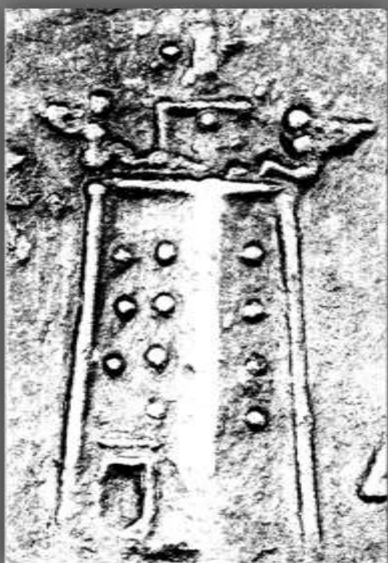
Ancient Greek Optical instruments and the Pharos of Alexandria:

Insights on its Functions and Technology

This research suggests that historical evidence on available scientific knowledge in the Hellenistic Period justifies that the mechanism of the Pharos in Alexandria could have incorporated complex optical systems to achieve the dispersion of light in long distances.

Published in Hellenistic Alexandria
Celebrating 24 Centuries
Papers presented at the conference held on December 13–15 2017
at Acropolis Museum, Athens
edited by
Christos S. Zerefos and Marianna V. Vardinoyannis

Preprint to be published by Archaeopress



XENOPHON MOUSSAS
PAOLO VITTI
STYLIANOS ZEREFOS
1/9/2018

2018

Ancient Greek Optical instruments and the Pharos of Alexandria: Insights on its Functions and Technology

XENOPHON MOUSSAS[1],

PAOLO VITTI[2],

STYLIANOS ZEREFOS[3]

1) Department of Astrophysics, Astronomy and Mechanics, Faculty of Physics, School of Science, National and Kapodistrian University of Athens, tel. +30 6978792891, xmoussas@phys.uoa.gr, xmoussas@gmail.com, xmoussas@yahoo.com
2) Dipartimento di Architettura, Università degli Studi Roma Tre, Italy
3) School of Applied Arts, Hellenic Open University, Greece

2018, Preprint University of Athens

published in *Hellenistic Alexandria: Celebrating 24 Centuries,* edited by Christos S. Zerefos and Marianna V. Vardinoyannis, Archaeopress, 2018

Ancient Greek Optical instruments and the Pharos of Alexandria:

Insights on its Functions and Technology

XENOPHON MOUSSAS[1], PAOLO VITTI[2], STYLIANOS ZEREFOS[3]

1. Department of Astrophysics, Astronomy and Mechanics, Faculty of Physics, School of Science, National and Kapodistrian University of Athens, tel. +30 6978792891, xmoussas@phys.uoa.gr, xmoussas@gmail.com, xmoussas@yahoo.com
2. Dipartimento di Architettura, Università degli Studi Roma Tre, Italy
3. School of Applied Arts, Hellenic Open University, Greece

Abstract

The present study deals with the history and application of advanced optical technology in antiquity. Ancient Hellenistic optical instruments, mirrors, lenses and their combinations, allowed to perform astronomical observations. Moreover, philosophers like Euclid, Heron and Diocles studied in the laboratory and in theory the qualities and properties of mirrors and possibly lenses.

This study is based on existing ancient lenses that are in Greek Museums and Greek, Latin and Arabic literature. Some of them have been measured and their optical characteristics are described. Ancient scientific books by Greek philosophers also refer to optics, lenses, mirrors and multiple refection instruments.

The oldest lens measured in this study is probably 4000 years old (from Crete, Greece) while others come from various time periods of antiquity. Several other lenses of various focal lengths of the 8th or 7th century BC from Rhodes are also presented. These exhibit a range of focal lengths and magnification and are provided with handles for the user.

There are ancient texts from the Greek philosophers and studies by prominent scientists like Euclid and Heron, both from Alexandria, that refer to complex optical systems made up of more than one mirror or, possibly, lenses. Even

Aristophanes -the theatrical comedian writer- gives many detailed descriptions. Ancient natural philosophers and other authors mention optical systems of two or more mirrors, concave and convex, that have appropriate qualities that enable the user to create real or imaginary idols, that they call images and spectra respectively. In some of these texts it is evident their astronomical use.

This research suggests that historical evidence on available scientific knowledge in the Hellenistic Period justifies that the mechanism of the Pharos in Alexandria could have incorporated complex optical systems to achieve the dispersion of light in long distances. Unfortunately, Pharos was already more than a millennium old, when the edifice and the remnants of this optical system were destroyed by earthquakes and tsunamis. This work aims at proposing an alternate theory on the optical system that was used in the lighthouse of Alexandria. Through classical literature on optics from Heron of Alexandria, Euclid, Archimedes, Ctesibius and many others, along with more recent accounts on the development of the Pharos' deterioration, it is suggested that the Pharos used the sun as a light source during the day and fire as a means of shedding its light into the night seas.

Introduction to ancient optics

Astronomy is part of every culture from prehistoric times. Humans admire and study the sky initially by naked eye; they observe the motion of the stars, the Sun, the Moon, the planet.

They notice the changes of the seasons, the yearly change of the altitude of the sun, the changes of the position of sunrise and sunset. Eventually they develop various instruments, poles, simple stelae, buildings and cities according to various astronomical orientations. These astronomical observations probably lead to the development of reasoning, to the notion of causality and, with it, the laws of physics that are described by appropriate mathematics to predict properly nature, to "save the phenomena[1]".

Based on ancient Greek texts and actual finds, it is evident that they do not only mention lenses and mirrors of various types. They even study nature with scientific methods, experimental and theoretical, as in Euclid's On Catoptrics[2]. Perhaps the most famous quotation on the use of lenses in antiquity is the one in Aristophanes, who mentions that Greeks can buy from a pharmacy lenses to light a fire[3], and can falsify the minutes of a

---

[1] In Heraclides Ponticus (c390–310 BC) τὴν γῆν καὶ κύκλῳ κινουμένην, τὸν δὲ οὐρανὸν ἠρεμεῖν Ἡρακλείδης ὁ Ποντικὸς ὑποθέμενος *σῴζειν ᾤετο τὰ φαινόμενα*, Eudemus (270-300 BC), the oldest historian of science, mathematician, astronomer and student of Aristotle who edited his teacher;'s books before been published, writes *σώζειν τὰ φαινόμενα* and it is repeated by Plutarch (46-120AD) in his book *On the Face in the Orbit of the Moon*, … φαινόμενα σῴζειν…

[2] It is suggested by O'Conor and Robertson that the text cannot be attributed with certainty to Euclid, rather its contents are a mixture of work dating from Euclid's time together with work which dates to the Roman period. It has been argued that the book may have been compiled by the 4th century mathematician Theon of Alexandria.

[3] Aristophanes, *Clouds (*Strepsiades: Have you seen the transparent stone that you can buy from the pharmacy to light up a fire? Socrates: yes, you mean the glass (lens), you can use it to melt and delete from a distance the writings of your suit in the court.).

court from a distance using a lens[4]. By addressing the use of lenses in a comedy, it is most probable that Aristophanes refers to something known to the general public. Several lenses and many mirrors are exhibited in Greek and other archaeological museums[5], but there are many more important ancient texts about optics, especially mirrors.

The science of optics was called *catoptrics* by the Greeks, as was initially the study of the mirrors that are called Catoptra (Κάτοπτρα) in Greek. Optics becomes a science mainly in Alexandria probably before the time of Euclid. Euclid's *Catoptrics* explains theoretically the phenomena of reflection, multiple reflections and the formation of images, reversed, magnified etc. Euclid explains why certain mirrors reverse the image, making it left and right handed or inverse, up and down. He also explains why images appear diminished and warped in convex mirrors and how they can be seen in concave mirrors[6]. Another very important theoretical study is the one on burning mirrors by Diocles (c240–c180 BC)[7] of which an Arabic translation exists. It proves that ancient scientists treat optics purely theoretically, using geometry without involving the eye of the observer or vision.

---

[4] The minutes of proceedings of the court were written on tablets covered with a thin layer of wax that *Strepsiades* could delete from a distance focusing sunrays on the layer of wax.

[5] Twyman, F. (1942, 1952, 2nd ed.). Prism and Lens Making, Hilger.

[6] Irby G. L. (editor), (2016), A companion to science, technology, and medicine in ancient Greece and Rome, 2016 John Wiley & Sons, Inc.

[7] Toomer, G. J. (2012). Diocles, On Burning Mirrors: The Arabic Translation of the Lost Greek Original (Vol. 1). Springer Science & Business Media.

According to some scholars[8], Greek philosophers' texts explain the nature of vision as rays of light emitted from the human eye. However, this belief is based on a misunderstanding, since Greek texts simply mention the mathematical method to draw lines to study and understand vision. The confusion is probably due to the use of term *opsis (όψις)* which has three meanings at least a) the eye, b) the vision, and c) the rays of light and the straight lines used in the theory of optics[9].

That optics is to be considered as part of Geometry is proven by the lack of any reference to the vision or to the human eye, whereas lines are used to explain the phenomenon. This is ascertained by the almost identical sentences used by Euclid and Heron of Alexandria[10], reported by S.M. Medaglia and L. Russo[11], on the geometry of vision. Euclid in his *Catoptrics* states: "*let us draw straight lines form the eye that deviates as the distance increases"* and even introduces the solid angle as a cone[12]. Geminus of Rhodes (1st century BC) and Theon of

---

[8] Neugebauer, O. (1975) *A History of Ancient Mathematical Astronomy In Three Parts,* Springer-Verlag Berlin Heidelberg

[9] Thibodeau, C. f. P. (2016). *Ancient Optics: Theories and Problems of Vision*, in: A Companion to Science, Technology, and Medicine in Ancient Greece and Rome, First Edition. Edited by Georgia L. Irby. John Wiley & Sons, Inc. pp 130–144.

[10] Heron of Alexandria (1900) *Opera quae supersunt Omnia. Mechanica et catoptrica*, ed. L. Nix and W. Schmidt. Leipzig: B. G. Teubner.

[11] Medaglia, S. M., & Russo, L. (1995). Sulla prima "definizione" dell'Ottica di Euclide". Bollettino dei classici, 41-54.

[12] Eucl. Opt.:. (Let it be established that visual rays move along straight lines from the eyes and produce some distance between one another; 2) and that the shape inscribed by the visual rays is a cone that has its vertex

Alexandria give the same geometrical description, almost the same sentence. Heron in his book *Definitiones*[13] says that light rays are straight lines that deviate from the eye and the same is repeated by Geminus in his *Fragmenta optica*[14]. (Evans and Berggren, 2006)

Geminus and Heron divide *Optics* in three parts, as (a) *Optic,* (b) Catoptric and (c) *Scenographic*[15].

a) *Geometrical optics* is used for reflection of light on surfaces like water, metallic plates, and also for refraction in crystal and lenses. Light follows *straight lines or at times refracted as in lenses* [ἀκλάστους, τότε δὲ κατὰ δυομένας, ὥσπερ ἐπὶ τῶν ὑέλων].
b) *Spectroscopy (Ἶρις)* is the study of colours that appear in air, water, shadows, around the rays of the sun.
c) *Scenography* is the study of the images of buildings in 3 dimensions, i.e. projective geometry and descriptive

at the eye and its base at the limits of the things being seen; 3) and that those things are seen against which the visual rays fall, while those things are not seen against which the visual rays do not fall;)

[13] Heron, *Definitiones*:Ὅτι ὑποτίθεται ἡ ὀπτικὴ τὰς ἀπὸ τοῦ ὄμματος ὄψεις κατ' εὐθείας γραμμὰς φέρεσθαι, καὶ τοῦ ὄμματος περιφερομένου συμπεριφέρεσθαι καὶ τὰς ὄψεις, καὶ ἅμα τῷ ὄμματι διανοιγομένῳ πρὸς τὸ ὁρώμενον γίνεσθαι τὰς ὄψεις.

[14] Geminus, *Fragmenta optica*:Ὅτι ὑποτίθεται ἡ ὀπτικὴ τὰς ἀπὸ τοῦ ὄμματος ὄψεις κατ' εὐθείας γραμμὰς φέρεσθαι καὶ τοῦ ὄμματος συμπεριφερομένου συμπεριφέρεσθαι καὶ τὰς ὄψεις καὶ ἅμα τῷ ὄμματι διανοιγομένῳ πρὸς τὸ ὁρώμενον τὰς ὄψεις γίνεσθαι. ὑποκείσθω τὰς ἀπὸ τοῦ ὄμματος ὄψεις κατ'εὐθείας γραμμὰς φέρεσθαι διάστημά τι ποιούσας ἀπ'ἀλλήλων.

