures on the terrain using mathematical modeling.

Research Material and methods. Description of the algorithm and modules. The article describes programs for the spatial display of three-dimensional bodies, taking into account their illumination on an ordinary raster monitor.

The program is intended for the spatial image of the surface relief (given in the form of a matrix of heights) taking into account its illumination on graphic devices of a raster type. The input information is a regular numerical matrix of surface heights. The illumination matrix can be calculated during program execution. Parametric information is entered in the dialog mode. The shadow effect (according to the illumination value of each node) is created by changing the density of the line drawing near each vertex of the matrix of heights.

The program for the spatial image of the surface relief, taking into account screening and illumination, is intended for a graphic three-dimensional image of a function of two variables. The main area of application of the program are the processes of studying the behavior of various functions in geophysics, geodesy and other sciences, modeling aerospace images of the surface relief. The program allows processing matrices (the matrix of the applicate function and the illuminance matrix) recorded as a data set on a magnetic carrier. The program outputs the resulting graphical information directly to the graphical output device.

The program requires a minimum of 150K bytes of RAM to run. The speed of the program execution is affected by the size of the initial matrix of terrain relief heights.

The execution time of the program is determined by the requested functions, the size of the initial numerical information and the amount of RAM allocated for the task. The time spent can be estimated from the listing of the given test cases.

The main task solved by the program is to display a three-dimensional image of the surface relief on a graphic device, taking into account its illumination. A three-dimensional image is obtained by projecting a surface onto a plane. The program implements the central projection method, which allows you to set an arbitrary observation point, relative to which the projection is built. The projection plane is drawn perpendicular to the line of sight (line) passing through the given observation point and the center of the volume formed by the surface of the function and the lower base, the applicate of which coincides with the lowest point of the function (minimum value) or is forced. The designed surface elements are formed as lines of intersection of the function surface with vertical planes (sections) parallel to the coordinate axes. Regardless of the illumination, the main sections are drawn through the vertices of the nodes of the displayed matrix. If the volumetric image mode is set taking into account the illumination, then, depending on the degree of illumination of each node, a number of additional sections are made. Moreover, the number of sections is determined by the illumination of the node. In the case when additional sections are drawn, a linear interpolation of the function to the section line is performed.

The projection of any point A of the section line onto the projection plane is defined as the point of intersection of the line of sight passing through point A with the projection plane. A set of projection points are connected by line segments, forming a projection of the section line. When constructing an image, only those lines are drawn that are visible to the observer, i.e. 3D image with screening.

Graphic display of three-dimensional bodies, taking into account their illumination, is carried out in three stages.

At the first stage, the numerical matrix of surface elevations is entered and corrected. The result of the program execution is a set of data on the disk (by default, the file name is NamFi.txt).

At the second stage, the illumination of the surface relief is calculated. The result of the program execution is a set of data on disk (by default, the file name is NamFo.txt).

At the third stage, the direct display of three-dimensional bodies on raster graphics devices is carried out. The input information is the elevation matrix of the terrain and the matrix of its illumination. Parametric information is entered in the dialog mode.

It should be noted that the software tools and algorithms that directly provide the process of graphic display of a three-dimensional body on the screen of a raster graphics device are not related to the presentation of the initial information in a rigidly fixed format and allow subsequent three-dimensional display of various three-dimensional bodies.

The program consists of the main MAT module and a number of modules, the main of which is MatGrafUnit, developed in the Delphi environment.

The MatOswUnit module is designed to calculate the illumination intensity of the surface relief (represented as a regular matrix of heights) by a natural light source or two artificial light streams, one of which illuminates the relief from above, and the other provides side illumination (Khlebnikov et al., 2010).

When the surface relief is illuminated by two artificial light sources, the illumination intensity is calculated by the formula:

$$J = S_1 * \cos\alpha + S_2 * \cos\alpha_{п} \qquad (1)$$

where

S_1 is the power of the side light source;

S_2 is the power of the vertical light source;

α is the angle between the normal to the illuminated area and the direction to the side light source;

α_n is the angle between the normal to the illuminated area and the vertical.

To calculate the intensity of sunlight, the formula is used:

$$J_C = \frac{I_0^x}{1 + c * \sec\beta} * [(1 + a * H^{0.8}) * \cos\alpha + b * (1 - c\sqrt{H})] \qquad (2)$$

where

β is the angle between the vertical and the direction to the light source;

H is the relief amplitude measured from the sea level;

α is the angle between the normal to the illuminated area and the direction to the light source;

I_0^x – solar constant;

a is the vertical illumination gradient;

b is the coefficient for taking into account the proportion of scattered light falling on the Earth's surface;

c is the coefficient that determines the optical properties of the atmosphere.

