Global Journal of
Archaeology & Anthropology
ISSN: 2575-8608

Juniper PUBLISHERS key to the Researchers

Research article
Volume 13 Issue 5 - June 2023
DOI: 10.19080/GJAA.2023.13.555857

Glob J Arch & Anthropol

The Simplest Assessment of the Possibility of Microgravimeters Using to Search for Unknown Voids Inside the Khufu Pyramid

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Submission: April 22, 2023; **Published:** June 7, 2023

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Abstract

The ancient pyramids keep a lot of mysteries and attract the attention of historians, archaeologists and just tourists from all over the world. Their assignment, construction methods and especially the discovery of previously unknown voids and structures inside them require further study using new technical solutions. The most famous of these structures is the Great (Khufu's) Pyramid on the Giza plateau in Egypt. Since the middle of the last century, several non-destructive technical methods have been proposed for examining the internal structure of the Pyramid. Electromagnetic translucence in the radio frequency range and the use of muon sensors are among them. Although the use of muon sensors has supposedly revealed two previously unknown voids within the Pyramid, independent confirmation of their presence is required. The article discusses the fundamental possibility of using gravimetry to examine the internal structure of the Great Pyramid, and analyzes combining it with other modern technical means including unmanned aerial vehicle (UAV) for the implementation of this project. The paper proposes the simplest model that allows evaluating the required accuracy of a microgravimeter capable detecting the supposed voids in the Pyramid. The advantage of this approach, in addition to its simplicity, is the ability easily checking the presented in paper results. The main purpose of writing the article is to draw the attention of the scientific community to another method of non-destructive testing for the study of the internal structure of the Great Pyramid and discussion further needed steps in this direction.

Keywords: Great (Khufu) Pyramid; Void; Gravimetry; Non-Destructive Testing; Cultural Heritage; Unmanned Aerial Vehicle

Introduction

The architectural objects of antiquity, especially the pyramids, attract the attention of scientists of all specialties because many details of their construction, assignment and features of their internal structure are still unclear. The most famous such objects are the pyramids on the Giza plateau in Egypt, the Mayan pyramids on the Yucatan Peninsula in Mexico, the pyramids of Cambodia and the Pyramids of Güímar in the Canary Islands. The construction of pyramids is characteristic of many ancient civilizations, even, according to modern concepts, not too developed [1]. Undoubtedly, the Great Pyramid (or Pyramid of Khufu) of Giza is of the greatest interest as a monument built by long-vanished ancient civilization that left a noticeable mark on the history of mankind [2,3]. Its construction was ended presumably in 2540 BC, i.e. the Pyramid is over 4500 years old now. The Pyramid is the largest architectural object of antiquity and has attracted the attention of historians, researchers and robbers of all kinds since ancient times. The ancient Greeks considered the Pyramid to be one of the wonders of the world.

The first, who tried to get inside the Great Pyramid, seems to have been Abu al-Abbas Abdallah ibn Harun al-Rashid (better known by his regnal name Al-Ma'mun). He was the caliph of Baghdad, and was also known as a scientist and an astronomer. However, his methods of government were quite consistent with his era. After the conquest of Egypt and the harsh suppression of the Coptic uprising, Al-Ma'mun ordered in 831 the opening the Pyramid of Khufu. After several unsuccessful attempts, the entrance to the Grand Gallery was found. The caliph was most likely the first person to enter the pyramid after its construction. To his dismay, nothing was found inside the Pyramid. Other than a thick layer of dust and an empty granite sarcophagus. All other internal compartment inside the Great Pyramid accessible by that time to him also turned out to be empty. Given the level of technology of that time, it was possible to penetrate inside the Pyramid only by destroying part of it. Now this entrance to the Pyramid has turned into a tourist attraction.

Since Al-Ma'mun's time, there has been an assumption that there must be some still unknown internal rooms where burial objects are hidden: the Khufu mummy accompanying by funerary items and jewelry. This assumption is substantiated by the conclusion that such a majestic structure, which was worth a lot of money, effort and time for its construction, could not be left empty. Moreover, the Khufu mummy has not been discovered so far. Further attempts to detect unknown premises were made in the middle of the last century using already with non-destructive, noninvasive methods. One of the first on this path was the famous physicist, Nobel Prize winner for 1968 L. W. Alvarez. He proposed and implemented a method for transilluminating the internal structure of the Egypt pyramids by using muon detectors [4].

