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Modeling the Moon's Motion in Al-Majisti and Its Compatibility with Modern Astronomical Models

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Abstract

Objective: This study aims to analyze the lunar motion models presented in Al-Majisti and evaluate their compatibility with modern astronomical models. The modeling of lunar motion has occupied a central position in the history of astronomy because it illustrates the evolution of mathematical approaches to explaining celestial phenomena. **Theoretical framework**: The research is grounded in the theoretical framework of the history of astronomy, mathematical modeling, and comparative scientific analysis, which together provide a basis for examining the continuity and transformation of astronomical knowledge from antiquity to contemporary science. **Literature review**: Previous studies have primarily discussed the historical significance of Al-Majisti and Ptolemy's influence on Islamic astronomy, while relatively few have systematically compared its lunar motion models with modern astronomical modeling. **Method**: To address this gap, the present study employs a qualitative literature review using a descriptive research design and content analysis. Primary data are derived from Al-Majisti, while secondary sources include scholarly works on the history of astronomy and modern planetary theory. **Results**: The findings reveal that Al-Majisti contains three successive models of lunar motion, each representing a progressive refinement of mathematical representation. The third model demonstrates the highest degree of sophistication and provides the closest approximation to the Moon's observed motion. The analysis further shows that the relative simplicity and effectiveness of Ptolemy's approach stem from the geometric combination of circular motions, which enabled increasingly accurate predictions despite the limitations of ancient observational techniques. When compared with modern lunar motion models, the Ptolemaic framework exhibits remarkable conceptual consistency, although contemporary models achieve substantially greater precision through advanced mathematics and observational data. **Implications**: These findings highlight the enduring scientific value of Al-Majisti as a milestone in the historical development of astronomical modeling and demonstrate its contribution to the transmission of scientific knowledge into the Islamic Golden Age. **Novelty**: The novelty of this study lies in its systematic comparative analysis of the three lunar motion models in Al-Majisti against modern astronomical models, offering new insights into the evolution, continuity, and scientific relevance of historical astronomical thought for contemporary scholarship.

Keywords: almagest, mean motion, anomaly motion, moon motion model, planetary theory.

INTRODUCTION

Al-Majisti is the name given by the Muslim scientific community in the 8th century AD or the 2nd century AD to a great work of Ptolemy in the field of astronomy. The Latin-speaking community of Europe named it Almagesti or Almagestum [1] in the form of a direct transformation of the Arabic sound al-Majisti into the Latin language and writing, which in the Middle Ages became the language of science on the European continent. And became an Almagest in English by taking a source from that Latin [2]. The work was originally in Greek under the name *μαθηματική σύνταξις* (Latin transliteration "*mathi̱matikí̱ sýntaxis*") meaning mathematical compilation [i.e. astronomy] [1]. While Ptolemy's full name is *Claudius Ptolemaeus* or *Claudius Ptolemy* [3] which in Arabic text is written بطلميوس[4] or بطليموس or القلودي بطليموس[5]

Ptolemy is a phenomenal astronomical book that for 8 centuries in the golden age of Islamic power has been the subject of discussion among astronomical scholars. Practitioners of astronomy in the Islamic world today have partly followed the development of modern astronomy, and some continue the relay of astronomy in the golden age of Islam, eight centuries since 700 ad [6].

Those days were the time of the development of many brilliant Muslim scientists with their works. Among the Muslim scholars that can be mentioned are Ulugh Beik in Samarqand, Nasir al-Din al-Tusi in Maragha and then in Baghdad, and Ibn Yunus in Egypt [7]. The three are basically the successors of Ptolemy in his basic astronomical thinking; the difference is in terms *of* updating data and his research methodology, especially in terms of the use of tools and his criticism of al-Majisti and his solutions by the Muslim scientist.

Egypt became a transit of Indonesian Astronomy with the discovery of the figure of Sheikh Hassan Zaid with his book of Falak *Mathla' al-Sa'id*. This figure combines Islamic astronomy based on *Al-Majisti* Ptolemius with modern mathematics, "Logaritma" from France, which he took through Lalande. Evidence of the flow of the scientific bond between Indonesian Falak science and Egyptian Falak can be seen from the reference to the Indonesian astronomical book *al-Khulashah al-Wafiyah,* which states that the book refers to the Kitab *al-Manahij al-Hamidiyah*. And Kitab *al-Manahij al-Hamidiyah* refers *to al-Mathla' al-Sa'id*.

Al-Khulashah al-Wafiyah by K.H. Zubayr Umar al-Jaylani, an Arabic book of astronomy, which is still used by astronomy practitioners in Indonesia, wrote in its introduction that the main points of the book are sourced from the book *al-Manahij al-Hamidiyah*. Kitab *al-Manahij al-Hamidiyah*, in its introduction, states that the main points of the book's content come from al-Mathla*' al-Sa'id*. The two compilers of the books *al-Manahij al-Hamidiyah* and *al-Mathla' al-Sa'id* were Egyptian scholars of different generations – from the data of the date of writing of the two different books of about 40 years. The relationship between these references can be seen in Figures 1 and 2. And it is known that Egypt is the birthplace of the famous Muslim astronomer Ibn Yūnus: Abū al-Ḥasan 'Alī ibn 'Abd al-Raḥmān ibn Aḥmad ibn Yūnus al-Ṣadafī (d. 1009 AD) with his great work *Zīj al-Ḥākimī* [7]. Although it does not mean that only Ibn Yunus's works were studied in Egypt, because during the Fatimid dynasty, the scientific activities in Egypt could be said to be similar to those in Baghdad.

