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Astronomical Computation as a Performance: Determining Planetary Positions with the Manuscript Erfurt, Angermuseum, 3134

Abstract: In this paper we argue that hand computation is not a mechanical endeavour, especially in the case of the long and complex procedures that astronomers need to follow. On the contrary, in addition to specialised skills, it also requires choices and anticipation 'on the spot'. These choices produce variations in the procedure followed and its meaning, as well as discrepancies in the numerical results, which can drastically change the description and comprehension of the celestial phenomenon under scrutiny. Our approach is to consider one specific manuscript and to reproduce the computations to the best accuracy of our historical knowledge. We show that, as historians, we cannot consider computations in the abstract, disregarding the manipulation of the manuscript, without essential loss of meaning and understanding. On the side of manuscript studies, by highlighting some features of these artefacts and their possible uses by historical actors, we demonstrate the way in which they become scientific tools.

1 Introduction

Fifteenth-century astronomers had at their disposal some of the most significant astronomical works from the Hellenistic period, Al-Andalus times, and the Latin Middle Ages. All these astronomical works share a 'Ptolemaic' approach, broadly construed. They nevertheless differ markedly in some structural details of the geometrical models and in the numerical values of certain parameters on which the computational tools depend. The numerical results they produce are clearly distinct in most cases. Yet despite the circulation of this variety of works in the fifteenth century, the then common practice of astronomical computations was to rely on just one family of such works. This family constitutes what we today call Alfonsine astronomy because these works derive from a table set that had begun to circulate in Latin around Paris, under the name of Alfonso X, king of

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Castille in the 1320s.[1] While a given astronomer could in principle choose to compute celestial positions relying on non-Alfonsine material, those of the numerous yearly prognostications and horoscopes produced in this period, and that have been analysed, show Alfonsine positions.

It turns out that most of the several hundred astronomical manuscripts produced and assembled during the fifteenth century and extant in patrimonial libraries are ‘toolbox manuscripts’, as described in recent scholarship.[2] These typically consist of texts, numerical tables, diagrams and volvelles (moveable diagrams featuring rotatable parchment discs and threads). Their purpose is not only to propose an astronomical theory and a (mathematical) view of the cosmos, but primarily to provide the means to execute the long computations required to establish the celestial positions of the luminaries and planets, or to predict the time and number of eclipses. While some of these aggregations were based on the criteria of a book collector, or a librarian, some others can be singled out as being the idiosyncratic deed of an astronomical practitioner, or a group of university masters specialised in astronomy. These manuscripts were often assembled by the astronomers who used them.

The use that can be made of such a toolbox manuscript depends on the specialised skills, experience and habits of the astronomers as much as on what the manuscript objectively offers in tabular, instrumental or theoretical content. It stands to reason that the same material consisting of tables and instruments will be used differently, even if the aim were the same, namely, to compute planetary positions. In this paper we argue that hand computation is not a mechanical endeavour, especially in the case of the long and complex procedures that astronomers need to follow. On the contrary, in addition to specialised skills, it also requires choices and anticipation ‘on the spot’. These choices produce variations in the procedure followed and its meaning, as well as discrepancies in the numerical results which can drastically change the description and comprehension of the celestial phenomenon under scrutiny. We assume that the use of the same toolbox manuscript by a beginner would certainly have been different to that of an experienced expert in astronomical computation, particularly concerning the choices and anticipation. Understanding the non-mechanical dimension of hand computations as they were conducted by astronomers is the main reason why we approach them as a performance. We understand performance here as the execution of a task requiring specialised skills and implying choices which result in significant variations in the process and result of the task.

1 North 1977; Poulle 1984; Chabás and Goldstein 2003; Kremer, Husson and Chabás 2022.

2 Husson 2021a; Kremer 2022.

For the sake of simplicity, two of the potential sources of variations in the computation procedures and results will not be considered here. Both were probably obvious to historical actors, but bear little or no intentionality on their side. First, one can wrongly execute a given arithmetic operation, thus creating a variation in the computation procedure and probably its result. We will consider that astronomers did not intentionally produce this kind of errors, although this is not to say that their arithmetic rules were the same as ours. In fact, we know for sure that they used other numbers, quantities and arithmetic rules to those of today's mathematics. It is crucial to our analyses that we follow as closely as possible their arithmetical practices: converting all numbers to a modern format would in many cases erase or deeply transform the choices that astronomers had to make when computing. Second, astronomical computations relied on hand-produced texts, tables and instruments, which can show variants of different sorts in different witnesses. We are not comparing here the results of the same procedure executed with variants of the same tables or instruments as they may appear in different manuscript copies.[3] Of course, a given astronomer could have different witnesses of the same work or even collate different versions of a procedural text or of a numerical table and select one which seemed fit in the context of a given computation. Many of these toolbox manuscripts show traces of such collation processes or even, though more rarely, instances of two copies of the same work in the same codex. Our point here is that while astronomers were aware of those discrepancies between manuscript witnesses and had strategies to address them, including explicit strategies of emendation of numerical tables, they would not intentionally create scribal randomness in their computational tools.

In this chapter the object of inquiry will be those sources of variation which imply some sort of intentionality lying between the supra-intentional level of the choices of a community (namely that of preferring Alfonsine astronomy against other astronomical traditions), and the infra-intentional arithmetical and scribal mistakes. Such sources include the choice of the computational tools within the Alfonsine tradition; the choice of the procedure to apply with these tools; and the way to handle approximation, interpolation between values, and precision. Our approach is to consider one specific manuscript and to reproduce the computations to the best accuracy of our historical knowledge. Along the way we analyse the various elements of choices left to the astronomer's appreciation, and the various ways in which the manuscript itself – given its material, visual and intellectual dimensions – orients or constrains these

3 For such analyses see Husson 2021b.

choices. We argue that, as historians, we cannot consider computations in the abstract, disregarding the manipulation of the manuscript, without an essential loss of meaning and understanding. From the point of view of manuscript studies, in highlighting some features of these artefacts and their possible uses by historical actors, we demonstrate the way in which they become scientific tools. From the history of astronomy perspective, we seek a more embedded understanding of astronomical computations, which constitute one of the central practices of the whole discipline.

In the first section we describe the manuscript selected for this analysis and justify our choice: Erfurt, Angermuseum, 3134. The following section is dedicated to the computations of five positions of the Sun and Venus on consecutive days around the spring equinox of 1459 in Erfurt. Each part is devoted to a different computational tool, respectively the *Parisian Alfonsine Tables*, the *Theorice novelle* and the *Tabule magne* (the latter two being included in the manuscript Erfurt, Angermuseum, 3134). These tools, all belonging to the Alfonsine tradition, will be presented in more detail in their respective parts. The *Parisian Alfonsine Tables* are the most widely used table set of the Alfonsine tradition and we use it as a point of comparison for the other two computation procedures.

2 The manuscript and its context

The manuscript codex Erfurt, Angermuseum, 3134, presents itself first as a leather and wood box that is 39 cm long, 35.5 cm wide, and a few centimetres thick. The box shows traces of four clamps, which were used to keep it closed. This leather and wood structure forms the fifteenth-century binding of a thirty-nine folio codex that combined parchment (fols 1–5, 12–13, 20–21, 27–28, and 32–39) and paper (fols 6–11, 14–19, 22–26, and 29–31).[4] Since we had access only to pictures of the manuscript it is not possible for us to determine the exact quire structure of the codex. It is however clear that the document in its current state was assembled in the fifteenth century from different materials deemed to be pertinent by the astronomers who produced the codex.[5] This is one of the frequent and characteristic features of such toolbox manuscripts.

