

INSIGHT

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Non-Destructive Testing and Condition Monitoring



This month's cover



Recent innovations at Guided Ultrasonics Ltd (GUL) mean that it is now possible to have a fully automated and self-contained system for monitoring the integrity of pipework.

The new guided wave monitoring system from GUL, shown on this month's front cover, is solar-powered with a choice of data transmission options, including 4G, so the system is standalone. Guided wave data is collected automatically several times a day, allowing for use of highly sensitive automatic analysis to screen along the length of the pipe for early detection of local damage mechanisms.

In addition, the system monitors the wall thickness at eight positions around the circumference of the pipe, which enables the measurement of corrosion rate and the detection of uniform damage mechanisms. This data arrives directly to the desktops of integrity managers, helping them to optimise operations by removing uncertainty about pipeline condition.

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A proposed radar method for non-destructive investigation of Egyptian pyramids

S Ivashov, T D Bechtel, V Razevig, L Capineri and M Inagaki

The study of ancient Egyptian monuments attracts the attention of experts from around the world. A recent event that confirms this is the discovery, using muon sensors, of previously unknown cavities in the Great Pyramid of Giza (or Khufu's Pyramid). Since it is unfeasible to directly confirm this discovery by drilling, another independent non-destructive method is necessary to confirm this discovery and provide accurate determination of the locations and shapes of the cavities. Following a literature review of the different methods used in evaluating cultural objects, this paper analyses a possible framework for simulation of a holographic radar for detecting openings or other unknown structures of interest to archaeologists/Egyptologists and the public.

Keywords: Great Pyramid, Khufu's Pyramid, void, muon sensor, holographic, subsurface radar, non-destructive testing, dielectric constant, attenuation, cultural heritage.

1. Introduction

The study, preservation and restoration of the cultural heritage of humankind require careful verification of the physical condition of artworks and architecture, including such important characteristics as:

- Internal structures
- Heterogeneity
- Hidden voids, objects and components
- Presence and geometry of cracks and other defects
- Locations of moisture intrusion.

Many ancient cultural objects are made of dielectric materials: natural stone (granite, sandstone, marble, etc), ceramics (including glass), wood and other non-metallic materials. These materials, as well as many soils, are semi-transparent to electromagnetic waves in the radio and microwave ranges and can be investigated using subsurface radar methods^[1-5]. Non-destructive testing (NDT) is also applied to metallic structures and artefacts (for example sculptures, ancient weapons, etc), but such objects require other methods, such as X-ray or ultrasound imaging, because electromagnetic waves penetrate metal to only a very shallow skin depth.

Although the most common subsurface radars are impulse-type ground-penetrating radars (GPRs), the continuous-wave holographic subsurface radars (HSRs) developed by the authors have also found many applications in several fields of NDT^[6-8]. The basic principles of recording and reconstructing radio holograms of objects located in optically opaque media have been described previously in several published works^[9,10].

The same NDT technologies that are traditionally used in engineering and construction can also be applied to the study of cultural heritage objects. These include various types of tomography^[11], radiography^[12], infrared imaging^[13], acoustics^[14] and, in some cases, shearography^[15]. HSR can also be added to this list as a completely non-destructive and relatively low-cost method. Recently, the use of electromagnetic waves in the terahertz range for the diagnosis of artworks has attracted attention^[16]. The use of GPR in archaeology for site mapping and prospection, which significantly accelerates some archaeological research and excavations^[17-21], is also worth noting.

● Submitted 10.06.20 / Accepted 02.10.20

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Lorenzo Capineri received a degree in electronic engineering in 1988, a doctorate in NDT in 1993 and a postdoctorate in 1994. He became Associate Researcher, 1995, and Associate Professor of Electronics, 2004, with the Department of Information Engineering at the University of Florence, Italy. In 2017, he received the National Scientific Qualification as Full Professor in Electronics. Lorenzo's current research activities are in the design of ultrasonic guided wave devices and buried object detection with ground-penetrating radar and holographic radar.

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However, new scientific advances and technologies also open new possibilities. An excellent recent example is the use of several types of muon detector^[22] to examine Khufu's Pyramid, also known as the Great Pyramid^[23]. Built around 2540 BCE on the Giza Plateau in Egypt, it is the largest of the Egyptian pyramids and its size instils awe in researchers, tourists and locals alike. The use of elementary particle detectors in the ScanPyramids project in 2015-2017 made possible an amazing discovery: previously unknown voids^[22]. In the ScanPyramids study, sensors were used to detect muons arising from collisions of cosmic rays with air molecules. These collisions create showers of secondary elementary particles in the Earth's atmosphere, which can penetrate tens of metres into rock and other dielectric materials.