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بسم الله الرحمن الرحيم

حمدا لمن خلق الشمس والقمر بحسبان . والسماء رفعها ووضع الميزان . ويقلب
الليل والنهار . ان فى ذلك لعبرة لأولى الأبصار . وهو الذى جعل الشمس
ضياء والقمر نورا . وجعل الليل والنهار خلفة لمن اراد ان يذكر او اراد شكورا .
وصلاة وسلاما على من خاطبه مدبر الأملاك . بقوله : « لولاك لولاك لما
خلقت الأفلاك » . وعلى آله ذوى الشجاعة والصبر . واصحابه نجوم الهدى
فى البر والبحر . ومن تبعهم باحسان الى يوم البعث والحشر ٭ ٭ ٭
« اما بعد » فيقول كثير المساوى زبير بن عمر الإندونيسى الجاوى احسن
الله عمله وبلغه فى الدارين امله لما اشتد احتياج اكثر الطلبة الى معرفة الأعمال
الفلكية من الكتب المؤلفة بالعربية ولم يجدوا مختصرة فى ذلك كافية
والكبار تعييهم او مفقودة عن اكثرهم اسرت لى نفسى بأن اضع المختصرة الكافية
الشاملة هادية لأمثالى ممن كانت همته قاصرة لكن منعنى انتظارى اقدام من
اوفى بوضع الكتاب الذى هو له اولى واكفى لعلمى بوجوده وكثرته وامكانه
لذلك وقدرته . ولما يئست توكلت على الله الوهاب فاهتديت ووضعت
هذا الكتاب وسميته « الخلاصة الوفية فى الفلك بجداول اللوغارتمية » .
وبنيت اصوله فى التاريخ وطولى القمرين والهلال والكسوفين على اصول
المناهج الحميدية فى حسابات النتائج السنوية وفى اطوال الخمسة المتحيرة
على اصول اللمعة فى حل السبعة واقتطفت الباقى من متفرقة كتب
الفلكيين مما سنح لى اتماما لمقاصد الراغبين فيكون الكتاب إن شاء الله
نهاية

Figure 1. Page 2 Kitab Al-Khulashah Al-Wafiyah

الزيج المصرى الجديد

بسم الله الرحمن الرحيم

لله الذي خلق الانسان وعلمه البيان ٭ الشمس والقمر بحسبان والنجم والشجر يسجدان ٭ والصلاة
سلام على سيدنا محمد الذى جاءت بعثته للعالمين أشهر أثر ٭ وعلى آله وأصحابه ما سارت الكواكب
الدهر (وبعد) فيقول الفقير الى ربه الغنى ٭ عبد الحميد مرسى غيث الفلكى الشافعي ٭ ان علم
علم جليل القدر عظيم المنفعة جم الفوائد اى العبادات الشرعية ولذلك أحله الغربيون من نفوسهم
نية الاولى حتى صارت تصانيفهم فيه ومؤلفاتهم لا تعد ولا تحصى ومع هذا فلم تفتر هممهم في البحث
تنقيب لكشف أسرار غوامضه وتقريبه الى الافهام بطريقة ترغب فيه وتكثر من طلابه فيتسع
قه وتعم فوائده . يموت عالمنا فيدفن علمه معه وتقبر ثمرة جهاده طول حياته فلا حول ولا قوة الا
. أصبحنا ولم يوجد فى أيدينا كتب من هذا العلم الا القديمة المطولة التي لا تأتى بالفائدة فضلا عن
صحة جداولها والتى لا يصح العمل بها الآن وقد حدثتنى نفسى ان أضع كتابا فى هذا العلم
الرصد الجديد يكون قريب المنال سهل العبارة مختصر فى العمل غير انه كان يمنعنى من ذلك
ارى أقدام أحد الفضلاء ممن هم أكفاء منى على هذا العمل حتى يئست مع علمى بامكان بعضهم على
به ولما لم أجد من يقوم بهذا العمل غيرى توكلت على الله واهتديت ووضعت هذا المختصر وقد
أصوله فى التواريخ والاطوال على أصول المطلع السعيد تأليف شيخنا المغفور له الشيخ حسين
رحمه الله وهو قد بنى أصول كتابه على أصول كتاب لا يلند الفلكى وجملت حسابه على خط

Figure 2. Page 2 of the Book of Manahij al-Hamidiyah

The primary source for this research is the book "Ptolemy's Almagest" [3], which is a translation plus annotation by G.J. Toomer of Ptolemy's al-Majisti (Almagest. Al-Majisti consists of 13 books [3] or maqalah [5] or qaul [4]. The first book contains about the universe and the earth's position in the universe as well as trigonometric theory; The second book contains about spherical astronomy; the third book on the theory of the sun; the fourth book on the theory of the moon; the fifth book on the continuation of the theory of the moon and parallax; the fifth and sixth books on eclipses; the seventh and eighth books on fixed stars; The ninth, tenth and eleventh books contain about the five planets: Mercury, Venus, Mars, Jupiter and Saturn especially about the longitude of the planets; the twelfth book about retrogradation; and the thirteenth book about the latitude of the planets [3]. It appears that al-Majisti deciphered almost all the subjects of astronomy that were necessary for the time when this book was made, which was apparently still in use until the 16th century.

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The core material discussed by al-Majisti is the motion of the Sun, Moon, planets and stars. Basically, this core part is the determination of the position of the Sun, Moon and Planets in the form of the longitude of the Sun, longitude and latitude of the Moon and planets. However, al-Majisti also elaborates on the basic philosophy of the universe and the motion of celestial bodies in it, and the concept of time that underlies the determination of the position of celestial bodies. Al-Majisti, in discussing the position of the celestial bodies, began his description from observations, then averages, then research on the deviation/difference in the quantity of motion between the average motion and the actual motion he studied, then designed and made a model and then elaborated on the algorithm for determining it. Thus, it can be said that the scientific flow of a theory from observation to the execution of calculations is described in this al-Majisti. In fact, the description is very detailed, especially when discussing how to make a model. Meanwhile, astronomy in the Islamic world today, as well as in Indonesia, can be said to focus more on determining the position of the sun or moon, namely astronomy that studies the times of worship, it is also mostly on how to use data on the position of the Sun and Moon, while the determination of its position is left to other sources. That is, the determination of the position of the Sun and the Moon itself is not discussed in the astronomical literature [8] [9] [10] [11]. Several fields of astronomy in the Islamic world specifically involve the sun and moon, namely astronomy, which is related to determining the beginning of the moon and eclipses.

