Learning Medieval Astronomy Through Tables: The Case of the *Equatorie of the Planetis*

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Abstract.† Medieval tables can be rich sources of evidence about the practices of the mathematicians and astronomers who used them. This paper analyses an important set of tables, revealing their compiler's learning practices and elucidating a valuable document of inexpert science. Peterhouse, Cambridge MS 75.I, 'The Equatorie of the Planetis', is a late-fourteenth-century compilation. It contains a treatise describing the construction and use of an equatorium (an astronomical instrument that computes the positions of the planets), bound with a collection of related astronomical tables. It was long thought to be written by the English poet Geoffrey Chaucer, but has recently been shown to be the work of a Benedictine monk, John Westwyk. This paper reassesses the manuscript as a monastic compilation. Westwyk copied a set of astronomical tables that suited his needs; their use supported and complemented the equatorium he describes in his treatise. He experimented with different techniques, cited astronomers whose work he admired (including Chaucer) and refined his tables in order to obtain the greatest possible precision. By reconstructing Westwyk's mathematical practices in compiling, computing and using tables that required and enabled a range of astronomical techniques, this paper paints a vivid picture of inexpert science in medieval Europe.

Keywords. Tables, astronomy, medieval, instruments, practices

> The fifthe partie shal be an introductorie, after the statutes of oure doctours, in which thou maist lerne a gret part of the generall rewles of theorik in astrologie. In which fifthe partie shalt thou fynden tables of equaciouns of houses after the latitude of Oxenforde; and tables of dignitees of planetes, and othere notefull thinges [Middle English quotations are translated in endnotes].[1]
>
> Geoffrey Chaucer (1988, p. 663)

Chaucer's desire to help his son Lewis – and perhaps other readers – 'lerne sciences touching nombres and proporciouns' is familiar to readers of his *Treatise on the Astrolabe* (Chaucer, 1988, p. 662).[2] But while the potential for learning through the use of an instrument has been accepted and widely discussed since Chaucer's time, less has been written about the connection between tables and learning practices in astronomy. Tracing past learning processes is always

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difficult, particularly if we wish to focus on the reception and absorption of knowledge rather than the mechanisms and institutions through which knowledge was communicated: learning, rather than teaching (Bernard and Proust, 2014).[3] Moreover, although the abundance of tables in medieval scientific manuscripts is testament to their popularity, identifying the methods by which astronomers learnt to use tables, or learnt theories and techniques through tables, is especially difficult since they are rarely accompanied by didactic text; explicatory canons which do sometimes direct their users are invariably written in spare instructional prose, and there are few clues as to how, or by whom, such canons were followed.

Nevertheless, medieval tables can be rich sources of evidence about the practices of the astronomers who used them. And where those astronomers lack expertise, we can draw conclusions about the ways that they learnt and practised mathematical techniques through such use. The *Equatorie of the Planetis* (Peterhouse, Cambridge MS 75.I) is a valuable document of such unpolished astronomy. It comprises a fourteenth-century draft treatise describing the construction and use of an equatorium, an instrument that computes the positions of the planets, bound with a collection of related astronomical tables. Its first editor, Derek Price, suggested that this treatise was 'obviously intended for the amateur rather than the professional' reader (Price, 1955, p. 159). His implication, supporting his contention that the *Equatorie* represented Chaucer's completion of his *Treatise on the Astrolabe* (it incorporates much of the content Chaucer had promised for the *Astrolabe*'s third, fourth and fifth parts), was that its author was a competent astronomer writing for a less learned pupil. But Price, concerned above all to prove Chaucer's authorship of the treatise, did not consider it in its codicological context. He dismissed the tables that comprise the bulk of the manuscript as 'of comparatively slight interest since they are a simple modification of the well-known Alfonsine tables', and thought it 'only necessary to indicate their content and the manner in which they have been modified' (Price, 1955, p. 75). Similarly, John North, despite stating that 'the sheer aptness of *all* the tables in the codex for use with the equatorium cannot be too strongly emphasized', gave almost no explanation of that use (North, 1988, p. 176; his emphasis).