In this case, the muon flux intensity recorded by a detector depends on the density of a material and the path length in it. Variations in the muon flux intensity in different directions make it possible to infer the presence of voids along their path since air absorbs muons much less than the dense limestone and granite that constitute the pyramid.

It should be noted that the idea of examining the Giza pyramids using muon detectors was proposed as early as 1965^[36]. Cosmic ray spark detectors were installed in the inner Belzoni Chamber of the Second (Chephren's) Pyramid at Giza in 1967. However, this experiment yielded no interesting anomalies^[37].

The ScanPyramids evidence of voids based on passive muon detection^[22] is convincing but, as with all NDT, independent confirmation is required. Of course, tunnelling or drilling is impossible. The use of NDT methods for examining the pyramids is driven by the contemporary Egyptian authorities' prohibition of any actions that violate the integrity of cultural objects. The 2011 unrest in Tahrir Square in Cairo, which led to the partial looting of the Egyptian National Museum and a fire in the papyrus library, focused attention on the preservation of historical relics and structures as close as possible to their original state. Thus, active NDT methods based on other physical principles must be used: for example, scanning using metre or decimetre radio waves. This can not only confirm the presence of the inferred voids, but also determine their locations and dimensions.

Examination of optically opaque objects using electromagnetic signals across a wide range of wavelengths, from metre to millimetre, is common in NDT. There are two possible approaches: a two-sided configuration (as implemented, for example, in medical X-ray machines), with the transmitter and receiver on opposite sides of the study object, or the recording of backscatter when only one side is accessible^[32]. The latter is especially valuable for surveys of the earth (for example GPR for archaeological mapping), where there is no 'underside' of the site. GPR has previously been used to study the Giza Plateau pyramids and other monuments of ancient Egypt^[4,5,18]. In fact, recent GPR scans have rekindled a long-running debate over whether there are chambers (possibly the long-sought tomb of Nefertiti) adjacent to the tomb of Tutankhamun^[38,39]. The main advantage of GPR is the ability to examine the pyramid with the receiving and transmitting antennas on the same surface, whether inside the pyramid (in the well-known and accessible galleries and chambers of the King and Queen) or on its outer surfaces.

It should be noted that the main obstacle restricting the use of electromagnetic waves for 'seeing through' optically opaque media is their loss or attenuation, which can reach 100 dB/m or more in some media^[24]. This loss limits many potential applications of electromagnetic imaging. Since attenuation as a rule increases non-linearly with increasing frequency, f , and image resolution improves with higher f , it is always necessary to seek a compromise in terms of f that optimises the trade-off between sounding depth and spatial

resolution. In the following section, the authors describe what is known from the literature regarding the structure of the pyramid to obtain quantitative information about the five points mentioned at the beginning of this section.

2. Description of the Great Pyramid of Giza

Of great interest among the objects of the cultural heritage of humankind are the monuments and architectural masterpieces of ancient Egypt. While these have, for the most part, been studied thoroughly for hundreds of years, at the same time they still contain many mysteries. For example, it is not known for certain how the ancient Egyptians built such grand structures as the pyramids and, in particular, Khufu's Pyramid. Figures 1 and 2 are a photo of the exterior and a sketch of the interior of the pyramid, respectively, illustrating the known internal passages and rooms, including the King's Chamber, the Queen's Chamber and the connecting galleries. Today, tourists enter the pyramid through a 17 m gap, which was made in 820 CE by the Baghdad caliph Abdullah al-Mamun. He hoped to find treasure and papyri containing the wisdom of the ancients, but he found only elbow-deep dust and an empty granite sarcophagus.



Figure 1. The Great Sphinx of Giza with Khufu's Pyramid in the background

According to available descriptions, the parameters of the Great Pyramid are as given in Table 1^[26].

Participants in the ScanPyramids project (2015-2017) used three different methods of muon tomography to study the interior of the pyramid and found evidence consistent with a 30 m void above the Grand Gallery^[22]. The centre of the void is located 40-50 m above the floor of the Queen's Chamber and its length is comparable to the Great Gallery. Researchers do not know the exact characteristics of the suspected chamber; it may turn out to be an inclined corridor or several adjacent rooms. The estimated location of this so-called 'big void' and an additional 'small void' are shown in Figure 3^[27].