Muons are elementary particles that are formed in cosmic rays as a result of the penetration of high-energy space particles into the Earth's atmosphere and their collision with air molecules. Muons are very similar in their parameters to electrons, but more than 200 times heavier. Due to their mass, muons propagate quite well in the dense material of the pyramids. If there is a void on their way, then the absorption of muons in this direction will be less. And this is possible to detect. There are a few methods to detect elementary particles including muons. One of them was proposed by Alvarez [5]. Unfortunately for Alvarez and his team, their attempt to find voids inside the Khafre's Pyramid was unsuccessful [4].

Almost at the same time, in the 70s and a little later in the 80s, attempts were made to sound the Great Pyramid by electromagnetic waves of the radio frequency range [6,7]. Both attempts were unsuccessful due to the anomalously high level of absorption of electromagnetic waves in limestone in the range in which the studies were carried out, about 100 MHz. Perhaps this is due to the high humidity level up to 80%, which is observed inside the Pyramid [6,8], and the high salt content [8]. Water, dissolving salt, forms an electrolyte with high electrical conductivity, which is a good attenuator of electromagnetic waves of all frequency. This reason is the main problem for communicating with submarines in underwater position in the sea. And if the origin of salt can be associated with the antiquity of the Pyramid and its proximity to the Mediterranean Sea, then the high humidity inside the Pyramid is a mystery because Giza Plateau is located in a desert area at an altitude of about 80 meters above sea level and quite high above the level of the Nile.

The method using electromagnetic waves is active, in contrast to the passive muon one, because it allows variation of some parameters of the probing signal. An analysis of the possibility of sounding of the Khufu's Pyramid in the radio frequency range and the factors affecting it are presented in [9,10]. Recently, the experiments of L. W. Alvarez were repeated at a new technical level by a Japanese team of researchers. By placing muon sensors both inside the Great Pyramid and outside it, it was possible, presumably, to detect two previously unknown cavities, Figure 1 [11].

Muon tomography is an indirect method as all non-destructive testing technologies and does not give an accurate representation of the size and shape of the possibly detected cavities, which could be obtained using on-the-spot measurements. However, the existence of the discovered voids cannot be confirmed, for example, by drilling holes or making passages (as Al-Ma'mun did in his time), because this is prohibited by the legislation on the protection of cultural heritage sites. Muon technology could be improved by designing sophisticated antenna array of muon detectors as this was proposed in [12]. However, another independent non-destructive examination method is also desirable for verifying results.

Possibly, microgravimetry can turn out to be such a method. It should be noted that the idea of using gravitational measurements in archeology is not completely new. Thus, gravimetric survey for the study of archaeological objects has already found its application in some cases [13, 14]. There were also frustrating attempts in 1986–1987 with the support of the largest French company for the operation of nuclear power plants EDF to use gravimetry for surveying the Great Pyramid [15-17].

These studies were carried out only in the interior of the Pyramid. A small gravity anomaly of 30 microgals (1 microgal = 10^{-8}m/c^2) in the corridor leading to the Queen's Chamber was detected [16]. At that time, it was possible to obtain permission from the Egyptian authorities for drilling. To the disappointment of the researchers, the drill fell into a cavity with quartz sand after 3 meters. And since the information got into the press, the drilling took place in the presence of a crowd of journalists of about 50 people. Publicity and general disappointment led for many years to the termination of the entire gravitational project [16]. However, the Scan Pyramid muon project and its discoveries [11] has returned attention to alternative methods of surveying the Giza Pyramids, including gravitational measurements. An evaluation of the possibility of microgravimeters using to detect voids predicted in [11] is given in the next sections.

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Gravimetry of the Task

The main property of the gravitational field, which is of interest for the purposes of this project, is its ability to propagate without attenuation in matter. Gravity cannot be shielded or weakened in one way or another. The intensity of the gravitational field depends only on distribution of the mass of the substance and the distance to the measurement point. After correcting for centrifugal forces resulting from the Earth's rotation, an equation for gravitational force $\vec{F}$ can be written as [18]

$$\vec{F} = -G\mu \int_M \frac{dm}{R^2}\frac{\vec{R}}{R} + \mu\left(\vec{\omega}\times\vec{r}\right)\times\vec{\omega} \quad (1)$$