[15] Geminus and Heron say exactly the same, using the same phrase

geometry. They are suitable and important for design, architecture, engineering and in art to show diminution of size with distance. Claudius Ptolemy (2nd century AD) has written five extensive books about optics, on mirrors and reflection and we can conclude that it was a very detailed study on a science that was very advanced during the Hellenistic times.

Ancient lenses

Ancient lenses have been studied and presented mainly by archaeologists. Sines and Sakellarakis (Sines and Sakellarakis 1987) present lenses from prehistoric Greece found in Knossos. J. M. Enoch (Enoch 1998, Enoch 2000) presents a lenticular crystal man-made object, considered as simply ornamental. Giovanni Pettinato (Willach, 2008) believes that this Assyrian lens discovered by Sir John Layar in 1850, was possibly used for the magnification of objects. Ancient lenses are described by G.L Irby-Massie and P. T. Keyser (Irby-Massie and Keyser 2002) in their book about Greek science of the Hellenistic era. Russo gives an account for ancient lenses from various sites in his book on the "Greek scientific revolution" (Russo 2013). Russo reviews the scientific presentations regarding lenses in antiquity and discusses Ptolemy's text, where tables with refraction angles of different mediums are given and even discusses the possible existence of telescopes in antiquity.

The Archaeological Museum of Heraklion in Crete, Greece, exhibits more than 20 lenses, some dating to c. 2000 BC, which are intact and in good condition. Their focal length ranges around some tens of cm. The visual image that these lenses produce is reasonable, more than just acceptable. Despite the distortion of their refractive properties, the lenses produce visual images that can be useful and suitable for practical purposes. For example, the magnification produced by a lens may be used for engraving and working with small objects, such as the construction of jewels and seals, like those found in prehistoric Greece as mentioned by Sines and Sakellarakis.

Another 20 magnifying lenses with handles made of copper are available at the Archaeological Museum of Rhodes. They are believed to date to the 8th century BC. Most probably these were lenses used in a workshop. Measurements of their focal lengths showed that more than one or two of these lenses provide the same magnification and thus we can probably conclude that they could have been meant for sale, possibly even to mitigate presbyopia, the aging eye condition. Around forty lentoid, lens-like crystal objects, found by H. Schliemann at Troy are now at the Pushkin Museum, Moscow. These are assumed to be meant probably for decoration of a ceremonial suit of royalty or something equivalent. However, one of the lenses is definitely a lens having good quality image depiction. All these lenses are converging lenses with a spherical one and one with plane surface. Some lens-like objects are real lenses used for magnification[16] and perhaps others are just for decoration[17]. At least two or three very impressive lenses that are suitable to mitigate myopia, near-sightedness or short-sightedness, have been on display at the exhibition of objects from Vergina at the Archaeological Museum of Thessaloniki.

[16] Sines, G., & Sakellarakis, Y. A. (1987). Lenses in antiquity. American Journal of Archaeology, 191-196., believe that are lenses for magnification.

[17] D. Plantzos (Plantzos 1997) suggests that lent-like objects are just for decorative purpose.

The use of magnifying lenses is evident from the details of seals dating to many historical periods, including the Hellenistic period in Alexandria. A recently discovered seal form a ring of the 15th century BC from Pylos proves that humans managed to construct immaculate details. The fingers of one of the warriors depicted on the seal are accurately displayed with an accuracy of 0.2mm, i.e. half the diameter of a human hair, with details visible only through photography techniques as photomicroscopy[18].

The theory of optics flourished in the Hellenistic Period and continued to develop in the Roman times, as proven by Heron and Ptolemy, who lived in Alexandria. In this period refraction is clearly understood on a theoretical basis. Euclid in his book Catoptrics described the theory of the construction of images from spherical mirrors giving details on left handed images and right handed images from spherical mirrors, as well as on the size of the image, thus providing a mathematical explanation why the image from the smaller spherical mirror is also smaller. Heron of Alexandria in his *Definitions* explained how refraction happens as the rays of light following straight lines enter from one transparent medium to another denser, like water, glass or films or membranes.

[18] Davis, Jack L. and Stocker, Sharon R., (2016), *The Lord of the Gold Rings: The Griffin Warrior of Pylos*, Hesperia: The Journal of the American School of Classical Studies at Athens, 85, pp. 627-65.

Ancient mirrors

The Greeks use three terms of mirrors: *Κάτοπτρον, Ἔσοπτρον* and *Ἔνοπτρον*. In Greek Ἔσ, Εν means inside, *Κάτ* means against, *οπτ* means to look and–τρον, means and implies an instrument, so these three terms mean an instrument to look through or against. According to Greek mythology the first mirror has been made by god Hephestos (Vulcan) for god Dionysus as described by Proclus In *Platonis Timaeum commentaria*. Construction of a convex mirror is described by Agathias in *Historiae* who states that the convex mirror focuses the rays of the sun on a point [αἴγλη, focal point].

The use of bronze mirrors was well known in the Minoan and Mycenaean civilizations. Corresponding artefacts are exposed in the Archaeological Museums in Crete and the National Archaeological Museum at Athens. Some terracotta shallow vessels found around the Aegean Sea and mainly in Cyclades, the so-called frying pan vessels of the 4th and 3rd millennium BC, peculiar containers for liquids that were painted black on the inside, could have been used as mirrors[19]. These vessels were filled with water and used as mirrors.

[19] Tsountas, C., 1899, Cycladic, Κυκλαδικα II, ArchEph, 74–134.; Coleman, J. E., 1985, ‘Frying pans’ of the Early Bronze Age Aegean, American Journal of Archaeology, 89, 191–219.; Papathanassoglou, D. A., & Georgouli, C. A. (2009). The ‘frying pans’of the early Bronze Age Aegean: an experimental approach to their possible use as liquid mirrors. Archaeometry, 51(4), 658-671.; Tsikritsis, M., Moussas, X., & Tsikritsis, D. (2015). Astronomical and mathematical knowledge and calendars during the early helladic era in

Apollonius in his work *Apotelesmata* gives a recipe on how to construct a metallic mirror alloy using copper, mercury, silver, gold, lead, tin and crystal[20]. Mirrors had many applications. Naturally they were meant and used for cosmetics, to mirror oneself, but also for reflecting light as in the case of the Pharos of Alexandria, possibly to observe images of astronomical objects, and even for hunting, trapping animals as Athenaeus states many times in his book *Deipnosophistae*[21].

According to literature the first scientists to understand the physics and mathematics of reflection are Pythagoras and his followers, as the so called Pseudo-Galenus (Galen of Pergamon, 2nd century AD) states in his book on the history of science (*De historia philosophica*)[22]. He refers that Democritus and Epicure studied the formation of images produced by reflection on mirrors, plane or spherical, and how the images thus produced are inversed. Plato in *Theaetetus* uses such an expression as *ὥσπερ εἰς κάτοπτρον ἢ ὕδωρ* (as in a mirror or water), referred to an image produced by reflection. Aeschylus in the play *Agamemnon* says that we use mirrors made of the chemical element copper [*κάτοπτρον εἴδους χαλκός*], hence mirrors to be used in a theatrical play have to be common

Aegean" frying pan" vessels: Mediterranean Archaeology & Archaeometry, 15(2).

[20] For the construction of a mirror… take copper, mercury, silver, gold, lead, tin and crystal in equal quantities and you can construct any type of mirror, with a similar texture as glass)

[21] *…if you put a mirror and a noose in front of it against quails when in mating season, they run towards the mirror and get caught in the noose*

[22] Pseudo-Galenus, De historia philosophica

place, known to all. It is evident that there were mirrors made of various materials. Aristoteles[23] in his treatise on colours refers to various colours of various mirrors, and we can conclude that he had in mind mirrors made of water in a container with black bottom onside, polished black stones, copper, silver, even gold. Hence, mirrors were not used only by very rich people. Familiarity with reflections and on the formation of the image must have been more common than thought.

A very important description of astronomical observations with a set of mirrors used as a telescope to observe celestial objects is given by Flavius Arrianus (c. 85 to c. 160 AD) who wrote the history of Alexander the Great [*Alexandri anabasis*] in his *Fragmenta de rebus physicis* [about physics] where he refers to Democritus, the teacher of Hippocrates using a "telescope" to observe planets and the he observed their images and he managed to understand the constituents of the comets. Philosopher Apollonius in his book *Apotelesmata* states that we cannot know everything that happens on the Earth at all latitudes and the sky, unless we use a mirror to see clearly[24].The great mathematician and astronomer Eudoxus wrote a popular astronomy book entitled "Phenomena and Mirror" (Φαινόμενα και Ἐνοπτρον) where he gave a

[23] Aristoteles *De coloribus* in water the image is rather water-like, and in mirrors it has the colour of the mirror.

[24] Apollonius, *Apotelesmata*

description of the sky[25]. One can assume that he used the title mirror for a book that describes the sky, since observation of the sky was done by means of mirrors.

The philosophers observing comets[26] realize that they contain gasses, jets of gasses, which make them rotate. Another astronomical use is mentioned by the very influential philosopher Aristoteles[27]. In his book *De Mundo* (Περὶ Κόσμου) when referring to the spectrum of light (Ἶρις) writes that iris appears in the reflection of a part of the Sun or of the Moon when it is in a humid and hollow cloud. The same description of observations of *spectra* seen with mirrors is given by Posidonius in his book *Meteorologica* in a description given by Diogenes Laertius. Apollonius of Laodicia in his astrological book *Astrologia Apotelesmatica* says that we use mirrors as a telescope to see clearly object in the sky and on the ground.

Plutarch in the book *De facie in orbe lunae* stresses that concave mirrors can be used to light fire, while convex mirrors cannot. Plutarch uses the term concave mirror, in his *Moralia* on *De Pythiae oraculis* where he states that one can have distorted images using plane and concave mirrors, in fact he refers to imaginary images [*φασμάτων*] and real images

---

[25] Dicks, D.R. (1970). Early Greek Astronomy to Aristotle. Cornell University Press

[26] Moussas, X. (2014). *Early Greek astrophysics: the foundations of modern science and technology*. American Journal of Space Science, 1(2), 129.

[27] Aristoteles, *De mundo*

[*εἰδώλων*]. An even more interesting observation going back to Thales observing the eclipse using a mirror. The earliest predicted eclipse according to Greek literature, is given by the so called Pseudo-Plutarchus, in *Placita philosophorum* in the section about eclipses of the Sun[28], where it is written that Thales first predicted the eclipse of the Sun by the Moon and underlines that during the solar eclipse one can see the earth-like nature of the Moon (as one can see the irregularities of the mountains of the Moon). Lucianus in his book *Hippias*[29] says that children study the theory of optics concerning the reflections on mirrors and astronomy.

The theory of multiple reflections is studied in Euclid's *Catoptrics*. Euclid[30] describes geometrically the reflection of light on a spherical mirror without the involvement of an eye and this proves that the notion of rays emitted by the eye is a misunderstanding of interpreters (see also O'Connor and Robertson, 2003). He takes the sun as a source of light to have parallel beams of light and describes the focusing of these lines (rays). Not surprisingly, Archimedes[31] constructs hexagonal

[28] Pseudo-Plutarchus, *Placita philosophorum "On solar eclipses. Thales first predicted a solar eclipse as the Moon will cover the Sun and he understood that the Moon is of Earthly nature as he observed it with a mirror* ".

[29] The theory of light rays reflection and the theory of mirrorsand even astronomy.

[30] We can set fire using sunrays and concave mirrors. Suppose we have a concave mirrors ABC, the sun EZ, the centre (focus) of the mirror F and a point D is joined with the focus.

[31] Diodorus Sicasulus in his, *Bibliotheca historica* "… the old man (Archimedes used a set of hexagonal mirrors that can move is all direction

mirrors that he can move (in four variable angles, probably two for every hexagonal mirror and two angles for the system of all mirrors together) remotely and direct them from a distance, regardless of the position of the Sun, using strings to focus at a target in the way we use today (even NASA for the James Webb Space Telescope)[32].