North surmised that the *Equatorie of the Planetis* was the work 'of a generally competent if not fully confident astronomer' (North, 1988, p. 170); that astronomer has recently been identified, on palaeographical grounds, as John Westwyk, a monk of St Albans monastery and Tynemouth priory (Rand, 2015). This paper will analyse the fascinating, varied tables, all either written or annotated by Westwyk, alongside the instrument they accompany. When one examines the tables closely and considers their use both with and without the instrument, their heterogeneity stands out, and the conclusions of Price and North quoted above begin to seem rather bold.[4] These scholars, influenced by the seminal history of mathematical astronomy of Otto Neugebauer, rightly saw the *Equatorie* within a wide-ranging, enduring network that communicated astronomical theories and instruments across the medieval world. I take a different approach. Rather than emphasizing the continuity visible through these tables, this paper will emphasize the individuality of their production, the specific historical context of their use. It takes the manuscript's 78 folios together as a personal compilation, revealing much about its producer's priorities, learning processes, and level of expertise. At the same time, this paper has a mathematical focus, exploring what we can learn through a reconstruction of Westwyk's practices in compiling, computing and using tables that required and enabled a range of astronomical techniques. It is hoped that this combination of computational and contextual methodologies will provide new insights into these astronomical tables and instrument, as well as the man and environment that produced them.[5]

The *Equatorie*: instrument and tables

John Westwyk's equatorium (Figure 1) was, he writes, 'compowned the yer of Crist 1392 complet the laste meridie of decembre' (Peterhouse, Cambridge MS 75.I, f. 71v; all folio

