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The Antikythera Mechanism: The Prove of the Accuracy of the Astronomical Calculations Based on It

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Abstract: The Antikythera Mechanism is the oldest extant complex geared device, an amazing analogue computer. It was built approximately 2150 years ago. The device was operated manually by a user, setting a date in a dial. All necessary calculations were made using a set of gears (at least 39), while the results were displayed on several scientific scales. The Mechanism was used to calculate astronomical phenomena, such as solar and lunar eclipses. After an extensive description of the Mechanism, the main objective of the following paragraphs is to demonstrate the accuracy of its predictions.

Keywords: Antikythera Mechanism; Gears; Ancient Astronomy; Ancient Technology; Egyptian Calendar

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1. Introduction

The Antikythera Mechanism is a gear device, made between 100 and 200 BC, which was operated by hand. A user could put a pointer to the desired date and the Mechanism simultaneously calculated various astronomical phenomena. More than 39 cooperating gears were rotated simultaneously to rotate seven pointers with eight indications on various scientific scales. It was used to calculate the diurnal and annual motions of the Sun, the Moon and probably the planets among the stars. The Mechanism implemented the astronomical knowledge of ancient Greeks about the motion of these heavenly bodies with astonishing accuracy, considering the anomalous orbit of the Moon using a system of eccentric gears. It could also predict eclipses of the Sun and the Moon based on the Saros period, which was found in one of its scales. It calculated the dates of the major crown games that took place in ancient Greece (e.g., Olympic Games). Finally, it was accompanied by an extended User's Manual [1,2].

The first part of the present paper provides an extensive overview of the knowledge about the Mechanism regarding its discovery, investigation, importance and handling. The construction of the Mechanism, as well as the astronomical and technological knowledge that were necessary for its construction are also described. In addition, the front and back sides of the Mechanism are described and information is given concerning the Egyptian, Julian and Gregorian calendars.

The second part of the paper deals with the accuracy of the Mechanism's predictions. In order to verify its accuracy, an application has been developed in a virtual reality environment, which simulates the operation of the physical models. The indicators on both sides of the Mechanism are presented in an image format and not as a numerical result. The results of the forecasts are automatically compared with those of the NASA website. The results support the view that the Antikythera Mechanism was a scientific instrument for accurate astronomical predictions.

1.1. *The Antikythera Shipwreck and the Discovery of the Mechanism*

In first century BC a large Roman ship battled with the waves on the rough sea between the mainland of Greece and Crete. Finally, the boat sank on the shores of the small Greek Island Antikythera. The ship was loaded with works of art and other precious artifacts. Two thousand years later, at the Easter of 1900 AD sponge-divers from the Greek Island Symi, discovered accidentally the ancient shipwreck off the coast of the Greek Island of Antikythera. Underwater excavation began at the end of November 1900, and a few months later, important findings were recovered, such as the famous Antikythera Ephebe (Figure 1), most of which are now exhibited at the National Archaeological Museum of Athens [3]. Based on Pergamon coins that were retrieved, the wreck is dated between 86 and 67 BC [3,4].

Figure 1. 1900 underwater excavation on the shores of the Greek island of Antikythera (**left**). The Antikythera Ephebe (**right**) [3].

Among the findings, a strange bulk of material, broken, worn and calcified, was located with obvious signs of bronze plating (Figure 2) [3]. In the first publication of the Antikythera shipwreck [5], the existence of the Mechanism was mentioned with the suggestion that it was an astronomical instrument. The Antikythera Mechanism, after 2000 years on the seabed, was expected to change the accumulated knowledge so far on the technological skills of the ancient Greeks.

Figure 2. The fragments of the Antikythera Mechanism, National Archaeological Museum of Athens [3].

1.2. The Investigation of the Antikythera Mechanism

Derek de Solla-Price was the first scholar to study the function of the Mechanism extensively, with the assistance of Charalambos Karakalos from the Research Centre Demokritos, Greece. He worked for more than 30 years and eventually published an extensive account, known as "Gears from the Greeks" [6]. He declared that "the Antikythera Mechanism is the oldest proof of scientific technology that survives today and completely changes our view of ancient Greek Technology".

The baton was taken by Michael Wright and Alan Bromley. Unfortunately, Alan Bromley died in 2002. However, Michael Wright published a series of papers, where he correctly postulated that the back dials of the Mechanism were spirals and that the upper dial was built to follow the draconic lunar month. He also elaborated on the pin and slot mechanism (see Section 2.1.2) and proved its epicyclic function [7]. He made strides in reconstructing the Mechanism and he produced superb bronze replicas.

In 2001, John Seiradakis (Aristotle University of Thessaloniki, Greece), Mike Edmunds and Tony Freeth (Cardiff University, UK) and Xenophon Moussas and Yanis Bitsakis (National and Kapodistrian University of Athens, Greece) created the "Antikythera Mechanism Research Group". They received a grant from the Leverhulme Foundation, U.K. and permission to undertake a new investigation from the Ministry of Culture of Greece. After permission was granted, Eleni Magkou and Mary Zafeiropoulou (National Archaeological Museum of Athens, Greece) and Agamemnon Tselikas (Cultural Foundation of the National Bank of Greece) joined the team, which was soon supported by an international team of astronomers, archaeologists, mathematicians, physicists, chemists, computer engineers, mechanical engineers, epigraphologists and papyrologists.

In September 2005, they undertook a major new investigation of the Antikythera Mechanism, using an innovative and state of the art high power micro-focusing X-ray tomography, especially constructed by X-Tek Systems [8] (Figure 3, left) and the Hewlett Packard, USA, PTM Dome technique [9] (Figure 3, right). In November 2006, the results of the investigation were announced during an international conference in Athens and published in the international journal Nature [10]. The three-dimensional images that were obtained when the fragments of the ancient mechanism were examined revealed internal details of gearing and inscriptions that remained hidden on the seabed of the Antikythera more than two thousand years. All inscriptions are written in Greek. A new font (True type font) has since been developed at the Aristotle University of Thessaloniki, Greece, reproducing the fine art letters.

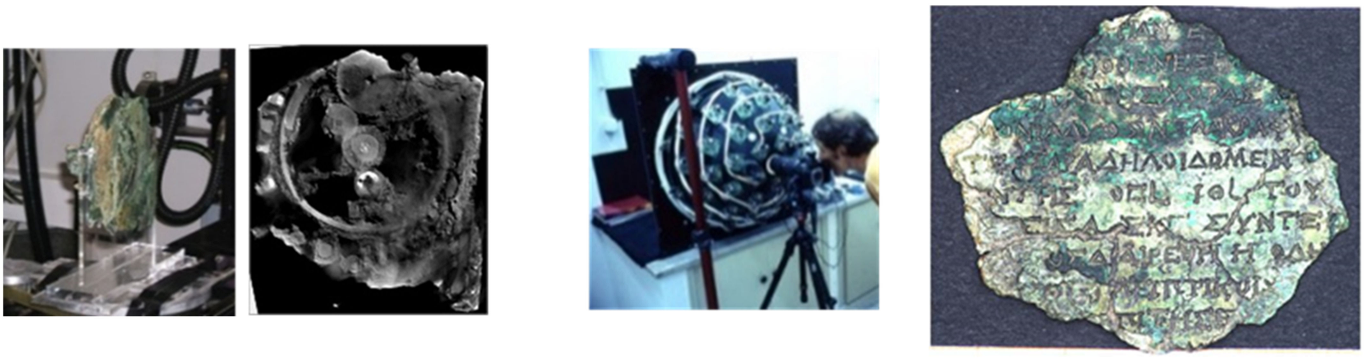


Figure 3. X-ray tomography of the fragment A by Roger Hadland (**left**) and investigation of the fragment 19 using the PTM Dome technique by Tom Malzbender and Dan Gelb (**right**).

Realizing the importance of the Antikythera Mechanism in the Aristotle University of Thessaloniki (AUTH), Greece, an active group of researchers was formed. Several new results have been revealed and published, or currently under publication [11–19].

2. Results

2.1. Description of the Antikythera Mechanism

Based on the results of these investigations [2,3,10,11,13–15], the Mechanism contained a manual with detailed instructions. It had front and back doors with astronomical, geographical and technological inscriptions covering much of the exterior of the Mechanism. Its dimensions were approximately 30 × 20 × 10 cm; slightly larger than a current Laptop. Similar ancient mechanisms have not yet been found.

The Antikythera Mechanism was a complicated instrument. Therefore, it is not surprising that it was accompanied by an extensive User's Manual. New inscriptions that had not been read for more than 2000 years were revealed, mainly with the X-ray micro-focusing tomography. Approximately 3500 letters and symbols have now been deciphered. They all fall into three broad categories: astronomical inscriptions, geographical inscriptions and technical inscriptions. Several astronomical terms have been read referring to the Sun, the Moon, the ecliptic (or Zodiac Cycle), the Metonic and Saros cycles and other astronomical phenomena. The word "ΣΤΗΡΙΓΜΟΣ" (stationary point) is mentioned several times, obviously referring to stationary points of the planetary orbits.

The Mechanism had 7 pointers, which provided 8 indications in its scales (the pointer of the Moon gives two indications). It had three main dials; one at the front side with two concentric scales and two at the back in the form of spirals.

2.1.1. The Front Site, the 12 Zodiac Constellations and the Egyptian Calendar

A very careful analysis of the gears' co-action revealed their use in calculating the exact (within a degree) position of the Sun and the Moon on the Zodiac Cycle. This position was shown by the pointers of the front dials [1–3,10,11,13–17]. Simultaneously, a crown gear was found to drive a black and white colored spherule, showing the current phase of the Moon (see Figure 4).

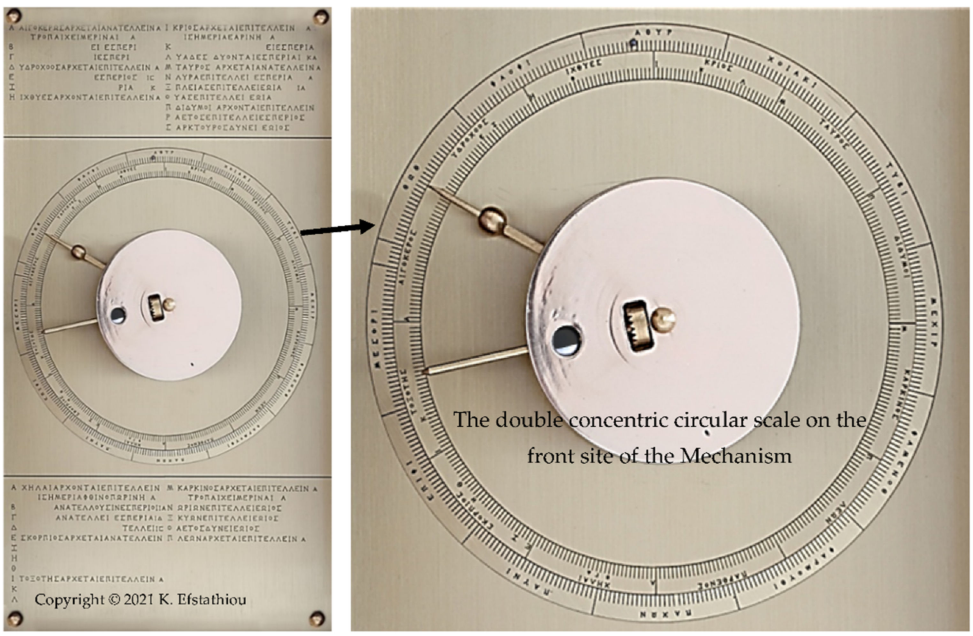


Figure 4. The front side of the Mechanism.

Parts of the front plate of the Mechanism, which testify to its structure, have been saved only in fragment C, with the exception of some very small parts of the 'parapegma' (see Section 2.3.2) that have been read in some of the small fragments. A 'parapegma' is a precursor to the modern-day almanac. Originally, it was a table that related to star phases and corresponding weather. In fragment C, about 1/4 is preserved by a double concentric circular scale that was probably placed approximately in the center of the front plate, as shown in Figures 4 and 5 [16].

Figure 5. PTM image from the C fragment showing a part of the rings on the front side of the Mechanism that has been saved. Some of the letters and subdivisions of the two rings have been imprinted in white to be clearly visible [16].

The date scale had the shape of a ring (Figure 6), which is removable. Behind this date ring, there were 365 holes and the ring was secured at one of the holes using a pin. Every four years, the operator was able to remove the ring and move it by one hole, to take leap years into account. The leap year was established with the Julian calendar by Julius Caesar in 40 BC, a date later than that of the construction of the Mechanism. Ptolemy-III-Euergetes (246–221 BCE) reformed the calendar introducing the leap years.” The Canopus decree, a declaration published by a synod of Egyptian priests, suggests that the true duration of the year (365 $^1/_4$ days) was recognized, and an extra day was added to the calendar every four years. The new calendar failed, which achieved popular acceptance [20]. Nevertheless, the manufacturers of the Mechanism, 100 years later, were aware of the phenomenon.