where G — gravitational constant, μ — unit mass, dm — earth mass element, $\vec{R} = \vec{r} - \vec{r}'$; $\vec{r}, \vec{r}'$ — radius vectors of the measurement point and mass element, ω — angular velocity of the earth's rotation; the integral is taken over all masses *M*. It is more convenient to transform the equation into a form in which the integral over mass is replaced by integration over volume $dm = \rho(\vec{r}')dv$, where $\rho(\vec{r}')$ — density of matter at a given point in space, dv — volume element, and force $\vec{F}$ is replaced on acceleration g. Then (1) can be transformed to the form

$$\vec{g} = -G\int_V \rho(\vec{r}')\frac{dv}{R^2}\frac{\vec{R}}{R} + \left(\vec{\omega}\times\vec{r}\right)\times\vec{\omega} \quad (2)$$

Thus, if the mass in the considered volume has a variable density, this affects the force of gravity and, consequently, the value of the free fall acceleration becomes equal to $g_0 + \Delta g$. Here g_0 is the standard free fall acceleration at the Earth level, and Δg is the change of this value caused by the presence of subsurface inhomogeneities. The gravitational acceleration depends on the latitude at which it is measured. It is greater at the poles of the Earth, and less at the equator due to the centrifugal forces caused by its rotation. Usually, the value of g_0 at the equator at sea level is taken as the standard value g_0 = 9.81 m/c^2. The effect of variable measured g has long been used in geophysics and geology, for example, to detect ore bodies under the earth's surface, which may have a substance density different from the surrounding space containing them, as well as to detect cavities, such as tunnels or karst voids [19]. An illustration of this effect is shown in Figure 2.

To assess the possibility of cavities detection inside the Pyramid, let's simplify the task as much as possible. Let's neglect the influence of the Earth's rotation in (2), the tidal forces of the Moon and the Sun, and other similar factors. Of course, they are important in the processing of measurement results, but they are insignificant in assessing the capabilities of modern gravimeters for solving the problem under consideration.

Figure 3 shows three options for calculating the integral (2):

a) A homogeneous half-space with a density of ρ_0. Here the assumed cavity with volume of V_M has the same density of matter as the space containing it and mass of *M*. In this case, the gravitational acceleration force on the surface is equal to g_0. So that g_0 does not become equal to infinity, the half-space can be limited to a layer of finite thickness. The thickness of the layer does not matter for our estimates.

b) The same layer with arbitrarily shaped void (ρ = 0 and zero mass) and the same volume V_M. Now the acceleration force over the void at some central point is equal to $g = g_0 - \Delta g$.

c) The void has the same shape, but is filled with matter with a density of ρ_0, and the density of the layer is zero.

Obviously, the sum of the integrals for cases b) and c) is equal to g_0. Therefore, the acceleration calculated for case c) is equal to Δg. Let's make one more simplification that the object of mass $M = \rho_0 V_M$ has the shape of a sphere. Then the gravitational field generated by it in the surrounding space is equal to the gravitational field of the equivalent mass, but concentrated in the center of the sphere. Then the force acting on a unit mass on the surface is

$$\Delta g = -GM / L^2 \quad (3)$$

where *L* is the distance from the center of the sphere to a point on the surface of the imaginary layer. This equation will always be valid for the case *L* >> l, where l is character dimension of the void. The relation (3) is also intuitive understandable and easily proved by the dimensional analysis [20,21] because there is single combination of task parameters ρ_0 , V_M , *L* and *G* that has dimension of acceleration *g.* There are only assumptions regarding real size of two voids in the Great Pyramid discovered during the ScanPyramids project. It was assumed in [11,22] that the length of the Big Void is at least 30 m long and has the cross section similar to the Great Gallery of the Pyramid, i.e. $2\times 8\ m^2$. At these assumptions the volume of the Big Void will be about 480 m^3. The main part of the Pyramid's blocks consists from crystalline limestone that has density of ρ_l = 2800 kg/m^3. Taking into account this parameter, the mass *M* in (3), which is equivalent to the mass of limestone that could fill the volume of the Big Void, is equal to 1.34·10^6 kg.

Let us evaluate the effect of such a mass at a distance of 10, 25, 50, and 100 m. The value of the gravitational constant is G = 6.67·10^{-11}m^{3}kg^{-1}s^{-2}. Given that the force was calculated for a unit mass of 1 kg, the acceleration Δg generated by this force in the measurement unit 1 Gal = 1 cm/s^2 is is shown in Table 1.