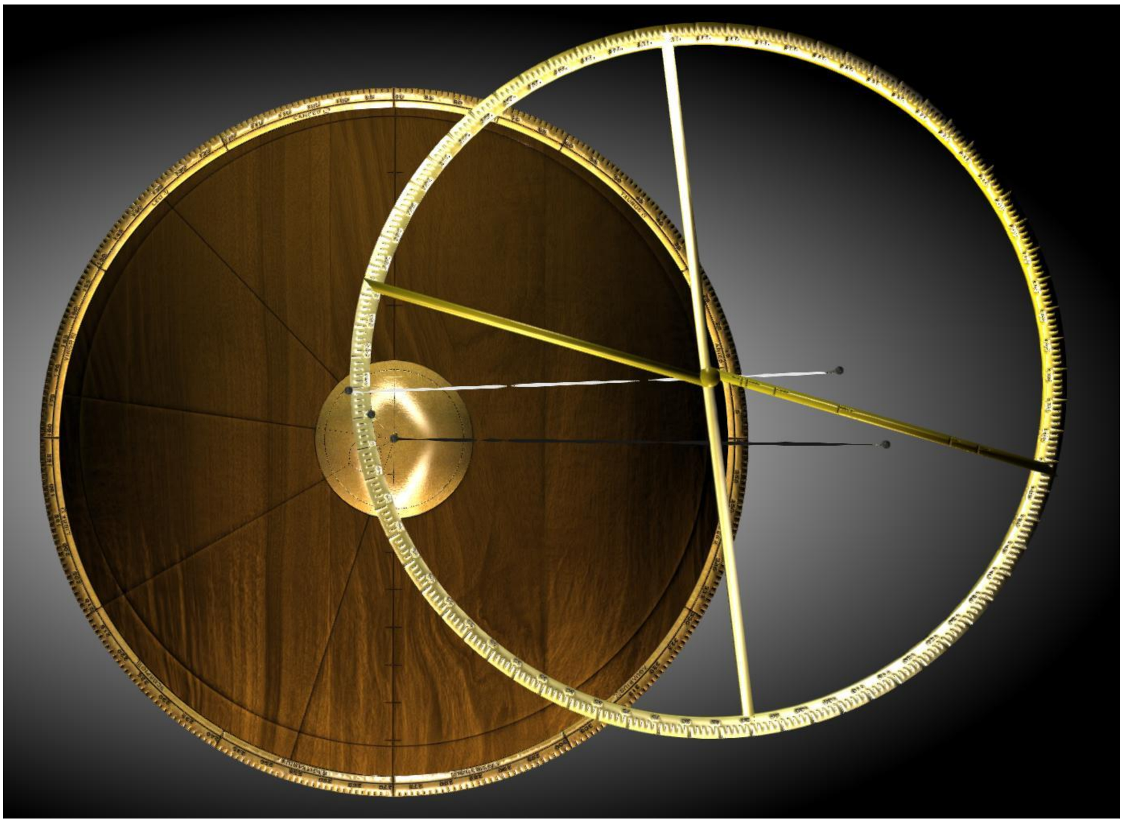


Fig. 1: Virtual model made according to the instructions in Peterhouse MS 75.I, by Ben Blundell and Seb Falk for the Cambridge Digital Library. See http://cudl.lib.cam.ac.uk/view/MS-PETERHOUSE-00075-00001 for further explanation and interactive model. See also Price (1955), pp. 93-118. Reproduced by permission of the Master and Fellows of Peterhouse, Cambridge.

references will be to this manuscript, unless stated otherwise).[6] Like other equatoria, this instrument requires an input of mean motion data in order to compute the longitudes of the planets (including the Sun and Moon); the necessary tables of mean longitudes and mean anomalies, with radices for 1392, are found, written in Westwyk's hand, in the first folios of the manuscript.[7] Westwyk names Chaucer as a source for these radices and elsewhere cites the *Treatise on the Astrolabe*; the influence of Chaucer's remark that 'smallist fraccions ne wol not be shewid in so small an instrument as in subtile tables calculed for a cause' (Chaucer, 1988, 663)[8] is apparent in Westwyk's opening statement that 'the largere þat thow makest this instrument, the largere ben thi devisiouns; the largere þat ben tho devisiouns, in hem may ben mo smale fracciouns; and evere the mo of smale fracciouns, the ner the trowthe of thy conclusiouns' (f. 71v).[9] From the very beginning of the treatise, then, Westwyk shows awareness that instruments and tables represented competing (and complementary) methods of computing planetary positions; these methods had to balance speed and convenience against precision.[10] It may also be suggested that learning different techniques was an objective in itself, separate from the ultimate outcome of finding positions. Peterhouse MS 75.I reveals how Westwyk tried two alternative techniques: the use of an equatorium with tables, and the use of tables alone.

For the former, the first set of tables in Westwyk's hand (folios 1r-13v) is perfectly sufficient; of them it would be correct to say, as North rather exaggeratedly said of the whole codex, that they are entirely apt for use with the equatorium, and it seems likely that Westwyk drew them up for that purpose. They are broadly standard tables in the Parisian Alfonsine tradition, supplying daily and annual changes in position of three sets of data: the planetary apogees, mean longitudes and mean anomalies (see Table 1).[11] The equatorium incorporates two further sets of data – the eccentricity of each planet's deferent circle, and the relative sizes of their deferents and epicycles – so that the user is required only to extract radices and mean motions from the tables, perform some simple additions or subtractions, and lay out the instrument's brass ring and black and white threads as Westwyk explains, in order to read the true planetary longitudes on the ecliptic scale on the equatorium's limb. The 72-inch diameter Westwyk stipulates would allow planetary longitudes to be read at a precision of around 2' of arc; the whole process for each planet can be accomplished within a few minutes. It would probably have taken him somewhat longer to carry out the calculations and interpolations involved in using the tables on their own. (Those methods, using the tables on ff. 45r-61r, are discussed later in this article.)