4 Hauber 1916, 59–63.

5 See below for a suspicion of an undocumented restoration intervention in one part of the manuscript at least.

Fig. 1: Erfurt, Angermuseum, 3134, fol. 37r. Theory of the motion of Mercury as a parchment volvelle. In its central volvelle the 'children' of Mercury are represented, including a musician, a sculptor, a painter, a writer, an astronomer and a smith (see Hauber 1916). Photo: Dirk Urban, 2023. Courtesy of Angermuseum Erfurt.

The visual configuration of the manuscript reflects its material characteristics. One can broadly distinguish two large sections of the document on a visual basis. The last one from fol. 32 to fol. 39 has a strong coherence on the level of material, visuals and content (Fig. 1). It was probably an independent codicological unit at some point in the process of production of the codex, although its *explicit* shows that it was completed in the same year, 1459, as were the other parts (fol. 37v). This part contains no text, only a richly decorated series of volvelles (e.g. revolving paper discs attached to the page) dedicated to the computation of celestial positions, which probably deserve an analysis from an art history perspective along with those of astronomy and astrology. The first thirty-three folios of the codex appear as a more complex compilation, given its material and visual diversity. Generally, these folios have much less elaborate decoration than that which is found in the last section of the codex. They contain tables, volvelles and texts presented in diverse ways (Figs 3–5). Tables and instruments are usually presented with two colours – black and red – but significant portions of tables use three colours – black, red, and blue – with a computational meaning attached to this use of colours, indicating different reading directions in the table (e.g. fols 10^r–13^v). The ruling used for the various tables is not uniform and also varies between the tabular and textual parts. While it might be very difficult to decide on palaeographical grounds whether different portions of the manuscript were copied by different hands, this seems highly probable to us. As the changes of hands and page layout do not correspond in obvious ways with the material structure of the codex, it is likely that different actors were cooperating in producing this first part of the manuscript.

Different elements allow us to situate the context of production of this codex with a fair level of confidence and accuracy. At several points in the document (fols 27^r–29^r) the mention of Erfurt and 1458 are attached to some specific astronomical parameters which astronomers call *radices* ('roots'), and are possible initial values for astronomical computations. The historical actors mentioned in the manuscript were masters of arts at Erfurt University or linked to university institutions:

1. Wilhelm Muetlin of Wimppina (fol. 26^r).[6]
2. The 'Bursa lapidis leonis' (College of Steinlauen), the name of a master's college in Erfurt located centrally, next to the town's fish market (fols 26^r, 37^r).
3. Nicholaus Hartmut of Meiningen who was a *baccalaureus* at Erfurt University in 1454, he executed the seven Campanus type volvelles (fol. 37^v).[7]
4. Johannes Pistoris of Herrenberg, a master in Erfurt in 1450, he was the prepositus of the 'Bursa lapidis leonis' (fol. 37^r).

This link to Erfurt University is interesting because this centre was, with Leipzig, one of the early sites for the pursuit of astronomy in German lands. In the middle of the fifteenth century, it was well connected with many other universities with strong traditions in astronomy, like Paris, Oxford, Prague, Krakow, Padova and Vienna. From 1420 onwards, Erfurt and Leipzig Universities, like many others in Europe during the fifteenth century, had the ambition to publish yearly astrologi-

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6 'finite Sunt hec tabule de veris et medijs motibus necnon tabule proportionum omnium planetarum per me Wilhelmum muetlin de vonipina anno domini 1459 Erffordie in bursa lapidis leonis' ('Here ends the table of true and mean motion, not the proportion tables of all planets, by me Wilhem Muetlin of Wimppina on the year 1459 in Erfurt at the "Bursa lapidis leonis"').

7 'Anno 1458 completo hec theorice de motibus septem planetarum Sunt finite per bacc Nicolaum' ('On the complete year 1458 these theories of the motion of the seven planets are achieved by Nicholaus baccalaureate').

cal prognostications. These were complex documents that sought to anticipate the main meteorological, economic and political events of the coming year based on a detailed astrological analysis of the figure of the sky (essentially Sun, Moon and planetary positions as seen from a specific location) at key moments of the year like the solstices, equinoxes, possible eclipses, and so on.[8] Before any such astrological analysis can be done, the luminaries' and planets' positions must be established. If we exclude the cases where this position was directly read on an ephemerides, this required extensive and highly specialised computations, entailing several days of work for an expert astronomer. These prognostications were therefore as much a demonstration of the mathematical, astronomical and astrological skills of those who produced them, as a document for the consideration of the educated public and political elite of those cities.

The established tradition of publishing annual prognostications was a relevant element of the production context of the manuscript, although not unique to Erfurt and Leipzig. More characteristic of these universities was the fact that the astronomers of this period showed particular interest in a certain type of astronomical instrument. They developed a novel type of *equatorium* (instrument for planetary astronomy) which appeared in these milieus for a few decades before vanishing. They named these instruments that were dedicated to the computation of planetary positions *Theorice novelle* (*New Theories*).[9] Erfurt and Leipzig masters produced manuals for their production and use. Built instruments are also usually found as a collection of volvelles in a manuscript. Each volvelle can be used to perform computations to obtain a planetary position. They may or may not be accompanied by texts explaining their uses. This feature of the Erfurt and Leipzig astronomic communities singles them out in the overall late mediaeval astronomical tradition. In most cases, when an active community of astronomers was formed over a few generations of masters and disciples, they usually produced a new arrangement of the astronomical tables, which would become their central contribution. For Erfurt and Leipzig this contribution presented not as a table set, but as a new type of astronomical instrument which developed from 1458 to 1484, as extant sources indicate today.[10] Only very few later copies are known, dating from the early sixteenth century.

One particular version of a *Theorice novelle* instrument is present in the Angermuseum manuscript. The first four folios contain the volvelles dedicated to the computation of the luminaries and planets. It is only on fols 27^{r}–29^{v} that a set of

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8 Tur 2018.

9 Poulle 1980, 375–392.

10 Poulle 1980, 392.

tables and a procedural text indicating the use of the instruments is copied. Between these two portions of the *Theorice novelle* one finds a long tabular work: the *Tabule magne* of John of Lignères, a Parisian master of the 1320s. The *Tabule magne* themselves were not copied in one go. Near the last third, on fols 21^{r}–25^{v}, a long division table was inserted which did not strictly belong to John of Lignères's work, although it could be very useful for computing planetary positions. This way of combining different works into one composite unit was also very typical of toolbox manuscripts in general. We will see in the following section that this entanglement goes beyond the organisation of the content in the codex. It has concrete implications in the way the manuscript can be used as a computation tool, especially to adapt it to the local needs of the astronomer. As mentioned above, the last portion of the codex, from fol. 32^{r} to fol. 39^{v}, contains another type of planetary instrument which is a version of that initially designed by Campanus of Novara in his *Theorica planetarum*. This textbook was very common in mediaeval universities, and many versions of the *Campanus equatoria* are extant in manuscripts.[11] Some of the moving parts of the instrument are now lost so that it would be difficult today to actually use it to produce positions.