Anthemius describes focusing light in burning mirrors, using seven convex mirrors each one with each own fire, like the cluster of mirrors used by Archimedes. Possibly a system similar to the mirrors in the Pharos [33]. The Byzantine philosopher and historian Michael Psellus (c. 1017 to c. 1096) in the book *Oratoria minora* adds to the description that Archimedes' mirrors could focus automatically and set fire at a distance[34] and he adds that [cat]optrician and engineer have not only to follow the appropriate education but theoretical proofs as well[35]. Psellus adds that mirrors made of glass with a layer of tin are much better as the anomalies of the surface of glass are very small and tin doubles the reflectability of the mirror and that all smooth bodies reflect light regardless if they

---

(four angles) using blades to focus together and direct the light of the sun at will to burn the Roman fleet ….

[32] Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., ... and Lunine, J. I. (2006). *The James Webb space telescope*. *Space Science Reviews*, 123, 485-606.

[33] Better concentration of light with four or five "burning" mirrors …

[34] He made a mirror for me that from a distance burns to ashes an object automatically

[35] The student of optics and automata or anyone that learns together with the basic four disciplines … without the use of theoretical principles (of theoretical geometry with proofs

are a coin, or mage of silver or proper mirrors and this shows that theory of reflection is taught during the Christian times in the Byzantium[36].

The theory on the applications of hexagonal mirrors is given by Anthemius of Tralles (c. 474 – 533 or 558), an excellent mathematician and renown architect in Constantinople, the capital of the eastern Roman Empire, who designed and constructed together with Isidorus of Miletus the *Hagia Sophia* (532-537) at the time of emperor Justinian. Anthemius wrote an important work "*On surprising mechanisms*" (*Περὶ παραδόξων μηχανημάτων*) in which he gives theoretical proofs of theorems concerning reflection on mirrors. Anthemius describes the burning mirrors of Archimedes (without mentioning the great mathematician) with multiple reflections on many hexagonal mirrors moved remotely with a system of strings and blades used to burn from a distance[37].

---

[36] Michael Psellus, *Opuscula psychologica, theologica, daemonologica:* Every object that receives light reflects it and especially smooth surfaces, like coins, mirrors and water.

[37] On surprising mechanisms by Anthemius of Tralles, whose manuscript tradition depends entirely on the opening bifolium of the Vat. gr. 218 (critical editions in MGM, 78–87, and CG, 349–59)," to facilitate reflection (and focusing) assume hexagonal mirror ABCDF and four similar mirrors next to it adjacent at the edges of the hexagonal AB, BC, CD, DE, EF, FA … the mirrors are directed using metallic blades and strings …, See also Acerbi, F. (2011). The geometry of burning mirrors in Greek antiquity. Analysis, heuristic, projections, lemmatic fragmentation. Archive for History of Exact Sciences, 65(5), 471–497. https://doi.org/10.1007/S00407-010-0076-8.

The Pharos of Alexandria

The lighthouse of Alexandria, the *Pharos*, was considered one of the Seven Wonders of the World. The light could be seen on the sea from some 300 *stadia* away (ca. 50km) guiding sailors to the harbour[38]. This remarkable building was particularly well built, since it has been standing from 280 B.C. until 1350 A.D.[39], withstanding all natural extreme events until it was completely ruined by earthquake. For 1630 years, this building remained a masterpiece of architecture and technology. Its use was not restricted to help navigation, but also as a military outpost, being a tower located at the entrance of the port.

The precise starting date for the construction of the Lighthouse is unknown. We know that it started and finished in the decade 290-280 B.C., i.e. during the kingship of Ptolemy I Soter (305/4-282 BC) and completed by the son and successor of Ptolemy II Philadelphus (284-246 BC), the great monarch who connected his name with the brilliant buildings of the Museum, a multidisciplinary school, as well as the great Library of Alexandria. The name “Lighthouse” (Pharos) was provided by the homonymous islet Pharos delimiting the port of Alexandria, on which it was built. Since then lighthouses were

[38] Josephus (Titus Flavius Josephus, 1st century AD), b. J. IV 613.

[39] H. Thiersch, (1909), Pharos, Antike Islam und Occident – Ein Beitrag zur Architekturgeschichte; B. G. Teubner, Leipzig und Berlin 1909. See also Vitti in this volume.

called "*Pharoi*". Arabs named it "El-Manara" (the lighthouse) and served as model for many minarets built in similar fashion. In this way, some Arabic (Muslim) minarets preserved the form and the name (el manara-minaret) of the Lighthouse of Alexandria[40].

On the side facing the sea was a huge inscription with metal letters and with each letter having a height of 50 cm[41], which, according to Lucian (2nd century AD) recited: "Sostratus of Cnidos, the son of Dexiphanes, to the Divine Saviours, for the sake of them that sail at sea"[42]. The Divine Saviours must be interpreted as Ptolemy I Soter and his wife Berenice (as Zeus Soter and Hera), who, by the end of the construction, had already been deified by their successor, Ptolemy II. Lucian writes also that Sostratus had the letters bearing his name covered with gypsum, in order to have them hidden and the name of the King painted on it. His account highlights the by all means exceptional mention of Sostratus instead of the king. According to Pliny the Elder (Ist century AD) Sostratus was the architect[43]. Pliny refers to the "magnanimity of Ptolemy to let Sostratus of Cnidos the architect to engrave his name on the monument". Other sources state that he was also a military general and diplomat[44] and his skills as a scientist must not be

[40] See Vitti in this volume.

[41] The dimension is reported by many Arabic sources. See *infra*.

[42] Lucian, *Quom. hist. sit. scrib*. 62.

[43] Plinius, *Naturalus Historia*, 36,18.

[44] Meeus 2015.

underestimated, given the exceptionality of the lighthouse. Strabo, who omits the dedication to the Divine Saviours, reports the inscription as follows: “Sostratus of Cnidos, friend of the kings, dedicated to the safety of the travellers”[45]. Many people assume that an epigram wrote by Posidippus of Pella, a famous poet in the beginning of 3rd century B.C., to praise the beginning or the completion of the Lighthouse, is another reliable source which confirms Sostratus being the builder of the tower [46]

[45] Strabo, *Geographica, XVII, i,6.*

[46] Hellmann 1999: 109-111 and Vitti in this Volume.

The architecture of the Lighthouse

Which was the architectural form of the Lighthouse? Today we can represent the Lighthouse based on a plethora of relevant iconographic and literary sources. The lighthouse is depicted on stone sarcofagi (as three in the Glyptotec of Copenhagen), or in mosaics and coins. A glass vase from Begram (Afghanistan) shows a tower topped by an immense statue and tritons at the corners. These tritons appear also in the coins of the *Pharos*. They are overdimensioned compared to the proportions of the tower, thus they cannot be considered merely a sculptural decoration, but, more likely, they must have been one of the exceptional features of the lighthouse. Since the coast of Alexandria is frequently hidden by sudden haze, we can suggest that a pneumatic mechanism emitted a sound from horns held by the tritons. In oil lamps discovered in Egypt we are confirmed what shown also in Roman coins (from Domitianm Trajan and Hadrian times, up to the end of the 2nd century AD): many windows opened on the exterior.

The first scientific attempt to reconstruct the architecture of the building was offered by Hermann Thiersch in 1909[47]. His exterior reconstruction still remains extremely accurate and new studies have not offered any important addition to the general layout of the tower. The Lighthouse consisted of 3 sections, with different dimensions. The first section occupied

[47] Thiersch 1909.

about half of the total height of the building, with dimensions of its base being a 30.6m cuboid 70m high. This section was slightly pyramid-formed and rested upon a platform with 10m height. A second section was octagonal and 34m high. The last one was circular and 9m height. The total height was 113m.

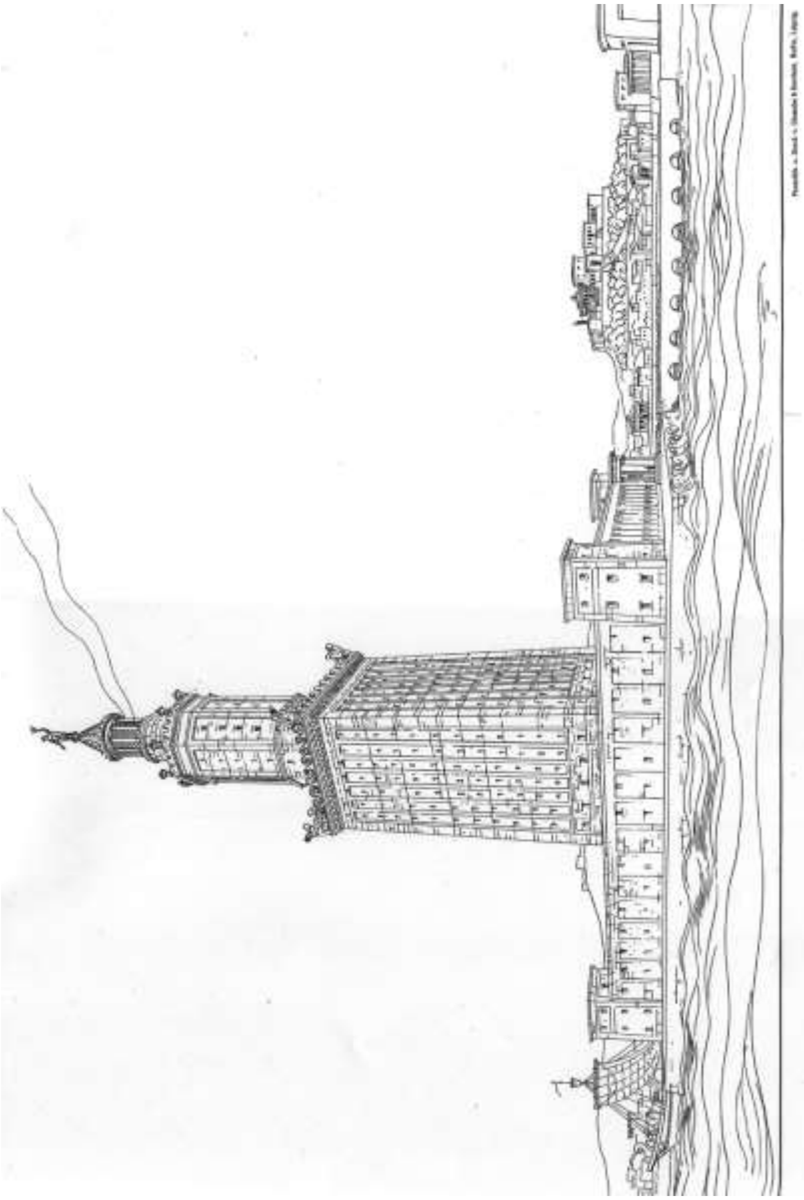
The abovementioned measures are assessed by later Arabic sources. However, while we have many descriptions of the building and its interior, there are no sources referring to the mechanism on the top that emitted light. By a matter of fact the descritpion of the interior results more difficult and the understanding of where and how the mechanism was located and functioned remains still quite confused. Thiersch himself attempted to give a graphic reconstruction of the lighting system with reflecting mirrors, based on the Arabic accounts, but his interpretation is less persuasive than his understanding of the exterior architecture[48].

What we know from the interior is that the centre of the tower was hollow, having a well-like void, which went all through the height[49]. Many rooms were located along the itinerary from the main gate to the top of the cuboid volume. They were accessible by means of a ramp, wide enough as to have two horsemen crossing along the ramp. This well must have been relevant to the lifting of any material necessary to the tower, including both the fuelling of the light source, the possible feeding of the

[48] Thiersch 1909: 89-96.

[49] An explanation of this cavity is given in Vitti (2018), this volume.

pneumatic alarm with water and wood and, of course, all the military material used for the defence of the harbour and the city.



ANSICHT DES PHAROS VOM MEERE AUS

Figure 1. The Pharos of Alexandria as depicted in Thiersch.