The internal circular scale depicts the Zodiac Cycle has 360 subdivisions with each of the 12 zodiac constellations having 30 subdivisions. The Zodiac Cycle is the path followed by the Sun during its ‘apparent’ motion in the sky during a solar year, and is thus essentially the same as the solar year. Namely, the 360 degrees ‘apparent’ movement of the Sun around the Earth, projected on the Zodiac Cycle, corresponds to a period of about 365 days (solar year).

The part of the Zodiac Cycle that has been saved (Figure 5) is the part of the zodiac constellations Virgo *(ΠΑΡΘΕΝΟΣ)*, Libra *(ΧΗΛΑΙ)*, Scorpio *(ΣΚΟΡΠΙΟΣ)* and Sagittarius *(ΤΟΞΟΤΗΣ)*, with Virgo and Sagittarius only partially surviving.

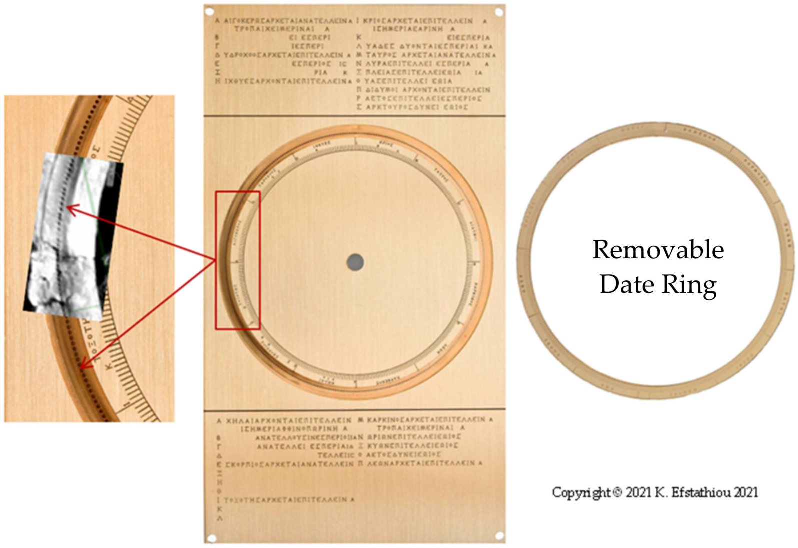


Figure 6. The front site dial plate and the removable date scale ring.

The Egyptian Calendar

As mentioned before the months on the Mechanism are those of the Egyptian calendar, written in the Greek language. The ancient Egyptian calendar [20–26] is important as it included, for the first time in history, the basic principle that the length of the year is equal to 365 days. In addition to this civil calendar, the ancient Egyptians simultaneously used a second calendar based on the phases of the moon.

The ancient Egyptians were the first of the ancient peoples to release their calendar from the synodic lunar month. They associated the course of the year with two almost simultaneous natural phenomena:

- the annual floods of the Nile and
- the appearance of Sirius shortly before sunrise.

The phenomenon of almost simultaneous rises of the Sun and Sirius is called Heliacal rising of Sirius (morning rising, ΕΩΙΑ ΕΠΙΤΟΛΗ or ΕΩΘΙΝΗ ΕΠΙΤΟΛΗ). The Heliacal rising of Sirius occurred around the end of July and determined the beginning of the Egyptian year, which for this reason was called "Dog" or "Cynical", since Sirius (known colloquially as the "Dog Star") is the brightest star in the constellation Canis Major (Big Dog, ΜΕΓΑΣ ΚΥΩΝ), while at the same time it was identified with the dog-headed god Anubis [25].

An ivory plaque found in a tomb of the first dynasty in Abydos greets Sirius as "the bearer of the new year and the flood of the Nile". For the same reason, Plutarch, in his Isidore, characterizes Sirius as an "aqueduct" *(ΥΔΡΑΓΩΓΟΝ),* in order to emphasize that he was to blame for the floods of the Nile [25].

The calendar appearance date of Sirius, however, changed over the years and deviated from the real date, due to the fact that the Egyptians used an approximate solar year of 365 days and not 365.25 days.

The primary Egyptian calendar the older of the two systems was the lunar calendar, divided into 12 synodic months. Each lunar month began with the new moon. Since the lunar calendar was 10 or 11 days shorter than the solar year, a 13th month was intercalated every several years to keep the lunar calendar in rough correspondence with the agricultural seasons and their feasts. The first month of the lunar calendar, as well as of the solar calendar, which was established later, was dedicated to the great divider of time, the god of Astronomy Thoth *(ΘΩΘ)*, perhaps for religious reasons.

The Egyptian solar or civil calendar contained 360 days, with twelve equal months of 30 days. However, the dates, as the priests observed, were constantly ahead of the respective climatic seasons, and the annual error of 5 days created a difference of one whole year every 72 solar years ($5 \times 72 = 360$ days). To correct this discrepancy, they introduced the 5 extra days, probably during the time of the first historical pharaoh Menes (2900 BC) and called them "induced" (epagomenal *επαγόμενες*) days.

However, in order to justify them and not to upset the gods, they connected in their mythology these days with the myth of the goddess of the sky, Nut. Nut cheated on her husband Ra, the great god of the Sun, with Thoth from whom she became pregnant. To punish her, Ra ordered that should could not give birth to her child on any month of the year, but the wicked Thoth tricked the Moon into gambling and won her 5 days each year. However, these days did not belong to any month and were outside the calendar, so Ra's order did not apply to them. According to Egyptian mythological tradition, Nut gave birth to her child on the first of these five epagomenic days. The five sacred induced days were dedicated to the birthdays of the five main Egyptian gods, Osiris, Horus, Isis, Seth and Nephthys.

The names of the Egyptian months, mentioned by the great Greek astronomer of antiquity Claudius Ptolemy (second century AD), are listed in Table 1:

Table 1. The names of the months of the Egyptian calendar written in the Greek language.

Egyptian Months	
ΘΩΘ	Thoth
ΦΑΩΦΙ	Phaophi
ΑΘΥΡ	Athyr
ΧΟΪΑΚΙ	Choiak
ΤΥΒΙ	Tybi
ΜΕΧΙΡ	Mechir
ΦΑΜΕΝΩΘ	Phamenoth
ΦΑΡΜΟΥΘΙ	Pharmuthi
ΠΑΧΩΝΣ	Pachons
ΠΑΫΝΙ	Payni
ΕΠΙΦΙ	Epiphi
ΜΕΣΟΡΗ	Mesore
+5 induced *(epagomenal)* days.	

Sirius was called Thoth as his Heliacal rising coincided with, or indicated, Thoth, the first month of the Egyptian year. He was worshiped as Sihor, the star of the Nile, as Sothi, Sothis and Siris. The ancient Egyptians still believed that Sirius was the abode of souls, while at the same time they believed that radiation from the region of Sirius enlivened the creatures of the Earth.

The total duration of the year for the ancient Egyptians was, thus equal to 365 days and the error was reduced to about 0.25 days per year, since the duration of the tropical year was considered equal to 365.25 days.

The strange thing is that although the priests-astronomers were aware of this error of about 6 h per year, they nevertheless did not make any correction. This correction was probably mad due to the fact that the Pharaohs, ascending the throne, swore in the temple of Isis that they would keep exactly the current calendar, not due to the religion of the people.

The Julian Calendar

As mentioned before, the Egyptian civil calendar was altered by Julius Caesar about 46 BC with the addition of a leap-year day occurring once every four years; the revised system forms the basis of the Western calendar still used in modern times. By the 40s BC the Roman calendar was three months ahead of the solar calendar. Caesar, introduced the Egyptian solar calendar, taking the length of the solar year as 365 $^{1}/_{4}$ days. The year was divided into 12 months, all of which had either 30 or 31 days except February, which contained 28 days in common (365 day) years and 29 in every fourth year (a leap year, of 366 days). Leap years repeated February 23; the dated 29 February did not exist in the Julian calendar.

The Gregorian Calendar

The length of the Julian-calendar year was overestimated by 11 min 14 s. This error in mid-1500 had shifted the dates of the seasons by about 10 days from Caesar's time. Pope Gregory XIII' restored in 1582 the calendar to the seasonal dates of 325 AD, an adjustment of 10 days. Nearly all Eastern Orthodox churches use the Julian calendar to establish the dates of movable feasts such as Easter.

2.1.2. The Back Site

At the back side of the Mechanism (Figure 7) were two spiral scales. The upper spiral consists of 5 windings, with its total length divided in 235 sections. Using this dial, the user could read the position of the Moon within the Metonic Cycle (432 BC) of 19 tropical years of 365.2422 days, which is almost equal to 235 synodic (lunar) months of 29.5306 days.

The difference between the two periods (of 19 tropical years and 235 synodic months) is only 2 h. This knowledge allowed the calculation of the exact day of full Moons, a very useful knowledge for agricultural or nautical activities 2000 years ago, when no electricity was available. The accuracy of the position of the Moon was achieved by a pin-and-slot mechanism [7,27] that reconstructed Hipparchus' (190–120 BC) first anomaly of the Moon's motion (due to its elliptical orbit around the Earth). This anomaly is, in fact, Kepler's second law.

Calippus (370–300 BC) 100 years later corrected Metons calendric system. Each of the four periods of Meton, i.e., every 76 years, one day needed to be removed. The Callippic pointer of the subsidiary dial within the upper back spiral of the Antikythera Mechanism is indicated when the correction takes place.

A subsidiary dial within the upper back spiral of the Antikythera Mechanism displayed the celebration date of the ancient Panhellenic crown games. On the circumference of the dial, the words Olympia, Pythia, Isthmia, Nemea, Naa and Halieia were deciphered. Internally, in each quadrant, the four years of the Olympic cycle are indicated (see Section 2.3.2).

The lower back dial is a Saros eclipse-prediction dial, arranged as a four-turn spiral. This dial contained the 223-month eclipse Saros Cycle (of approximately 6585.3213 days, or nearly 18 years and 11 1/3 days). A total of 223 lunar months (one Saros Cycle) after an eclipse, the Sun, Earth, and Moon return to approximately the same relative geometry, and a new, nearly identical, eclipse cycle begins. The Saros Cycle was marked with the dates (month, day, and hour) when a possible solar or lunar eclipse would occur. The markings were engraved with symbols (*"Η" ΗΛΙΟ*Σ Sun, "Σ" Σ*ΕΛΗΝΗ* Moon, etc.).

A subsidiary Exeligmos dial, within the Saros dial, extended the eclipse prediction capabilities to three Saros Cycles, indicating that 8 and 16 h should be added, respectively, in the second and third Saros Cycles to the eclipse times, as indicated by the inscriptions.

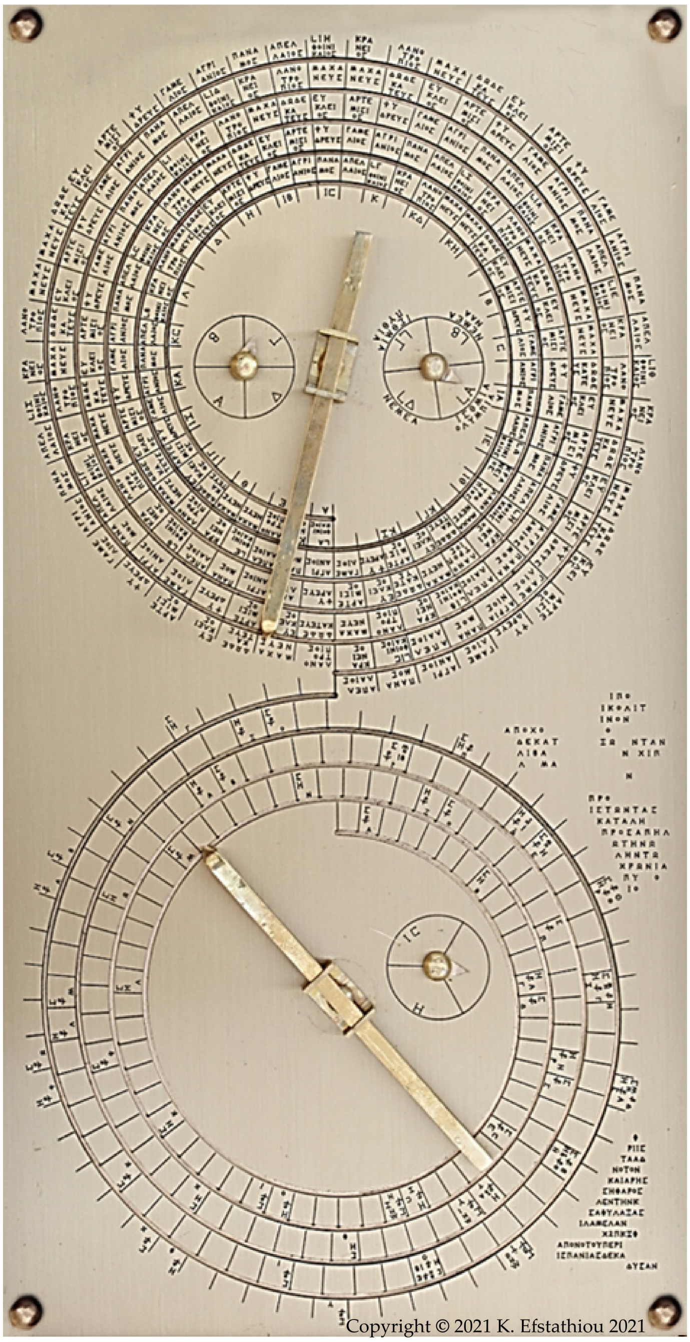


Figure 7. The back side of the Mechanism.