Table 1: Contents of Peterhouse MS 75.I

ff. 1r-13v in John Westwyk's hand	
1r	Note with sexagesimal equivalent of 1392, 1393 years; table to convert years to days Radices of mean longitude and mean anomaly of planets for 31 Dec 1393 Table of annual motion of deferent centre of Moon (radix for Incarnation, London)
1v-3r	Annual motion of mean longitude and mean anomaly of Moon, Caput Draconis and planets, with radices for Incarnation, London
3v	Annual values for mean motus of ascendant for latitude 51;34°; radix for 28 Feb 1393
4r-4v	Ascensions of signs for latitude 51;50° Tables to convert between hours and sexagesimal fractions of day
5r	Radices of mean longitudes and anomalies, 31 Dec 1392 and Incarnation, London Radices of mean apogees, Incarnation, London
5v	'Radix chaucer' note giving number of days in 1392 years; note with days in 1395 years Multiplication table for orders of sexagesimals; table to convert between years and days
6r	Daily motion of mean argument of 8th sphere
6v	Apogees of planets for Incarnation, 1392, 1400 Radix for mean elongation of Moon, Incarnation, Toledo
7r	Annual motion of mean longitude of apogees; annual motion of mean argument of 8th sphere
7r-13r	Annual and daily motions of mean longitudes and mean anomalies of Sun, Moon, Caput Draconis and planets. Radices for 13 Dec 1392, London
13v	Daily motion of apogees (linear precession)
ff. 14r-62r in 'Hand S', with annotations by 'Hand A' and Westwyk[12]	
14r-16v	Calendar for motions of apogees; table of equation of the 8th sphere
16v-30r	Calendars for mean longitudes and mean anomalies of Sun, Moon, Caput Draconis and planets, and for motion of deferent centre of Moon
30v-31v	Calendar for mean centre of Moon; radix for 28 Feb 1392
32r-38r	Tables for latitudes of Moon and planets
38v-44v	Tables of proportion for multiplication of sexagesimal numbers
45r-61r	Double-entry tables for planetary longitudes (headed 'Equatio [name of planet]')
61v	Table of ascensions of signs and houses for latitude 50;50°
62r	Table of precession for 1349-1468, at rate of 1° in 98-99 years
ff. 62v-78v in John Westwyk's hand	
62v	Hourly values (excess degrees) for motion of Moon, 1-12 hours[13]
63v	Difference in length of half of longest day over equinoctial day, for latitudes 0-60° Planetary longitudes and latitudes for 31 Dec 1393 (attributed to John Somer, Oxford)
64r	Solar declination and differences in ascensions of signs for latitudes 0-60° Radices (including mean centre), 28 Feb 1394, London
64v	Horoscope with accompanying Latin text (Kennedy, 1959)
65r-70v	Ascensions of signs for latitude of Oxford, 51;50° (John Walter's tables) (North, 1988, p. 191)
71r	Incomplete star table, with altitudes at Oxford (partial) and London
71v-78v	Canon to the equatorie of the planetis