METHODOLOGY

This scientific paper is a descriptive type literature study using the *content analysis* method [12]. This paper tries to explore the model and modelling of the Moon in the book al-Majisti, which in most Indonesian astronomical books does not receive in-depth discussion. Meanwhile, the concept of modern astronomy, which also discusses the determination of the position of the Moon, will be displayed. Then, how is the position of the modelling of al-Majisti designed and made in the 2nd century AD compared to the modeling of the moon motion in the modern era of the 21st century [12].

RESULTS AND DISCUSSION

The core material of al-Majisti is the determination of the position of the Sun, Moon, and planets. The first core material is the theory of the Sun, which is elaborated in Book III. The reason why the theory of the Sun became the first discussed material is stated in Book III, Chapter 1, page 131 of the late 132 beginning, " ... Even the theory of fixed stars cannot be thoroughly investigated without first establishing the theory of the sun and the moon ...". Meanwhile, the material about the Moon is discussed in Book IV.

Talking about the positioning of celestial bodies requires talking about time or timing from micro-clocks, minutes, seconds, to macro timeframes (calendars) in days, months and years. In this timetable discussion, there is a discussion about which epoch, chronology and micro and macro (dating) are chosen. *Al-Majisti* chose the chronology of the throne of kings for its chronology, the Egyptian calendar for its reckoning, and the micro-time system of equal duration in the daily cycle starting from midday, when the sun is at its highest peak in the sky. While the epoch chosen is the beginning of the throne of King Bukhtanashir [4] or Nabonassar [3]. What is meant by a timetable with the same duration is that each unit of time in its time, such as a clock of the same duration at all times, minutes and seconds of equal length at all times. Outside of that base, sometimes there was also an Egyptian-style timetable at that time, which started the day at sunrise and had a clockwise length according to the season. In this *seasonal time*, the duration of one hour in summer is different from one hour in winter, as well as in the time between the two. However, because the focus of this paper is on the modeling of the Moon, this discussion of timing is not explored. Meanwhile, an epoch is a point in a time span or date that is used as a reference for dating, a celestial reference framework system, a catalog of stars or the motion of objects in their orbit [13].

Al-Majisti describes the determination of the position of the Moon in Books IV and V. Ptolemius was well aware that, because of its proximity to the Earth, the determination of the position of the Moon was parallax-influential. The Moon's parallax is observed daily. With parallax considerations, the moon position talks discuss the mean position, visible position and true position. The determination of the position of the Moon must be made against its true position (Book IV.1, page 174)[3]. Based on this, Ptolemy emphasized the importance of observing lunar eclipses to develop the theory of lunar motion (Book IV.1., page 174)[3]. Observations of lunar eclipses eliminate the influence of parallax on the determination of the position of the Moon. Ptolemy's predecessors had already used this phenomenon of lunar eclipses to obtain a theory of the Moon's motion.

The second thing that is important in building the theory of lunar motion is the determination of the periodic cycle of the duration of the Moon's motion, which is associated with 4 types of lunar movements based on the lunar eclipse, namely the eclipse cycle. The cycle of the duration of the moon's motion is the motion of the Moon according to longitude (synod), according to anomalies, according to latitude and according to elongation to the sun.

Talking about the modeling of the Moon's motion, al-Majisti (Ptolemius) begins with a description of the period of the Moon's motion, and the average motion of the Moon for each type of Moon's motion. Ptolemy chose the periodization of Hipparchus from the lunar eclipse to the next lunar eclipse. Hipparchus periodization has a range of 126007 days and 1 equinoxal hour. In this interval, there are 4267 moons, 4573 complete repetitions in anomalies, 4612 revolutions on the ecliptic less than 71/2o, and 345 revolutions of the Sun, with reference to the movements of the moon and the Sun with respect to fixed stars. Hipparchus divided the number of days 126007h1h by 4267 months, thus obtaining the length of the month (synod) 29; 31,50,8,20 days (Book IV.2, p. 176) [3].

Rotation in the ecliptic is not in integers. It turns out that the number 126007h1h does not produce repeats in latitude in integers either. In these last two cycles of the moon's motion, Hipparcus – still according to Ptolemy – proposed another periodization which yielded 5458 moons equal to 5923 repetitions in the latitude. According to him, this number produces repeats in anomalies as well with no difference. This priodization is what Ptolemy used to calculate the average motion of the Moon.

Periodisasi Hipparchus menghasilkan kelompok angka-angka 4267 bulan (sinodis) sama dengan 4573 ulangan lengkap dalam anomali dan 5458 bulan (sinodis) sama dengan 5923 ulangan kembalian dalam lintang. Bilangan 4267 dan 4573 jika sama-sama dibagi 17 diperoleh angka-angka 251 dan 269. Mengalikan gerak rerata harian Matahari yakni 0;59,8,17,13,12.31$^{o/h}$ dengan bilangan hari dalam satu bulan sinodis 29;31,50,8,20$^{h/b}$ dan menambahkannya dengan satu putaran 360° diperoleh gerak rerata satu bulan sinodis sebesar 389;6,23,1,24,2,30,57°. Membagi hasil ini dengan bilangan hari dalam satu bulan menghasilkan gerak rerata harian bulan dalam bujur 13;10,34,58,33,30,30$^{o/h}$. Kemudian mengalikan 269 putaran dalam anomali dengan satu putaran 360° menghasilkan 96840°. Mengalikan angka ini dengan bilangan hari dalam 251 bulan (7412;10,44,51,40°) menghasilkan gerak rerata harian dalam anomali 13;3.53,56,29.38,38°. Mengalikan 5923 ulangan kembalian dalam lintang dengan satu putaran 360° menghasilkan 2132280°. Membagi hasil ini dengan bilangan hari dalam 5458 bulan (161177;58,58,3,20^{h}) mendapatkan gerak rerata harian dalam lintang 13;I3,45.39,40.17,19°. Kemudian mengurangkan gerak rerata harian Matahari dari gerak rerata harian Bulan, keduanya dalam bujur, menghasilkan gerak rerata harian Bulan dalam elongasi sebesar 12; 11,26,41,20,17,59°.