As shown in Figure 3, the big void is located at approximately half the height of the pyramid where the width is about 100 m. The small void is much lower but is close to the edge of the pyramid, possibly about 10-15 m from the outer face. These depths and dimensions constrain possible approaches for imaging the voids in the radio waveband (decimetre- and metre-scale wavelengths). The void positions also allow both the forward scatter technique with two-sided access to the object and the backscatter (or reflective) technique with only one-sided access.

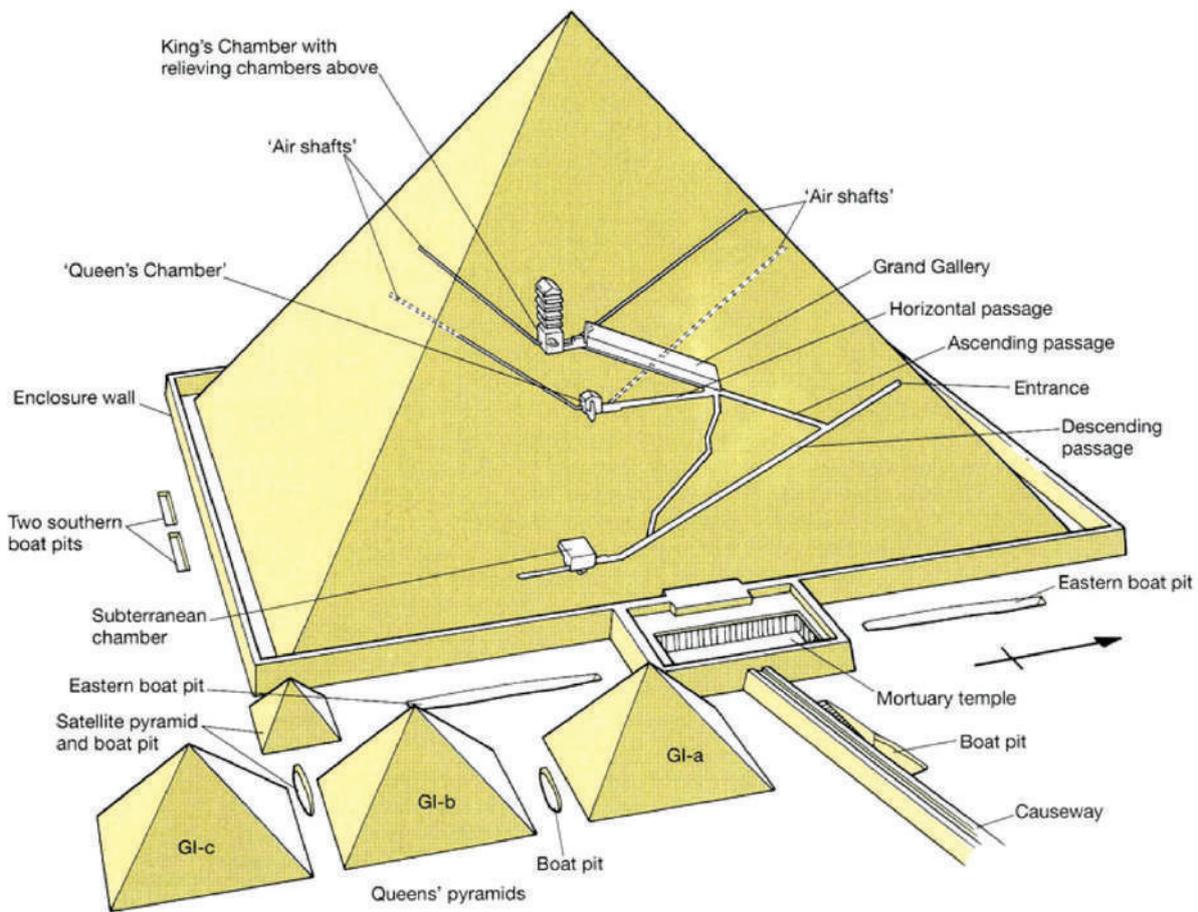


Figure 2. Drawing of the known interior of the Great Pyramid from ScanPyramid^[22]

Table 1. Parameters of Khufu's Pyramid

Parameter	Value
Number of stone blocks	2,300,000 stones
Stone layers	Originally probably 210 stone layers, now only 201 layers
Weight of the stone blocks	With an average density of 2.6-2.9 t/m ³ the large limestone blocks weighed 6.5-10 tons
Special blocks	For the King's Chamber, granite blocks weighing 40-50 tons were used
Length	The average length of the edge is ~230.360 m (~500 cubits): northern edge = 230.328 m; eastern edge = 230.369 m; southern edge = 230.372 m; and western edge = 230.372 m. The largest difference is only 4.4 cm
Height	Originally 146.59 m high (~320 cubits), the pyramid is now only 138.75 m high