For each vertex of the face, according to the formula (1) or (2), its illumination is calculated taking into account possible shading. If the face under consideration is shaded by more than 50% of its area, then for it the illumination intensity is calculated only from the vertical light flux or only diffuse illumination.

The program execution time is determined by the size of the initial numerical information and the amount of RAM allocated for the task.

The main initial information is a regular numerical matrix of heights recorded on a magnetic medium.

Parametric information includes a number of parametric variables:

- azs is the azimuth of the light source (sun). Default = 0.
- zs is the zenith angle to the light source. Default = 80.
- azlrm is the azimuth of the left frame of the illuminance matrix. Default = 0.
- sk1 is the power of the oblique illumination source. Default = 1.
- sk2 is the power of the vertical illumination source. Default = 0.2.
- nf – way to calculate the illumination:
- 1 – illumination, calculated by formula (1),
- 2 – illumination is calculated by formula (2). The default is nf=2.

After entering the parameters for calculating the illumination and selecting the menu item «Calculation», the actual calculation of the illumination of the terrain matrix is performed.

The result of the MatOswUnit module execution will be placed in the NamFo.txt file and can be viewed in the «view» mode.

The MatGrafUnit module is designed for graphic display of three-dimensional bodies, taking into account its illumination on raster graphics devices.

The main initial information is regular numeric matrixes of heights of the function and illumination, which can be set or calculated in the program, recorded on magnetic media in a certain format.

The result of executing the MatRelfUnit and MatOswUnit modules can serve as input information. The program execution time is determined by the size of the main source information.

Parametric information includes a number of parametric variables. All parametric variables can be set online. Below, when describing variables, each time the rule of formation by the program is indicated - the value of the variable, if it was not mentioned in the input information.

A three-dimensional image is obtained by sequentially projecting sections onto a plane. The program implements the method of central projection, which allows you to set an arbitrary point of observation, relative to which the design is carried out. The projection plane is drawn perpendicular to the line of sight (line) passing through the given observation point and the center of the parallelepiped bounding the three-dimensional body.

The graphics are implemented using the properties and methods of the Canvas object of the Delphi programming system (Kultin, 2012).

The output data consists of text and graphic parts.

The graphic part is issued directly to the graphic device. The graphic part includes, as an obligatory element, a surface relief drawing.

Samples of the final graphical result of the program execution are shown in fig. 1-7.

Result and discussion. Input data: function $f(x, y) = 5 * (1 - \sin\sin(x))/ /(x^2 + y^2 + 0.3)$. The function is not symmetrical, it can be observed from different points. Choosing different observation squares.

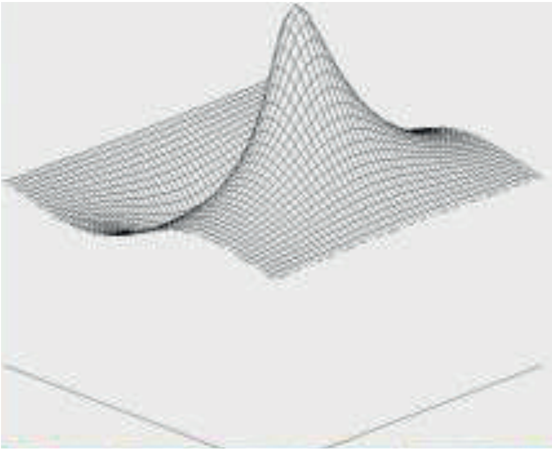

Figure 1 – Azimuth in rays angle 0; zenith angle 80: square 1

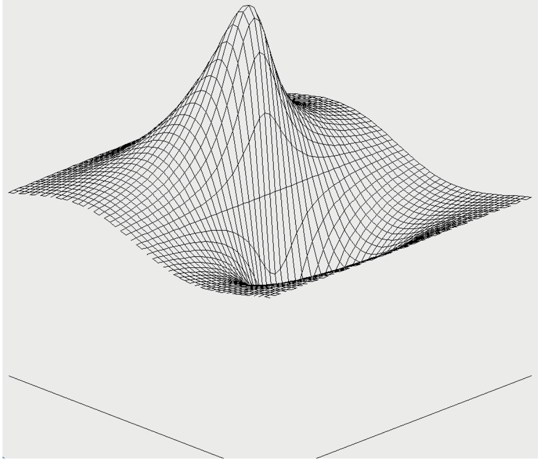

Figure 2 – Azimuth in rays angle 0; zenith angle 80; change viewing angle: square 2