When John of Lignères composed the *Tabule magne* in around 1325 in Paris, he had the idea to associate it with an instrument for planetary computation of his own design. None of the twenty-four manuscripts that contain parts of the *Tabule magne* contain a copy of John Lignères planetary instruments. Thus, the close association of the *Theorice novelle* with the *Tabule magne* in the Erfurt, Angermuseum, 3134 manuscript is an interesting feature, which somehow revisits John of Lignères's initial idea with his work. We will thus follow the path suggested by the manuscript itself and compute positions for Venus and for the Sun using the *Theorice novelle* and the *Tabule magne*. This will also be a way to analyse the entanglement of the two tools in this specific context.

11 Benjamin and Toomer 1971.

3 A few positions for the Sun and Venus

3.1 The *Parisian Alfonsine Tables*

The *Parisian Alfonsine Tables* are a set of astronomical tables contained in at least 174 manuscript witnesses from the fourteenth and fifteenth centuries.[12] At least six manuscripts containing this table set extant today were probably available in Erfurt during the fifteenth century.[13] The total number is a measure of the success of this table set within the Alfonsine tradition: it appears to surpass the diffusion of the *Tables of 1322* by John of Lignères, of which a little more than sixty witnesses were identified. This large diffusion began in Paris around the 1320s. While this is the reason why modern scholarship included the word 'Parisian' in the title of this table set, astronomers in the fourteenth and fifteenth centuries were mostly referring to this work with expressions like 'the tables of King Alfonso'. This points to a second essential historical fact about this table set: the elements originate in Al-Andalus and more specifically from the work patronised by King Alfonso X in the later part of the thirteenth century.[14] The exact content of the *Parisian Alfonsine Tables* is subject to variations from one witness to another. It seems clear, however, that the tables pertaining to the topics of chronology, motions of the eighth sphere, and planetary motions are core elements.

The computation of planetary positions with the *Parisian Alfonsine Tables* followed a series of broad steps, common not only in Alfonsine astronomy but more generally in most of the works available to Latin astronomers. In first approximation, positions were computed as if the planets and luminaries had a constant motion: the mean motion. This provided a mean position which was then adjusted by one or two equations in order to find the true position of the celestial object. The important point in the context of this study is to note that the principle of successive approximations to the target celestial position was deeply inscribed in the logic of the computation. How these successive approximations were handled, not only on the level of the individual operations but also more broadly by the design of tools and procedures for computations, is an essential element of the choices that we want to analyse.

12 Figures for the number of manuscripts that attest to Alfonsine works provided in this paper come from a collectively established survey of about one thousand manuscripts collectively in the context of the ERC project ALFA. The survey will soon be available online.

13 Erfurt, Universitätsbibliothek, CA 2° 237, CA 2° 37, CA 2° 384, CA 2° 395, CA 4° 360, and CA 4° 362.

14 North 1977; Poulle 1984; Chabás and Goldstein 2003; Kremer, Husson and Chabás 2022.

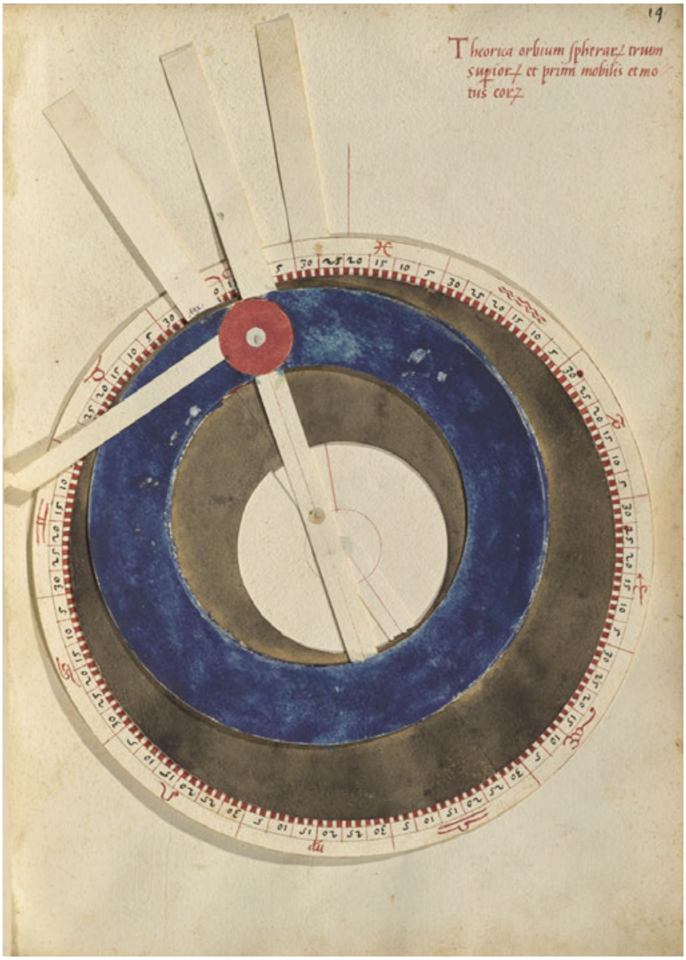

Fig. 2: Paris, BnF, Latin 7276A, fol. 19r. See the eccentric blue ring for the equation of centre, and the epicycle red disc for the equation of argument. Courtesy of Bibliothèque nationale de France.

The computation of the mean position itself is broken down into several steps. First, one needs to know the root (*radix*) of the motions, which is the position of the celestial object at a specific date and place, its initial position. This information is usually found in the Alfonsine tradition in a dedicated table of roots (*radices*) for celestial motion. Then one must use a mean motion table in order to know how much the celestial object has moved between the date of the root and the date chosen for the computation. The addition of the root and the motion found in the mean motion table produces the mean position of the celestial object. This mean position bears the information concerning the date and place of the computation. If the root is not set for the location for which you compute, you also have to consider the difference of meridians between the two places and add or subtract the mean motion of your celestial object during the time separating the two meridians.

Equations must then be applied to the mean position to take into account variations of the celestial object's velocity. These equations can be additive, if the celestial object happens to be faster than its mean motion, or subtractive, if the celestial object happens to be slower than its mean motion. Equations have a geometrical rationale and do not directly depend on the time and place of the computation. We illustrate this with a volvelle instrument of the Campanus type, clearly showing this rationale (Fig. 2). Note that this instrument is not part of the manuscript we are analysing here, and that we have selected it mainly for convenience, for the demonstration. The first equation, usually known as the equation of centre, depends on the eccentricity of the luminary or planet. You can see the eccentric blue ring on the folio in Fig. 2. The Sun, Moon and five planets have an equation of this type. As the planets and the Moon have a more complex motion they require a second equation, known as the equation of argument. It depends on the position of the planet on its epicycle, which is shown as the red circle on the folio in Fig. 2. This geometrical configuration has an important symmetry around the line joining the planet's apogee (the place where the planet is farthest from the Earth) and perigee (the place where the planet is closest to the Earth). This symmetry often plays an important role in the design of computation procedures for planetary positions. This is the case of the *Parisian Alfonsine Tables* one begins by computing the position of the apogee which is assumed to share the same motion as the fixed stars. Then, from the difference of the apogee and the mean position one deduces the equation of centre. In the case of the Sun, the computation stops after the mean position of the Sun has been corrected by adding or subtracting the equation of centre. In short, the computation of the solar position comprises the following steps:

1. Take the *radix* of the Sun.
2. Compute the Sun's mean position and adjust for your place.
3. Find the difference of the Sun's mean position and the apogee (previously computed or given).
4. Compute the Sun's equation.
5. Compute the Sun's true position by correcting its mean position with the equation.