The most impressive part of the Mechanism is related to the moon phases and the moon's movement anomaly. In the 17th century, in relation to the Sun and Moon movements, Johannes Kepler claimed that the "holy circular motion was not circular" and suggested that it was an ellipse orbit (first and second law of Kepler). Inside the Mechanism, a gear system is identified, which simulates this motion with astonishing accuracy.

The display of this movement, considering the moon's movement anomaly caused by its eccentric orbit around the Earth, was achieved by the use of two eccentric gears (Figure 8).

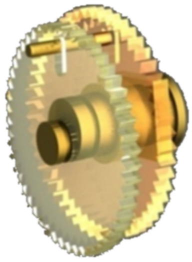


Figure 8. The pin-and-slot mechanism [17].

The axial distance of the rotation's axis of the two gears amounts to approximately 1.1 mm. The lower gear has a pin that engages with a slot on the upper gear, forcing it to rotate by the pin-and-slot arrangement. The epicyclical movement of the upper gear tracked the motion of the Moon in the sky with great accuracy [17,27,28].

The latest outcomes of the AUTH team are related to the investigation of fragment D. In all modern studies of the Mechanism, fragment D is considered a lone fragment and does not exist in any constructed model of the Mechanism. Following a long-term study, it was proven that Fragment D is indeed part of a mechanical arrangement that calculates the equation of time, i.e., the deviation between the real-time shown by the sundials and the average time shown by the current clocks [1,16]. Newer research on fragment D has recently been published [29] and suggests an alternative use of fragment D.

The gears found in the Antikythera Mechanism are the earliest known to resemble the shape and design of modern gears. Their triangular teeth were designed to transmit angular motion, not power. Detailed studies of the fragments of the Mechanism revealed that it had at least 39 gears (37 gears and 2 crown gears), 27 of which have been identified in the largest of the calcified fragments (Fragment A). The existence of ten more gears has been determined using astronomical calculations [10,11,17,30,31]. A functional diagram of the gear trains is presented in Figure 9.

The Antikythera Mechanism also incorporated 2 crown gears, as well as 19 shafts and axles with complex geometry. Two pairs are concentric, which means that one out of the two shafts passes through the other. The two shafts rotate independently. Moreover, there is an axis, which has two eccentric cylindrical bearing points for two gears. At various locations, mainly inside the Mechanism, there were also various components that supported the shafts and other parts of the device to make the construction robust and functional.

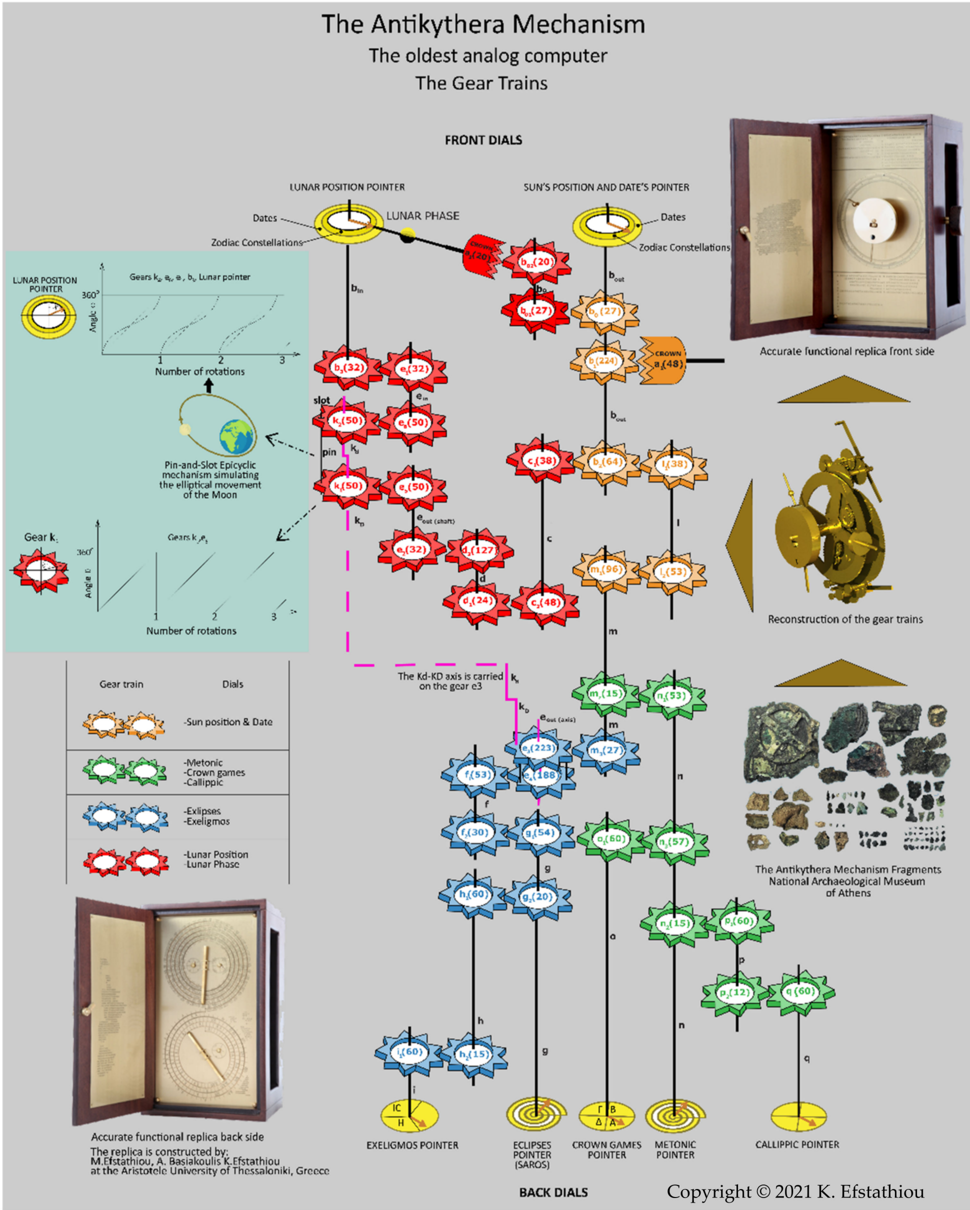


Figure 9. A functional diagram of the gear trains.

2.2. *The Antikythera Mechanism, from Physical to Digital 3D Representations*

Based on the three dimensional images obtained from the X-ray tomography and the PTM Dome techniques, and using the Volume Graphics specific software system VGSTUDIO MAX (https://www.volumegraphics.com/en/products/vgstudio-max.html), the 3D digital objects of the four basic fragments (Figure 2) were developed. The entire Mechanism was designed using the same data [17]. Figure 10 shows the three-dimensional digital reconstructions of the gear trains and the entire Mechanism. An example of how the front of the Mechanism and gear system was designed based on components found in the tomographies, is shown in Figure 11.

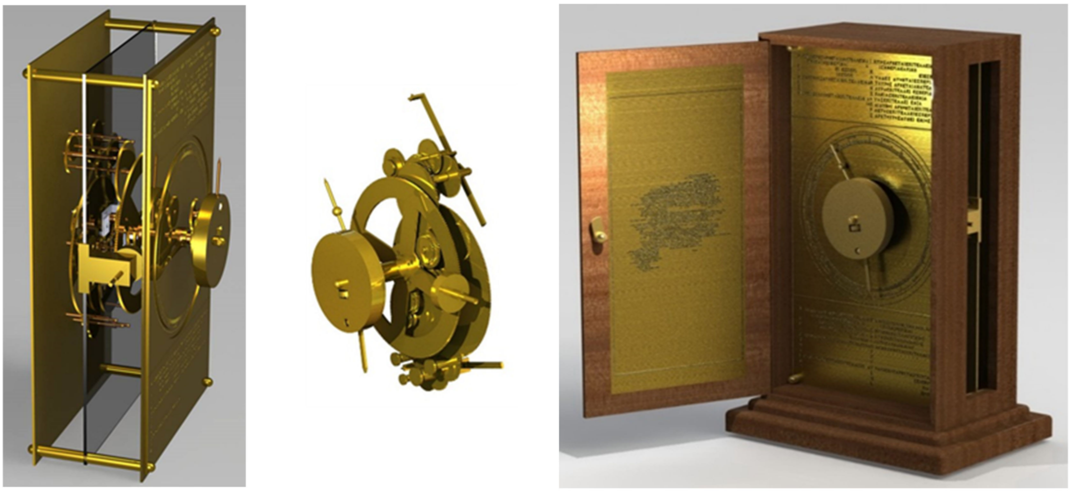


Figure 10. Three-dimensional digital reconstruction of the Mechanism [17] (Copyright © 2021 M. Efstathiou).

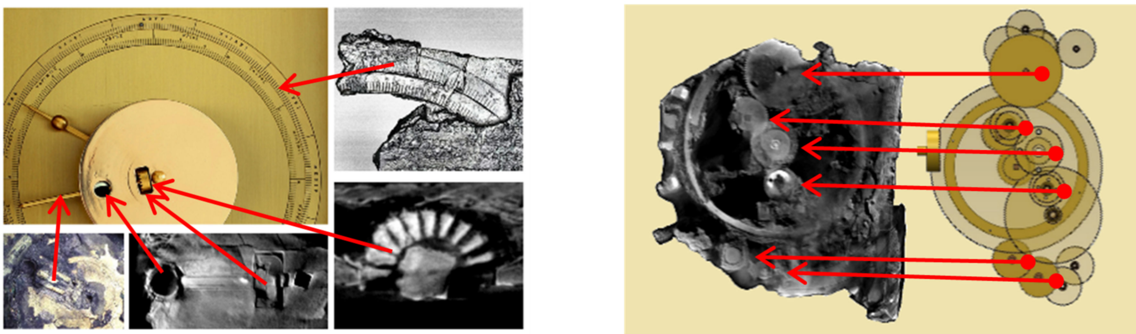


Figure 11. Mechanical parts localized in the tomographies and corresponding designed parts.

2.3. Importance, Purpose, Utility, Operation and Handling of the Mechanism

2.3.1. Importance and Purpose of the Mechanism

The Antikythera Mechanism is an epitome of high technology in antiquity, as the Parthenon is an epitome of Architecture. Considering the theoretical and technological knowledge required for the construction of the Mechanism, it can easily be ranked among the Wonders of Ancient World [1,2].

The Antikythera Mechanism was the first surviving geared analogue computer in history. The next extant geared device is a Byzantine clock calendar, which was built in the fifth or sixth century. More than 800 years later, the next mechanical calculators were built. At the beginning of the 13th century, the astronomical indicator of Wallingford, 50 years later (1348–1364) the astronomical clock of Dondi, and in 1410 the Prague astronomical clock of similar complexity to the Mechanism. Later, in the 17th century, the calculator of Schickard (Kepler's collaborator) and the Pascaline of the great French scientist Pascal were built.

The purpose of the construction of the Mechanism is not yet known. The identity of the manufacturer is also unknown (see Section 2.4), but considering the variety of skills and knowledge required, in order to build such a complex device, a collaboration between an astronomer/mathematician and a mechanic was necessary. The inscription on the back cover is in a different hand to the rest, showing that at least two people worked on the machine [1].

2.3.2. Utility, Operation and Handling

The main utility of the Antikythera Mechanism was to calculate the exact position of the Sun, the Moon and possibly the planets in the sky, as well as the phases of the Moon and the lunar or solar eclipses. It is interesting that besides the predictions of astronomical events, the Mechanism could determine dates related to religious, social and agricultural rituals and events.

The subsidiary dial within the upper back spiral of the Antikythera Mechanism displayed the dates of the Olympic Games, which were held during the first or the second Full Moon after the summer solstice. To learn the exact date, someone had to be able to calculate this phase of the full moon. The Mechanism could accurately calculate this date. Not only the Olympic Games but the crown games of Isthmia (Corinth), Nemea (Nemea), Pythia (Delphi), Naa (Dodona) and Halieia (Rhodes) (Figure 12) were included in the subsidiary dial [17].