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The above calculation data is the basis for revealing the average duration in the groups of hours, days, months, years and 18-years. In a brief form, the description is as follows:

In an hour of average lunar movement

by longitude : 0; 32,56,27,26,23,46,15°

by anomaly : 0; 32,39,44,50,44,39,57,30°

by latitude : 0; 33,4,24,9,32,21,32,30°

According to elongation : 0; 30.28,36,43,20,44,57,30°.

In one day, the average moon movement

by longitude: 13; 10,34,58,33,30,30°

according to anomalies: 13; 3.53,56,29.38.38°

by latitude: 13; 13,45.39,40.17,19°

according to elongation: 12; 11,26,41,20,17,59°

In one month, the average moon motion

by longitude: 35; 17,29,16,45,15°

according to anomalies: 31; 56,58,8,55^59.30°

By latitude: 36:52.49,54,28,18,30°

according to elongation: 5; 43,20,40,8,59,30°

In one year, the average lunar motion

by longitude: 129; 22,46,13,50,32,30°

according to anomalies: 88; 43,7,28,41,13,55°

by latitude: 148; 42,47,12,44,25,5°

according to elongation: 129; 37,21,28,29,23,55°

In an 18-year group, the average lunar motion

by longitude: 168; 49,52,9,9,45°

By anomaly: 156:56,14,36,22,10,30°

by latitude: 156; 50,9,49,19,31,30°

by elongation: 173:12,26,32,49,10,30°

From this data, a table of the average motion of the Moon in 18 years, one year, one month, one day and one hour was compiled. It should be noted that the positions in the Epokh for Increments in Longitude 811; 22nd (41; 22o), Increments in Anomaly 268; 49°, Increment in Latitude 354; 15o and Increment in Elongation 70; 37° should be included when using the values from the table of motion averages of the month.

The theory of the motion of the Moon that has been put forward by Ptolemy's predecessors, namely Hipparchus, has the main characteristic in the form of the application of only one kind of anomaly as the theory of the motion of the Sun. This anomaly will then be referred to as the first anomaly. However, Ptolemy himself stated that there were two anomalies. And Ptolemy stated that the second anomaly could not be obtained if the first anomaly was unknown, while the first anomaly did not depend on the second anomaly (Book IV, p. 181) [3]. For this reason, Ptolemy first elaborated the basic (first) theory of lunar motion, which was based on one anomaly, and then the theory of the motion of the complete moon (second), which was based on two anomalies.

Basic lunar motion model with one anomaly

The basic theory of the Moon's motion with the application of the first anomaly is built on the application of the same epicyclical model that is applied to the Sun. Actually, the application of the eccentric model can also be applied with the same result, but this second model, according to Ptolemy, is more suitable to be applied to build the theory of the motion of the Moon with the second anomaly when the two anomalies are combined. The same results from the use of the two models in the application of the first anomaly are obtained if the ratio of the epicycle to the deferens (carrier circle) and eccentricity to the eccentricity is the same (Book IV, p. 181, paragraph 2)[3]. Ptolemy modeled the basic Moon theory by imagining a circle in the Moon's celestial sphere that is as central and plane as the ecliptic. Then another circle is also imagined that is tilted towards the circle with an inclination equal to the deviation of the maximum latitude of the moon from the ecliptic (Ptolemy takes the number 5 °), which moves uniformly forward, referring to the centre of the ecliptic at a speed equal to the difference between the motion in latitude and motion in longitude. In this oblique circle, an episcopalian is imagined carried by the oblique circle that moves uniformly backwards towards the sky in accordance with the motion in latitude. This motion shows the average motion in the oval, referring to the ecliptic. In this episcopacyte, it is imagined that the moon moves in such a way that at the arc near the apogee, its forward motion refers to the sky at a speed corresponding to the period of change in the anomaly. For simplification, forward motion in temporary latitude is ignored because its value is small enough that it does not so appear to affect position in longitude (Book IV, 6, page 191) [3], see figure 3. Figure 4 shows the First Model of the Moon's motion, with the Moon depicted as P, the episcopal center C and Earth O, so a is the anomaly and q is the center press.

Ptolemy's calculations for R (radius of the Moon's carrier circle) and r (the radius of the Moon's epicyclical circle) yielded r = 5p; 14, if R = 60p (Book IV, page 202)[3]. However, for the next calculation, Ptolemy rounded the number using r = 5p;15.