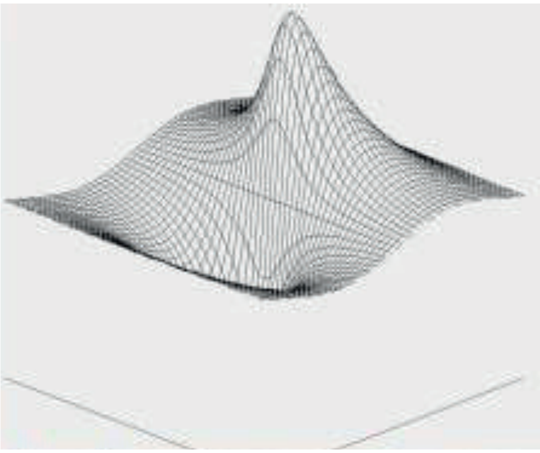

Figure 3 – Azimuth in rays angle 0; zenith angle 80: square 3

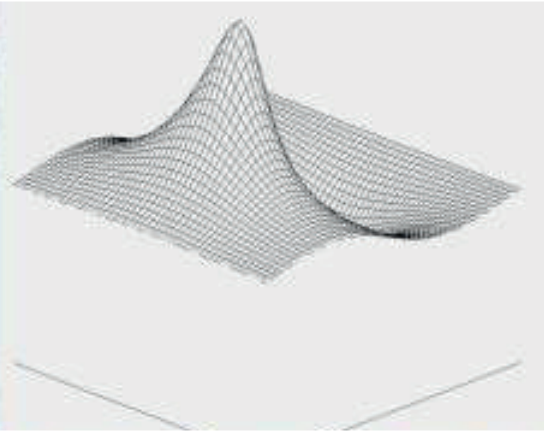

Figure 4 – Azimuth in rays angle 0; zenith angle 80: square 4

Figure 5 shows an aerial photograph of the Shunak crater located in the Karaganda region.

Figure 5 – Aerial view of the Shunak crater

The corresponding samples (from two different sides) of the graphical result of the program execution are shown in Fig. 6-7.

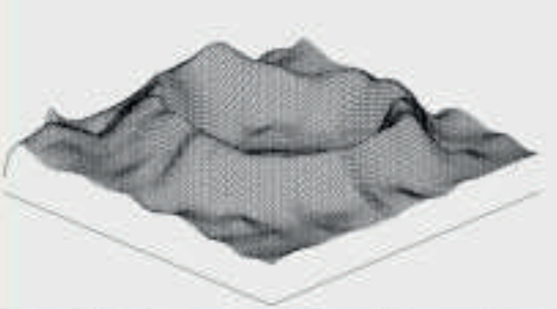

Figure 6 – View of the Shunak crater from the north

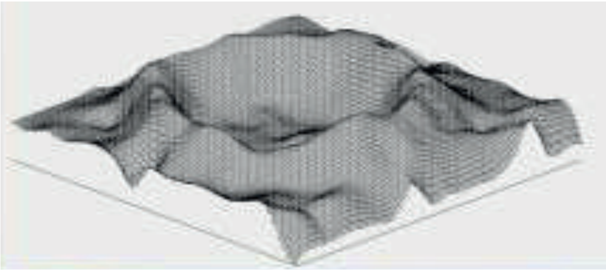

Figure 7 – View of the Shunak crater from the east

Conclusion. The article provides a description of the program for the spatial display of the surface relief, taking into account its illumination on graphic devices of a raster type.

The presented work contains research and development, which can be considered as a solution to an urgent scientific problem devoted to the development of a technology for automated search for ring structures using digital data (the terrain height matrix).

The main theoretical results of the work are the following:

1) mathematical apparatus and theoretical foundations of a new technology for automated search for ring structures from digital data (matrix of terrain heights);

2) mathematical model of taking into account the illumination of the terrain due to the density of the lines;

3) algorithms and software modules that implement the developed technology for automated search for ring structures.

The practical value of the work lies in the fact that the technology and algorithms developed in it allow solving the problem of automated search for ring structures using digital data and can be used in scientific and practical research aimed at searching for new mineral deposits.

Acknowledgements. *The work was carried out at the expense of program-targeted funding of scientific research for 2021-2022 under the IRN project OR11465437.*

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http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Заместитель директор отдела издания научных журналов НАН РК *Р. Жәлиқызы*
Редакторы: *М.С. Ахметова, Д.С. Аленов*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 18.02.2023.
Формат 70x90 $^{1}/_{16}$. Бумага офсетная. Печать – ризограф.
20,0 п.л. Тираж 300. Заказ 1.

Национальная академия наук РК
050010, Алматы, ул. Шевченко, 28, т. 272-13-19