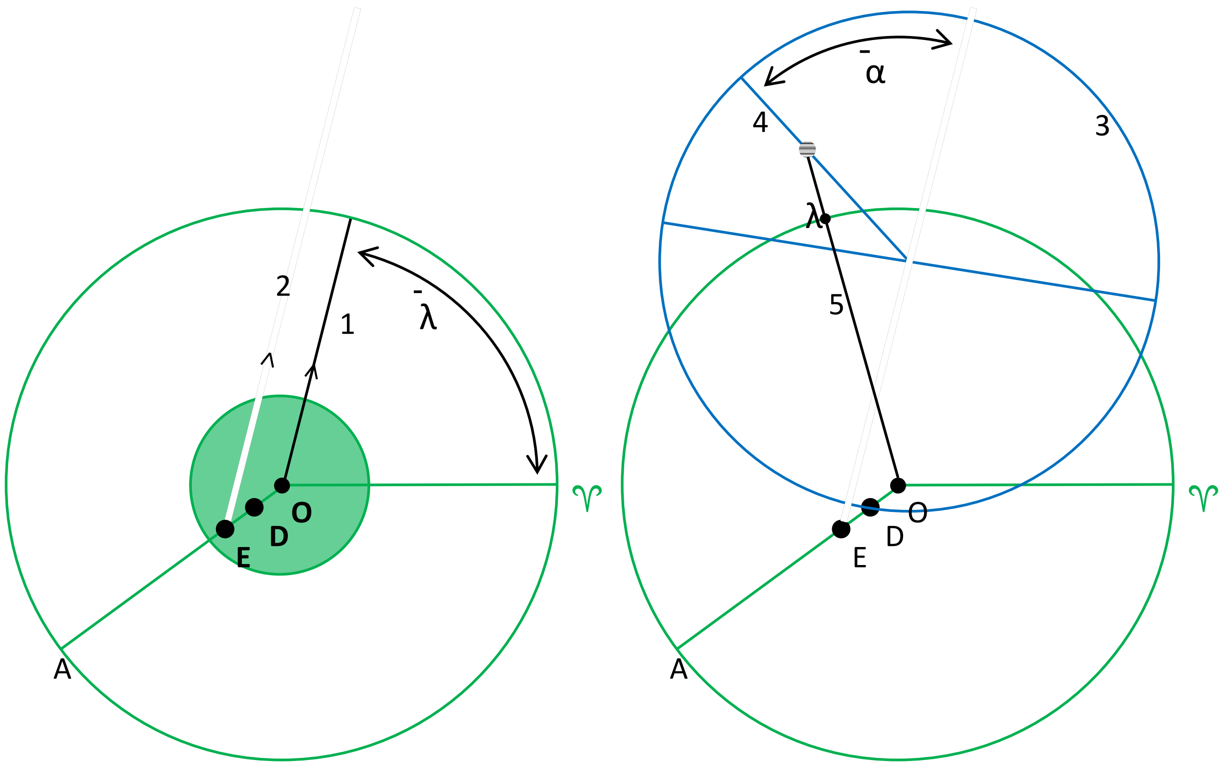


Fig. 2: Steps (numbered) in the use of the Peterhouse equatorium to find the true ecliptic longitude (λ) of a superior planet.

Calculation and copying; precision and accuracy

Before the mean longitude and mean anomaly of a planet were laid out to find its true longitude (as shown in Figure 2), the equatorium could be calibrated so that the lines marking the planetary apogees, on which lay the deferent centre and equant, were up to date. This task was not particularly important for a user soon after the equatorium's production, and it did not have to be done every time it was used, but it is clear that John Westwyk attached some importance to it. The parts of the tables and treatise pertaining to this task shed important light on Westwyk's methods and priorities in composing and compiling his manuscript.

The Alfonsine apogees were thought to move in two ways: a linear precession, increasing in longitude by one revolution every 49,000 years, also known as the mean motus of apogees and fixed stars; and accession and recession of the eighth sphere, an oscillating motion of up to 9° in each direction, with the period of oscillation being 7000 years (Dobrzycki, 1965). The relevant tables are on ff. 5r-7r and 13v. Radices are given for *auges medie* (the apogees incorporating only linear precession) and *auges vere* (apogees fully corrected to include accession and recession of the eighth sphere). To find the apogee for the desired date, the radices were to be corrected first by the addition of the linear component. This was provided in tables of annual and daily motion (on ff. 7r and 13v); the former was laid out with 1-3 years of 365 days, followed by 4, 8, 12... 56 years of 365.25 days, and then 1-3 years of 365.25 days; the latter as 1-59 days. The linear movement of the apogee since the date of the radix could be added to the radix value to give the 'mean apogee'.