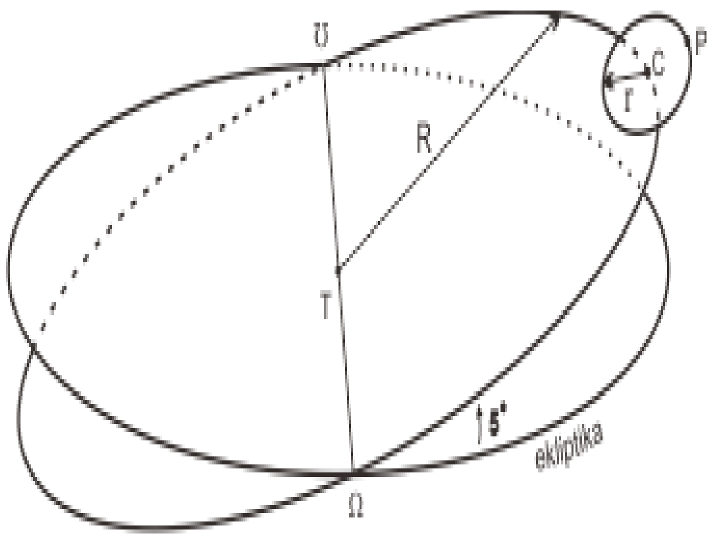

Figure 3. Basic Model of Moon Theory

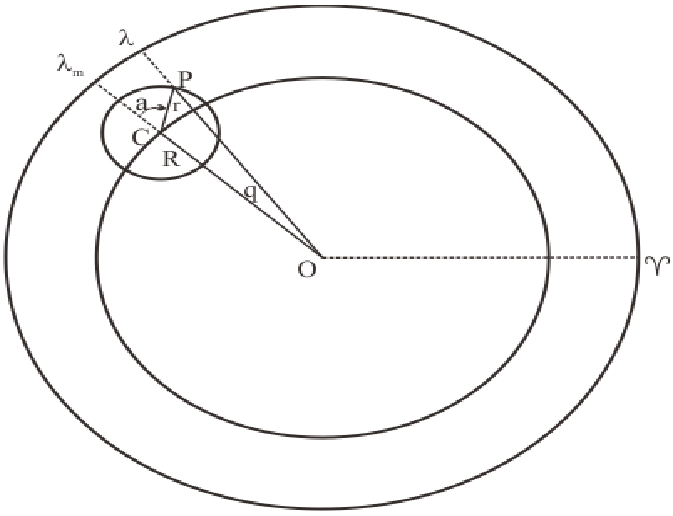

Figure 4. The First Model of Moon Motion

Second moon motion model with two anomalies

The theory of lunar motion with one anomaly still leaves a mismatch between observations and theoretical certainties. Ptolemy discovered the problem and then provided the solution. From this, the theory of motion with two anomalies was produced. This theory was obtained by Ptolemy from the observation of the longitude of the Moon compared to its average longitude at the position of the intersection, which, when calculated, exceeds the permissible maximum, namely in the first and third quarters according to the first model of the motion of the Moon. The maximum value is 5o; 1 while the result of the calculation of the above observation with the first motion model is 7 °;40. Meanwhile, at the time of ijtimak and istiqbal between the observation and calculation of the first moon motion model, there was no difference. It means that the radius of the episclelium when the intersection increases/is greater than the radius at the time of ijtima and istiqbal. This mismatch is related to the Moon-Sun distance. Ptolemy stated that there was a second anomaly related to the distance of the Moon from the Sun (Book V, p. 217) [3]. This correction is what in modern times is called eviction correction.

Ptolemy made two corrections to the previous model. The difference in the size of the episicle at the intersection and ijtimak-istiqbal was corrected by making the eccentric motion of the episicle carrier circle compared to the concentric first model. The second correction relating to the elongation of the Moon with respect to the Sun is made by adding a circular motion opposite the direction of the Moon's epicyclic centre of motion (not the epicyclic center itself) to the solar motion as far as the value of the eccentricity of the carrier circle. This last model combines an epicyclic model with an eccentric model at the same time, plus a rotating eccentric point. The rotation of this eccentric point with the rule of the distance between the Sun and the Apogee Longitude is equal to the elongation of Mataheri averaged to the center of the moon's epicyclic η_m).

Berputarnya titik eksentrik ini menyebabkan Apoge bulan selalu berubah. Ukuran jejari episikel mengikuti ukuran pada model pertama yakni 5^p;15. Sedangkan eksentrisitasnya, setelah melalui perhitungan yang dijelaskan juga di dalam uraiannya, mengambil angka 10^p;19 yang berputar dari Timur ke Barat dengan kecepatan konstan. Untuk sementara masalah teratasi. Model kedua ini dilukiskan dengan Gambar 5.

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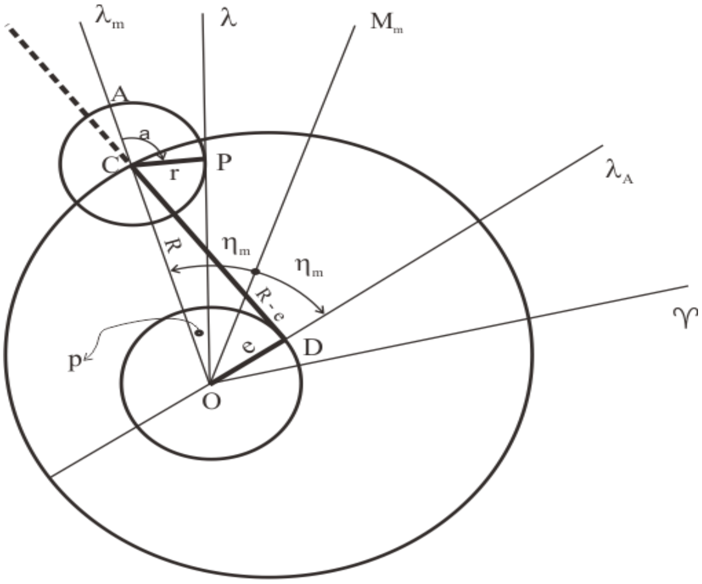

Figure 5. Second Model of Moon Motion

Third moon motion model

After the problem at the intersection was solved by adding to the first model an eccentric point of the center of motion that rotates around the center of nature by OD = 10p; 19, it turns out that there is still a problem when the Moon is in the horizontal position, the general price is not in the extension of OC or DC in the lunar epcycle. It turns out that the price is at an extension of D'C with OD' spaced the same as OD but in a diametrically opposite direction with D on the apogee-perigee line of the carrier circle as seen in figure 4.10. Am is at the extension of D'C, so Am is calculated from CAm to CP. The final solution to the problem in the theory of lunar motion is Ptolemy's third model of lunar motion. This third model is described in Figure 6.