In all the other cases, a second correction (equation) is needed. To obtain it, one has to find the mean position of the planet, or Moon, on its epicycle (the dot at the foot of the paper tab on the red disc, Fig. 2), a value generally named the 'mean argument' in mediaeval sources. From this value, and the previously calculated equation of centre, one computes the second correction, the equation of argument. The equation of argument depends both on the position of the epicycle (red disc) on the eccentric (blue ring) and on the position of the planet on the epicycle (the dot at the foot of the paper tab of the red disc, Fig. 2). It is thus a quantity dependent on two others. Such a mathematical relation between three quantities is not easily presented in a tabular format. In the *Parisian Alfonsine Tables*, as in all tables following the layout of Ptolemy's *Handy Tables*, 'equations' for the Moon and the planets are presented as five dependent tables (all presented on the same grid and sharing the same argument column): one table for the equation of centre; one for the equation of argument; and three tables to interpolate and take into account the interdependence of the two equations which are named *minuta proportionalia* ('proportional minutes'), *longitudo longior* ('farther distance'), and *longitudo propior* ('closer distance'). It is not essential here to explain in detail how this arrangement of tables works; we simply need to remember that it allows one to take into account the fact that when the epicycle is closer to the Earth, the effect of the planetary position on the epicycle is more important than when the epicycle is far from the Earth.[15] Briefly put, in order to compute the position of Venus with the *Parisian Alfonsine Tables* one follows these steps:

1. Take the *radix* of Venus's mean motion (epicycle position).
2. Compute Venus's mean position and adjust for your place.
3. Find the difference of Venus's mean position and the apogee (previously computed or given).
4. Compute Venus's equation of centre (+ *minuta proportionalia*).
5. Take the *radix* of Venus's mean argument (planet on the epicycle).
6. Compute Venus's mean argument and correct it with the equation of centre.
7. Compute Venus's equation of argument and adjust it according to the *minuta proportionalia* and *longitudo longior* or *longitudo propior*, depending on whether the epicycle is closer or farther than the mean distance from the Earth.
8. Compute Venus's position by correcting its mean position with the equation of centre and the equation of argument.

15 Van Brummelen 1994.

To obtain a numerical reference against which to compare the astronomical tools in our manuscript witness Erfurt, Angermuseum, 3134, we have selected six dates around the spring equinox of 1459 and computed the position of the Sun and Venus for the Erfurt meridian with the *Parisian Alfonsine Tables*. It is not necessary to give the detailed computation here since only the results are pertinent for us here as a point of comparison (Table 1).[16] Between 12 and 13 March the Sun is entering Aries, thus marking the spring equinox and the beginning of the (astronomical) year. Venus for its part is slowing down: from 9 to 10 March, it is making a progression of almost eight minutes, while from 12 to 13 March the progression is only thirty-one seconds (almost sixteen times slower). Venus is approaching its 'stationary point' and will soon after begin retrogradation, as can be seen with Venus's position on 14 March. In other words, both the Sun and Venus are near astronomically important points of their trajectory. Finally, it is also significant to keep in mind that naked eye observation would typically not discriminate between differences in positions in the precision of arcseconds. The computations presented here are thus beyond what a fifteenth-century observer could assert. This is a mathematical endeavour.

Table 1: Positions in longitude of the Sun and Venus for Erfurt noon mean solar time, computed with the *Parisian Alfonsine Tables*. The positions are given in degrees in sexagesimal notation (signs of 60°, degrees; minutes, seconds of arc), where the semicolon separates the integer degrees from the minutes.

	Parisian Alfonsine Tables	
	Sun	**Venus**
9 March 1459	5,56;43,47	29;33,13
10 March 1459	5,57;43,03	29;41,09
11 March 1459	5,58;42,15	29;47,15
12 March 1459	5,59;41,24	29;51,30
13 March 1459	0,0;40,32	29;52,01
14 March 1459	0,1;39,40	29;51,06

16 Values have been computed with the 'astromodels' spreadsheet of Richard L. Kremer and Lars Gilsen, which can be downloaded from <https://dishas.obspm.fr/resources> (accessed on 18 July 2023). 'Astromodels' is based on Erhard Ratdolt's princeps edition of the *Parisian Alfonsine Tables* dated 1483 (*Alfontij regis castelle illustrissimi celestium motuum tabule*). The time difference between the meridian of Erfurt and that of Toledo has been taken as one hour according to Kremer and Dobrzycki 1998.

3.2 The *Theorice novelle*

The *Theorice novelle* instruments were devised in the context of Erfurt University around 1450. This type of planetary instrument relies on general principles that are closely connected to those of the above computation with tables like the *Parisian Alfonsine Tables*. The two-step procedure of determining first a mean position and then one or two equations in order to find the true position is maintained. The mean position is found from a mean motion table and a root (*radix*). In the *Parisian Alfonsine Tables,* the time quantity with which one enters the table, and which corresponds to the amount of time between the date for which the root is fixed and the target date of the computation, is expressed as a sexagesimal number of days (and possibly some additional sexagesimal parts of days). This is quite peculiar. In contrast, most of the other table sets in the Alfonsine tradition expressed this time quantity in calendrical units of Julian years, months, days, and hours. This is also the case of the *Theorice novelle* in the Angermuseum manuscript. The roots for Erfurt and the (elapsed) year 1458 are also given in small tables.

While the mean motion part of the operation is obtained through tables, the equations are found through the manipulation of the volvelles and the reading of their scales (Fig. 3). Relying on several ingeniously designed uneven scales, one first reads an equation of centre from the instrument, and second an adjusted equation of the argument, taking into account the varying distance of the epicycle from the Earth (actually changing the size of the epicycle instead of changing its distance). There is a fixed external zodiacal scale serving as a reference for the position of the epicycle on the eccentric. Outside of this scale, a first uneven scale provides the equation of centre. The scale allowing the reading of the equation of centre has a step of 1° comparable to the step of the *Parisian Alfonsine Tables* for that quantity. A second uneven scale, with a step of 1, provides the *minuta proportionalia* and ranges from 0 to 6 on this instrument, while the corresponding table of *minuta proportionalia* in the *Parisian Alfonsine Tables* is much more precise, ranging from 0 to 60. Moreover, a centrally fixed moving volvelle can be adjusted with a paper tab, named the *almuri*, to the fixed zodiacal scale (on the upper part of fol. 3^r, Fig. 3). Pivoting on the same centre there is a second paper tab, the *regula*, used for the equation of argument (at the bottom of fol. 3^r, Fig. 3). A second-degree scale is found on this volvelle. It is divided both into natural signs (twelve times 30°) and physical signs (six times 60°), and serves as a reference for the position of the planet on the epicycle. A second more complex uneven scale associated with a bundle of converging straight lines is spread symmetrically over the volvelle disc. It allows the adjusted equation of argument to be read. This second uneven scale has a step of 1°

and is numbered every 3° (see the central part of the instrument in Fig. 3). We assume that interpolations between the marked graduations are made ‘visually’ when reading these scales. Step by step the value of each of these two equations is found, then added to or subtracted from the mean position by turning the *almuri* by the equation’s quantity, as the instrument scales themselves prescribe (the numbers on the scales are tagged by ‘a’, for addition, or ‘m’, for subtraction), until the true position results.