Calculating the 'true apogee' was slightly more complicated, as none of the tables in Westwyk's hand gives the oscillating component directly. Instead, he wrote out daily and annual tables of what is called *argumentum medium vel accessus et recessus 8^e spere* (ff. 6r, 7r).[14] These tables, which are laid out in the same way as those just mentioned, give daily and annual fractions of a complete revolution in 7000 years. The values are therefore 7 times those in the tables of linear precession. To convert these fractions of a complete revolution into the correct fractions of a complete oscillation of ±9°, Westwyk initially intended to use his equatorium. He instructs his reader to divide 'the line þat goth fro centre aryn to the hed of capricone which lyne is cleped in the tretis of the astrelabie the midnyht line' into 9: 'thise last seid 9 divisiouns in the midnyht lyne shollen serven for equacioun of the 8e spere' (f. 72v).[15] However, he does not explain the technique for using these divisions to compute the equation of the eighth sphere from the mean argument of the eighth sphere.

Why might he have left the treatise unfinished in this way? Beyond lack of opportunity or lack of knowledge, there are several reasons why Westwyk may have chosen not to explain this technique in full. First, although it is important for the long-term maintenance of the equatorium's capabilities, the effects of precession would only be noticed after some years; the explanation of this function was thus hardly likely to be a priority.[16] Secondly, the technique would have been analogous to that of computing the latitude of the Moon on the radius opposite the midnight line, which Westwyk explained at great length; he may have felt it unnecessary to explain a similar principle again, presuming that a reader could infer the analogy.[17] It should be noted that the function of accession and recession of the eighth sphere was not as simple as that for the latitude of the Moon, so a third (somewhat remote) possibility is that Westwyk realized that the same technique would not work so well for the latter function, and abandoned his attempt to use the equatorium in this way. However, a more likely explanation is that he found a simpler source of the necessary data. The large set of tables that are not in Westwyk's hand (ff. 14r-62r) contain a table of the equation of the eighth sphere (f. 16), as well as a smaller table containing additions to be made to the apogees for each year for 1349-1468 (f. 62r). The latter, which is computed using the two-component Alfonsine precession, functions as a ready-reckoner to allow the true apogee to be easily obtained. These 'Hand S' tables had been annotated by another hand ('Hand A') before Westwyk began to use them;[18] but Westwyk's annotations, and the repetition of some material, suggest that he at least began making his own set before using them (North, 1988, p. 176). The fact that he instructed his readers to mark the tool for the equation of the eighth sphere on the face of the equatorium, but did not explain how to use it, suggests that he may have obtained the larger set of tables before he completed the treatise, and realized that they obviated the need for that tool. Nevertheless, a reader who could work out its use (with or without reference to the explanation of lunar latitude), could still use it; Westwyk may have been presenting his reader the same choice of techniques that he enjoyed.

The tables of linear precession that appear in both Westwyk's own set of tables and those in 'Hand S' raise some important questions. In the first place, it may reasonably be wondered what the purpose was of tabulating daily values for an astronomical variable that changed by less than half a minute of arc in a whole year, an amount that could not be read on an equatorium even if it were constructed at the scale Westwyk recommends. More striking still is the fact that those daily values – and indeed many others in the codex – are given to a precision of sexagesimal ninths. The 37 that appears in the column of ninths for one day's motion of the apogees (f. 13v) is equal to one 98,000,000,000,000,000th part of a complete circle; an equatorium capable of displaying such precision would have to be around nine trillion times the size specified in Westwyk's description. Such precision clearly does not reflect observational accuracy, but arising from calculations carried out by standard methods in accordance with Ptolemaic theory, it was difficult to discard. And the same principle gives us the reason for the table of days: smaller divisions of the basic unit of one revolution in 7000 years simply seemed more precise.