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Table 1:

L, m	Δg, Gal, cm/s^2
10	$8.9\cdot10^{-5}$
25	$1.4\cdot10^{-5}$
50	$3.6\cdot10^{-6}$
100	$8.9\cdot10^{-7}$

For comparison, the standard gravitational acceleration in these units is g_0 = 981 Gal. Thus, the assessments made show that a microgravimeter with a sensitivity of at least $10^{-7} \div 10^{-6}$ Gal is needed to survey the Great Pyramid. By measuring the deviation of the gravitational field on the surface at taking into account the free-air correction [23] and then solving the inverse problem [24], it is possible to establish the mass distribution inside the Pyramid. [25,26]. The solution of the inverse problem is facilitated by the possibility of accessing the interior of the Pyramid. It becomes possible to carry out measurements not only on the surface of the Pyramid, but also inside it. Measurements of the gravitational field inside the Great Pyramid will provide additional data and improve convergence when solving the inverse problem. The geometry of the Khufu's Pyramid, including its inner part, is well known, Figure 1 and [27]. This gives hope to resolve inverse problem with rather well accuracy. Thus, this would confirm or disprove the discoveries that were made in the ScanPyramids project by muon detectors.

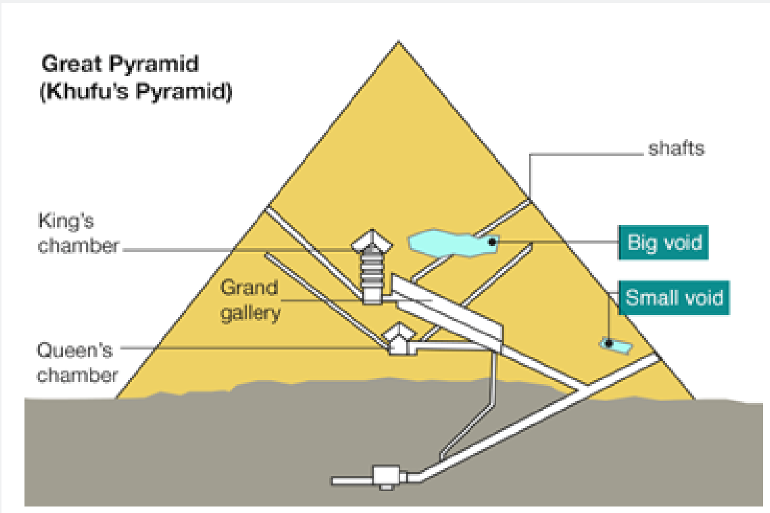

Figure 1: The estimated locations of the Big and Small voids detected by muon tomography in the Scan Pyramids project [11,12].

Gravimeters and Measurements

The task of determining the gravitational field on the surface of the pyramid with the required accuracy is rather difficult. Perhaps it is simpler than the detection of gravitational waves [28], but it will also require considerable efforts and time. Attempts to find out the nature of gravity were made in the late the Middle Ages in order to find out the nature of the motion of the planets of the solar system. The measuring technique of that time did not allow any precise measurements to be made under terrestrial conditions.

But with the improvement of experimental technology and instruments, it became possible to predict the presence of ore deposits under its surface measured variations in the value of the Earth's gravitational field [29-32]. Modern microgravimeters can be divided into two main categories: absolute gravimeters and relative ones. Absolute gravimeters determine the absolute values of the gravitational acceleration by direct measuring the acceleration of a freely falling body. Relative gravimeters can measure only acceleration changes regarding to some level. Absolute gravimeters are much more cumbersome and have lower accuracy than relative ones [29].

Therefore, we will further consider only relative gravimeters that determine relative changes in the gravitational acceleration by measuring the displacement of a control mass suspended on a spring, for example, in the Scintrex CG-5 [32], or due to superconducting levitation, for example, in the GWR superconducting gravimeter. Considering the complexity of working with superconducting gravimeters, we will focus on conventional spring-type relative microgravimeters. The CG-5 gravimeter is one of the best gravimeters of its type. It

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has a sensitivity of 10^{-7} Gal with a signal accumulation time of 5 min [29,33]. This, according to the data given in Table 1, will apparently be sufficient to solve the problem. The gravimeter has a moderate weight of about 8 kg and dimensions of 30 cm $(h) \times 21\ cm \times 22\ cm$ [32].