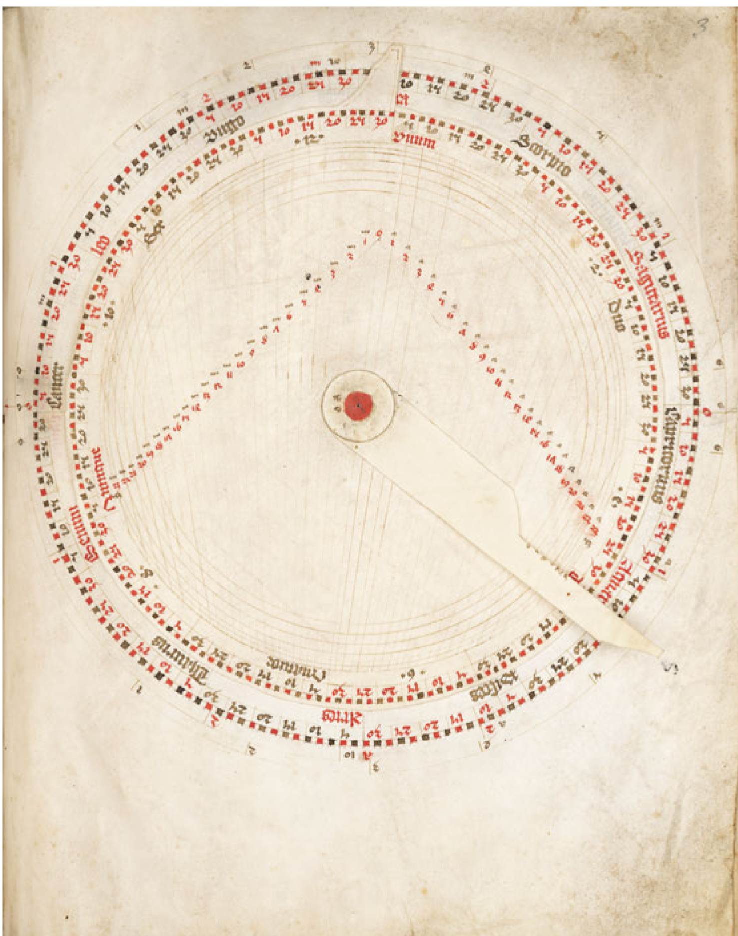

Fig. 3: Erfurt, Angermuseum, 3134, fol. 3^{r}. *Theorice novelle* for the Sun and Venus (during a restoration, the volvelle of Mercury, with maximum equation of *c.* 22°, has been wrongly inserted on this page during a restoration). Photo: Dirk Urban, 2023. Courtesy of Angermuseum Erfurt.

To compute a mean solar position at noon in Erfurt for 12 March (incomplete)[17] 1459, one begins by reading on fol. 27v the root (*radix*) of the Sun for Erfurt in 1458 *completo* ('complete'), meaning that 1458 Julian years have elapsed since incarnation at the time for which the root value is given. The value 4,48;31° is found. Then, on the same folio, one reads from the mean motion of the Sun table, the motion of the Sun for the first two elapsed months of the year, and adds the value of eleven elapsed days to it. This amounts to 1,8;59°. One then has to add the value of the root to the value of the mean motion in order to find the mean position. This produces 5,57;30. However, looking closely at the format of the numbers, the experienced astronomer will be able to deduce that they are expressed in physical signs of 60°, in the fashion of the *Parisian Alfonsine Tables*, from which these roots and mean motions were very likely computed. The outer scale on the *Theorice novelle* instruments uses natural signs of 30°. In fact, they are marked with their names (*aries*, *taurus*, *gemini*, etc.) rather than numbered. Thus, before entering the instrument scale, a conversion needs to be performed so that the mean position number depends on the same numeration system as the outer scale. Converted to natural signs of 30°, the mean position is 11s 27;30. While this conversion is a rather trivial operation, the scales of the argument on the epicycle of the instrument have a nice layout that mixes the 30° and 60° types of signs. This allows the conversion between the two notation systems to be obtained graphically.

To find the equation of centre for the Sun, one opens the codex on fol. 3r where the instrument for Sun and Venus is inserted, and one adjusts the small paper tab of the central volvelle, named *almuri*, on the outer zodiacal scale to the required value of the mean position. In our case, it is *pisces* 27;30°. There is no need to look for the position of the apogee or perigee, for they are materialized on the instrument as the origin (zero) of the uneven graduation for the equation of centre. In other words, when the instruments were designed the apogees were fixed once and for all. They do not share the motion of the eighth sphere and fixed stars as they do in the *Parisian Alfonsine Tables*. Given the very slow motion of the fixed stars this approximation is of little numerical consequence if the instrument is used for dates close to the date for which the apogees were fixed. So once the *almuri* is positioned, one estimates from the outer uneven scale the value of the equation of centre. Our estimation is 2;7° in this particular case (Fig. 4). This estimation is by essence very subjective. It depends, specifically, on the understanding one has of the quantitative behaviour

17 According to the convention in the *Parisian Alfonsine Tables*, 12 March begins at noon. Correspondingly, the eleventh day has elapsed at 12 noon on the day that has the date 12 March.

of the equation of centre in the region of the scale where it approaches its maximum value. Given that the two authors have already spent several years examining tables and instruments of this kind, the proposed estimation is certainly informed by this long previous experience, perhaps not unlike an estimation made by the masters using this manuscript in the fifteenth century. Readers are encouraged to make their own estimation and experiment. The values of this equation's graduation are marked with an 'a', indicating that it must be added to the mean position to get the true position. This addition can be done in two ways. The first is by manually moving the *almuri* by 2;7° in the positive direction and reading the true solar position from the scale at the *almuri's* new position. When performing the addition manually (i.e. graphically) it is impossible to achieve accuracy by taking into account single minutes of the equation. Thus, in this case the true solar position obtained is around *pisces* 29;30. One can also, however, perform the addition arithmetically. In this case the value *pisces* 29;37° is found. For the sake of comparison with the *Parisian Alfonsine Tables* we will consider this second more precise value. This again is a subjective choice.

For some astronomical reasons which are not relevant here, Venus and the Sun share exactly the same mean motion and equation of centre.[18] For the instrument design, this means that the Sun and Venus share the same volvelles. Only the equation of centre part is used when computing a solar position, while the central volvelle must be used to compute Venus's equation of argument. However, in the manuscript in its current state, the central volvelle of fol. 3^{r} is not that of Venus but that of Mercury. The volvelle for the equation of argument of Venus is found on the next page on fol. 3^{v}. We think this disorder is the result of a later undocumented 'restoration' of the instruments in the codex. This points to the fragility of these paper or parchment instruments with moving parts that could easily lose connection with their original location. As far as the computation is concerned, the first steps of computing Venus and solar positions are exactly the same. The mean position of Venus's epicycle centre is equal to the mean position of the Sun, so for Erfurt, noon of solar mean time on 12 March 1459, equals *pisces* 27;30°. Corrected with the equation of centre, this produces *pisces* 29;37°.