Khufu's Pyramid consists of blocks of limestone and granite. It is reported^[23,34] that, according to various estimates, out of 5.5 million tons of the total weight of the pyramid only 8000 tons are granite blocks (*ie* granite is only 0.15% of the mass). This is understandable, since granite is much harder than limestone. Since the pyramid was built during the Bronze Age, it was a difficult task for builders to procure granite blocks of 40-50 tons (according to other estimates 25-80 tons) from the quarry near Aswan (800 km upstream on the Nile). One such granite block (apparently the largest known) is placed above the entrance to the King's Chamber.

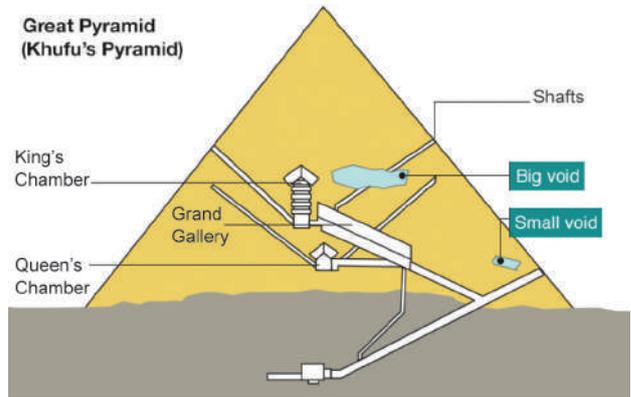


Figure 3. The estimated locations of the big and small voids detected using muon tomography^[22,27]

The dielectric properties of dry granite and limestone^[18,24,29,33,35] are shown in Table 2. It should be noted that the relative permittivity (ϵ_r) data range from 4 to 10, but attenuation varies widely (by a factor of 50) between 0.5 dB/m and 25 dB/m. The level of attenuation is critical for evaluating the feasibility of electromagnetic imaging because high attenuation could prevent transmission of a recordable signal along the required path length (whether a one-way path for two-sided imaging or two-way for one-sided methods). Although Table 2 lists properties for granite and natural limestone, there is evidence for a controversial proposition (based on scanning and transmission electron microscopy and geochemical analysis) that many of the 'limestone' blocks are reconstituted – essentially an ancient and astoundingly realistic and durable concrete^[34].

Table 2. Dielectric properties of granite and limestone

Material	Relative permittivity, ϵ_r	Attenuation (dB/m)	Frequency, f (MHz)	References
Granite (dry)	5	0.5-3	100	18, 24
	4-6	0.01-1	Not available	33
Limestone (dry)	7	0.5-10	100	18, 24
	5	1.6	0.5-1.5	29
	4-8	0.4-1	Not available	33
	8.75-10	6	10	35
	8.75-10	25	150	35

Attenuation is strongly related to electrical conductivity, which is dominated by moisture content and chemistry. The climate on the Giza Plateau is quite arid, so it might be expected that attenuation in the stone blocks of Khufu’s Pyramid be near the lower boundary of these ranges. However, preliminary measurements, made in 1974 with now-antiquated systems, indicated unexpectedly high attenuation^[35], possibly related to the microscopic hydrated limestone and dolomite minerals that suggested the concrete hypothesis^[34]. Determination of the true attenuation can only be established using direct measurements with modern equipment on the pyramid.

The presence of a contrast in ϵ_r between granite and limestone is worth noticing. Although most of the bulk of the pyramid blocks is limestone, granite blocks will lead to additional reflection and diffraction of electromagnetic waves. This contrast is less than for a stone-air boundary. However, this should be considered when interpreting experimental results and comparing them with mathematical modelling.

The pyramid has been studied for many years and numerous chambers and tunnels are well known. These can be used for the calibration of numerical models and actual measurements. The presence of internal openings also makes possible the placement of radar receivers and transmitters, not only on the surface of the pyramid but also inside it.

3. Simplified mathematical model

Based on the above analysis of the range of possible electromagnetic properties of the pyramid, a simple model was considered that would allow for an evaluation of the possibility of detecting voids in the Great Pyramid using electromagnetic radiation at $f = 100$ MHz, corresponding to a wavelength in air of approximately 3 m. Mathematical modelling was performed using the Altair Feko program^[28]. It is a multi-functional software package for the modelling of electromagnetic wave propagation based on modern rigorous and approximate computational methods, designed to solve a variety of research and engineering problems.