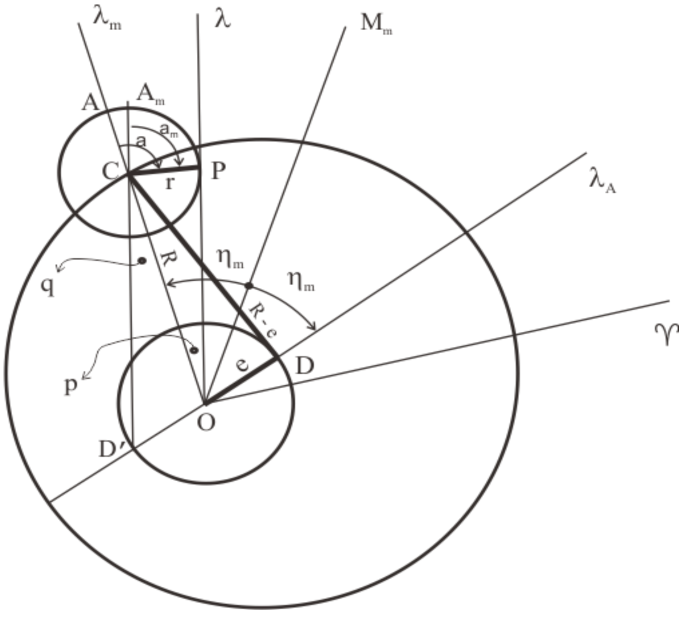

Figure 6. Third Model of Moon Motion

Ptolemy's theory of lunar motion is based on the well-established theory or modeling of his predecessor, Hipparchus (190-120 BC) [14], i.e. the theory of lunar motion with pure episicle modeling (see figure 4). It turns out that compared to the empirical data on the positions of the moon that he has, Hipparchus' model has problems when the position of the Moon is in the first and third quarters of the model. The problem is that it seems that when this position is taken, the radius of the ellipse becomes larger than when the Moon is in position at apoge and perigee. And according to Ptolemy, Hipparchus was aware of this oddity, but from Hipparchus, Ptolemy had not found a solution. So Ptolemy took it even further to make corrections by giving the Second Moon Motion Model.

The second correction to the first lunar motion model, realized by Ptolemius, was due to the Moon-Sun distance factor. The second correction is given by changing the pure episcial model combined with the eccentric model, but with an eccentric point that rotates constantly (see figure 5). This correction is what in modern times is called eviction correction. This discovery was one of the greatest discoveries of Ptolemy.

After the second correction in the first model of the Moon's motion, the calculation results should follow the magnitude of the value according to the anomalous tabulation in the existing table of the Moon's average motion. In the simple theory of the Moon's motion, the angle of the general anomaly is calculated from the epicycle epoch. But the apoge in this new (second) model is not unique in the sense that it can be considered as a continuation of OC or DC. It turns out that Ptolemy showed that both are not possible choice when calculated from existing empirical data. Empirical data show that the angle of Am meets the theory and empirical data if Am is placed on the continuation of the line D' to the center of the episclele C at the episicle. Point D' is a point equal to D from the center of the universe, but its direction is 180 ° opposite (and always opposite) to D. Again, the power of accurate data that Ptolemy held in building his theories and models and the gradual corrections to his modeling brought about the compatibility of models made with empirical data.

Al-Majisti and the modern planetary theory

This section is used by the author to compare the theory or model of lunar motion, al-Majisti-Ptolemius, with modern astronomical theory and motion models. To facilitate comparison, the theory and model of the Moon's motion are taken. The use of the model of the motion of the Moon for comparison is because the modeling in both theories (al-Majisti-Ptolemius and Modern Astronomy) is based on the same base, namely the motion of the moon centered on the Earth, so that direct comparisons can be made without the need for model transformation.

The first comparison, the lunar longitude calculation model. In modern astronomy, the position of the planet or moon is shown in a diagram such as Figure 7, with the form of an equation for the Moon:

$$\lambda_b = \Omega + \lambda_1 = \Omega + \arctan(\tan\omega \cdot \cos i)$$

With λ_b the longitude of the Moon, Ω the point of the moon's node on the ecliptic, i the tilt of the moon's orbit on the ecliptic, ω the perihelion argument, and λ_1 arc projection ω on the ecliptic.

Ptolemy simplified his calculation of the longitude of the moon by considering

$$\lambda_1 \approx \omega$$

Namely by calculating λ_b from:

$$\lambda_b = \Omega + \omega$$

Consequently a correction c will be added to $\lambda_{both\ b}$ and ω (Neugebauer, 1975:82).
$\lambda_b = \bar{\lambda}_b + c$

$$\omega = \overline{\omega} + c$$

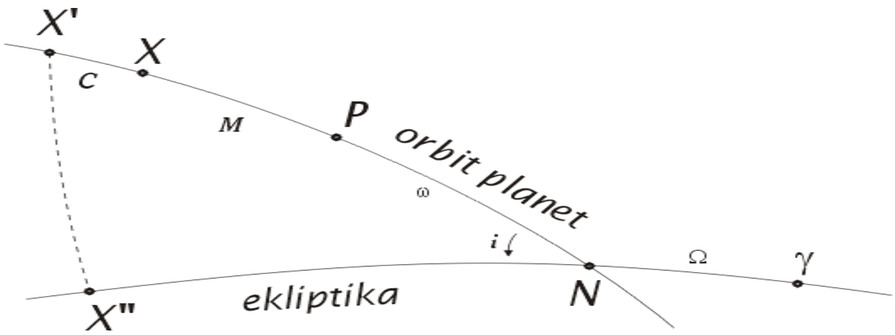

Figure 7. Planetary or Moon Orbital Elements in Modern Planetary Theory (Meeus, 1998:198)

Description of Figure 7 :

The γNX" arc is part of the ecliptic as seen from the sun, and NPXX' is part of the orbit of a planet or moon (a slice of the plane of the orbit of a planet or moon with a celestial sphere). γ is the vernal equinox (oval 0o), N node ascending orbit, P perihelion of the planet or perige of the Moon. At any given moment, the average Planet or Moon is on X, the true planet or Moon on X'.

Ω = arc γN = longitude of ascending node,

ω = NP arc = perihelion argument (for Planet), perige (for the moon)

π = arc γN + arc NP = Ω + ω = longitude perihelion,

L = arc γN + arc NX = Ω + ω + M = the longitude of the planet or the average moon,

C = arc XX' = center equation

With λ and ω in the upper line is the average price of λ and ω. With this approach the error is 0; 6o to ω from 30o to 60o [16]. As for Ptolemy, he modeled the orbit of the Moon on the ecliptic as figure 8.