18 Pedersen 2011, 295–328.

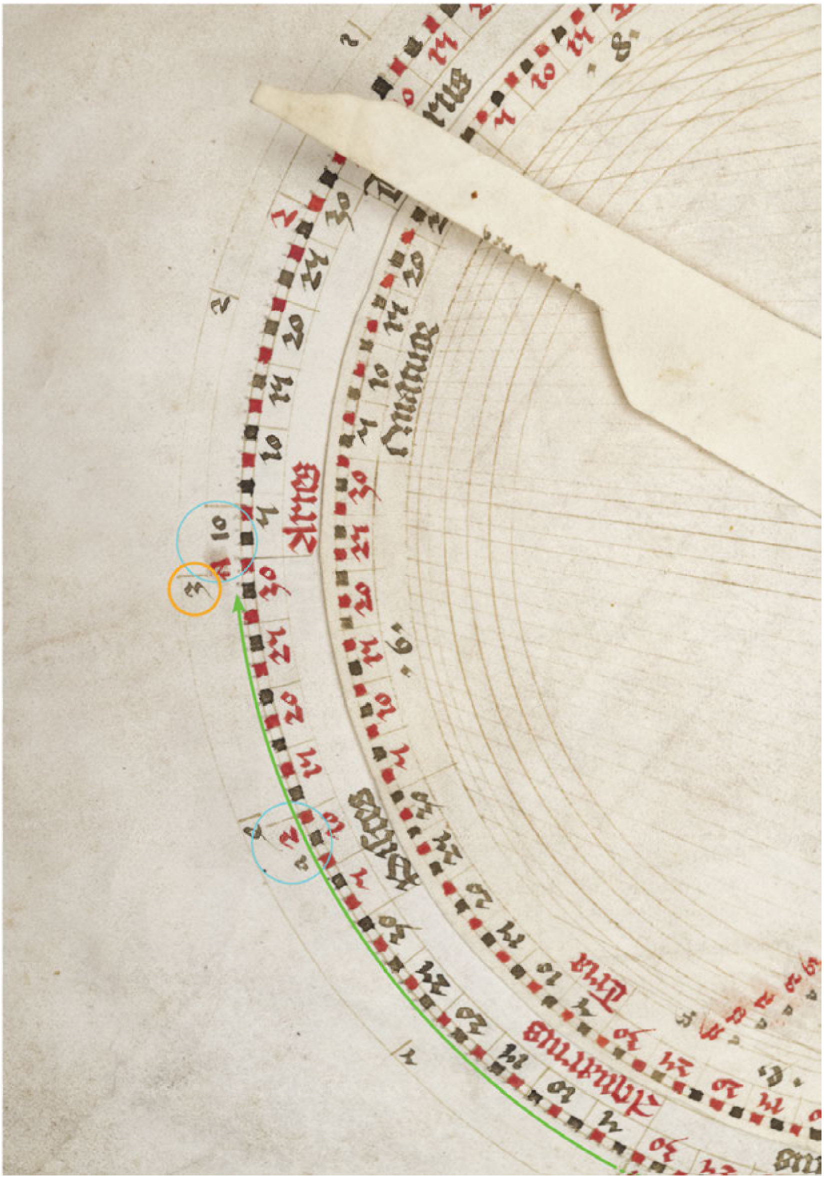

Fig. 4: Erfurt, Angermuseum, 3134, fol. 3r, detail. The green arrows mark the mean position of the Sun 11s, 27;30°. The number 3, circled in orange, gives the value of the *minuta proportionalia* for this position. The two blue circles mark, ‘a 2’ and ‘a 2;10’, corresponding to the value of the equation of centres between which we visually estimate a value of +2;7°. Photo: Dirk Urban, 2023. Adapted and annotated by the authors. Courtesy of Angermuseum Erfurt.

To obtain the second equation of this position one needs to compute Venus's position on its epicycle (true argument). The corresponding process using the *Theorice novelle* instrument is very similar to the one we have already described starting with mean motion. On the folio opposite the one with the mean solar motion, fol. 28r, one reads the root of Venus's argument as 2,4;56°. Using the table on the same folio one adds up the mean motion for two months and eleven days, yielding a mean motion of the argument of 1,13;19°. Adding the root and the mean motion of Venus's argument produces 2,48;15°. Now, the *regula* (the long, centrally fixed paper ruler) is positioned at the same step as adjusting the *almuri* on the solar mean position. That means that one uses the mean motion information from the tables on fols 27v and 28r, gathered in advance, to set the two volvelles of the instrument (*almuri* and *regula*) to their initial position. One begins by setting the *almuri* to the mean position of the Sun, holding the *almuri* with the 'epicycle' volvelle to which it is attached in its position. One then adjusts the *regula* to 2,48;15° on the scale inscribed on the rim of the 'epicycle'. As before, because this scale is graduated in natural signs of 30°, one can convert 2,48;15° into this format, that is, 5s 18;15°. Alternatively, as the signs of 60° are also marked on that scale, one could enter directly with 2,48;15°.

This is the moment when a crucial operation with the volvelles needs to be carefully performed. While the *almuri* of the 'epicycle' volvelle is moved from the mean position of Venus (and the Sun), that is, *pisces* 27;30, to the true position by manually/graphically adding the equation of centre 2;7°, it is crucial that the previously set *regula* be maintained in its absolute position in order to obtain *pisces* 29;37. This shift will automatically affect Venus's argument: it amounts to graphically subtracting the equation of centre 2;7° from the mean argument of Venus 5s 18;15°. Although the scale division is not detailed enough, showing slightly more than 5s 16;0°, a trained computer will quickly mentally subtract the numbers and find 5s 16;8° for the true argument of Venus. Once this is done, it is possible to read on the outer scale of the fixed zodiacal ring the *minuta proportionalia*: 3, in our case.

The configuration of the instrument now allows one to use the last uneven scale and read the equation of the argument (Fig. 5). One first looks at which of the three concentric circles corresponds to the *minuta proportionalia*. In our case, with a value of 3, the central concentric circle is selected. Then from this circle one follows the closest lines in the bundle of straight lines and reads off the equation of argument, finally interpolating by a graphically estimating a value. In our case this produces 28;0° with a sign 'a' of addition. The final step is a simple addition of 28;0° to *pisces* 29;37°, which produces *aries* 27;37° or simply 27;37° because *aries* is the first zodiacal sign.

Fig. 5: Erfurt, Angermuseum, 3134, fol. 3ᵛ, detail. The green arrow marks the true argument of Venus 5s 16;8° between the *almuri* and the *regula*. Selecting the inner circle corresponding to the value 3 of the *minuta proportionalia*, one follows the closest straight line from there to the v-shaped graduation in the centre of the volvelle and reads ‘a 28’. This is the value (*a* for additive) of the equation of argument in degrees. Photo: Dirk Urban, 2023. Adapted and annotated by the authors. Courtesy of Angermuseum Erfurt.