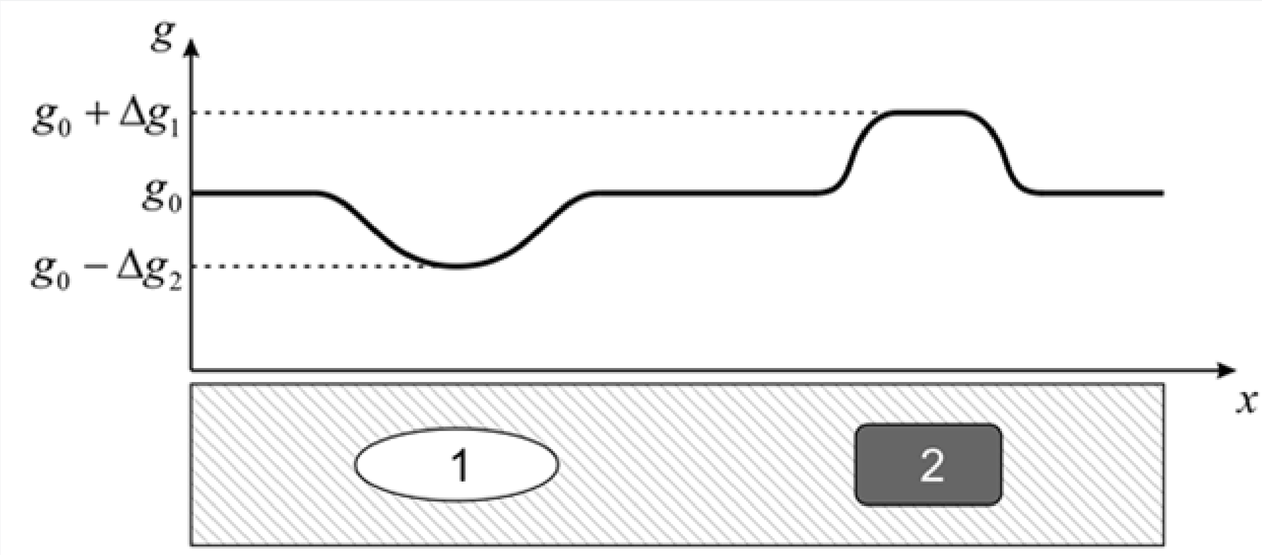

Figure 2: The influence of different underground geological structures on the local gravity field on the Earth surface. A void 1 reduces g, while ore deposit 2 as a rule increases g above standard level g0 because of greater density in comparison with surrounding earth matter.

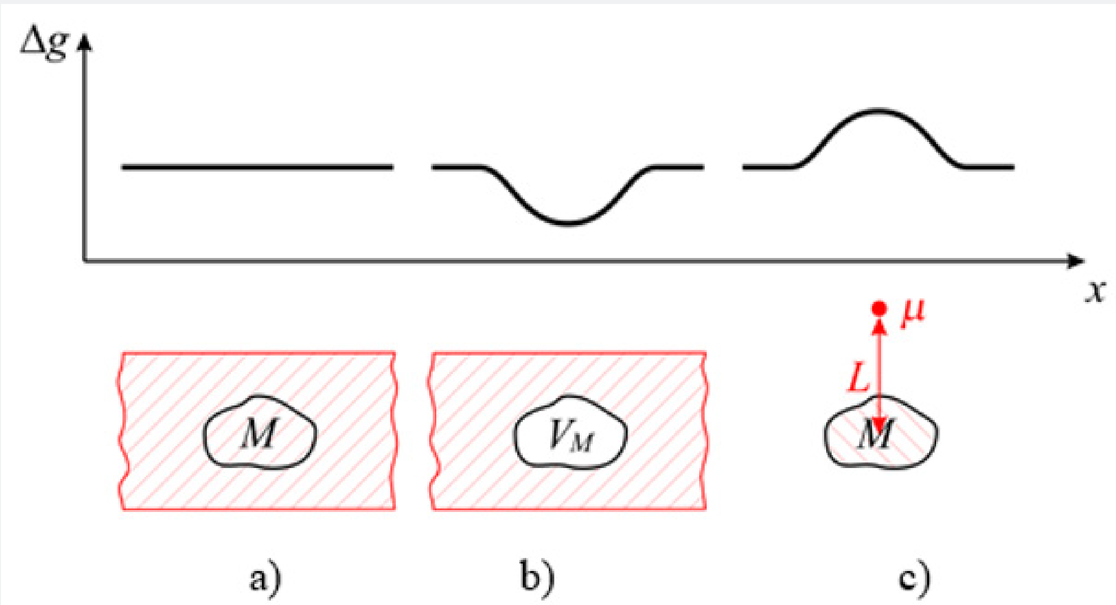

Figure 3: a) an uniform media; b) media with void; c) void is filled with matter.