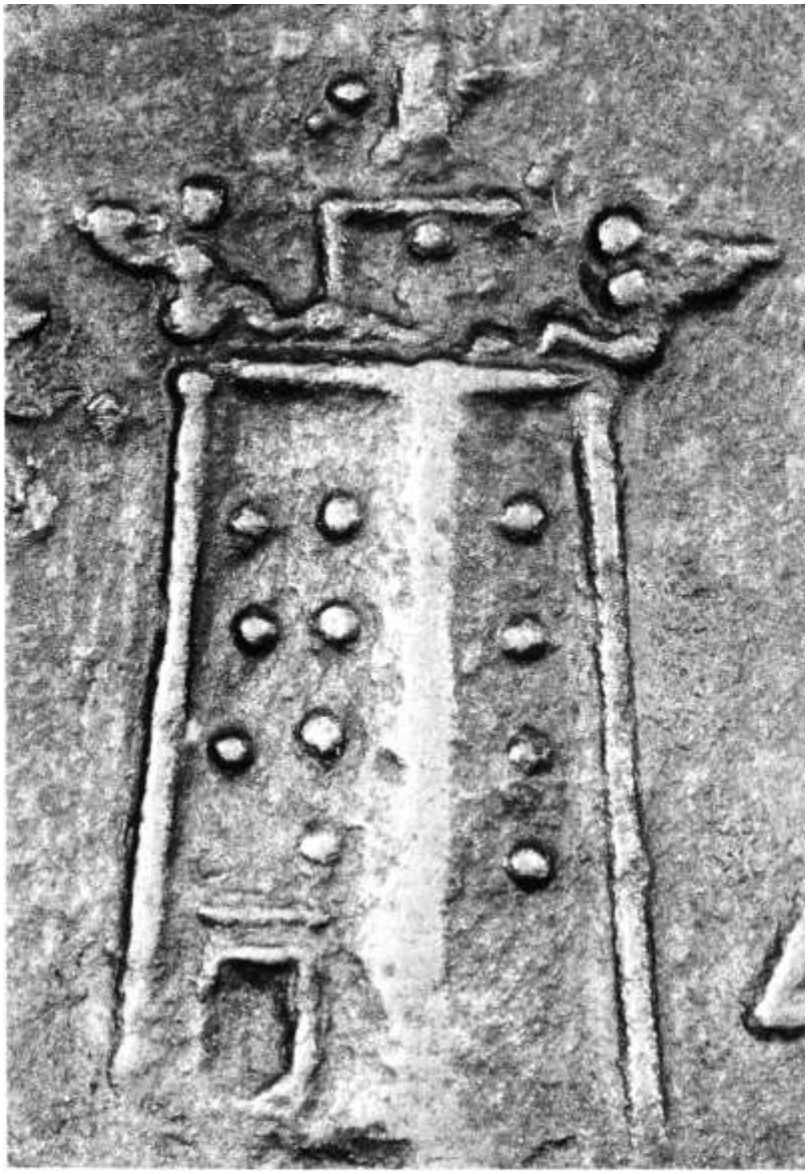


Figure 2. Coin of Antoninus Pius depicting the lighthouse of Alexandria.

Descriptions by travellers

The descriptions of historians and travellers are important because they give the ability to observe the lifetime of the monument, the damage that it suffered, mainly because of earthquakes, and generally many elements about the Lighthouse. In parallel, when comparing the descriptions to archaeological findings (coins, mosaics etc.), they provide appropriate elements for the restoration of its form. From 300 B.C. until 30 B.C., Alexandria was a Greek city. From 30 B.C. until 390 B.C. it belonged to Rome, from 390 A.D. until 640 A.D. to Byzantium and from 640 it was conquered by the Arabs when the Lighthouse was already 670 years old.

Throughout the years, the height of the building, the lack of maintenance and the climatic and geological conditions ruined it. Rain and earthquakes damaged at first the third section, as it appears on a currency made in Alexandria owned by Domitian in the 90 A.D. It seems that the island called Pharos, upon which the Lighthouse was built, was precipitated and this is the reason that the Lighthouse collapsed. Procopius of Gaza states that the emperor Anastasios, in 500 A.D., asked from the architect Ammonio to repair the Lighthouse and the seabed of the harbour that has been corroded. In 870 the Arab Yakoubi of Bagdad a civil servant in Egypt refers to the good appearance of the Pharos, but four years after that an earthquake took place and destroyed the third section. In 874 the Sultan Ahmet

Ebn Tulun tried to repair the Lighthouse, mainly the dome that was destroyed. In the middle of 10th century Arab historian and geographer Ali al-Masud "...tells the story of the decay of the Lighthouse and Alexandria from the earthquakes and corrosions. He lists the damages, the fear of the population and the consequences on the city".

Al Muqaddisi, in the year 1000 AD, in his "Guide for Alexandria" writes:

> "Al-Iskandariyya (Alexandria) is a delightful city on the shores of Bahr El Rumi [Greek Sea]. It is headed by an impregnable fortress, it is a prominent city with a remarkable group of respectable citizens. The residents' drinking water comes from the Nile, which reaches them during the period of floods via an aqueduct which fills their tanks... The city was founded by Dhu al-Qarnayn [Alexander the Great] and indeed has an admirable citadel... The Pharos of Alexandria has firm foundations on a peninsula and one may approach it from a narrow street. Its bases have been placed firmly in a rock and water rises to the lighthouse from the west side. The same applies with the fortress of the city with the exception that the lighthouse is in the peninsula where there are 300 buildings, some of which only a mounted knight can go to. A visitor is accepted provided he is using the right watchword. The lighthouse is at a higher level than all the cities along the coast and it is said that a mirror was used there, with which they could see every ship which left the

coast or that approached throughout the sea/ from every point of the sea. A guard observed day and night and as soon as he saw a ship, he informed the governor, who would send birds to inform other guards on shore so that they would be on standby."

For the 12th century we have descriptions from two famous Arab travellers, one of which is the famous Moor Al Idrisi, a Mauritian from Spain, who in 1115 toured in the Mediterranean and Egypt and was impressed by the Pharos, for which he wrote the following:

"For the famous lighted tower, there is no-one like it in this world concerning the harmony of its construction and its stability. It is built by a wonderful stone called al-kadhdhan and we highlight the fact that the stones were united with molten led and they were so solid, that in its whole it was unbreakable, despite the fact that the sea from the north side wildly "attacked" the building. The distance between the Lighthouse and the city is 1 mile through the sea and 3 miles through the land.

The visitor could go at the top from a spacious staircase built in the interior, so spacious like those that exist in the traditional minarets. The first section ended about halfway to the top and from this point the four sides of the building becomes narrower. In the interior and under the staircase there were rooms. In all the sections of the Lighthouse there were windows providing the necessary

> lighting. This building is extremely important for its height and its resilience. It is very useful because it shines day and night like a lighthouse for the sailors that travel throughout the year. The sailors know the light (of the Lighthouse) and adjust their route respectively, since it is visible in a distance of a day (100 miles = 182 km). At night it looks like a shining star, while in the day someone can recognize its smoke".

Even more detailed is the description of the Arab traveller Abu Hagag Yusef Ibn Mohamed el-Balavi el-Andalusi[50], who visited the Lighthouse in 1166 and reports the following:

> "The Lighthouse rises in the edge of the island. The building is square, with its side approximately 85 m. The sea surrounds the Lighthouse except from the east and south side. The length of its base is 65 m. and the platform rises above the sea surface at an equal height. However, the platform is wider to the sea due to its construction and has a steep slope like a mountainside. As the height of the platform increases, the width narrows.
>
> In this side it is firmly built, the stones are well-formed and well-placed and elongated with a finish rougher than anywhere else in the building. This section that I have just

[50] Asin Palacios, M 1932. El Abecedario de Yúsuf Benaxeij el Malagueño. *Boletìn de la Academia de la Historia*, tomo C, cuaderno I, enero-marzo: 195-228

described is recent because from this side the ancient construction was replaced.

On the wall to the sea, i.e. in the south side, there is an inscription that writes something that I cannot read. It is not a normal inscription, because the shapes of the letters are made by black stone. The combination of the sea and the air has corroded the stone behind the letters, and the letters protrude. “A” has length a little more than 54 cm. The top of “M” protrudes like a big hole in a boiler made of copper. The other letters are generally in the same size.

The door of the Lighthouse is high. A slope level with a length of approximately 183 m. leads up there. This uphill path is supported upon a series of curved arches; my partner went under one of the arches and raised his hand to touch one of them but he could not reach them. There are 16 arches like these, each one of them reaching a higher height, until they reach the entrance, with the last one being very tall (this may be the scale that we see in the coins)”.

They explored the ruins on the island:

“We entered approximately 73m. after the entrance. We found a closed door in our left that we did not know where it leads. After 110 m. we found an open door. We entered through that door and we found ourselves in a room, which was followed by another room and then another room; in total 18 rooms along a corridor that are connected with each other. Then we realized that the Lighthouse was uninhabited. Moving forward for another 110 m. we counted 14 more rooms, left and right. After 44 m., we found 17 more rooms. Finally, after walking 100 m. we reached the first floor (of the Lighthouse). There was an uphill level that gradually climbed around the cylindrical core of this huge building. On our right, there was a wall that was not very thick and on our left, the side of the building that we have already explored. We entered a corridor with a length of 1.6 m., the roof of which was built with stones that were carefully smoothed; two of my partners could not enter.

When we reached to the top of the first floor, we counted the height from the ground with a piece of rope, in the edge of which we hung a stone; it was 57.73 m.; the parapet was 1.83 m. tall.

In the middle of the platform of the first floor, the building continued upward with an octagonal shape, with a width of its side of 18.30 m. and 3.45 m. from the parapet. The wall was 1.5 to 2 m. thick; the number I wrote in my initial notes is not very clear, but next to the point that I have written down the length of the rope, I wrote details with ink that are clear. This is very weird…but I am sure it was 2 m.

This floor is higher compared to its base. Entering that floor we reached the middle of the upper floor. We measured again with the rope and we found that it was 27.45 m. from the first level.

In the middle of this platform above the second level, the building continued upwards in a cylindrical form with a perimeter of 75.20 m. We entered again and we climbed 31 stairs to reach the third level. The height of the third level was measured by the rope and was 7.32 m. In the platform of the third level there is a window with four doors and a dome. Its height is 5.49 m. and 36.60 m. perimeter. The parapet has a height of 46 cm and only 1.51 m. separates it from the wall of the window.

Briefly, the building that we explored had 67 rooms, except from the first that we found its door closed, which we heard that it led to the sea underground. The height of the Lighthouse, according to these dimensions is 96.99 m. and from its base to the sea is 9.15 m.; the visible part under the surface of the sea is approximately 1.83 m."

In approximately 1200 AD Ibn Jubayr, in his famous "The Trip" states:

"First of all is the beauty of the place of the city with its broad buildings, to an extent which we have not seen in any country or city with larger roads, higher buildings, nor older and richer. Its cosmopolitanism is incredible and its markets are perfectly full, and in abundance and festive. The noteworthiness is its placement, how it is built either below or above the earth, its buildings are so old and so resilient. A remarkable thing with the construction of the city is that the buildings that are located beneath the surface of the earth are like those that are above the ground and are even better and more solid, because the waters of the Nile enter underground beneath the houses. We saw marble columns and slabs in height, size and of insurmountable brightness. In some major roads the colonnades ascend high and cast shadows on the sky. The reasons for these building colonnades' erection are not known and no one can provide an explanation in relation to them. Perhaps in ancient times these columns supported buildings that were reserved for philosophers and the elite class of the time. Perhaps these buildings served for astronomical observations as well. One of the greatest miracles that can be seen in the city is the Pharos, built by the great and glorious God with the hands of those who foretell and determine the fate of others, as mentioned also in the Koran [x.v.75, Koran], which served as a guide for travellers. This is because without the Pharos, which appeared from a distance of 70 miles from the sea, nobody could find the city of Alexandria".

In the 14th century, Al Makrizi in his three volumes entitled "Al-Khitat" (the Plans of the Cities) also describes the knowledge which was available in his time and refers to the oldest exceptional destruction of Alexandria in the 3rd century

AD from an earthquake and tsunami. Finally, Al-Asyuti also wrote a travel geographical treatise, especially referring to the earthquakes that hit the Middle East.

An intense earthquake in 1303 followed by a tidal wave totally destroyed the Pharos (Shaw et al, 2008). -The Lighthouse is flattened in 1349, as referred by Ibn Battuta: "After visiting the Lighthouse, in 750 (Egira's date), I have noticed that the disruption state of the Lighthouse is the point that no-one can either enter or reach the entrance". That was the end; since then this situation continued for more than 150 years, up until the 15th century where sultan Kait Bey used the building material of the Lighthouse to build a fortress and a small lighthouse that exist until today.

From everything stated here, we have to admit that before the Lighthouse of Alexandria there are many holy fires the names of which are not rescued.

Indeed, after the large earthquake in the 3rd century AD, which Al-Makrizi describes, and especially after the huge tsunami which struck Alexandria, it seems that the submersion / landslide of a large area of ancient Alexandria was accelerated. In a recent scientific work, Shaw and his colleagues calculated that the height of the tsunami created by the earthquake described by Al-Makrizi exceeded 20 meters in height.