Examining the positions on successive noons between 9 and 14 March obtained with the *Theorice novelle*, two things come to the mind (Table 2). First, while the spring equinox occurs between 12 and 13 March as with the *Parisian Alfonsine Tables*, in comparison the Sun appears to be slightly behind with the *Theorice novelle*. A more striking difference concerns the behaviour of Venus. While using the *Parisian Alfonsine Tables* Venus was slowing down in direct motion before reaching a stationary point, the *Theorice novelle* Venus is neither stationary nor direct or retrograde but somehow erring randomly between these different states. Such behaviour cannot be ascribed to the real motion of Venus. In fact, astronomers in this tradition usually assume that the first differences of any astronomical quantity should change slowly and smoothly. This assumption grounded their practices of interpolation and some of their practices of table emendation. In our case, these assumptions completely exclude, even on purely mathematical grounds, the behaviour here witnessed for Venus. Thus, in all likelihood, Erfurt masters would have identified it as a mathematical artefact pointing to the structural limit of their instrument.

Numerically, this erratic behaviour occurs because the order of magnitude of the approximation made during the interpolation operations are similar to the order of magnitude of the variation of the quantity that is interpolated. This occurs when the quantity is near one of its boundaries and when the step of interpolation is too large. This computational phenomenon, we surmise, was probably familiar to many astronomers. However, the cost of overcoming it is high, and there are only two options. First, one can refine the step of interpolation, which would require changing the instrument, being able to compute a more precise and accurate value of the target quantity and being able to draw more precise scales. Or, one can try to improve the interpolation procedures themselves to adapt them to these situations, which is a non-trivial mathematical problem. Both of these strategies were adopted by different astronomers, including John of Lignères in his *Tabule magne*.

Table 2: Position for the Sun and Venus with the *Theorice novelle*. While the Sun's position increases at a close to uniform pace, Venus shows erratic behaviour. It seems to move backwards, slowing down dramatically, then moves forwards and backwards again.

	Theorice novelle	
	Sun	**Venus**
9 March 1459	*pisces* 26;39	*aries* 28;9
10 March 1459	*pisces* 27;39	*aries* 27;39
11 March 1459	*pisces* 28;38	*aries* 27;38
12 March 1459	*pisces* 29;37	*aries* 27;37
13 March 1459	*aries* 0;37	*aries* 28;37
14 March 1459	*aries* 1;36	*aries* 27;36

3.3 The *Tabule magne*

The *Tabule magne* were composed and compiled in around 1325 in Paris by the Parisian master John of Lignères. They had a much more modest diffusion than the *Parisian Alfonsine Tables* (twenty-four known witnesses) but a considerable reception nonetheless, as in the mid-fourteenth century they inspired in one way or another the *Oxford Tables*, an important table set of the Alfonsine tradition.[19] The *Tabule magne* adhere to the overall structure of planetary computation: the mean position is determined first, then adjusted with an equation in order to obtain the true position. Unlike the *Theorice novelle*, they use exclusively natural signs of 30°. Usually, the roots and positions of the apogees are given for Paris in dedicated tables. Interestingly, these tables for the roots and the apogees, not directly pertinent for Erfurt, were not copied in the Angermuseum manuscript. Instead, to use the tables one has to rely on the roots given in the mean motion tables for the *Theorice novelle* and, on the apogee, values that can be read on the instrument dials. In particular, in this configuration the apogees of the *Tabule magne* are fixed once and for all, and the approximation inherent in the *Theorice novelle* will also affect the *Tabule magne*. This shows that the entanglement of the works contained in the manuscript also impacts the way the computation can be performed. By not including the roots for Paris belonging to the *Tabule magne*, a selection is made, which adapts the toolbox for the location of Erfurt. More prosaically, this will also imply some further number conversion between the systems of natural and physical signs.

The main feature of the *Tabule magne* concerns the treatment of the equations (except for the Sun). Instead of two successive equations which then need to be combined through a complex procedure and the use of three auxiliary tables, John of Lignères prepared a single large double-argument table. The two arguments are the mean centre and the mean argument. Entering the table with these directly gives the values of the equation of centre and the equation of argument combined. These tables are generally presented with steps of 6° for the value of the mean centre (position of the centre of the planet's epicycle) and mean argument (position of the planet on its epicycle). In the cases of Venus and Mars, however, a step of 3° is used for the argument around the value where the equation of argument reaches its maximum. In other words, John of Lignères, probably tried to avoid or mitigate exactly the kind of numerical phenomenon seen in the case of the *Theorice novelle*. He used the above-mentioned first strategy of mitigation by refining the step of interpolation. John of Lignères also explored the strategy of working on the interpolation procedures. In fact, this was a necessity because no standard practices for double argument table interpolation were explicitly available in Paris during the fourteenth century. The instruction text circulating with the *Tabule magne*, not extant in our manuscript but extant in other manuscripts, presents two distinct interpolation pro-

19 North 1977.

cedures.[20] It is sufficient for our argument here to rely only on the simpler one of these two procedures.[21]

In order to compute the position of the Sun in Erfurt for 12 March 1459, one first looks for the root of the Sun's motion on fol. 27^{v} in the small tables copied with the *Theorice novelle* instruction text. The value 4,48;31° (corresponding to the Sun's position at the very end of the year 1458) is found, which needs to be converted in natural signs of 30° in order to operate within the *Tabule magne*. This produces 9s 18;31°. One then reads from the mean motion tables on fol. 6^{r} the mean motion of the Sun for two months and eleven days, to obtain 2s 8;59,43°. Added to the root of the Sun motion this gives a mean solar position of 11s 27;30,43°, after which the position of the apogee must be read on the volvelle of the Sun and Venus on fol. 3^{r}. As the scale is divided into degrees, the value cannot have a precision beyond a simple fraction of one degree; it is approximately 3,1;0°. This value is then subtracted from the Sun's mean position, which produces 8s 26;30,43°, corresponding to the Sun's 'mean argument': the mean anomaly. Reading and interpolating from the single-argument table of the solar equation on fol. 21^{r}, one finds a solar equation of 2;10,0° with this value. The true solar position, finally, is obtained by the addition of the equation to the mean position, that is, 11s 29;40,43.

As before, the computation of Venus's position begins with exactly the same steps so that the mean position of the centre of Venus's epicycle is 11s 27;30,43° and the 'mean centre' of Venus is found by subtracting the apogee read on the scale of the *Theorice novelle* instrument. Venus's mean centre equals the mean anomaly of the Sun, 8s 26;30,43°. The root of Venus's mean argument (position of Venus on its epicycle) is read on fol. 28^{r} in the small tables associated with the *Theorice novelle* which give, as above, 2,4;56° or 4,4;56° when converted to natural signs of 30°. Using the mean motion table of the *Tabule magne* on fol. 6^{r} to find a mean motion of the argument is easy, as it presents the final value for each calendar day of the year. Entering at 11 March (completo), which corresponds to noon on 12 March, one finds a mean motion of argument of 1s 13;9° which, added to the root, gives 5s 18;5 as the mean argument.