The dimensions of the device do matter because of the need to place the gravimeter on the steps, which are formed by separate layers of limestone blocks forming a pyramid. The width of the base of the Great Pyramid is $230\ m \times 230\ m$, and the number of layers of blocks is currently 201. It is easy to understand that the average width of the steps of the Pyramid is about 57 cm. This is quite enough to accommodate a device like the CG-5. It is need also to note that the average height of the steps of the Great

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Pyramid taking into account its modern height of 140 m is 0.7 m.

To determine, although the approximate dimensions of the internal voids of the Great Pyramid, a resolution of 5-10 m is required. The area of the four faces of the pyramid for its modern size is about 83·103 m^2. Thus, if measurements of the gravitational field are made with steps of 10 m, approximately a thousand measurements may be required, and if after 5 m then respectively four times more. Since one measurement with the CG-5 gravimeter requires 5 min, and moving the device to a new location and setting it up requires at least 15 min, the total time of continuous operation can be about 300 hours. Of course, you can use several devices but in any case the time to perform measurements will be quite large. The complexity and duration of the gravity project are comparable to the ScanPyramid muon project [34].

A method that could automate the work and reduce the use of manual labor is to apply the UAV to deliver the gravimeter to the desired point on the step surface of the Pyramid. Unfortunately, modern quadrocopters with a payload of 10 kg are not capable of landing on a narrow platform of half meter wide due to their size. In addition the gravimeter, which is once delivered to the measurement site, needs alignment and leveling, which is currently done manually. The use of UAV in this project is very tempting but needs further study as it is not excluded possibility development of a specialized UAV capable of landing on a stepped surface, taking into account the width and height of the Pyramid steps.

Conclusion

The problem of using microgravimeters to detect supposed voids in the Great Pyramid has recently been considered in [35]. The authors of this work claim that they built a fairly accurate geometric model of the Pyramid, with the help of which the calculations of the gravitational field on its surface were carried out. The results obtained in it largely coincide with those presented in this paper. But since in [35], there is no description of the model itself, and the verifiability of the obtained conclusions is rather difficult. In general, it can be concluded that these preliminary estimates show that modern microgravimeters, taking into account all the necessary the Bouguer's corrections affecting measurement accuracy [36-38], are potentially capable of detecting the alleged voids in the Great Pyramid [11].

Further research is needed for a detailed technical study of the project, including the development of an accurate gravity model of the Giza Plateau, which describes not only the geometry of the Great Pyramid in terms of its well-known interiors and galleries, but also the influence of other surrounding Giza pyramids. Such a model would be useful in gravity measurements to verify predicted and obtained results.

It should be noted that this task is complex, and is complicated by the fact that the exact internal structure of the Khufu Pyramid is still unknown, except for the premises available for study at the present time. It is possible only to assume that inside the Pyramid may be cavities filled with sand and stones [34], as well as internal ramps that were used by the builders during its construction [37] or room predicted in [11] as the Small void, confirmed in [39] and at last was discovered recently [40]. The joint use of various physical methods and traditional historical and archaeological research technologies, perhaps in the future, will make it possible to unravel the mysteries of the Great Pyramid associated with its purpose and construction.

The main purpose of writing the article is to draw the attention of the scientific community to another method of non-destructive testing for the study of the internal structure of the Great Pyramid and discussion further needed steps in this direction. It would like to note with regret that people have created the most beautiful mathematical apparatus of quantum mechanics, have learned to register gravitational waves, but still cannot unravel the secrets of the structure built by the ancient civilization four and a half thousand years ago.

Funding: This paper was supported by the Russian Science Foundation under project # 21-19-00043, https://rscf.ru/en/project/21-19-00043/

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How to cite this article: Sergey I, Alexander B, Vladimir R, Dmitry A.The Simplest Assessment of the Possibility of Microgravimeters Using to Search for Unknown Voids Inside the Khufu Pyramid. Glob J Arch & Anthropol. 2023; 13(2): 555857. DOI:10.19080/GJAA.2023.13.555857

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