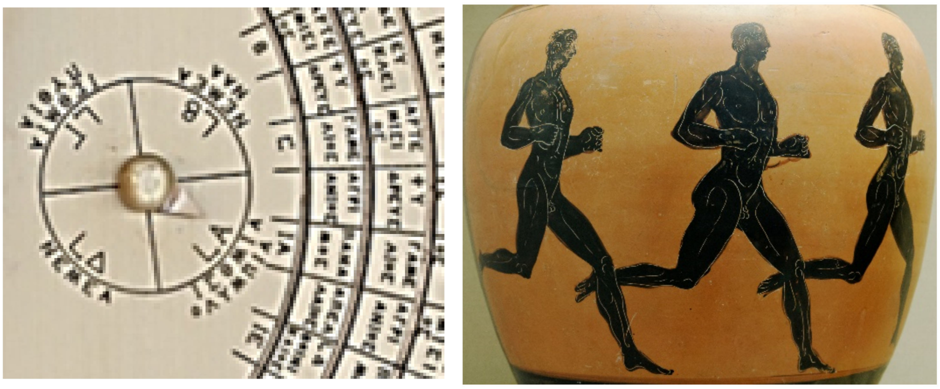


Figure 12. The subsidiary dial displayed the dates of the Panhellenic games (**left**). Three runners featured on an Attic black-figured amphora. British Museum, by Marie-Lan Nguyen (2011), CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=15468713, accessed on 5 August 2021 (**right**).

In Figure 13, the Parapegma of the Mechanism is shown [15]. The Parapegmata were essentially calendars of astronomical and meteorological events, which were widely used in ancient Greece. The astronomical events referred in the Parapegmata are events that associate the rise and set of stars or constellations with the sunrise or sunset. For many years, seasons with different climatic conditions were an important time unit as they played a crucial role in people's lives. Over time, however, it was found that the start date of each season could not be determined with the usage of classic calendars, based on lunar months. Therefore, people turned to stable natural phenomena to define the seasons. Some of these phenomena were the rising or sinking of some brilliant stars. These phenomena appear every year at a fixed date in the sky. The annual occurrence of these events during a solar year has contributed to use them in order to organize practical-social activities, such as agriculture and navigation [15]. Hesiod, in the "Works and Days", mentions the harvesting period as the season when the constellation of Pleiades appears for the first time in the sky and as time of plowing, the time after the temporary disappearance of the Pleiades. The grape harvest must take place when Arcturus appears in the sky for the first time. Such phenomena and the date on which they occur are predicted using the Parapegma on the Mechanism [15].

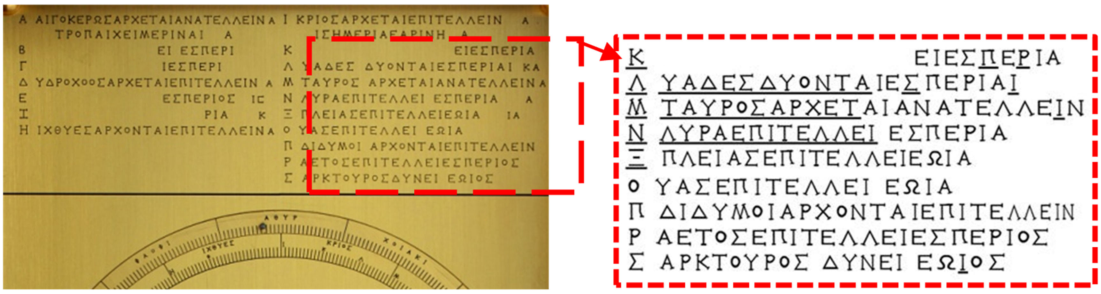


Figure 13. Part of the Parapegma of the Mechanism.

The rotation of any of the gears or any of the pointers results in simultaneous movement in all gears, and thus in the seven pointers, which show various astronomical phenomena in related mathematical scales. Based on an analysis of the applied torque of the operator while handling the Mechanism, and the necessity of precisely positioning the pointers, e.g., the Sun/Date pointer on the front of the Mechanism, the most probable scenario for the handling of the Antikythera Mechanism is the rotation of the Moon pointer [19]. By rotating the moon pointer and choosing a date, the operator can observe the astronomical phenomena occurs on that day. By choosing an astronomical phenomenon, he can observe the date on which it occurs.

2.4. Place and Date of the Construction of the Antikythera Mechanism

The Mechanism was possibly built in Rhodes, during the second century BC. Earlier evidence of similar machines report on Archimedes (287–212 BC) as a constructor of devices, which were depicted the celestial bodies [1,2]. The Mechanism cannot be built later than the coin-based shipwreck date within a few years (86 and 67 BC).The inscription letter style suggested its construction in the period 50–200 BC. An important limit could be set if we understood when the parameters required for the pin- and-slot lunar anomaly Mechanism were first deduced. It is known through Ptolemy that Hipparchus (190–120 BC) did characterize and quantify the anomaly by epicyclic and eccentric models of the lunar orbit. The manufacture took place after 170 BC and required that Hipparchus's values were involved [1].

The optimum latitude for fitting the astronomical phenomena listed in the parapegma on the Mechanism is consistent with the mid-Mediterranean, being around 35 degrees [15]. Rhodes (36 degrees) remains the most likely candidate. The Antikythera ship may have called there before the wreck, as it was known as a highly technological naval port with a thriving bronze industry, it was home to Hipparchus, it is the place for which we have a record of sighting of Mechanism with comparable functions and it might explain the presence on the Games' dial on the Mechanism of the Halieia Games, held in Rhodes [2].Another connection of Rhodes with the construction of similar Mechanisms is Cicero's reference, that he visited the laboratory of the astronomer Poseidonius (135–51 BC) in Rhodes, where he admired a celestial sphere made by Poseidonius [2].

The Metonic Cycle (upper back dial) contained a full calendar (repeated 19 times). Comparing this calendar with the calendars of the ancient Greek cities, it was found that it coincided with the calendars of the cities of Kerkyra, Vouthrotos and Dodona (in NW Greece) and Tavromenion (in Sicily) [15,16]. No significant coincidence with the survived calendars of other Greek cities was found. This could indicate that the Antikythera Mechanism was used, but not, necessarily, constructed in NW Greece?

2.5. Construction's Materials of the Mechanism

The material used to make the various parts of the Mechanism, except for its wooden mounting box, is bronze, a copper tin alloy. 1970–1974 chemical analysis was performed to determine the chemical composition of the metal alloy used in the manufacture of the Mechanism. The chemical analysis was performed by the spectroscopic method. Two small fragments of the Mechanism were studied. The chemical analysis showed that they were made of bronze, with a tin content of about 5% [3]. Newer analyzes by Panagiotis Mitropoulos in 2018 revealed three alloys, the main components of which are copper, tin and lead [3]. The shares of copper tin and lead varied. In any case, it can be assumed that the individual parts consist of different copper alloys from case to case [32].

2.6. Documentation of the Existents of the Necessary Knowledge for the Mechanism Design, Construction and Manufacturing at the Time and at the Place of Its Construction

2.6.1. Scientific and Technological Knowledge Necessary for the Design of the Mechanism

A question, which arises, is whether the Greek astronomers 2200 years ago, had the necessary knowledge for the calculation of the astronomical phenomena, calculated by the Mechanism? Various sources show that they had them [21].

In ancient Greece there was a solar calendar and a lunar calendar. The difference between then was 11 days. Meton (fifth century BC) connected the moon calendar to the annual. He calculated that about 19 solar years include about 235 synodic lunar months [2]. Callipus (370–300 BC) has calculated that Meton was making a mistake one day every 76 years [2]. These calculations are performed by the Mechanism and appear on two scales at the back side of the Mechanism. The Callippic pointer of the subsidiary dial within the Meton scale (upper back spiral of the Mechanism) indicated when the correction must take place. Aristarchus (310~230 BC) was the first astronomer in the history, who talk about the heliocentric system and not Copernicus [17]. He calculated among others the size of Earth, Sun and Moon. Hipparchus [17] (190–120 BC) is considered as the greatest astronomer of all time. He lived in the time of the construction of the Mechanism in Rhodes, where probably the Mechanism was built. He calculated, among others, the transient motion of the Earth (precession of the equinoxes) which lasts 25,800 years (see Section 4.1). Another calculation of him is the determination of the distance between Earth, the Sun and Earth and Moon.

2.6.2. Technological Knowledge Necessary for the Manufacturing of the Mechanism

Another question, which arises, is whether the ancient Greek mechanicians had the necessary technological knowledge for the manufacturing of the Mechanism. Various sources show that they had them. Until the discovery of the Antikythera Mechanism the construction of the first real gears was dated centuries later. Aristotle describes the rotation of cylindrical objects by friction, due to the roughness of their cylindrical surfaces. The creation of surfaces with higher roughness slowly led to the development of teeth and gears. The gears of the Antikythera Mechanism (second century BC) are the first in world history. Two references related to calculations and constructions of gears are from Heron of Alexandria (10–70 AD) and Pappus of Alexandria (290–350 AD)

Heron of Alexandria was an engineer and geometer. He lived in Alexandria, Egypt. In his description of the construction of an odometer he mentions and describes gears. Pappus of Alexandria describes several machines that were described by earlier mathematicians and engineers, such as Archimedes, Heron, etc. and included gears [33]. For two gears to work together, they must have the same ratios of diameter to number of teeth. This relationship is called today "module". From Papus's writings, it is clear, without any doubt that the Greeks knew the module in antiquity. Very likely, the gears of the Mechanism were made of cold forged thin bronze plates by sawing, removing redundant material and leveling with a hammer [32]. The history of gear technology has been postponed for many centuries.

The Mechanism includes, besides gears, complex geometry axles and shafts, as well as other metal parts. For their manufacturing, machine tools were required. Did the Greeks have machine tools and corresponding tools at the time of construction of the Mechanism?

The text of the inscription from the fourth century BC shown in Figure 14 concerns the construction of bronze axes" *Πόλος*" for the Filonian gallery in Eleusis, Greece using lathe. On this marble inscription is written among others " . . . *a copper alloy from Marion*

(Cyprus) must be used, consisting of 11 parts copper and one-part tin . . . " This alloy is called bronze today. The parts of Antikythera Mechanism are made of bronze (see Section 2.5). Subsequently, it is written as " *. . . Turn the axes according to the example . . .* " This inscription shows that many years before the creation of the Mechanism, the Greeks had and used lathes. This is also apparent from other sources [17,32]. For the machining of bronze pieces, steel cutting tools are necessary. It follows from several sources that the Greeks at that time used such machine tools and cutting tools [17,32].

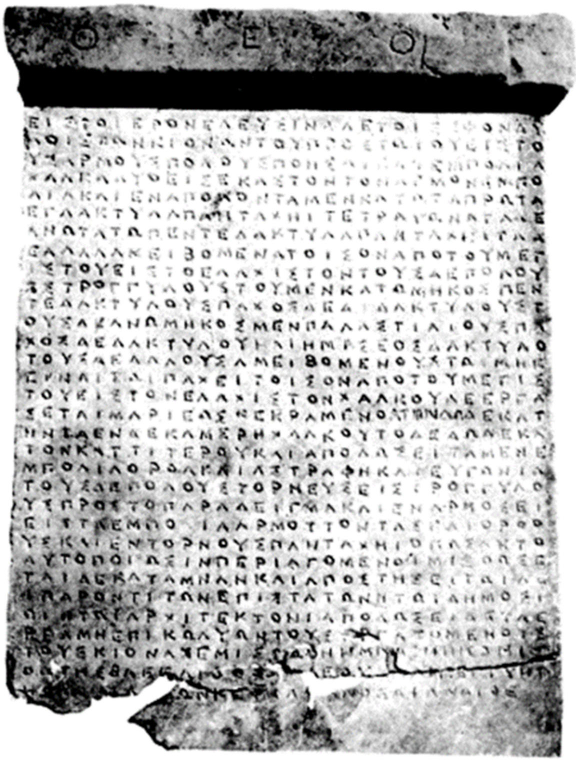


Figure 14. Marble inscription, fourth century BC. Archaeological Museum of Eleusis, Greece.

3. Construction of Digital 3D Representations and Reconstruction of Physical Functional Copies

From 1998, many animations and simulations of the Mechanism were created by M. Roumeliotis [34], which can be searched online. In relation to the physical models, from 1900 until today, many scientists have done research around reconstruction of the Mechanism. 1928 admiral I. Theofanidis with the contribution of E. Zinner, R.T. Gunther and W. Hartner, they listed the visible gears and circles from the back side of the Mechanism

and they characterized the Mechanism as an astrolabe. Admiral Theofanidis read 350 letters of the inscriptions and was the first who attempted to make a replica model of the Mechanism [3,17].

In 1985, A. Bromley continued the research of Price, including with respect to his remarks. On his first attempt, he worked with F. Percival to construct a replica of the Mechanism. Five years later in 1990, he worked with M. Wright, and they used X-ray Linear Motion Tomography, in order to define the array of gears in space. This method did not achieve the desired results. M. Wright claimed that the Mechanism could predict the movements of the Sun, the Moon and of five planets [27]. In 2005, he constructed a model using approximately 40 gears [7].

In 2008, a research team was created in the Aristotle University of Thessaloniki, which set as its main goal the construction of accurate and functional models of the ancient Mechanism. The first replica [11] was constructed using the mean data described in the publication «Decoding the ancient Greek astronomical calculator, known as the Antikythera Mechanism» [10]. This model was not functional, as the diameters of all gears were designed based on the mean values of the previously-mentioned article [10], with a tolerance of approximately 1 mm. This tolerance, in combination with the measured axial distances, led to non-functional gear trains, as some cooperating gears were blocked (due to larger diameters to the given axial distance) and others were not in contact (due to smaller diameters to the given axial distance).