Such a phenomenon seems to have been reiterated in the 12th century, which Jalal Al Asyuti in his memorable work on the history of Egypt and Cairo mentions that the year 702 of

Hegira, the largest earthquake took place and the destruction was greatest in Alexandria compared to all previous earthquakes and the previous disasters of the city. As Al-Asyuti mentions, “the sea rose up reaching the middle of the town, it drowned livestock and people, while ships were moved to land and countless houses, countless people disappeared beneath the ruins”. It is characteristic here to refer to Al Makrizi’s work “Al-Khitat” (The Plans of the Cities), in which he states that a large earthquake at the time of Constantine, son of Constantine, the sea stood up and struck several points and locations and many churches in the city of Alexandria and 17 towers of the wall of Alexandria collapsed. And Al Makrizi continues: “The sea has since continued ceaselessly swallowing little by little whole sections of the city”. Al Makrizi also refers to the description of an earlier historic visitor of Egypt who provides an interesting picture of the old city who states that “the sea beat the city which ended up in the sea... “Can you not see”, said the visitor, “the buildings and their foundations submerged in the sea today with the naked eye?!!!”

Al Makrizi also mentions the Mamluk Sultan Baibars (1260-1277 AD) who was the first of the Mamluk Sultans to be interested in Alexandria. He visited it four times. Every time he left monuments that historians recorded and reported. His first visit took place in 1262 AD. In his second visit, early in 1265 AD/664 Hegira, he ordered the removal and cleaning of the sandy settlement that had almost covered whole segments of the channel of Alexandria. In his fourth visit (1274 AD), the sultan restored and repaired the lighthouse. Al-Souyouti also mentions that the facade of the [lighthouse] from the side of the sea had collapsed and the beach/dock (Al-Rasif) of the region that was among the "hands/arms" of the lighthouse, was ready to fall.

Sultan Baibars continued to care for the fort of Alexandria. In his second term of governing in 702 Hegira, there was a powerful earthquake that struck a large number of the monuments of the city. The most important of all the monuments was the lighthouse of Alexandria, its walls and fortifications. Al Makrizi mentions that from its walls 46 "Banda" and 17 towers were destroyed. It was then that the Sultan wrote to the governor to rebuild it and he did. He also ordered the repair of sections that had collapsed from the lighthouse (with about 40 balconies) in 703 Hegira. It appears though that the damage was serious and that the repairs did not help and they collapsed again. This is evidenced by the reference Ibn Battuta makes of his trip there in 1325 AD. Indeed, Ibn Battuta mentions that he saw one of the sides of the lighthouse to be fallen. 25 years later when he visited the city again in 1350, he saw that the remains dominated to such an extent that one could not enter nor even climb from its gate. In summary, historical sources indicate that at least two natural events in the 3rd and the 12th century AD were the cause of speeding up the submersion of the ground in many areas of ancient Alexandria.

Accounts on the optical systems of the Lighthouse of Alexandria

In the previous paragraph we have briefly presented historical and architectural characteristics as described by Greek, western and Arab travellers and other scholars. In this paragraph we present what could be found on the "mechanism of the Lighthouse", historically, through legends, and present knowledge.

The research includes ancient philological or historical sources from the construction of the Lighthouse (297 B.C.) until its destruction (1354 A.D.) based on Greek (Hellenistic period), Roman, Byzantine and Arabic. Our search focuses specifically on the Arabic sources and on the descriptions of the travellers and others that speak about the Lighthouse, most of which come from the West. Finally, a discussion concludes as a fourth aspect by considering modern sources about the issue, mostly from the 19th and 20th centuries.

The existing ancient sources for the Lighthouse are incomplete and unfortunately the number of sources on the mechanism is minimal. None of the ancient sources, historical or philological texts, etc. makes any description or reference that may suggest a direct knowledge or contact with the mechanism. It is evident that almost everyone or at least everyone that has referred to the Lighthouse reproduced other people's opinions or descriptions. Even ancient Chinese scholars provide descriptions of the Pharos by accounts of travellers, without ever leaving China (Vorderstrasse, 2012). This has been concluded by Clayton-Price who concluded that “regardless of the visibility distance, everyone agreed that the light (from Pharos) was coming from a huge fire in the base that its flames are reflected with mirrors from the top of the building”.

Strabo (1st century B.C.) and Plinius (1st century A.D.) are describing the “tower” and its architecture with extraordinary marbles, as having a mechanism with a “mysterious mirror” that sent the light in a great distance, and according to the legend, the mirror was detecting enemy ships. Iosipos is more inhibited claiming that the ray reached 300 stadiums (34.5 miles or 48 km). Lucian and Plinius refer to a distance of 300 miles. Statius says that at night the Lighthouse looked like the moon.

It is important to highlight that the visible distance was dependent on the height of the building, so the statement by Iosipos concerning the distance of 300 stadiums (48 km) is the most reliable since it refers to the distance from the horizon. “We should also think that, as with modern lighthouses, the visibility limit is defined by the height of the building. In order for the light to be seen in such a great distance, a reflector is necessary and it is proved from Arab historians that a reflector existed”.

We will now turn our attention to Arabic sources. A large part of scientific works of Ancient Greeks that survived were translated into Arabic in the last two centuries of the first millennium and lasted until 1200. During these 500 years, large parts of knowledge were transferred in the Arabic culture. This process was very important as many disquisitions by Greek scientists were lost in their original form.

Al Idrisi, who visited Alexandria in 1154, wrote "The building is really remarkable both for its height and its resistance. The fact that it shines during the day and the night like a lighthouse is very useful for the sailors travelling all the year. The sailors know the light (of the Lighthouse) and adjust their route respectively, since it is visible in a distance of a day sail (100 miles = 182 km). At night it looks like a shining star, while in the day someone can recognize its smoke".

The descriptions by al Maasudi, an Arab historian and geographer and Al Bagdadi, Abudelfa and Kwarizmi, who have translated many works by Greek engineers and scientists, are incomplete as well. All of them describe very little on the mechanism.

At a lecture at the Museum Tareq Rajab by Professor Roshdi Rashed talked about an unknown Greek manuscript, translated in Arabic in 902 A.D. This rare manuscript is a translation of a Greek manuscript concerning a code and explores incendiary mirrors. The lecture by Professor Roshdi was titled "Incendiary Mirrors" and was given in the context of cultural events organized by the Institute of Dar al Athar al Islamiyyah. Roshdi said among other things that he recently discovered the manuscript and that it is an example of Greek and Arab geometry, which were developed, the latter as a successor of the former, introducing the definitions of reflection and dioptric. “There is a copy of the manuscript in Kuwait, which was copied later during 14^{th} century in Cairo, and was somehow moved to India” says Roshdi.

This issue is very interesting since it covers a large gap in the existing knowledge. Roshdi said that he discovered the manuscript while exploring “to find the ancient applications of geometry (for the mirrors) and their meaning in the ancient centuries, as the incendiary mirrors were in the spotlight during 3^{rd} and 2^{nd} century B.C. The manuscript (he said) is a Greek disquisition for the incendiary mirrors and belonged to a library that was established by kings and caliphs during the 9^{th} century. The subject of the manuscript was a proposal about the way light could be collected and transmitted”. Roshdi revealed that the Arabic manuscript is a translation of Greek manuscripts following the principles formulated by Archimedes and that were written between 125 and 180 A.D. and were lost afterwards. Roshdi claims that “Archimedes consolidated two studies on Optics, exploring arson, creating a whole new field of Mathematics, connecting hyperbola and parabola with Optics. With the combination of these two fields of mathematics, a new theory rose stating that from a determined distance we can direct the reflected sun rays”.

All of the abovementioned reveal that the research on incendiary mirrors did not stop from its first discovery by

Archimedes and continued from Arab scientists like Al Kindi. During the 8th and 10th century, the Arabs studied the abovementioned theory concerning directed sun rays. Al Kindi (died in 873), lover of antiquity and admirer of Greek science, translated a lot of Greek works and wrote a work on Optics and its Latin translation "…influenced Islam and the West on Optics during the Middle Ages…". Ibn Sahl used some of the translated (in Arabic) Greek texts. However, he claims that while the Greeks studied the combustion with mirrors, he was the first to study combustion with refraction. The fact that he studied ancient Greeks is evident as he referred to the parabolic mirrors by Greeks".

An ancient Arab scholar, the geographer Al Muqaddisi (also el-Mukaddasi or al-Maqdisī, 945/946 - 991)), in his book "Guide for Alexandria" [p. 104] states that a mirror was used as a telescope at the top of the Pharos with which they could see every ship passing by at a distance. Here we have a similar detailed description of telescope made of a mirror of glass from another book *The Itinerary of Benjamin of Tudela*[51], a Jewish geographer (born at Tudela, Kingdom of Navarre, 1130 – Castile, 1173) *On the top of the tower there is a glass mirror. Any ships that attempted to attack or molest the city, coming from Greece or from the Western lands, could be seen by*

[51] The Itinerary of Benjamin of Tudela, by Benjamin of Tudela, The Project Gutenberg EBook, Critical text, translation and commentary, By Marcus Nathan Adler, first published by Philipp Feldheim, Inc. The House of the Jewish book, New York, First edition: Henry Frowde, Oxford University Press, London, 1907

means of this mirror of glass at a distance of twenty days' journey, and the inhabitants could thereupon put themselves on their guard. Benjamin continues describing how a Greek captain destroyed the telescope so that they could not see the Greek and other boats travelling in the Mediterranean and thereafter the Greeks could recapture Crete and Cyprus.

Another source is Al-Hassan al-Haytham (Abū ʿAlī al-Ḥasan ibn al-Ḥasan ibn al-Haytham)[52], called Ptolemaeus Secundus (965 - 1040). He studied optics at Cairo. His studies include the eye, the lenses as well as mirror focusing of convex, concave and especially cylindrical mirrors. It is very probable that the Pharos had a "cylindrical" mirror used as a telescope. This type of cylindrical mirror could have been a paraboloidal mirror probably combined with a hyperboloidal mirror, inspired by the works of Archimedes. Al-Hassan al-Haytham wrote four books, but only one survived. One book summarized Optics based on the two books of Euclid and Ptolemy. Other works included a *Treatise on Burning Mirrors* and one on the *Nature of Sight and How Vision is Achieved*[53]. Three more treatises entitled *Treatise on Spherical Burning Mirrors, Treatise on*

[52] Rashed, Roshdi (2007), The Celestial Kinematics of Ibn al-Haytham, Arabic Sciences and Philosophy, Cambridge University Press, R. Rashed (1968), Le Discours de la lumière d'Ibn al-Haytham (Alhazen), Traduction française critique, Revue d'histoire des sciences et de leurs applications. *21*, 3.

[53] Alhacen's theory of visual perception: a critical edition, with English translation and commentary, of the first three books of Alhacen's *De aspectibus*, the medieval Latin version of Ibn al-Haytham's Kitab al-Manazir, edited by A. Mark Smith (2001), Transactions of the American Philosophical Society; *91*, 4 and 5, 14.

Parabolic Burning Mirrors and Treatise on the Burning Sphere are known. These medieval scientific books on optics are very important and they show that based on Alexandrian philosophers works of Euclid, Diocles, Apollonius, Archimedes, Heron, Ptolemy and other, medieval, mainly Islamic Arabic, scientific texts continue developing optics and that there is continuation in science. In some of these books optical systems of the Pharos are mentioned and this proves that there were advanced optical systems at the Pharos, for observing the ships at sea and to direct the light towards the Mediterranean.

Roger Bacon, in the 13^{th} century, referred to a mirror used to look in the British coasts (Albert Van Helden *et al.*, 2010). If this is true, we could argue that Bacon's reference for such important information may well refer to an ancient source. Not to forget that the 13^{th} century was the last century the Lighthouse existed, before its complete destruction in 1349. Hence, long before the destruction of the Lighthouse there were rumours for the mirrors and the magnifying glasses that it had. The identification of the mirrors of the Pharos with those defined by Archimedes is impressive. However, a question arises: how is it possible the mirrors of the Pharos to have been constructed by Archimedes since its construction was completed in 280 B.C. the year that Archimedes was born? There is another theory that the mirrors were placed later by Archimedes during his 20 year stay in Egypt. Unfortunately, no ancient source confirms this theory and the relevant references are not reliable.