In Feko, it is possible to create a three-dimensional model of targets and the medium surrounding them. The model is divided into grids with a cell size that depends on the required accuracy of the calculations. That is, cell dimensions must be a fraction of the wavelength of the probing signal. The number of cells into which the pyramid model was divided was too large for available computing resources. Therefore, to preliminarily assess the feasibility of scanning the pyramid, instead of the exact dimensions of Khufu’s Pyramid, the calculations used an infinite dielectric layer of thickness $L = 100$ m corresponding to the width of the pyramid edge at the height of the big void from the muon experiment (Figure 3).

Since the Great Pyramid consists mainly of limestone, ϵ_r was set to 7 at an f of 100 MHz^[24]. For this f and ϵ_r , the signal wavelength in limestone is approximately 1.1 m, which is less than the characteristic sizes of voids (chambers and galleries) already known in the pyramid. It can be expected that the voids proposed by the muon experiment have similar or larger dimensions.

Another critical parameter determining the feasibility of examining the pyramid in the radio range is the attenuation coefficient k_a , which is known only approximately for dry limestone (see Table 2). For the

dimensions of Khufu’s Pyramid, this variation is significant. With an attenuation coefficient of $k_a = 10$ dB/m and a path length of 100 m, the total attenuation would be 1000 dB, which makes recording the transmitted signal unfeasible. Since the pyramid is in a desert with low humidity, it can be assumed that the attenuation is closer to the lower boundary of the range. In^[29], for electromagnetic waves with a length of 200 m to 600 m (f of 0.5 MHz to 1.5 MHz), the value of the complex permittivity for the pyramid material $\epsilon = 5 + i0.1$ was taken, which in terms of the attenuation coefficient gives $k_a = 1.6$ dB/m^[24]. Attenuation, which is given in^[33], is rather low and is favourable for transmitting the probe signal for the required path length. However, data from the 1970s, cited in^[35], are discouraging. If the estimates of^[35] are believable, then the examination of the Great Pyramid in the radio range is almost an impossible task.

The frequency of 100 MHz selected for calculations is to some extent a compromise, because with increasing frequency the attenuation and reflection of the signal at small inhomogeneities increases and at lower frequencies the spatial resolution suffers. In the calculations, the effect of attenuation was studied by assuming values (in dB/m) of $k_a = 0, 0.5, 1$ and 3. Since the exact geometric dimensions and forms of the voids indicated by the muon experiment are unknown, the void in the pyramid was modelled using an elongated ellipsoid of revolution with size $D = 30$ m along the longitudinal axis and $d = 5$ m along the two transverse axes.

In the calculations, a plane wave (with $f = 100$ MHz and amplitude A_0) was incident on a layer of a homogeneous dielectric with a thickness of $L = 100$ m. The result of the computational experiment was the amplitude A_1 of the electromagnetic field scattered by the void on the back of the layer and measured on the line marked in Figure 4.

In the calculations for case 1, it was assumed that the major axis of the void was located along the propagation direction of the incident electromagnetic wave, as shown in Figure 4. The void in this

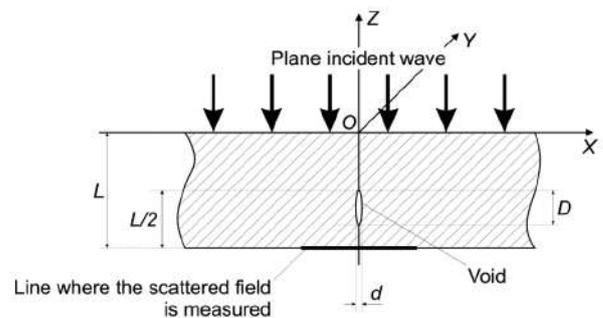


Figure 4. The geometric model for calculation of the scattered field with the location of the major axis of the void along the incident wave for case 1

variation had its leading edge located in the centre of the layer and the other end was shifted closer to the plane of signal registration.

Summarising the previous data, the parameters for the calculation were adopted as follows:

- Frequency $f = 100$ MHz
- The real part of the dielectric constant $\epsilon_r = 7$
- Attenuation coefficient $k_a = 0, 0.5, 1$ and 3 (all in dB/m)
- Layer thickness $L = 100$ m
- Void dimensions along transverse axes $d = 5$ m and along the longitudinal axis $D = 30$ m.