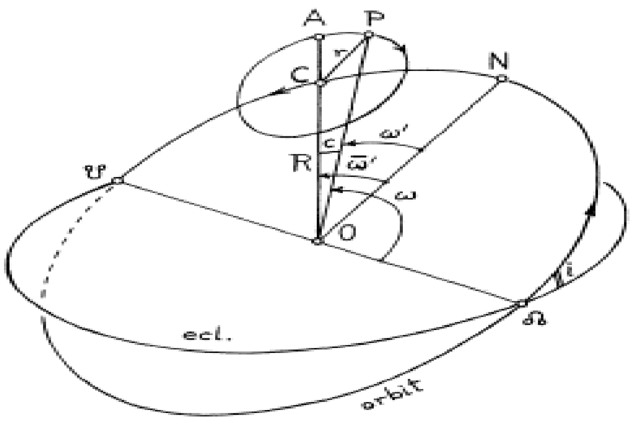

Figure 8. The Position of the Moon's Orbit with Respect to the Ecliptic According to Al-Majisti-Ptolemius (Neugebauer, 1975:1228)

The second comparison concerns the nature of the Moon's orbit. The second and third models of Ptolemy's Moon motion, if the position of the Moon during its continuous motion is described, would look like figures 9 and 10. With the simulation carried out by Pedersen and Neugebauer by plotting the path of the Moon's journey according to models 2 and 3 of Ptolemy, it appears that 1) the orbit of the Moon Model Ptolemius can be said to be oval, and 2) the orbit of the Moon rotates.

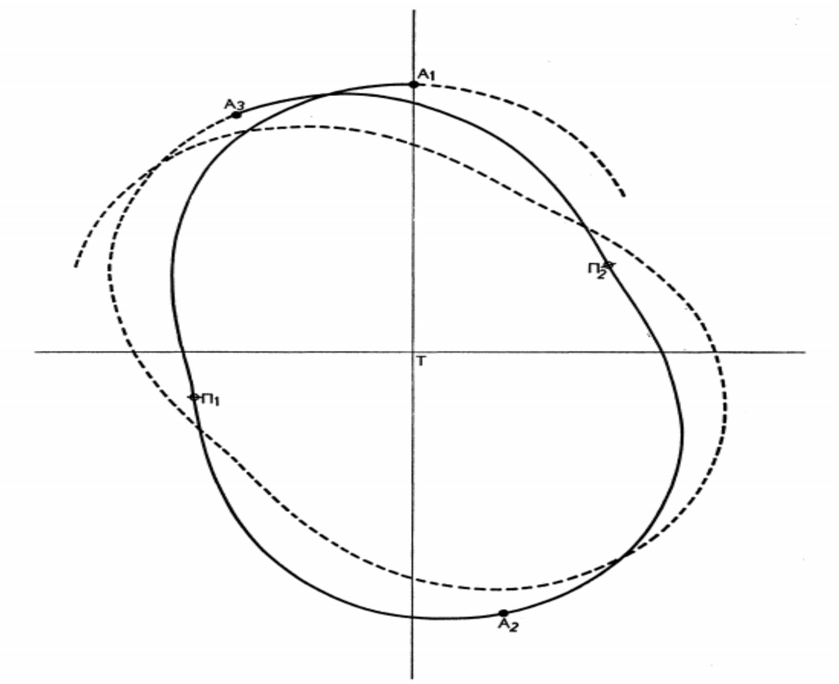

Figure 9. The path of the Moon according to Ptolemy's second model by showing the pairs of Apoge and Perige in two consecutive cycles (Pedersen, 2010:190)

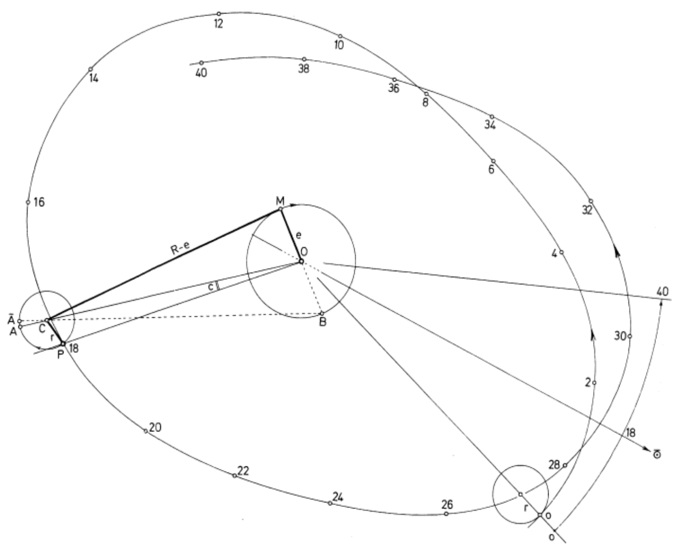

Figure 10. The position of the Moon was for 40 days with an interval of 2 days according to the third model of Ptolemy. (Neugebauer, 1975:1233)

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Caption of figure 10: the starting position is when the Moon-Sun is in an average conjunction occurs and the Moon is at its episicle apoge (symbol of the number 0). On Day 18, the Moon-Sun elongation was 219.5 °. A top-striped is the average position of the Sun on day 18.

Modern astronomy has told us that the orbits of the Planets and Moon according to Kepler's First Law, are oval. And according to the latest research, the ovals are not always in one direction but in a rotating direction.

> "From the equation (10.95), to the first level with a small parameter, the perige of the Moon is equal to ...
> ...
> ... Furthermore, it is clear that this precession is entirely caused by the *perturbation* of the Sun because this precession depends only on the parameter m, which is a measure of how big this influence is. Taking the value of m = 0.07480, we get a perigee progress of 34.36 ° per year. From this we can predict that the perige completes its rotation every 8.85 years." [17]

The progress of the Moon's perigee in modern astronomy as revealed by Pitzpatrick above is illustrated in figure 11. It appears that there are similarities between the model of al-Majisti-Ptolemius and Modern Astronomy.

Figure 11. The precession of the Moon's perigee in modern astronomy

The third comparison is in terms of the designation of numbers or values of longitude and latitude of the Moon. Neugebauer calculated the longitude and latitude values of the moon over 16 days using the Ptelomius model and modern astronomical models. The calculation was made from the Nabonassar Era 621 VIII 5 to 621 VIII 20 (-126 April 26 to -126 May 11) at 6 a.m. and produced figures that when displayed in the form of a graph look like figure 12.