To build a functional model, the parameters of the components of the Mechanism needed to be calculated with a higher accuracy than the mean values of the data of the aforementioned publication. Therefore, in 2009, two different algorithms were developed using FORTRAN code to make all these calculations [11,12].

The first algorithm uses the number of the teeth of each gear, as well as the root angle as constant variables, and calculates all the possible combinations of internal and external diameters. This is developed to find a ratio of the mean diameter and the number of teeth, which is common to all gears (similar to the "module" of the modern gears). Using the values of all gears from the first algorithm, the second calculates all the axial distances for the gears, taking into account the axial distances at the tomographies, as it had been measured from two different PhD fellows. Afterward, a new design was made, which included all the new data, and in 2011, five similar accurate and functional models were constructed (Figure 15) for museums and organizations, such as the National Archaeological Museum of Athens and the Musée des Arts et Métiers in Paris. From then until the present, many updated accurate and functional replicas in scale 1:1, as well as in scale 3:1 (Figure 16) have been constructed and exhibited in various museums and other institutions worldwide [17,18,35]. The updates refer to new letters and symbols of the inscriptions and some supporting mechanical components observed in the tomographies. The 1:1 model is made using the same materials as the original mechanism and represents the most accurate copy of the ancient device. The 3:1 model is made of bronze and Plexiglas, and is an educational model as the transparent materials reveal the internal of the device.

Figure 15. Accurate and functional model of the Mechanism scale 1:1 (research team of AUTH-2011).

Figure 16. Transparent educational and fully functional model of the Antikythera Mechanism in scale 3:1 (Research team of AUTH-2017).

4. Prediction Accuracy

4.1. Development of an Application to Calculate the Prediction's Accuracy of the Antikythera Mechanism

In order to verify the accuracy of the prediction of the Mechanism, an application has been developed in a virtual reality using Windows operating system. The indicators on both sides of the Mechanism are presented in an image format, rather than a numerical result. This application is also used to verify the accuracy of the predictions of the physical models developed by the research team of the Aristotle University of Thessaloniki. The application has been developed on Unity platform in 2D format. The dates and zodiac scales of the front side of the Mechanism are redesigned to correspond to the present. A peculiarity of the application, as well as the corresponding physical model is related to the scale of the zodiac signs.

Due to the passage of about 2150 years from the time of construction of the Mechanism, and due to the phenomenon of the precession of the equinoxes, the zodiac constellations have rotated by about 30 degrees.

The precession of the equinoxes is the motion of the equinoxes along the ecliptic, caused by the cyclic precession of Earth's axis of rotation with a period of 25,772 years. This means that 25,772 years correspond to 360 degree of precession of the equinoxes. If we consider that the Mechanism was built around 150 BC, it means that 2170 years have passed. Therefore, the equinoxes, and thus the Zodiac has shifted by 30 degrees ($2170 \times 360)/25{,}772 = 30.1$ degrees). For this reason, the scale of the signs was redesigned to reflect the current reality. The phenomenon of the earth's transient movement (see Figure 17) was known in antiquity, and Hipparchus was the first to calculate the movement. He is considered the father of astronomy, and most likely the maker of the Mechanism (see Section 2.4).

The implementation of the application's functions has been developed in C# programing language, which is compatible with Unity platform. By selecting a date, the data are exported to the date pointer, which shows the selected date on the Mechanism. The rest of the indicators demonstrate the astronomical phenomena that will take place that day. To verify the accuracy of the results, it is possible to compare the results for each prediction with corresponding predictions on NASA's website via a button, which includes the NASA website link. The application consists of two screens. The first screen contains the basic functions of an application, such as the "Play", "Help", "About Us" and "Quit" buttons. The Help button contains the necessary assistance for the correct interaction with the application. The functionality of the application become more understandable. The "Quit" category gives the command to exit the application. When the Play button is activated, the main screen opens, which contains the two sides of the Mechanism with the corresponding indicators and the calendar where the date of prediction of the phenomena is selected. By selecting the date and pressing the "Calculate" button, the Mechanism predicts the phenomena that play a role on the selected date. To decode the symbols of the Saros spiral dial (eclipses scale), further help is provided via an option.

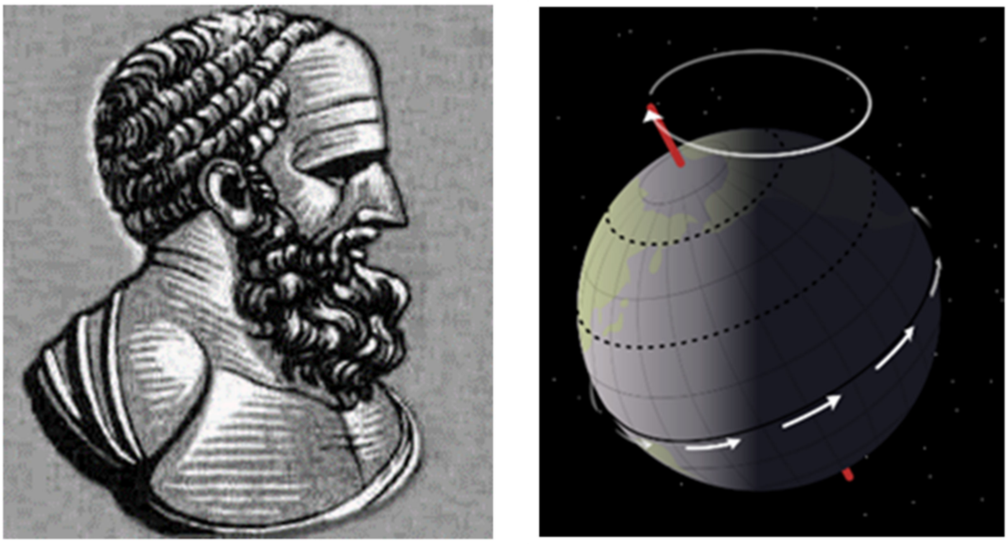


Figure 17. Hipparchus (**left**), the transient motion of the Earth, which lasts 25772 years (**right**).

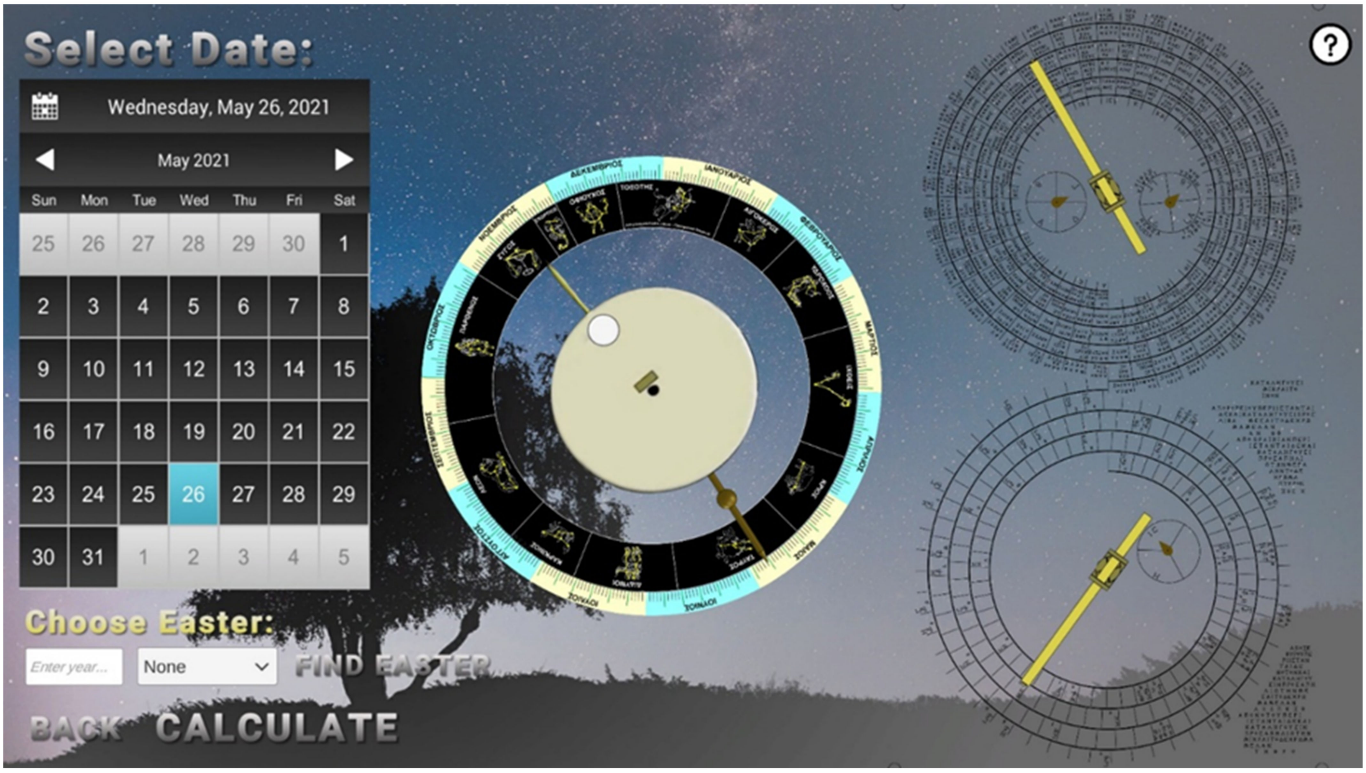
In order to verify the correction of the application, important information, such as the calculation of the leap years that the Mechanism took into account were also considered when implementing the application. Apparently, in leap years that occur every four years, the extra day does not appear in the calendar of the Mechanism. The subdivisions of the date dial on the front side of the Mechanism are 365, and as a result it is not possible to indicate the extra day every four years (29 February). This feature is integrated into the application, which calculates the leap years that have elapsed from the initial settings of the Mechanism and gives the value of the variable that counts these years, as a rotation of the date ring by as many holes as the leap years, thus considering these years for the correct indication of the Sun/Day pointer (see Section 2.1.1 and Figure 6).

To verify the accuracy of the results, it is possible to compare the results for each prediction with corresponding predictions on NASA's website (https://eclipse.gsfc.nasa.gov/, accessed on 5 August 2021) via a button with the NASA website link.

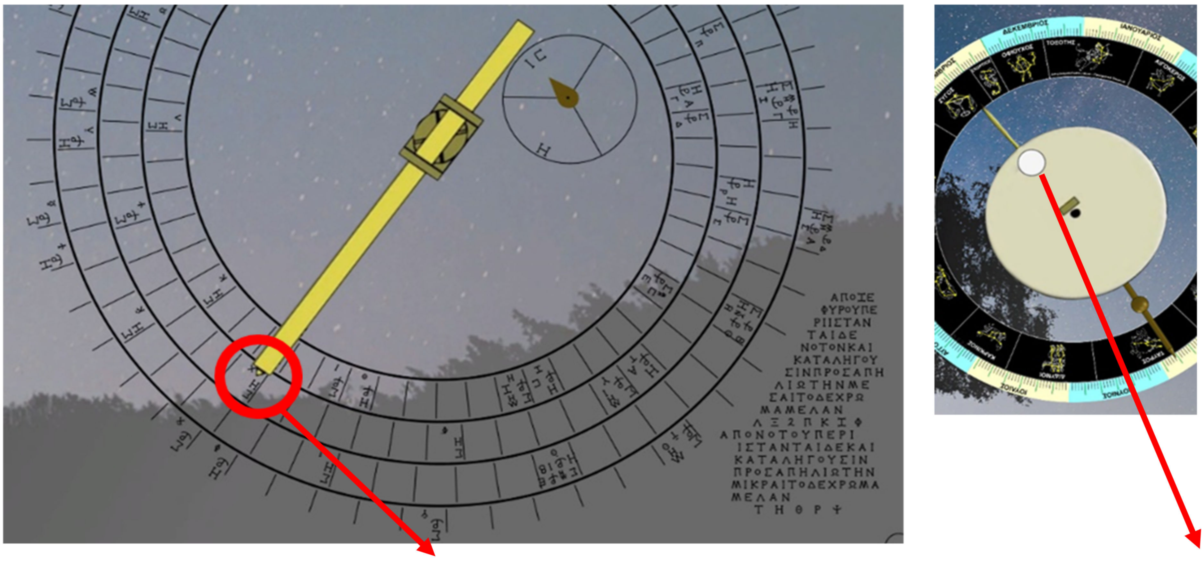
4.2. Examples of the Application's Predictions

4.2.1. 1st Example: Prediction of the Astronomical Phenomena for the 26 May 2021

Figure 18a shows the results of the application for the 26 May 2021 which are: Sun is projected on the constellation of Taurus, Moon is projected on the constellation of Libra, Full Moon and Moon Eclipse. In relation to the Lunar Eclipse, the results are explained in Figure 18b. Figure 18c illustrates the corresponding data from the NASA webpage for the same day (26 May 2021), in order to verify the forecasts of the Mechanism.