Figure 5 represents the relative amplitude $A_{1,k_a}/A_0$ of the electromagnetic field on the registration line obtained for different values of the attenuation coefficient $k_a = 0, 0.5, 1$ and 3 dB/m.

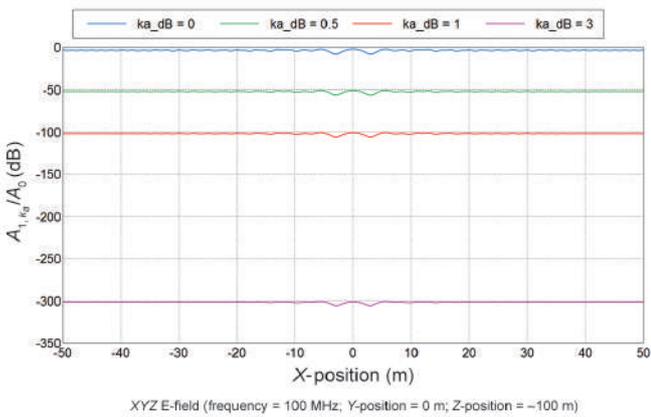


Figure 5. Relative amplitude of the electromagnetic field $A_{1,k_a}/A_0$ at four values of attenuation for case 1

To compare the nature of the curves obtained at different attenuations, Figure 6 shows the curves of the recorded amplitude A_{1,k_a} normalised to the maximum amplitude A_{1,max,k_a} . For increasing attenuation, the relative level of the sidelobes decreases but the shape of the main response remains almost unchanged.

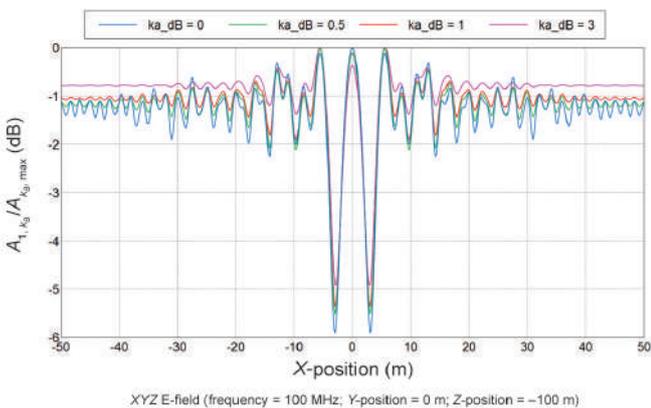


Figure 6. Normalised amplitude $A_{1,k_a}/A_{1,max,k_a}$ of the electromagnetic field on the registration line for case 1

In case 2, the void was rotated by 90° so that the wave fell perpendicular to the major axis of the ellipsoid, with the void located in the centre of the layer, as shown in Figure 7.

The calculations showed that the signal attenuation level for various values of the parameter k_a in case 2 is similar to the same level for case 1 in Figure 5. However, the normalised amplitudes differ significantly, as shown in Figure 8.

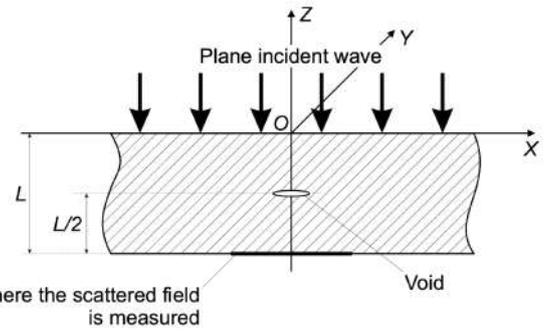


Figure 7. The geometric model for case 2

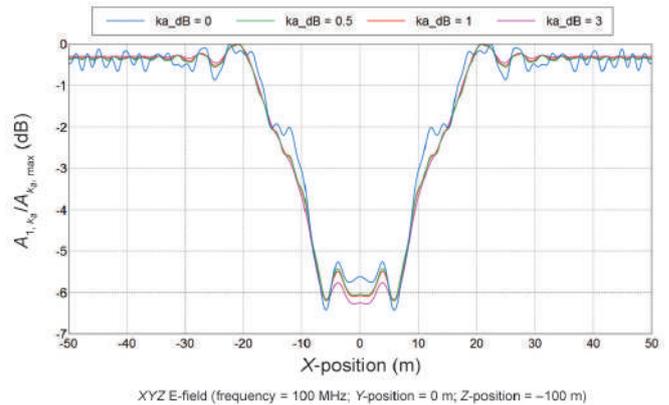


Figure 8. Normalised electromagnetic field for case 2

A comparison of the amplitudes of the recorded field for the two cases of the void orientation with respect to the incident wave at attenuation $k_a = 1$ dB/m is shown in Figure 9.