The polymath Giambattista Della Porta[54] (1535 – 1615) in the book *Natural Magic* (1589) describes the telescope of the Pharos as reported by Reeves[55] in her book *Galileo's Glassworks: the Telescope and the Mirror* presents the possible use of a telescope at the top of the Pharos, perhaps made with the combination of a mirror and a lens. In an English version of Della Porta *Natural Magic* a chapter is dedicated on how to use lights at a very large distance using a parabolic mirror obliquely (7th book, chapter XVI, On strange glasses). From its English version of 1658 we read the following:

"I will speak about marvellous and at the same useful things that happened in the ancient times but we still believe in them. I am referring to the lens of Ptolemy or maybe the telescope, which someone could see in a distance of approximately 600 miles (!) if the ship reaching was friendly or hostile and also read the smallest letters from a great distance..." In this text, it is claimed by Temple that "Porta described the construction of a telescope many years before Galileo, without giving any details". Guidonis Pancirolli and his publisher Heinrich Salmuth will later refer (1599) to the subject, in their work

[54] Giambattista della Porta, Magiae naturalis libri XX in quibus scientiarum naturalium, divitiae et deliciae demonstrantur, Napoli: Horatium Salvianum, 1589; 1658 English version, Natural Magick by John Baptista Porta a neapolitane in twenty books, London; Della Porta, G. (1957) *Natural Magic*, Basic Books. See also Della Porta, G. (1999). De refractione optices parte: libri novem... Ex officina Horatii Salviani, apud Jo. Jacobum Carlinum, & Antonium Pacem.

[55] Reeves, E. A. (2009) *Galileo's Glassworks: the Telescope and the Mirror*, Harvard University Press.

published 10 years after the work by Battista. In that work, the words by Giambattista are being reproduced but without any historical proof. The Latin title was referred to the history of many memorable things that were lost in time and were used by the ancients.

Temple highlights that the only thing that we know concerning the telescope is that it existed from ancient years. the proof of that is a letter by Tito Livio Burattini, written in 1672 to the French astronomer Ismael Boulliau were Burattini wrote that "…in Raguse (coasts of today's Croatia) on a tower there is an instrument that helped the citizens of the city to see the ships in a distance of 25-30 miles and the guard of the instrument attributed the construction to Archimedes…". G. Libri included Burattini's letter in his work published initially in Paris in 1835. He claims that this fact has been checked by moguls and the whole issue proves, in his opinion, the existence of ancient instruments. There is no historic proof except Libri's belief for the existence. Burattini says "Concerning me, I still believe that this instrument is used in the same way as in the Lighthouse of Alexandria during Ptolemy kingdom, used to see ships from a distance of 50 or 60 miles away." Temple claims that Burattini implies more things. "On the other hand, Burattini refers to the possibility of the existence of telescope in Cavtat, southern from Dubrovnik in Croatia, where a part of the Lighthouse of Alexandria might be saved there, when after an earthquake this part fell into the sea, broke into pieces and some of these pieces were retrieved by divers…"

It is interesting to observe the historical retrospective that Bonaventure Abat makes in 1763, concluding that the object or instrument of the Lighthouse was a mirror and not a lens. He says the following:

> we read in many authors that Ptolemy placed in the tower of the Lighthouse of Alexandria a mirror through which you could clearly see anything that happened in Egypt, in the sea as well as in the land. Some authors say that through the mirror hostile ships could be seen in a distance of 600 miles. Others say that the distance was about 100 leagues (400 km). But everything that has been said about this issue looks like a useless fairytale and somewhat non-realistic. There are many famous scientists that believe that if this is true it should be the result of a miracle or a miracle by the Devil himself. Among others, Athanasius Kircher, referred to events with excess prejudice including this issue in the same category...Experience taught me that a great number of objects which from many philologists have been claimed as fad, examined by non-philologists are considered as possible or even existent. I suspect that Ptolemy's mirror belongs to this category as well...'

Bonaventure refers to Paul Arese, archbishop of Tortonne, who in his work called Museo Settaliano says "... Ptolemy could see ships in a distance of 600 miles approaching the port of

Alexandria. But this was not because of his good vision but because of the usage a crystal or glass. “However” he says, “the existence of the crystal is doubtful because of Earth’s curve that makes it impossible”. He highlights that if a crystal like that existed it would be an achievement of the time and it would be logical that references about that would exist. Additionally, he says that the existence of a crystal that the man could see many things would be a miracle by itself. Bonaventure concludes that all relevant sources include doubtful clues and highlights that “the knowledge of the ancients concerning the mirrors and lens is older than we think today”.

Astronomer Francois Arago claimed that the lens or the crystal that are mentioned by previous authors is a common reflective mirror. It should be highlighted the fact that this is the first time that a scientist in a relevant field (astronomer) is referring to an instrument and not just fire.

It is surprising the fact that while there is a plethora of relevant literature concerning Alexandria and the Lighthouse, there are no credible references concerning its mechanism. The recordings claiming there was a fire at the top of the Lighthouse visible from great distance are simplistic for one reason. From where did they supply raw materials for this huge fire that was burning 24 hours nonstop (during the day they were seeing the smoke and during the night the fire) in a country like Egypt that there was no timber? The references claiming that they were burning reed or animal stools are not realistic. Reeds do not have the capacity to maintain a huge fire since they burn easily and produce a lot of smoke. Concerning animal stools, on the one hand there should be huge amounts and on the other hand it would pollute all Alexandria.

Clayton and Price observe: “There is another interesting issue concerning the logistics of the undertaking that is not calculated before. To maintain a fire always lit, someone would need a huge amount of fuel, wood or coal and Egypt is not a country that had timber. A potential solution might be dried animal stools (that is used until today in houses) but in this case the quantity needed would be a problem”. As a result, timber should be imported from other regions with a huge economic transportation cost. Even if we accept this point of view, there is a bigger problem concerning the conditions in the interior environment. A fire as huge as that entails huge risks for the people that were feeding the fire with wood etc. as they would not be able to get closer to it and the building itself would burn as well. The section where the fire supposedly was, was a small room, and had a height of 9 m. and 7 m. diameter. How is it possible in a small room like that to burn a big fire (that was visible in a distance of 30 miles, approximately 50 km.) without destroying the whole building?

The mechanisms in the Lighthouse were complex, especially the one that made the statue at the top to turn following the rotation of the sun even when the sun had set. This means that there was a rotation mechanism synchronized with a clock, otherwise the sun movement could not be calculated. Where was this mechanism? Maybe in the base of the statue which was at the same time the ceiling of the third floor that supposedly burnt the huge fire. How can we prove the coexistence of such a delicate complex mechanism and the huge fire? It could be that at the top of the Lighthouse there was a mechanism consisting of lens and mirrors that reflected the small (in terms of its dimensions) fire, which was burning in the third section or below that. This view tends to become accepted in the last few years and is harmonized with everything in detail that we know about the Lighthouse. For instance, many people refer to a large fire without describing it which means that almost no-one has reached the top of the Lighthouse to describe the fire, how it was fed and maintained. Was that because it was forbidden to enter that room in order not to reveal the secret? This is possible as in that section there were precious mirrors, made by crystals, and all the automatic mechanisms that made the statues move. Most probably, there was a team of people there that maintained the fire and the automatic mechanisms. Unfortunately, there are no proofs about that, only speculations. Furthermore, since all sources provide descriptions of others, it is only natural for them to describe something that they are accustomed to. How can there be light without a fire? How can you construct such a fire without a burning pyre?

Concerning the third floor E.M. Foster writes: “The third floor was cyclic. Above that was the fire. The light is an enigma as it seems that its limited space was shared by the fire on the one hand and some very sensitive instruments on the other. How large was this fire that every account states is not known. Early lighthouses were nothing more than pillars that used burning pyres from wood or coal in an open fire (Davenport Adams, 1870), which is not the case for the Pharos, since the light source was inside the building and smoke would definitely make the upper building part uninhabitable and also impair the light emitted. Moreover, the transport of fuel material would be a tedious and extremely expensive task, since wood is rare in Egypt.

Accounts from Science magazine (Science, 1885, 1886 and 1893) on lighthouse illuminance in the 19^{th} century provide information that, apart from gas lamps, widely used at that time, oil lamps were traditionally used in lighthouses. Oil lamps, along with candles, were also the main means of illumination in antiquity and produce significantly lower smoke than open pyres. Illumination measurements of ancient oil lamps by Moullou et. al. (Moullou et. al., 2012 and 2015) concluded that large clay lamps used in ancient homes could provide up to 30-40 lumens luminance with olive oil as fuel and a cotton wick. Although the illumination power seems low for a lighthouse, the type and structure of the wick, as well as the size of the lamp play an important role in the final light output. Furthermore, in 1790 A.D. the Cordouan lighthouse in Gironde, France, used parabolic Argand oil lamps along with a rotating Fresnel lens to project light to a distance of 11km.

Anderson (Science, 1893) on his account on lighthouse illuminants stated that a Mr. J. R. Wingham used a long focus lens to amplify the 8500 candle power gas burner light source (calculated to 300 lumens) 270 times, so that the light beam was apparent at a distance of 11km. Other accounts state a 70-times amplification using a lens. However, to reach the 50 km one needs a much stronger light source or a very concentrated light beam. Contemporary lighthouses use 250W halogen lamps that have a luminance of 4000 lumens in conjunction with Fresnel lenses. That is more than 13 times the luminance than the gas burners used in the 19th century and 100 times more than an ancient oil lamp. Even if we assume that a cylindrical wick was invented, such as the Argand oil lamp in 1780 A.D. which provided roughly 6-8 times more illumination than traditional oil lamps, it seems impossible to suggest that the artificial light source would reach the aforementioned distance of 50 km by any means. However, even with the means provided at that time, artificial light could travel at distances much longer than what the ancient travellers were used to, adding to the marvel of the Pharos. Taking into account that Heinle and Leonhardt (Heinle and Leonhardt, 1989) point out that ships in antiquity rarely travelled at night, the light of the Pharos could have acted mostly as daytime signage, using the sun's rays to direct light at a long distance.

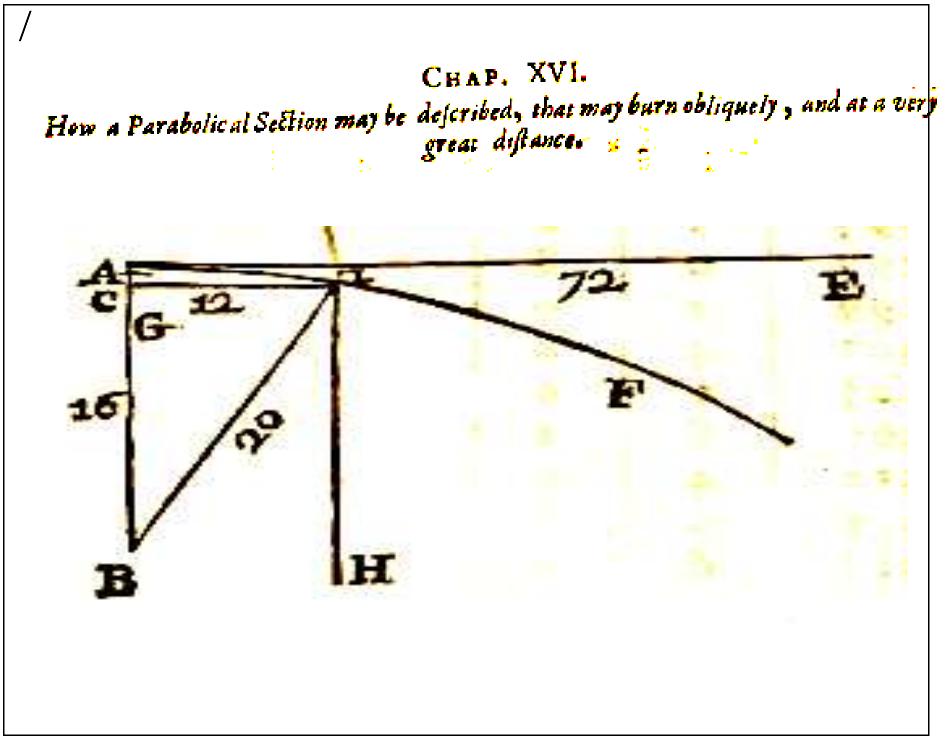
The visitors speak, for instance, for a weird "mirror" up there that caused a greater admiration, even more than the Lighthouse itself. Why this mirror could not crack and what was it? Was it a reflector to maintain the fire during the night? Some authors claim that it was made out of glass or transparent stone and reveal that anyone who sat underneath that could see ships with bare eyes. Was it a telescope? Is it possible that Alexandrian school of mathematics and engineering has invented the telescope and the knowledge was lost with the destruction of the Lighthouse? The only thing that is certain is that the Lighthouse was equipped with all scientific innovations of that time and was a place to apply the theories developed in the Museum, on the other side of the gulf".