(a)



Moon Eclipse (Σ = Σελήνη = Moon) or Sun Eclipse (Η = Ἥλιος = Sun) ⟶ **Moon Eclipse** ⟵ Full Moon

(b)

Lunar Eclipses: 2021 - 2030

Calendar Date	TD of Greatest Eclipse	Eclipse Type	Saros Series	Umbral Magnitude	Eclipse Duration	Geographic Region of Eclipse Visibility
2021 May 26	11:19:53	Total	121	1.009	03h07m 00h15m	e Asia, Australia, Pacific, Americas

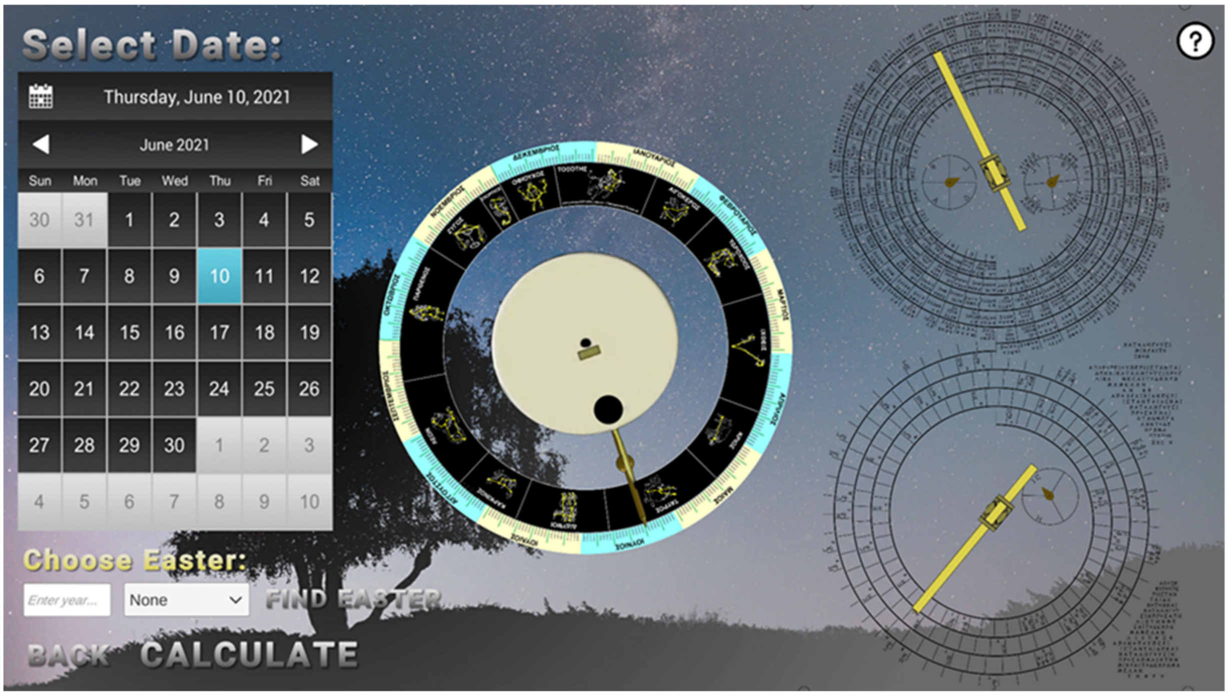
(c)

Figure 18. (**a**) Astronomical phenomena on 26 May 2021. (**b**) The Moon Eclipse on 26 May 2021. (**c**) NASA Website: Astronomical phenomena dated 26 May 2021 (Full Moon, Moon Eclipse).

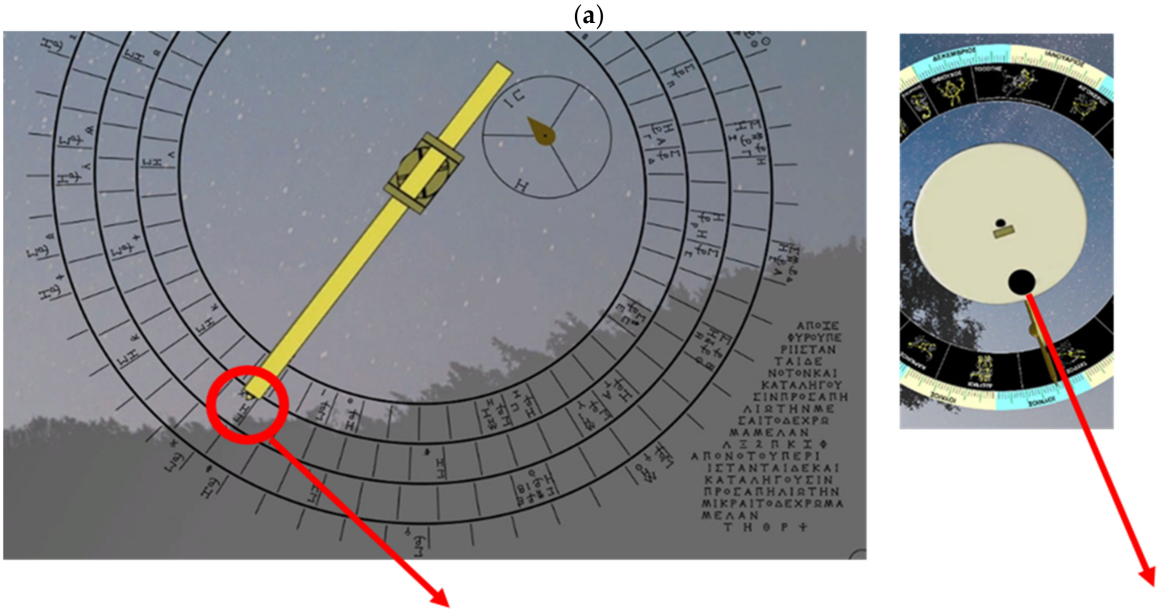
4.2.2. Second Example: Prediction of the Astronomical Phenomena for 10 June 2021

Figure 19a shows the results of the application for the 10 June 2021, which are: Sun and Moon projected on the constellation of Taurus, New Moon and Sun Eclipse.

In relation to the Solar Eclipse, the results are explain in Figure 19b. In Figure 19c, the corresponding data from the NASA webpage for the same day (10 June 2021).



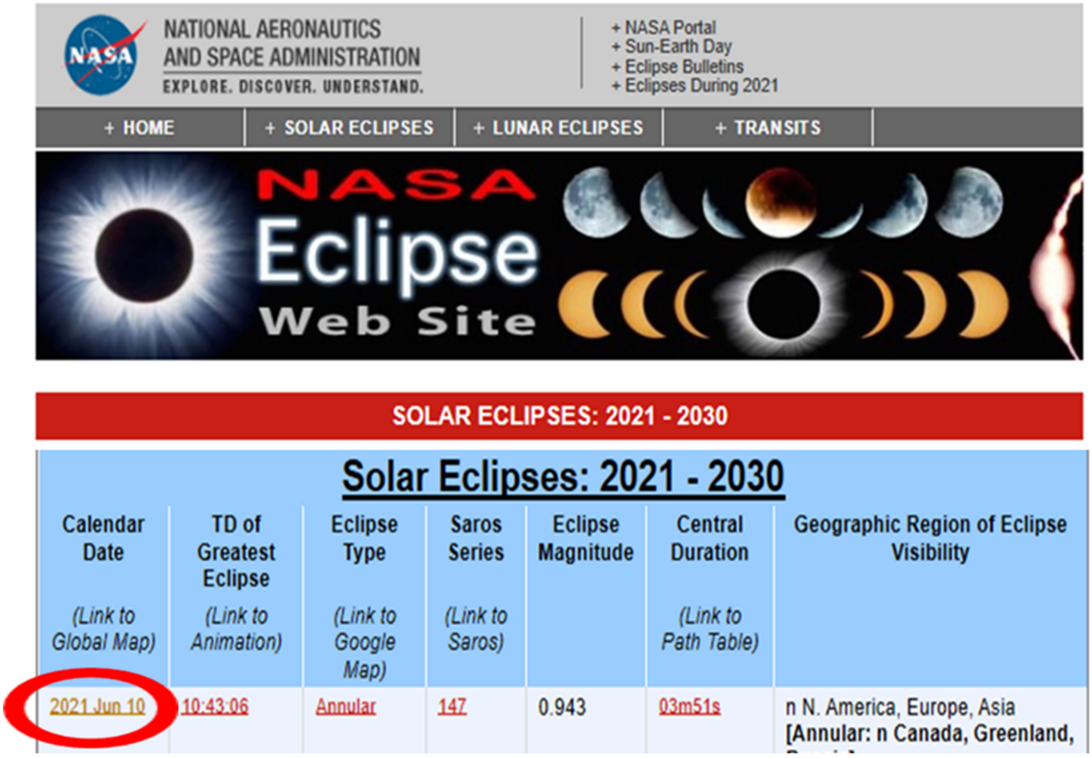
(**a**)



Moon Eclipse (Σ = Σελήνη = Moon) or Sun Eclipse (H = Ἥλιος = Sun) → Sun Eclipse ← New Moon

(**b**)

Figure 19. *Cont.*



(**c**)

Figure 19. (**a**). Astronomical phenomena on the 10 June 2021. (**b**) The Sun Eclipse on 10 June 2021. (**c**) NASA Website: Astronomical phenomena on 10 June 2021 (New Moon and Solar Eclipse).

More predictions of the Mechanism and those corresponding from the NASA webpage are listed in Table 2.

Table 2. Various predictions of the Mechanism and the corresponding results from the NASA webpage.

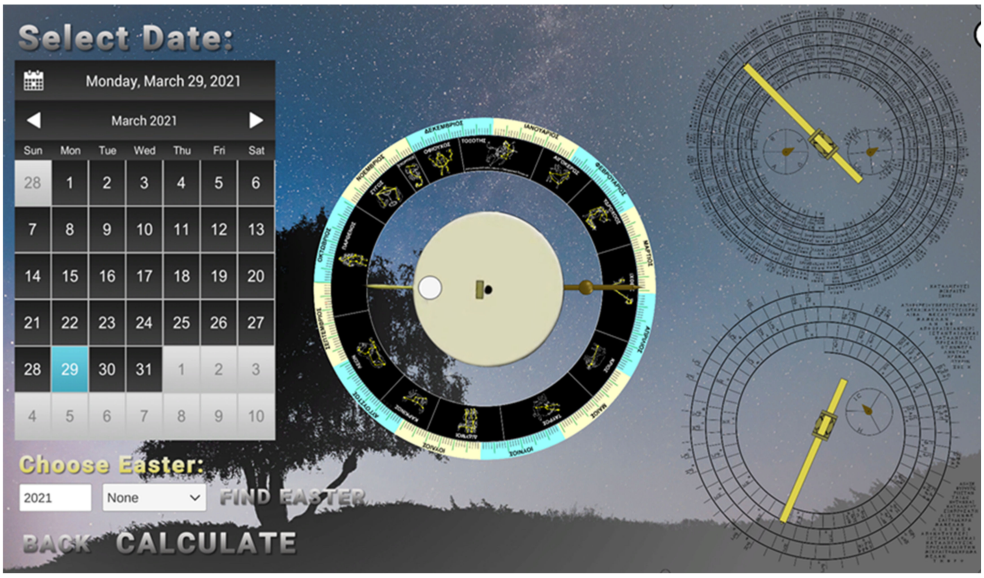
Date	Position (Constellation)		Astronomical Phenomena				NASA Predictions(NASA SKYCAL Sky Events Calendar)
	Sun	Moon	New Moon	Full Moon	Sun Eclipse	Moon Eclipse	
12 October 1977	Virgo	Virgo	✓	✗	✓	✗	Solar Eclipse on 12 October 1977
19 August 2001	Leo	Leo	✓	✗	✗	✗	New Moon on 19 August 2001
11 October 2007	Virgo	Virgo	✓	✗	✗	✗	New Moon on 11 October 2007
29 December 2035	Sagittarius	Sagittarius	✓	✗	✗	✗	New Moon on 29 December 2035
17 January 2056	Sagittarius	Sagittarius	✓	✗	✓	✗	Solar Eclipse on 31 January 1999
8 February 1982	Capricorn	Leo	✗	✓	✗	✗	Full Moon on 8 February 1982
31 January 1999	Capricorn	Cancer	✗	✓	✗	✓	Moon Eclipse on 31 January 1999
26 May 2021	Taurus	Libra	✗	✓	✗	✓	Moon Eclipse on 26 May 2021
5 May 2023	Aries	Libra	✗	✓	✗	✓	Moon Eclipse on 5 May 2023
11 August 2071	Cancer	Capricorn	✗	✓	✗	✗	Full Moon on 11 August 2071