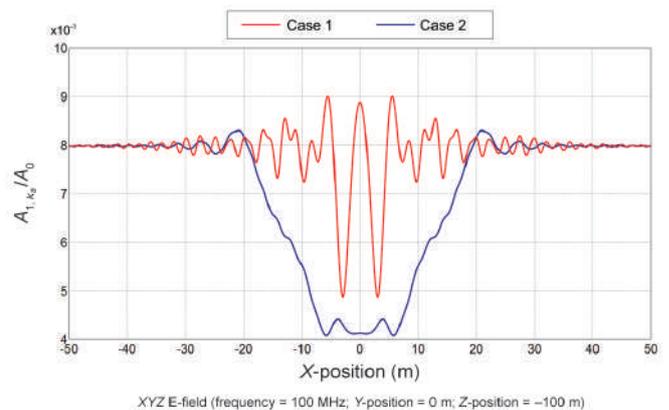


Figure 9. Normalised amplitude of the recorded electromagnetic field for cases 1 and 2 at $k_a = 1$ dB/m

As seen from the graphs, the shape of the detected electromagnetic field substantially depends on the orientation of the void. When solving the inverse problem, this will allow for the recovery of the shape and dimensions of the void^[30], although the void size can be estimated from the results of direct measurements, as shown in Figure 9; the width of the central lobe is approximately 8 m when the probe wave is incident along the major axis of the ellipsoid and 30 m when the transverse incidence occurs. These dimensions approximately correspond to the dimension of the void along the axis perpendicular to the incident wavefront.

Figure 10 represents the influence of the polarisation direction on the form and amplitude of the recorded signals for case 2. The polarisation angle of the electromagnetic wave is counted from the major axis of the ellipsoid. As seen from this Figure, at a polarisation angle of 0°, *ie* parallel polarisation, the recorded signal is noticeably stronger than at perpendicular polarisation at an angle of 90°. This effect could give additional information regarding internal objects in the pyramid. It is obvious that in case 1 the influence of wave polarisation is absent because of the symmetry of the target.

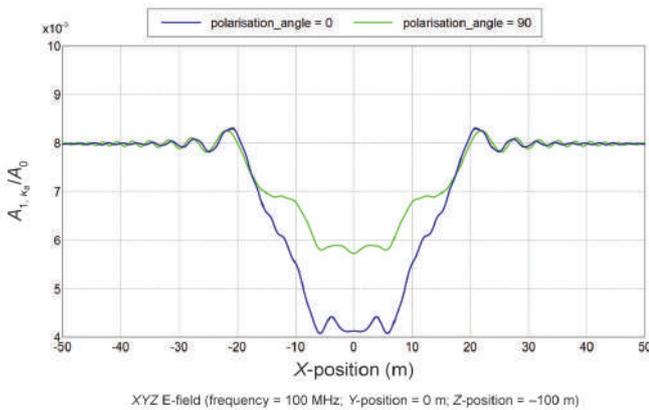


Figure 10. Influence of wave polarisation direction on the form of the recorded signals for case 2 at $k_a = 1$ dB/m

As the calculations show, the level of signal attenuation in the pyramid body is essential for solving the problem. Estimates were made of the possible values of the attenuation at which the reception of radio waves passing through the pyramid would be possible considering the intrinsic noise of the transceiver system, as well as external electromagnetic noise.

One way to improve the signal-to-noise ratio (SNR) is to integrate (or stack) the recorded signals. This technique is widely used in radar applications (and all types of geophysical and NDT methods). There are coherent and incoherent signal integration methods. Coherent integration produces the summation of complex signals that considers their phase. The integration gain in the value of SNR is proportional to the number of accumulated signals $N^{[31]}$. Incoherent accumulation of radar signals corresponds to the summation of their amplitudes or powers. Since incoherent accumulation does not consider the phase of the signals, its efficiency is lower and the integration gain in SNR is proportional to $\sqrt{N}^{[31]}$. However, the coherent accumulation time cannot exceed the signal coherence time, which is usually less than a second. Therefore, the advantage of incoherent accumulation is the possibility of a very long summation of signals, which, in principle, makes it possible to obtain a greater integration gain and increase the SNR.