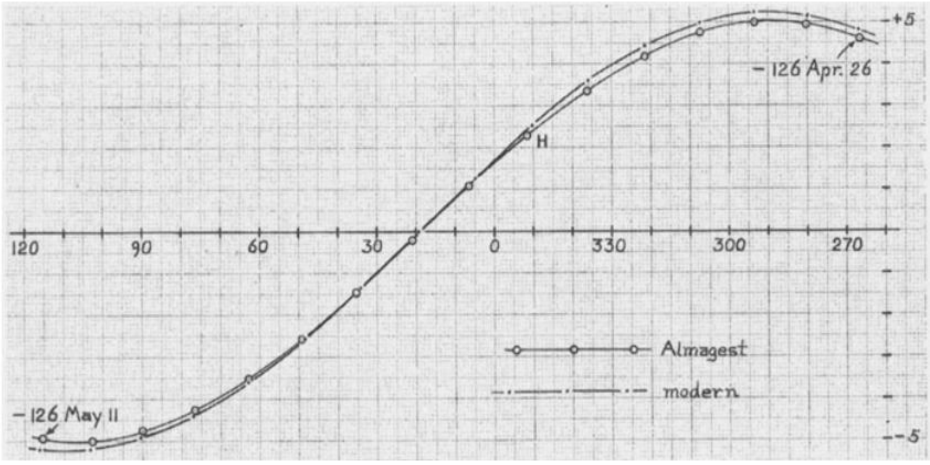

Figure 12. Longitude and latitude values of the Moon according to Ptolemy's Moon Model and Modern Astronomy (Neugebauer, 1975:1234)

If you look at the three comparisons above, between the al-Majisti-Ptolemius Model and modern astronomy, the three are very similar in both qualitative tendencies (models) and quantitative tendencies (calculation numbers). When the natural phenomena that are sunnatullah are approached very carefully and earnestly, a long distance shows the consistency of the nature of nature (sunnatullah), the same tendency differs only in terms of precision because today tools have been found that are much more sophisticated than in ancient times [18].

Simplicity and compatibility

The first modeling of the moon's motion using a carrier circle and an epicyclical circle smaller than the carrier circle was used to approximate the difference between the average motion and the actual state. While there was still a discrepancy with the empirical data on the quarter-position of the first model, it was soon discovered that it came from the distance factor with the Sun. Ptolemy provided a solution to this problem by adding to his model design a circle of radius equal to the value of its eccentricity at the center of the moon's motion around the center of the universe [19]. These two solutions are simple solutions with fairly accurate problem-solving capabilities, although there are still inconsistencies with empirical data when the Moon is in the eighth position in the second model. There is a problem when taking the Episclerotic Average Apoge as usual, namely the elongation of the episicle center of motion (in figure 5 there is a dotted line of the DC spacing). The solution turned out to be simple as well, namely by placing the Moon's Average Episcalal Apoge at the extension of the episcalal center (C) of D', a point that is in the opposite position from D [20].

The compatibility of the Al-Majisti-Ptolemian model with empirical data in the field is evidenced by the continuous use of this model by its users until the 16th century AD, a span that is very far from the time of al-Majisti's writing in the 2nd century. This means that in terms of the compatibility of the model with the data of the Al-Majisti Model, it was quite tested in its time. On the other hand, if you look at the calculation simulations by Pedersen [16] and Neugebauer [16], figures 9 and 10, al-Majisti's model is quite close to the modern model of lunar motion, figure 11. That proximity in terms of the moon's orbit is oval, and the moon's apogee changes by rotating. While this modern model is the most realistic model closest to the actual reality of motion. The Modern ELP2000 planetary peori from the French IMCCE provides an internal precision of 0.01". Meanwhile, other planetary theories, such as the DE4xx series from JPL-NASA are even better in accuracy than ELP.

Analysis. The findings demonstrate that Al-Majisti presents a systematic progression of lunar motion modeling through three increasingly sophisticated mathematical models. The first model establishes the fundamental epicyclic representation, while the second introduces eccentricity to accommodate discrepancies observed during lunar quadratures. The third model further refines this framework by incorporating a rotating eccentric point, significantly improving agreement with empirical observations [21].

This gradual refinement reflects Ptolemy's scientific methodology, in which theoretical models were continuously revised based on observational evidence rather than philosophical assumptions alone. Comparative analysis indicates that although modern astronomy employs gravitational theory, advanced mathematics, and high-precision observational data, several conceptual characteristics of Ptolemy's models remain recognizable, including the approximation of the lunar orbit, orbital precession, and iterative correction mechanisms. The remarkable compatibility between ancient and modern approaches highlights the enduring value of Al-Majisti in the history of astronomy. These findings confirm that Ptolemy's geometric models constituted a scientifically rigorous foundation that influenced astronomical development for many centuries thereafter.

CONCLUSION

The simplicity of the Bulan al-Majisti motion modeling lies in the use of the base of the circular motion model with its combinations. The Moon's complicated motion is simply modeled with 3 combinations of circular motion, namely the first circular motion of the carrier, the second circular motion of the episcopalian and the third circular motion of the eccentric of the center of the universe. Its gradual correction applied to the initial modeling and subsequent modeling results in a model that is close to actual motion. Meanwhile, the proximity of the al-Majisti model to the actual motion of the moon is represented by modern motion theory. The theory of motion of the modern Moon has been tested to produce the proximity of the motion model to the actual motion represented by the model and calculation results of the Modern Planetary theory ELP2000.

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Author Contribution

Ruswa Darsono conceptualized the study, conducted the literature analysis, and prepared the manuscript. Muhyar Fanani developed the theoretical framework, supervised the research process, and critically revised the manuscript. Ahmad Adib Rofiuddin contributed to data interpretation, content analysis, manuscript editing, and the final review. All authors approved the published version.

Conflicts of Interest

The authors declare that there are no financial, professional, institutional, or personal conflicts of interest that could have influenced the design, implementation, interpretation, or publication of this research. All findings and conclusions are presented objectively based on scholarly evidence, and all authors approve the submission and publication of this manuscript.

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