4.3. Calculate the Exact Date of the Celebration of Easter

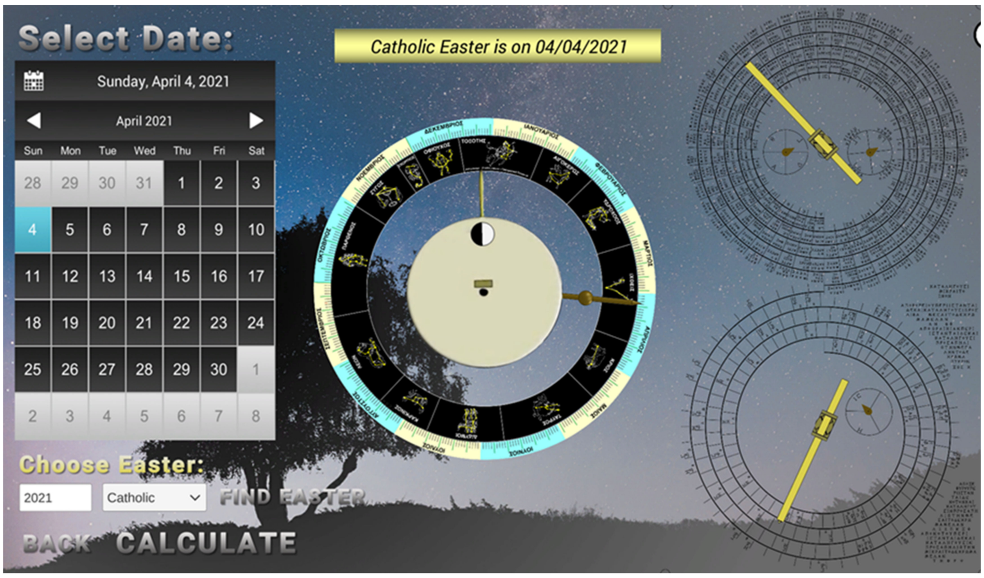
According to the rules of the Christian church, Easter must be celebrated on the first Sunday after the first full Moon following the Spring Equinox. Since the date of the Easter celebration is related to the astronomical phenomenon of the lunar phases, which is calculated by the Mechanism, it is possible to calculate the exact date of the celebration of Easter without any intervention in the structure of the Mechanism. Based on this, the possibility of predicting the exact date of the celebration of Orthodox, Catholic and Jewish Easter has been developed in the application.

4.3.1. Predictions of the Date of the Catholic Easter of 2021

Figure 20a shows the first full Moon following the Spring Equinox of 2021 (Monday, 29 March 2021) based on Gregorian calendar, as it is calculated by the Antikythera Mechanism application. Figure 20b shows the date (4 April 2021) of Catholic Easter using the application.



(a)

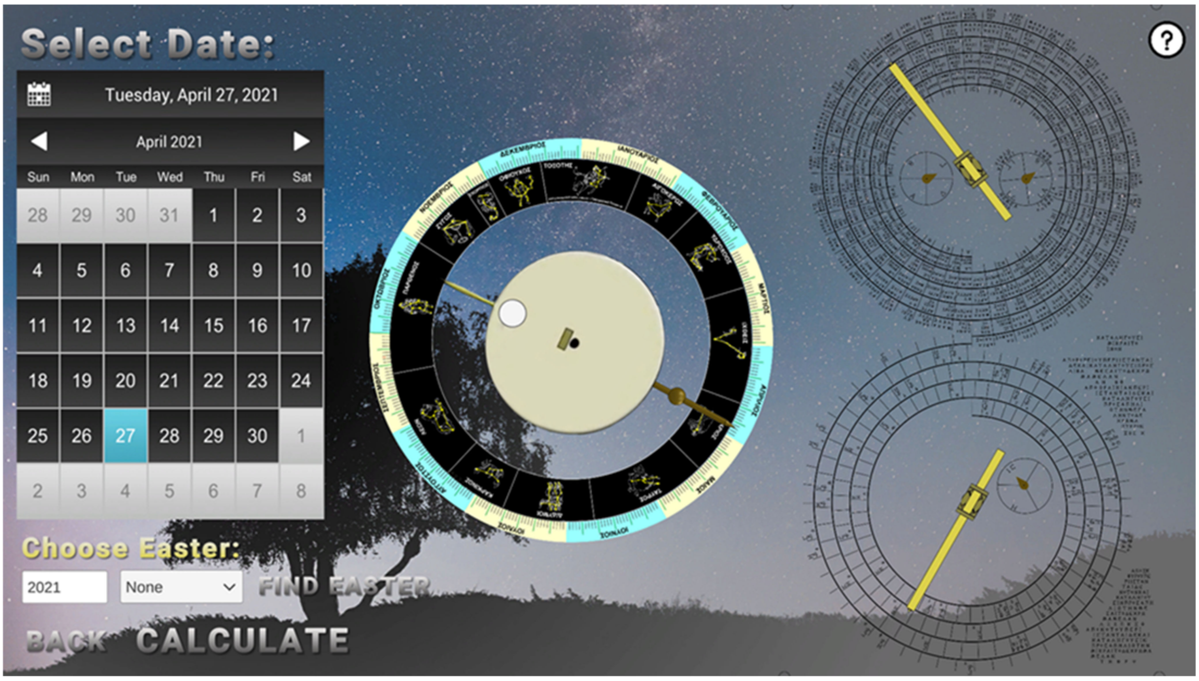


(b)

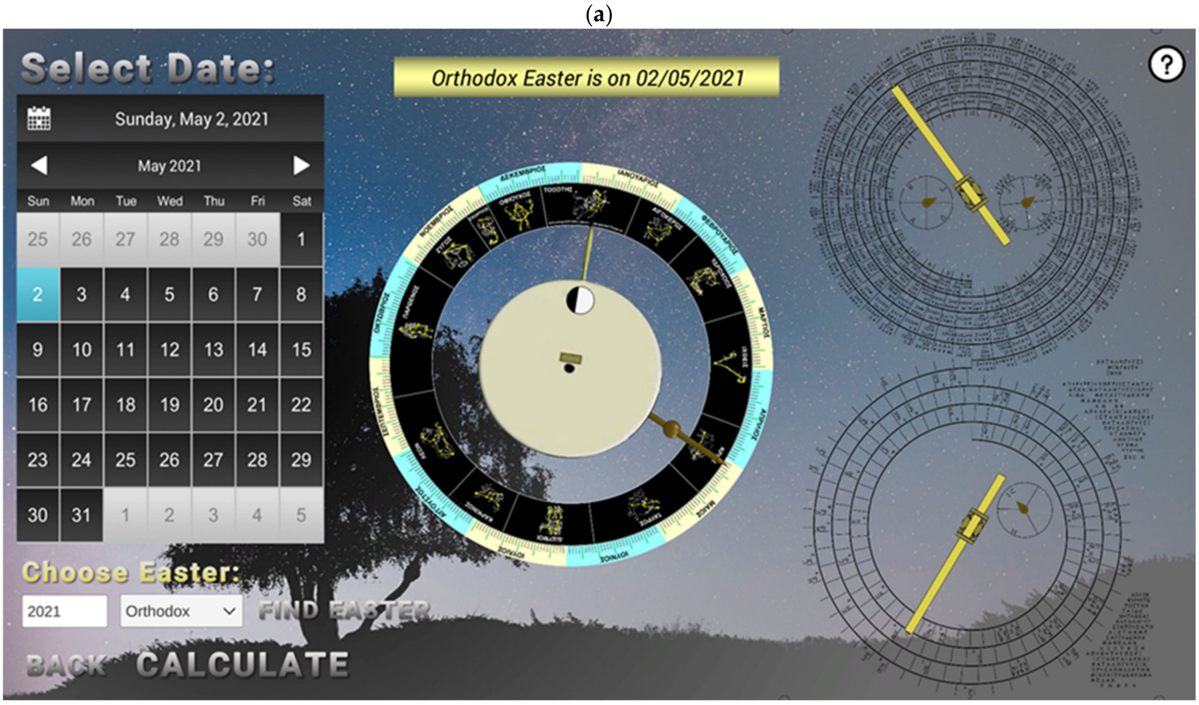
Figure 20. (**a**) The 1st full Moon following the Spring Equinox of 2021 based on Gregorian calendar. (**b**) Catholic Easter of 2021 (4 April 2021).

4.3.2. Predictions of the Orthodox Easter Date in 2021

Orthodox Easter follows the same rule, regarding the first full Moon following the Spring Equinox, but it is calculated based on the Julian calendar (old Calendar). Figure 21a shows the first full Moon following the Spring Equinox of 2021 (Tuesday, 27 April 2021) based on the Julian calendar, as it is calculated by the Antikythera Mechanism application and in Figure 21b the date (2 May 2021) of the Orthodox Easter following the application.



(**a**)



(**b**)

Figure 21. (**a**) The first full Moon following the Spring Equinox of 2021 based on the Julian calendar. (**b**) Orthodox Easter of 2021 (2 May 2021).

Table 3 provides some additional examples of the Easter date forecasts for different years from 2004 to 2044. For all the dates included in Table 3, the application calculates the same predictions.

Table 3. Catholic and Orthodox Easter predictions.

Year	Antikythera Mechanism Application		https://en.wikipedia.org/wiki/List_of_dates_for_Easter	
	Date of Celebration the Catholic Easter	Date of Celebration the Orthodox Easter	Date of Celebration the Catholic Easter	Celebration the Orthodox Easter
2004	April 11		April 11	
2009	April 12	April 19	April 12	April 19
2015	April 5	April 12	April 5	April 12
2020	April 12	April 19	April 12	April 19
2021	April 4	May 2	April 4	May 2
2022	April 17	April 24	April 17	April 24
2025	April 20		April 20	
2032	March 28	May 2	March 28	May 2
2044	April 17	April 24	April 17	April 24

4.4. Accuracy of Predictions of the Replica of the Antikythera Mechanism

Figure 22 shows a physical model, a replica of the Antikythera Mechanism, in which we have recorded on the front the current positions on the scales of dates and zodiac signs.

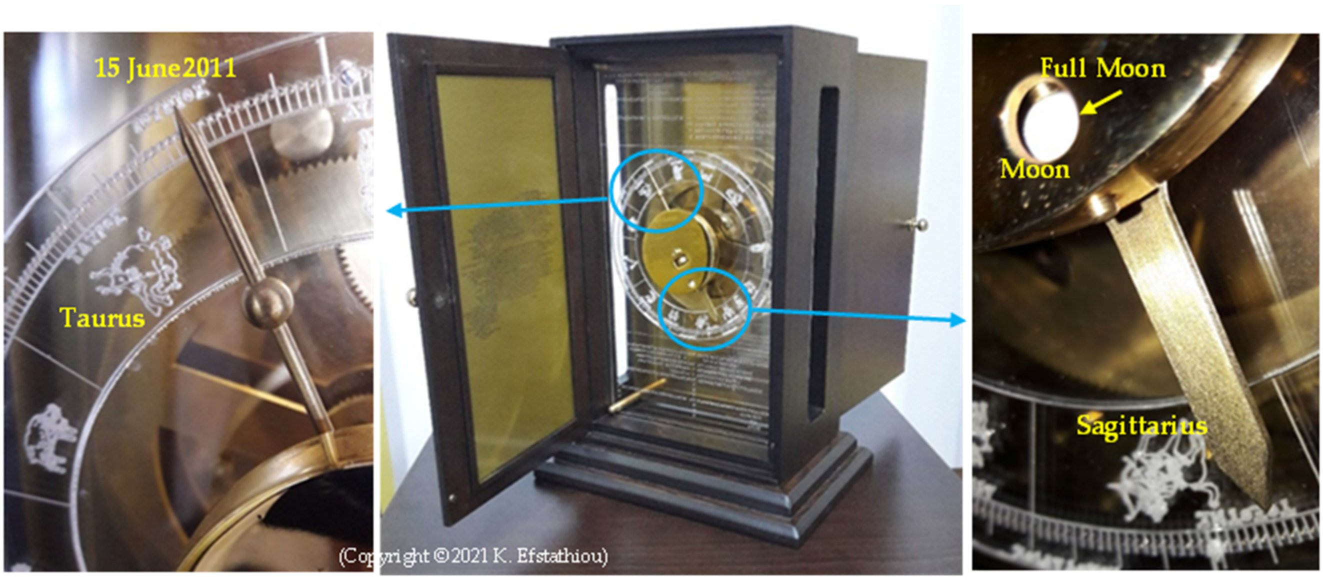


Figure 22. Displays on the front site of the Mechanism for 15 June 2011.

On 15 June 2011, the following astronomical phenomena occurred: The Sun was projected on the constellation of Taurus, the Moon was projected on the constellation of Sagittarius, there was a Full Moon and simultaneously there was a Lunar Eclipse at 23:00.

The corresponding indications of the replica are:

Front site (Figure 22):

15 June 2011, Sun in the constellation of Taurus, Moon in the constellation of Sagittarius and Full Moon. Thus, it is possible to observe a moon eclipse on this day.