In this case, the authors are interested in the maximum value of the attenuation of the useful signal when examining the pyramid using the forward scatter method, for which it is possible to record useful signals. The numerical estimates for both methods at reasonable values of the signal parameters give approximately the same value of 230 dB to 240 dB, which corresponds to an attenuation coefficient of 2.3 dB/m for probing of the pyramid thickness of 100 m. This value is close to the lower limit for signal attenuation shown in Table 2, according to^[18,24]. Considering the climatic character of the desert terrain in the Giza Plateau, where the main pyramids of Egypt are located, it is hoped that the real values for Khufu's Pyramid will satisfy this condition. However, a significant discrepancy in the data on attenuation given in survey^[33] and a

report to the USA National Science Foundation^[35] undoubtedly demonstrates the requirement for refinement and proofing using modern methods of measurement on the pyramid itself.

It should be noted that the described numerical model was built under the assumption that the body of the pyramid was translucent from one face to another. In this case, the distance between the transmitter and the receiver will be approximately 100 m in terms of the cross-section of the pyramid at the possible location of the big void (see Figure 3). At the same time, other options for the location of transmitters and receivers are possible. For example, the transmitter could be located in the King's Chamber, with receivers on the surface of the pyramid. In this case, the distance between them will be much smaller by about several tens of metres. All this may become the subject of further research and calculations, especially if there are more reliable data on the level of attenuation of electromagnetic waves in the stones of Khufu's Pyramid.

4. Conclusions

This paper has described a comprehensive analysis of the feasibility of the HSR method for possible confirmation of voids in Khufu's Pyramid detected by the ScanPyramid muon experiment. The analysis has considered data available from the literature on the physical properties of the structure and its components. A literature review has been presented to consider the range of methods that can be used to investigate such a voluminous object.

To support the feasibility of the proposed HSR method, voids have been simulated in a simplified model. Based on the results of computational experiments, the following conclusions can be drawn:

- Due to its large size, the critical parameter for examining Khufu's Pyramid is the level of attenuation of electromagnetic waves in the materials of the pyramid body. At an attenuation coefficient k_a of more than 2 dB/m to 2.5 dB/m, the registration of a useful signal is hardly feasible. Thus, there is an urgent need to measure k_a for the limestone and granite in the body of Khufu's Pyramid if further research is to be undertaken using the proposed method.
- Even raw field data can determine the position of a void and roughly evaluate its size. Digital reconstruction of recorded radar holograms will give more accurate data on inhomogeneities or voids inside the pyramid.
- In physical experiments with a real pyramid, it is possible to use a set of transmitting and receiving antennas to record images in three dimensions (somewhat analogous to medical tomographic imaging). In this case, the recorded radar data will allow variations of electrical properties to be mapped over the internal volume of the pyramid, which makes it possible to localise potential internal cavities and determine their shape with high accuracy.
- Using the Feko program, it is possible to build a three-dimensional model of a real pyramid considering already known galleries and chambers inside it and also to simulate the necessary antenna system. This will make it possible to test the mathematical model and develop methods for reconstructing radio holograms, as well as prepare for physical experiments directly on the pyramid.
- The proposed method of radar imaging of lossy inhomogeneous media using a signal of approximately 100 MHz can be used at other historical sites less voluminous than Khufu's Pyramid. Examples of such objects are stone fortress or monastery walls, or any ancient buildings or masonry structures with a thickness

of more than 1.5 m. Another possible subject for HSR imaging, well known around the world and surrounded by many mysteries and legends, is the Egyptian Sphinx.

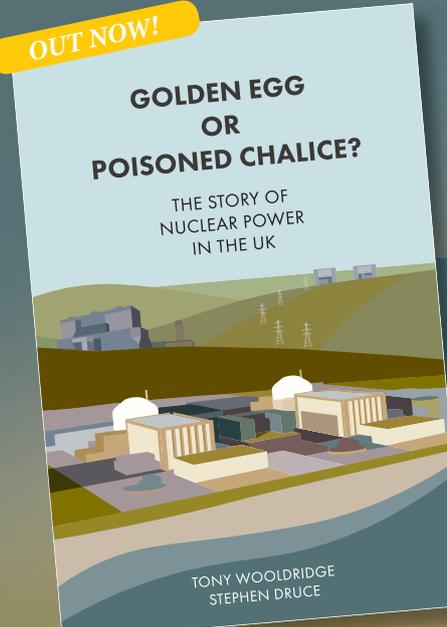
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