The mean centre, 8s 26;30,43, and the mean argument, 5s 18;5, are the values used to operate with the double-argument equation table for Venus of the *Tabule magne*. In the corresponding area of the table the steps are respectively 6° for the mean centre (step_cent), read horizontally, and 3° for the mean argument (step_arg), read vertically. In other words, one has to interpolate between the columns under the headings 8s 24;0° and 9s 0;0° for the mean centre and be-

20 Erfurt, Universitätsbibliothek, CA 4° 349 and CA 4° 366.

21 For a comparison and description of the two procedures, see Husson 2012.

tween the lines labelled 5s 18;0° and 5s 21;0° for the mean argument. We have represented a simplified version of the situation in Table 3 (without the vertical tabular differences that are given in the manuscript, added in black ink). The simple interpolation procedure is based on the three values printed in bold in Table 3. Following the description of the canons, we name these three values from their respective positions in the table: top_right, top_left and bottom_right values. In addition to these three values one needs to compute or read the vertical difference (diff_arg) between 32;25 and 27;39, that is 4;46, and the horizontal difference (diff_cent) 32;25 and 32;21, that is 0;4. One needs also to compute the excess of the mean argument over the value of the heading by which one entered the table (res_arg), that is in our case, 5s 18;5 minus 5s 18;0, equal to 0;5, as well as the excess of the mean centre over the value in the heading of the table (res_cent), that is our case 8s 26;30,43 minus 8s 24;0, equal to 2;30,43. The simple interpolation procedure can be expressed by the following algebraic expression

$$eq = top\_left + \frac{diff\_cent \times res\_cent}{step\_cent} + \frac{diff\_arg \times res\_arg}{step\_arg}$$

Table 3: Reading situation of Venus equation in the *Tabule magne* for 12 (incomplete) March 1459. In the column on the left, values of the mean argument (signs and degrees); in the top row, values of the mean centre.

		8, 24	9, 0
5, 18		**32;25**	**32;21**
5, 21		**27;39**	27;29

This algebraic formula involves executing divisions and multiplications as well as managing the positive and negative values of the differences. Rules for these steps are explained in detail in the procedural texts (canons), which are not included in the Anger manuscript, however. Each of these operations can be executed in different ways, especially the multiplication and division, for instance relying or not relying on the proportion table like the one found in our manuscript, transforming the numbers into decimal numbers or not, or using truncation or rounding differently in different steps.[22] We have performed these computations with a truncated precision to the second. Other choices, especially using a proportion table or not, will give different results. We have not explored this layer of complexity here. In the case at hand and under these conditions the simple interpolation gives a total value for the equation of 1s 02;24,54 and then a true position for Venus of 29;51,37.

Table 4: Solar and Venus positions computed with the *Tabule magne*. Note that the number format (visible for the solar positions only) uses signs of 30°, which is consistent with the usage in the *Tabule magne*.

	Tabule magne	
	Sun	**Venus**
9 March 1459	11s 26;43,42	29;26,23
10 March 1459	11s 27;42,19	29;30,38
11 March 1459	11s 28;41,32	29;37,19
12 March 1459	11s 29;40,43	29;46,05
13 March 1459	0s 0;39,51	29;45,47
14 March 1459	0s 1;38,59	29;45,29

Examining the positions produced for five successive days, one notices that the Sun of the *Theorice novelle* and of the *Tabule magne* have fairly similar behaviours when compared to the Sun of the *Parisian Alfonsine Tables*. The most intriguing series of discrepancies again appears in the case of Venus. With the simple interpolation, Venus reaches the stationary point some time between the noons of 12 and 13 March, after which the planet begins its retrogradation. The behaviour is a few days in advance compared to that of the *Parisian Alfonsine Tables* Venus but the series of values represents a motion consistent with theory.

4 Conclusion

By re-enacting a series of computations using astronomical tables and instruments available in one single historically bound codex, an obvious conclusion follows: fifteenth-century astronomers did not depend on the theoretical plane-

22 For a study of multiplication procedures in the context of Sanskrit mathematical sources, see the contribution by Agathe Keller in this volume.

tary models and certain traditional motional and structural parameters alone. The situation typically was much more complex. As soon as we consider computation as a practice performed with manuscripts, this insight becomes unavoidable. One realises that practical astronomers were confronted with a series of choices when performing their computations – choices that depended on the content available in a given manuscript and that often profoundly influenced the result and meaning of the computation.

The manuscript we have examined, Erfurt, Angermuseum, 3134, provides us with an illuminating example. At a first level, the physical examination of the document shows that the astronomers who assembled the manuscript deliberately chose to entangle two different works, the *Theorice novelle* and the *Tabule magne*, into one complex computational tool. This is the first level of choice and agency we have examined. The two works are complementary in many ways. The *Theorice novelle* are used as a means to adapt the *Tabule magne* to Erfurt rather than Paris. This is also achieved by not including in their copy of the *Tabule magne* the specific root tables which would link them to Paris. The *Theorice novelle* can serve to quickly find an approximate position while avoiding any arithmetic beyond addition and subtraction; interpolations are performed 'visually'. The *Tabule magne* offers more precise results than the *Theorice novelle* and a considerable reduction of computational work, which also reduces the risk of mistakes as compared to the usual procedure with the *Parisian Alfonsine Tables*. Moreover, including two different tools to find planetary positions in one codex offers the possibility of cross checking and comparing the results obtained by each of them. While the *Tabule magne* with their double argument tables, completely bypass and transform the understanding of the respective role of the eccentric and epicycle, the *Theorice novelle* proposes an ingenious graphical-mechanical device to separately analyse the computational influence of each of these two components.

The fact that the manuscript affords various different procedures is the second level of agency that was analysed. Our guiding question here was: how could a fifteenth-century astronomer have proceeded to get planetary positions from the tools available in this one manuscript? What we have numerically explored, represents only a small portion of these possibilities. For instance, one could use the *Tabule magne* mean motion tables with the volvelle of the *Theorice novelle*. We have explored neither the effect of alternative interpolation procedures, nor different ways to compute division and multiplication when computing interpolation. Even by limiting ourselves to this rather small set of computational choices, the range of discrepancies between the results and, most of all, their drastic effect on the very nature of the predicted astronomical phenomena is sufficiently clear. It is important to note that these differences appear even if the computational procedures give overall consistent results, usually diverging only within a few arc minutes, in rare cases up to one degree. Fifteenth-century astronomers, when adequately trained, were prepared to handle these discrepancies. They needed continuously to make choices resulting in discrepancies at this order of magnitude, for instance when doing an addition of numbers given with different precision, or deciding where to truncate the result from a division. Instruction texts of different kinds often contain warnings or advice on the importance of these choices. These practices, however, are mostly uncharted by modern scholarship and can only be analysed from the consideration of computations as performance with manuscripts. This highlights the extent to which performing and interpreting such computations depended as much on the document as on the astronomer's expertise.

Undoubtedly, adding more toolbox manuscripts to the analysis, considering more computation scenarios and computing more positions can only increase and never decrease the diversity of results and its potential astronomical and mathematical meaning for historical actors.

On both levels, the material, visual, and intellectual plasticity of the codex had a central role in allowing astronomers to compose their toolbox. In doing so they entangled tools they had recently composed with others established in their tradition for more than a hundred years, associating tables, texts and graphical elements that could then be combined in many different procedures. This custom-made capacity of the codex then afforded astronomers the opportunity to tailor their toolbox to their needs and to balance the mathematical and astronomical strengths and weaknesses of the different astronomical works they combined.

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