Back site (Figure 23):

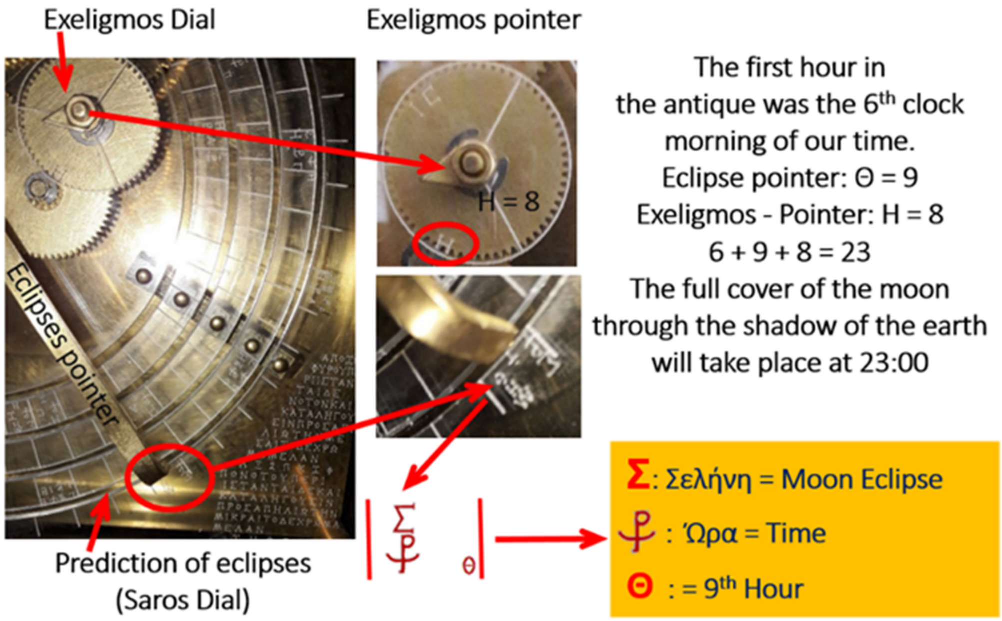


Figure 23. Displays on the back site of the Mechanism for 15 June 2011.

Observing the eclipse pointer on the back site of the Mechanism, a lunar eclipse will indeed occur. Specifically, regarding the lunar eclipse, the Mechanism showed:

(a) Eclipses pointer: Σ (Σελήνη = Moon), Θ = 9 (time of the event 9 o'clock); and
(b) Exeligmos Index: H = 8 h delay (must be added to Θ).

Considering that the first hour in antiquity was the 6th hour of the present era we have Θ + H + 6 = 9 + 8 + 6 = 23. That means the full coverage of the moon by the shadow of the Earth will take place at 23:00.

As it turns out, the predictions of the Antikythera Mechanism exactly coincide with the phenomena that actually occurred on 15 June 2011.

4.5. Example of Calculations That Simulate the Kinematics of the Mechanism

The transmission rate (GTR) between two gears is calculated by:

$$\text{GTR1},2\ (\text{between the drive gear 1 and the driven gear 2}) = \frac{\text{Z1 (Number of teeth of gear 1)}}{\text{Z2 (Number of teeth of gear 2)}}$$

In Figure 24, we observe the mechanical flow diagram of the gear train that starts from gear b_2 (mounted on the b_{out} axis), which moves the Sun/Date pointer and leads to the gear b_3 (mounted on the b_{in} axis), which rotates the Moon pointer.

To identify the Moon pointer's angle of rotation, for a given rotation of the Sun pointer, we need to know the transmission rate of the gear train shown in the Figure.

Based on the flow diagram in Figure 24, the whole transmission rate begins from gear b_3, which rotates the shaft b_{in}, and the lunar pointer until the gear b_2, which rotates the shaft b_{out} and thus the Sun/Date pointer is:

$$\text{GTR}_{b(3),b(2)} = (Z_{b(3)}/\ Z_{e(1)})\ (Z_{e(6)}/\ Z_{k(2)})\ (Z_{k(1)}/\ Z_{e(5)})\ (Z_{e(2)}/\ Z_{d(2)})\ (Zd_{(1)}/\ Zc_{(2)})\ (Z_{c(1)}/\ Z_{b(2)})$$

$$\text{GTR}_{b(3),b(2)} = \frac{32}{32} \times \frac{50}{50} \times \frac{50}{50} \times \frac{32}{127} \times \frac{24}{48} \times \frac{38}{64} = 0.0748$$

That means that for one rotation of the lunar pointer, the Sun/Date pointer will make 0.0748 rotations, which corresponds to 26.928 degrees or to 27.3 days. This is how long it takes for the Moon to complete one full rotation around Earth.

Therefore, given any fixed rotation value of an indicator (or a gear), one could reliably predict how much each gear and indicator would rotate.

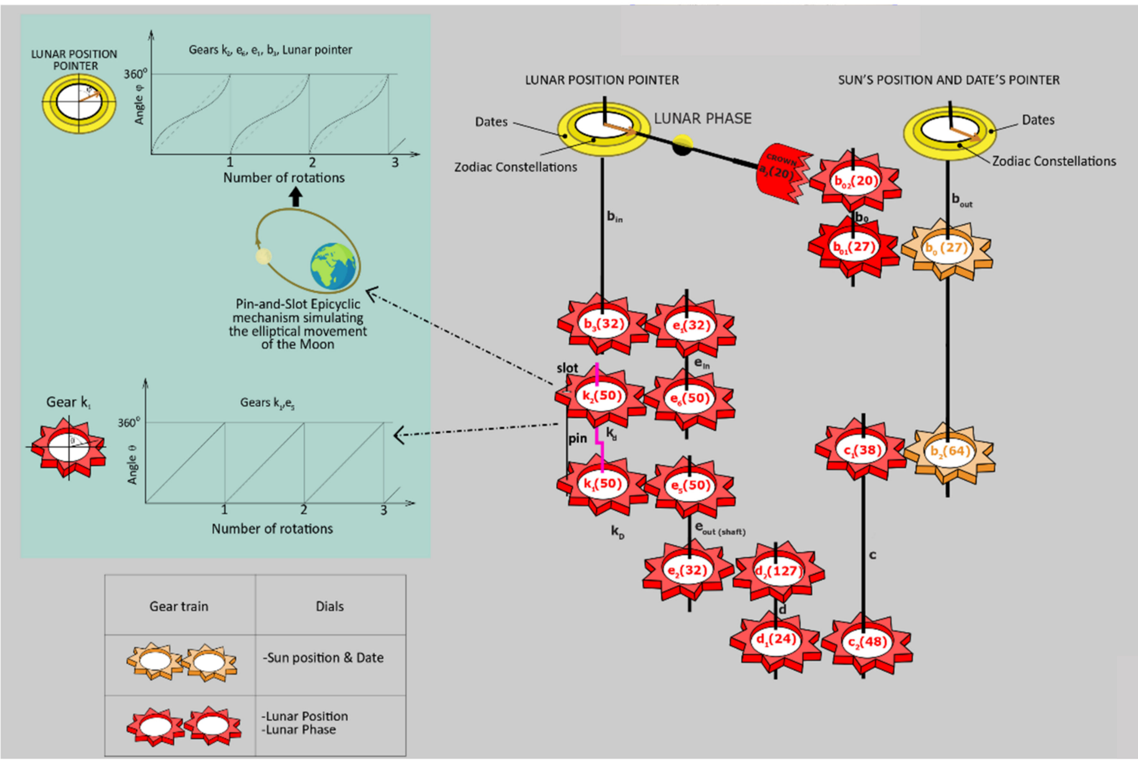


Figure 24. The gear train connecting the Sun/Date pointer and the Moon pointer.

In Figure 25, we observe the mechanical flow diagram of the gear train that begins from gear b_2 (mounted on the b_{out} axis), moves the Sun/Date pointer and leads to eclipses and exeligmos pointers.

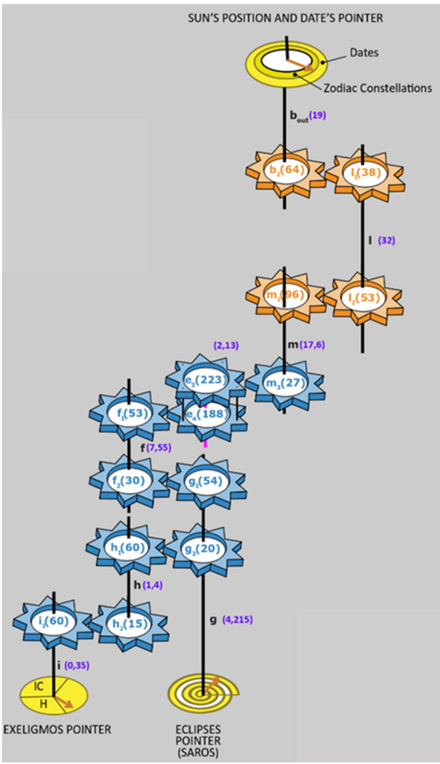


Figure 25. The gear train connecting the Sun/Date pointer and the eclipses and exeligmos pointers.

The application calculations are based on this logic. The corresponding part of the code, developed in the application for the calculations of the transmission rate of the gear train, are shown in Figure 25 and presented in Figure 26.

```
public void ExeligmosPointerDegree(double exeligmosDegree)
{
    double[] exeligmosPointerGears1 = {64, 53, 27, 188, 30, 20, 15};
    double[] exeligmosPointerGears2 = {38, 96, 223, 53, 54, 60, 60};
    double totalExeligmos = 0.0;
    double totalSumExeligmos = 1.0;
    double exeligmosAddedDegrees = 0.0;

    //Calculate gears ratio
    for(int i = 0; i < 7; i++)
    {
        totalExeligmos = exeligmosPointerGears1[i] / exeligmosPointerGears2[i];
        totalSumExeligmos *= totalExeligmos;
    }

    exeligmosAddedDegrees = (totalSumExeligmos * exeligmosDegree) + pointerExeligmos;
    pointerExeligmos = exeligmosAddedDegrees % 360;

    float vOut4 = ToSingle(pointerExeligmos);
    ExeligmosPointer.transform.rotation = Quaternion.Euler(0, 0, -vOut4);
}
```

Figure 26. Part of the code for the calculations of the transmission rate of the gear train, as shown in Figure 25.

4.6. Accuracy of the Mechanism's Predictions

The important elements that have to be considered for accurate forecasts of the Mechanism are:

(a) the accuracy of the equinoxes;
(b) the inaccuracy of the mechanism (mainly of the Saros scale) for in-depth predictions; and
(c) the experience of the operator in using the Mechanism and his knowledge of the astronomical phenomena.

4.6.1. Physical Accurate Functional Models (and Original Mechanism)

Handling Steps for Accurate Prediction of Future Phenomena

The handling steps for accurate prediction of future phenomena are as follows:

A. Rotate the gears until all the pointers move simultaneously. This will lead to the cooperating gears to be engaged, eliminating the gaps that occur due to the triangular shape of their teeth, or possible inaccuracies during their construction.
B. Adjustment of the indicator's position of the Mechanism, using data of a recent eclipse (within a period of about 100 years) and prediction of the future phenomenon.
C. If the next forecast refers to a date later than the previous one, no further action is required by the operator.
D. If the next forecast refers to a date earlier than the previous one, the Mechanism should be firstly turned backwards to a date earlier than the desired one and then forward to the desired date. By doing this, all the gaps that may occur, due to their opposite rotation, are eliminated.

Handling Steps for Accurate Prediction of Past Phenomena

The steps are the same, but with a different direction of rotation in each steps A, B, C and D.

4.6.2. Prediction with the Developed Application which Simulates the Mechanism

As in the computer application, the gears are considered ideal (without inaccuracies and gaps), all that is needed is to set the initial position of the indicators of the Mechanism, using the data of a recent eclipse (within a period of about 100 years). This can easily be done through this application.

5. Conclusions

One of the questions that concerns the international scientific research community is whether the Antikythera Mechanism was a scientific instrument for the safe prediction of astronomical phenomena or an educational tool for the schools of astronomy of antiquity. Based on the main goal of answering this question, but also to make the mechanism more accessible to the general public, we have developed an application, which simulates the exact operation of the physical model of the Mechanism. From all the tests that have been performed, it is concluded that the Mechanism accurately predicts the astronomical phenomena of the future and confirms with astonishing accuracy the astronomical phenomena of the past. The accuracy of the results of each prediction was determined by comparing its results with corresponding predictions on the NASA website. In combination with a physical functional model of the Mechanism, the application helped us to prove that the Antikythera Mechanism was a scientific instrument, the first computer in world history, which accurately predict astronomical phenomena.

It is important to emphasize that, from the study of the Mechanism, its usefulness in issues related to the present era have emerged. For example, it can be used to predict the dates of mobile church holidays, such as Easter. As the date of the celebration of Easter is related to the astronomical phenomenon of lunar phases, whereby the Mechanism calculates anyway, it is possible to calculate the exact date of the celebration of Easter without any intervention in its structure. Based on this, the possibility of predicting the exact date of the celebration of Orthodox, Catholic and Jewish Easter has been developed in the application. The results of all the tests proved to be accurate.

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