Foster focused on the reflection of the light. But from where did he acquire all this information? Since he did not provide any references it is hard to know. Agreeing with Foster, Clayton and Price say: "the conclusion is that the intensity of the fire was coming more from the reflection of light than from the fire itself. During the day the reflection was stronger using the rays of the sun". The sun of course is not staying in the same spot, but it is moving cyclically on the horizon. So, the reflector followed the orbit of the sun and it was automatically rotating!

All of the above conclude that possibly there was not a huge fire on the top of the Lighthouse but an instrument, a reflector that was very sophisticated in contrast with the other instruments. As L. Russo claims: "the only descriptions that survived are from Arab historians that visited the Lighthouse when it was not working, so we don't know a lot about its technology". We don't know for instance its lighting system. However, we can imagine that the reflector was constructed based on a parabolic mirror, since the theory of parabolic mirrors was at the same time as the construction of the Lighthouse. While we cannot prove the existence of scientists in the design of the Lighthouse, it is not a coincidence the fact that the first reflector in the history was invented in Alexandria in the first half of the 3rd century, at the place and time that scientists were initially intrigued by the "scientific theory" behind the construction of such mechanisms". And he continues: "because the ray of the light that has a steady direction is not useful for the orientation of ships, we can assume that the reflector of the Lighthouse was rotating. This could explain the cylindrical shape of the top that is observed in all the lighthouses that we know today".

So instead of a huge fire we can conclude that at the top of the Lighthouse there was an instrument, a reflector that was rotating equipped with some kind of crystals. Of course, if we accept the rotating reflector, there are more issues to be solved, for instance how it was moving. There is no way that workers were rotating it as the room had a diameter of 7-7.5 m. and this room included the fire, the reflection mechanism and a small staircase.

Concerning the kind of the reflector, we do not have clear information, and consequently we make speculations. The reflector could be a big concave mirror, spherical, conical or paraboloid and well-polished and maybe silvered in order to be more reflective. There is a speculation that the mechanism was using many small lenses or an array of Fresnel lens. It is bold to state that Fresnel lenses were discovered back then, but the hypothesis that there were many small lenses should not be rejected".



CHAP. XVI.

How a Parabolical Section may be described, that may burn obliquely, and at a very great distance.

Figure 3: Theoretical study of how a parabolic section can be described, that may burn obliquely and at very great distance

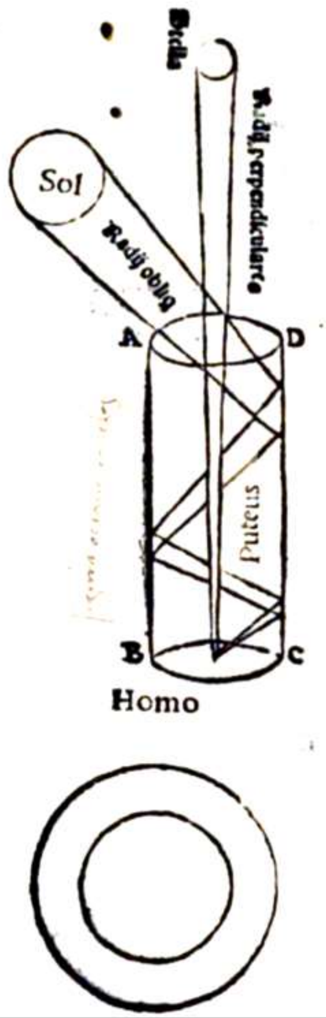


Figure 4: Theoretical study of a “cylindrical” mirror, or a hyperbolic mirror.

These can be used as a kind of telescopes. The principle of fiber optics is implied by this study (after Potamianos, 2000 and this study).

The “telescope” at the top of the Pharos could have been constructed by a mirror, a parabolic mirror, a hyperbolic cylindrical mirror, as there are scientific texts studying this type of optical instruments. Another optical system has been in use probably to direct the light at the appropriate directions. A simple and effective system based on the theoretical knowledge of conical mirrors, parabolic and hyperbolic and experience they could construct two cylindrical mirrors, one parabolic and one hyperbolic, with other possible variations. The reason to use cylindrical mirror is that the quality of reflection at very large reflection angles is better than at small angles, especially if the anomalies of the metallic mirror are large. This type of reflection is in use at space telescopes working at very small wavelengths, for X-rays. They have been used for the first time by ROSAT[56] to observe the Cosmos in X rays. A similar system of mirrors is suitable for the Pharos to focus the light from the fire at the base to the top to be redirected with a system of mirrors perhaps conical like the one suggested by H. Thiersch in 1909 and ancillary mirrors for the direction of beams along the surface of the sea. In fact, if the beams of light are directed towards the smoke above the Pharos or even better towards some nearby clouds then the lighthouse light becomes visible at much larger distances than the actual height of the building permits. This type of reflection of light at a height makes the lighthouse visible at very large distances, as much as 300 km

[56] Sumner, T. J., J. J. Quenby, R. Lieu, J. Daniels, R. Willingale, X. Moussas (1989), Susceptibility of soft X-ray grazing incidence telescopes to low energy electrons, Monthly Notices of the Royal Astronomical Society, 238, 1047–1054.

that are mentioned by some authors that otherwise seems more than an exaggeration.

Multiple reflections in cylindrical mirrors, parabolic and to hyperbolic, like the ones suggested in this study, have been in use in antiquity as the book by the Archbishop of Canterbury and important scholar proves. Johannes Peckham, who taught at Oxford, in his book, published two centuries after his death in Venice, entitled *Perspectiua communis* (Common Optics [*Perspectivness*]), contains the study of multiple reflections of light inside a cylinder. The use of parabolic geometry in buildings is also evident in the Byzantine Empire, since the version of the Hagia Sophia in Constantinople designed by Anthemios and Isidoros and inaugurated in 537 A.D. used parabolic window sills to direct sun-rays to the huge gilded dome, so that it would appear as light and "floating" above the temple. Unfortunately the dome was destroyed 20 years later by an earthquake, but simulations by Potamianos in his book "Light in the Byzantine Church" (Potamianos, 2000), prove these allegations.

It consists of two sets of concentric mirrors. One set parabolic mirrors and one set of hyperbolic mirrors. The use of a quasi-cylindrical mirror (hyperbolic or parabolic) gives better reflection for a given quality of the mirror surface. The combination of a parabolic and a hyperbolic mirror gives better focusing. The light source is at the bottom. The light is guided to the top. A conical mirror can shed the light parallel to the sea. The conical mirror can be shaped so that it directs the light is some directions only, not 360 degrees around. An angle of some 200 degrees is sufficient to direct the light to the sea all around Alexandria, taking into account the shape of the coast of Egypt, if the light was sufficient or could be visible to 300 km, with appropriate conditions of temperature and humidity.

Figure 5: Hypothetical mirror system of the Pharos

We can also speculate that this highly sophisticated optical system included a telescope mechanism to support all accounts that agree that the images of ships were shown as soon as they appeared on the distant horizon. Tiny openings in the walls of the optical system substructure could project inverted images of the sea on the opposite wall of the otherwise dark interior (Camera obscura.) Also, mirrors inclined at 45°, so they could project the images of the removed objects downwards and on the floor of the room at the level of the lower platform, could also enlarge the images appeared.

The main mirror, of which there is always talk, was evidently a large concave mirror, so attached in the dark interior of the central shaft, that the pictures of ships appearing on the horizon could be seen in great magnification. Be it that smaller mirrors, placed at the corners of the octagonal terrace, caught the light rays and appearances on the sea in the interior of the cylindrical projectile, whether this was done by simple gaps in the cylindrical wall of the uppermost floor: a hanging up here, The mirror pointing downwards, in the form of an eight-sided pyramid - as well as a quadruple number of obliquely inclined mirrors - was able to direct the rays vertically downwards, where they produced a strong enlargement of the image seen by the concave mirror placed at the level of the first terrace. In this case, the dark, closed central shaft of the octagonal edifice actually served the service of a giant telescope: it would have been an ancient forerunner of Herrschei's large telescope, that of a mighty tube with a large metal concave mirror consisting at the lower end, a magnification of more than a thousand times. The largest telescope built in such a way Lord Russel, with 17 m length and 1.80 m focal length. These instruments were surpassed in optical power by none else, but they proved too inconvenient to handle. That's why they got away from them and needed the refractors with lenses again. Here at the Pharos the tube was vertical and did not need to be moved yet to be turned. This was a great advantage: the telescope itself was immovable, and at its base it included the metal concave mirror, which in this case would indeed have been applicable to the observation of the stars, not only of the phenomena on the sea. Unfortunately not only was the whole upper mirror apparatus - and under it the "burning mirror" must have been lost - lost, but through the various Arabian renovations of the tower upper part, the original inner communication downwards had been completely destroyed and suspended.

The concave mirror combines the rays of light emanating from a distant object, near its focus to an inverted image. This image is a real one and is visible only when it is captured by a matte disk (as from the plate of a photographic apparatus) or when the eye is near the focal point and within the indicated beam. Since the doctrine of the lawfulness of the reflection of crooked surfaces was well known to antiquity, there is nothing to oppose the inner probability of our assumption. If an application of these catoptric experiences was made here in the way we suspect or a similar one, the upper part of the interior, which was completely dark, has a sensible and extremely reasonable purpose: to project magnified images of the surrounding areas and emanate light in great distances as a means of communication.

Concluding remarks

Historical sources provide proof that the science of optics was advanced in ancient Greece and consequently in Ptolemaic Egypt. The science of Catoprtics, as was called by Euclid of Alexandria, as well as archaeological finds in several museums across the world provide evidence that lenses and mirrors were used commonly in that time and the general population had good knowledge of the uses. Complex optical instruments that used multiple reflections, possibly even telescopes, are mentioned in ancient Greek philosopher texts.

It is quite probable that the Pharos of Alexandria, one of the seven wonders of the world, was equipped with such optical instruments in the manner indicated throughout the manuscript. The main item could have been a magnifying mirror, which seems to have been designed as a burning mirror. Both types of such catoptric instruments were well known to Hellenism. Already Pythagoras is said to have made optical experiments with a concave mirror (see Scholia graeca ad Aristophanis Nubes v. 750, Schneider, Eclogae physicae I, 406 and note 261). Other relevant passages from Plato, Lucrez, Plutarch, and Olympiodorus have been compiled by W. Schmidt in his introduction to Heron's Catoptrics (Heronis Alex, opera II, 1 p.31 Iff.). Then there is the rich collection of the most diverse pieces of mirroring in this same catoptric Heron (2nd century AD, W. Schmidt, II, 300ff.), Though preserved only in Latin translation, shortened and corrupted and long under the name hidden by G. Ptolemy. This is followed by the Katoptrik, which is based on Euclid and edited later, which also speaks directly for the design of focal mirrors.

The present study combined observations from travellers, texts on the knowledge of science by the ancient Greeks, as well as contemporary science to support the argument that travellers' accounts of the Pharos' characteristics and functions, which were considered as exaggerations by most historians in the past, have a sound base considering all of the facts stated. The lighthouse could project sunlight through a complex automaton that followed the sun's rays to a distance that reached 50 km or more. At night-time this distance could be reduced to 10 km if advanced optics were used and we support the fact that instead of burning wood, such as other scholars suggest, the Pharos had a light source fuelled by oil that allowed it to be placed inside the tower with minimal smoke emission. The light from this light source, could be amplified by a system of parabolic and hyperbolic mirrors and focused to project it to a distance of 10 km equivalent to most 19th century lighthouses using sophisticated oil lamps and Fresnel lenses. The optical system could also function as a telescope, projecting false images into the interior of the building, as a camera obscura, supporting the accounts that the users of the Pharos could detect ships from far away and warn the city of enemy invaders.

By considering all of the above, the Pharos of Alexandria was truly a wonder of the ancient world. The combined knowledge of science, optics and architecture culminated in a structure that all travellers marvelled in awe from the year it was built, until its final destruction by earthquake in the 14^{th} century A.D. As British writer Agatha Christie wrote in the short story “The Hound of Death”, “The supernatural is only the natural of which the laws are not yet understood”. In this way, the advanced ancient technologies existing in the Pharos and the loss of information from one generation to another have accumulated to its status as a magical wonder across the centuries.

References

Acerbi, F. (2011), *The geometry of burning mirrors in Greek antiquity. Analysis, heuristic, projections, lemmatic fragmentation*. Archive for History of Exact Sciences, 65(5), 471–497(https://doi.org/10.1007/S00407-010-0076-8)

Adler, M.N. (trans.) (1907), *The Itinerary of Benjamin of Tudela*, by Benjamin of Tudela, The Project Gutenberg EBook, Critical text, translation and commentary, By Marcus Nathan Adler, first published by Philipp Feldheim, Inc. The House of the Jewish book, New York, First edition: Henry Frowde, Oxford University Press, London

Aeschylus, *Agamemnon*

Al Kindi, Abu Yūsuf Yaʻqūb ibn ʼIsḥāq aṣ-Ṣabbāḥ al-Kindī, manuscripts

Al-Muqaddisi, Muhammad ibn Ahmad *Ahsan at-Taqdsim fi macrifat al-Aqdlfm,* M. de Goeje, Leiden 1877

Al-Asyuti, Jalal al-Din *Husn al-muhadara fi akhbar Misr wa'l-Qahira,* Muhammad Abu al-Fadl Inrahim (Ed.) Cairo 1998

Albert Van Helden, Sven Dupre, Rob van Gent, Huib Zuidervaart (2010), *The origins of the telescope,* KNAW Press, Amsterdam

Al-Idrisi, *Opus Geographicum,* Eds. A. Bombaci, U. Rizzitano, R. Rubinacci, L. Veccia Vaglieri from Instituto italiano per il medio ed estremo oriente (Naples-Rome, 1972). See also edition of E. Cerulli, F. Gabrielli, G. Levi deal Vida, L. Petech, G. Tucci, Instituto Universitario Orientale di Napoli, Naples-Rome, 1970.

Al-Makrizi, *Khitab al-Khitat* Bulaq 1270 Egira's date

Al-Masud, Ali ibn Al-Husayn *Les praires d'Or (Muruj al-dhahab wa ma'adin al gawhar),* 9 vol., transl. C. Barbier de Maynard & Pavet de Courteille (Paris, Societe Asiatique, Collection d'Ouvrages Orientaux 1861-77), Vol. 8, 1874

Anthemius of Tralles, *On surprising mechanisms*

Apollonius, *Apotelesmata*

Aristophanes, *Clouds*

Aristoteles, *De coloribus*

Aristoteles, *De mundo*

Athenaeus, *Deipnosophistae,* Loeb Classics

Bonaventure Abat (1763), *Amusements philosophiques sur diverses parties des sciences, et principalement de la physique et des mathématiques*

Clayton Peter & Martin Price (1989), *The Seven Wonders of the Ancient World,* Psychology Press, 178 p.

Coleman, J. E. (1985), *'Frying pans' of the Early Bronze Age Aegean*, American Journal of Archaeology, 89, 191–219

Christie Agatha (1933), *The Hound of Death,* UK

Davenport Adams, W. H. (1870), *Lighthouses and Lightships: A Descriptive and Historical Account of their Mode of*

Construction and Organization, New York: Charles Scribner and Co.

Davis, Jack L. and Stocker, Sharon R. (2016) *The Lord of the Gold Rings: The Griffin Warrior of Pylos*, Hesperia: The Journal of the American School of Classical Studies at Athens, 85, pp. 627-65

Dicks, D.R. (1970), *Early Greek Astronomy to Aristotle,* Cornell University Press

Diodorus Siculus, *Bibliotheca historica*

el-Andalusi, Abu Hagag Yusef Ibn Mohamed el-Balavi (personal communication with late professor N. Ambraseys)

Enoch, J. M. (1998) *Ancient lenses in art and sculpture and the objects viewed through them, dating back 4500 years*. In Photonics West'98 Electronic Imaging (pp. 424-430). International Society for Optics and Photonics

Enoch, J. M. (2000), *In Search of the Earliest Known Lenses (Dating Back 4500 Years).* In Optics and Lasers in Biomedicine and Culture (pp. 3-13). Springer Berlin Heidelberg,

Euclid, *Catoptrics*

Eudemus, *Heraclides Ponticus*

Eudoxus, *Phenomena and Mirror*

Evans, J., Berggren, J.L. (2006) *Geminos's Introduction to the Phenomena: A Translation and Study of a Hellenistic Survey of Astronomy,* Princeton University Press

Flavius Arrianus, *Fragmenta de rebus physicis*

Foster E.M. (1961), *Pharos and Pharillon*, Hogarth Press, New York

Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., ... and Lunine, J. I. (2006). The James Webb space telescope. Space Science Reviews, 123, 485-606.

Geminus, *Fragmenta optica*

Giambattista della Porta, Magiae naturalis libri XX in quibus scientiarum naturalium, divitiae et deliciae demonstrantur, Napoli: Horatium Salvianum, 1589; 1658 English version, Natural Magick by John Baptista Porta a neapolitane in twenty books, London; Della Porta, G. (1957) Natural Magic, Basic Books. See also Della Porta, G. (1999). De refractione optices parte: libri novem... Ex officina Horatii Salviani, apud Jo. Jacobum Carlinum, & Antonium Pacem.

Heinle, E. and Leonhardt, F., *Towers: A Historical Survey*. New York: Rizzoli, 1989

Hellmann 1999: 109-111

Heron of Alexandria (1900) *Opera quae supersunt Omnia. Mechanica et catoptrica*, ed. L. Nix and W. Schmidt. Leipzig: B. G. Teubner.

Heron, *Definitiones*

Ibn Battuta (704-779 Egira's date / 1304-1377 AD), *Rihlat Ibn Battuta,* Beirut 1985

Ibn Jubayr, Muhammad ibn Ahmad (540-614 Egira's date / 1145-1217 AD) *Rihlat Ibn Jubayr,* Cairo 2000

Ibn Sahl, Abū Saʿd al-ʿAlāʾ ibn Sahl

Irby, G. L. (editor). (2016). A companion to science, technology, and medicine in ancient Greece and Rome. John Wiley & Sons, Inc.

Irby-Massie, G. L., & Keyser, P. T. (2002). Greek science of the Hellenistic era: a sourcebook. Psychology Press.

Johannes Peckham, *Perspectiva communis*

Josephus (Titus Flavius Josephus, 1st century AD), b. J. IV 613

Libri, G., Paris, 1835

Lucian, *Quom. hist. sit. scrib*. 62.

Lucian, *Hippias*

Medaglia, S. M., & Russo, L. (1995). Sulla prima "definizione" dell'Ottica di Euclide". Bollettino dei classici, 41-54.

Meeus 2015.

Michael Psellus, *Opuscula psychologica, theologica, daemonologica*

Moullou, D., Doulos, L.T., Topalis, F. (2015). Artificial Light Sources in Roman, Byzantine and Post-Byzantine Eras: An Evaluation of their performance. Chronos. N. 32. pp.119-132

Moullou, D., Madias E.N.D., Doulos, L., Bouroussis, C.A. and Topalis, F.V. (2012). Lighting in Antiquity. Balkan Light Conference Proceedings, Athens, Greece, pp.237-244

Moussas, X. (2014). Early Greek astrophysics: the foundations of modern science and technology. American Journal of Space Science, 1(2), 129

Neugebauer, O. (1975). A History of Ancient Mathematical Astronomy In Three Parts. Springer-Verlag:Berlin-Heidelberg

O'Connor, John J.; Robertson, Edmund F. (2003), "Catoptrics", MacTutor History of Mathematics archive, University of St Andrews., http://www-history.mcs.st-andrews.ac.uk/Biographies/Theon.html

Pancirolli Guidonis (1646), *"The history of many memorable things lost"*

Papathanassoglou, D. A., & Georgouli, C. A. (2009). The 'frying pans' of the early bronze age Aegean: an experimental approach to their possible use as liquid mirrors. Archaeometry, 51(4), 658-671.

Plantzos, D. (1997). Crystals and lenses in the Graeco-Roman world. American Journal of Archaeology, 451-464.

Plato, *Theaetetus*

Plinius, *Naturalus Historia*, 36,18.

Pliny the Elder

Plutarch, *On the Face in the Orbit of the Moon*

Plutarch, *Moralia on De Pythiae*

Posidippus of Pella

Posidonius, *Meteorologica*

Potamianos, I. (2000). Light in the Byzantine Church. University Studio Press (in Greek: Το Φως στη Βυζαντινή Εκκλησία)

Proclus, *Platonis Timaeum commentaria*

Procopius of Gaza, Buildings of Byzantium

Pseudo-Galenus, De historia philosophica

Pseudo-Plutarchus, *Placita philosophorum*

Ptolemy Claudius, *L'Optique*, 5 books edited by Albert Lejeune, 1956

Rashed, R. "A pioneer in anaclastics: Ibn Sahl on burning mirrors and lenses", Isis 81, pp. 464–491, 1990.

Rashed, R., Géométrie et dioptrique au Xe siècle: Ibn Sahl, al-Quhi et Ibn al-Haytham. Paris: Les Belles Lettres, 1993

Rashed, Roshdi (2007), The Celestial Kinematics of Ibn al-Haytham, Arabic Sciences and Philosophy, Cambridge University Press, R. Rashed (1968), Le Discours de la lumière d'Ibn al-Haytham (Alhazen), Traduction française critique, Revue d'histoire des sciences et de leurs applications. 21, 3.

Reeves, E. A. (2009) Galileo's Glassworks: the Telescope and the Mirror, Harvard University Press.

Russo L., *The Forgotten Revolution*, Silvio Levy (transl.), Springer-Verlag Berlin Heidelberg, 2004

Science. (Apr 9, 1886). Lighthouse Illuminants. 7:166. pp. 332-333

Science. (Feb 6, 1885). Lighthouse Illuminants. 5:105. pp. 111-113

Science. (May 12, 1893). Lighthouse Illuminants. 21:536. pp. 260-261

Shaw B., Ambrayes N.N., England P.C., Floyd M.A., Gorman G.J., Higham T.F.G., Jachson J.A., Nocquet J.M, Pain C.C., Piggott M.D. Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake, *Nature Geoscience* I, 268-276, 2008.

Sines, G., & Sakellarakis, Y. A. (1987). Lenses in antiquity. American Journal of Archaeology, 191-196.

Smith, A.M. (ed.). (2001). Alhacen's theory of visual perception: a critical edition, with English translation and commentary, of the first three books of Alhacen's De aspectibus, the medieval Latin version of lbn al-Haytham's Kitab al-Manazir, Transactions of the American Philosophical Society; 91, 4 and 5, 14.

Strabo, Geography, *Geographica, XVII, i,6.*

Sumner, T. J., J. J. Quenby, R. Lieu, J. Daniels, R. Willingale, Moussas X. (1989), Susceptibility of soft X-ray grazing incidence telescopes to low energy electrons, Monthly Notices of the Royal Astronomical Society, 238, 1047–1054.

Thibodeau, C.f.P. (2016). Ancient Optics: Theories and Problems of Vision, in A Companion to Science, Technology, and Medicine in Ancient Greece and Rome, First Edition. edited by Georgia L. Irby. John Wiley & Sons, Inc. pp 130–144.

Thiersch, H. (1909), Pharos, Antike Islam und Occident – Ein Beitrag zur Architekturgeschichte;B. G. Teubner, Leipzig und Berlin 1909

Toomer, G. J. (2012). Diocles, On Burning Mirrors: The Arabic Translation of the Lost Greek Original (Vol. 1). Springer Science & Business Media.

Tsikritsis, M., Moussas, X., & Tsikritsis, D. (2015). Astronomical and mathematical knowledge and calendars during the early helladic era in aegean " frying pan" vessels. Mediterranean Archaeology & Archaeometry, 15(2).

Tsountas, C., (1899), Cycladic, Κυκλαδικα II, ArchEph, 74–134

Twyman, F. (1952). Prism and Lens Making. (2nd ed.) Hilger

Vorderstrasse, T. (2012). Descriptions of the Pharos of Alexandria in Islamic and Chinese Sources: collective memory and textual transmission. In: Cobb P. M. (ed). The Linaments of Islam. Studies in Honor of Fred McGraw Donner. pp.457-474. Leiden:Brill

Willach, R. (2008). Held at Philadelphia for promoting useful knowledge: NS Rolf Willach.-The long route to the invention of the telescope.-Cep. vol. 98, pt. 5 Transactions of the American philosophical society: held at Philadelphia for promoting useful knowledge. Amer. philos. soc.