This greater precision is a paradoxical indicator of an amateur compilation: perhaps partially motivated by the satisfaction of correct – albeit observationally meaningless – calculation, but lacking the sophistication necessary for purposeful rounding.[19] For historians, on the other hand, it is highly valuable, as it may indicate how the tables were adapted from earlier, more rounded versions, and the order in which they were produced. We can see this in the example of annual and daily motions of the mean motus of apogees. In Westwyk's table on f. 7r we find the motion in one year as 0;0,26,26,56,20,0,0,1,44,15°. It can immediately be seen, in the middle row of Figure 3, that the final 15 was added after the rest of the table was written. The two columns of zeroes in the middle of the figure also attract attention, suggesting that the

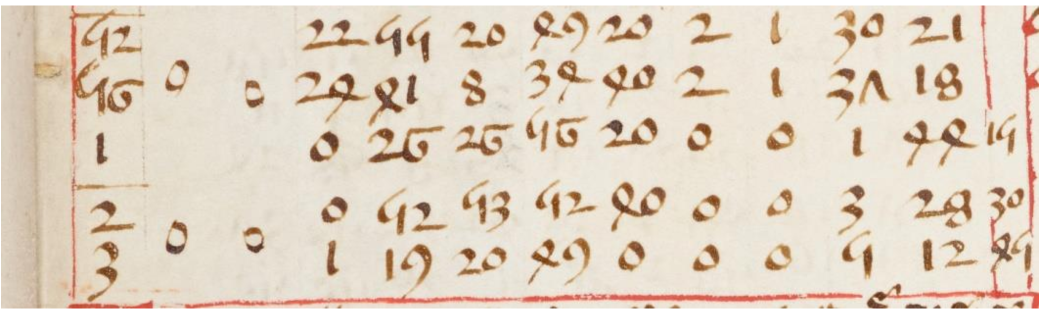


Fig. 3: Last five rows of table of annual motion of mean motus of apogees. Peterhouse, Cambridge MS 75.I, f. 7r. Reproduced by permission of the Master and Fellows of Peterhouse, Cambridge.

number was rounded at an intermediate stage. A full revolution divided by 49,000 years is approximately 0;0,26,26,56,19,35,30°; it is clear that this was at first rounded to 0;0,26,26,56,20°. We may identify the source of the extra 1,44 by comparing the values in Westwyk's table of daily motions (f. 13v). The value for one day found there (0;0,0,4,20,41,17,12,26,37°) is exactly equal to 0;0,26,26,56,20° ÷ 365.25 (or 6,5;15, as it would have been rendered), to the precision of sexagesimal ninths that seems to have been preferred by the creator of these tables. If that daily figure is multiplied by 365.25, again using nine sexagesimal places, we obtain 0;0,26,26,56,20,0,0,1,44°, which was the figure Westwyk first wrote. It seems most likely, then, that the table of annual linear precession was produced from a table of daily motions, which itself had been based on a rounded value for the annual motion. That may not have been done by Westwyk (though I know of no other extant tables, from which he could have copied, with as many sexagesimal places as his). But the last step is clearly Westwyk's own. He apparently noticed – perhaps as he was rubricating the table – that the figure for 4 years (0;1,45,47,45,20,0,0,6,57°) does not match the figure for a single year: the figure ending in 44, multiplied by 4, could not result in a number ending in 57. It was a simple exercise for Westwyk to split the difference, squeezing an extra column into the final three rows of the table and writing 15, 30 and 45. He thus made the table appear internally consistent – and gave it a precision of sexagesimal tenths.

Examination of such precise tables can also reveal how carefully they were computed. Here a useful source are the radices of planetary mean longitudes and mean anomalies for *era Christi* (noon, 31 December preceding AD 1), whose values were consistent across manuscripts based on the Parisian Alfonsine Tables (Chabás and Goldstein, 2012, pp. 59-61). These were generally given for the meridian of Toledo, but in the tables Westwyk wrote out for use with his equatorium, they are recomputed for the meridian of London. This was achieved by subtracting 8;26° of longitude (0;33,44h of time), which was thought to be the difference in longitude between London and Toledo (Price, 1955, pp. 80-82). In Table 2 Westwyk's radices for *era Christi* are shown alongside Toledo values at the same epoch.[20] They should differ by an amount corresponding to the correction for longitude, but this is not always the case: there are small scribal errors in six of the ten radices for the era of Christ.

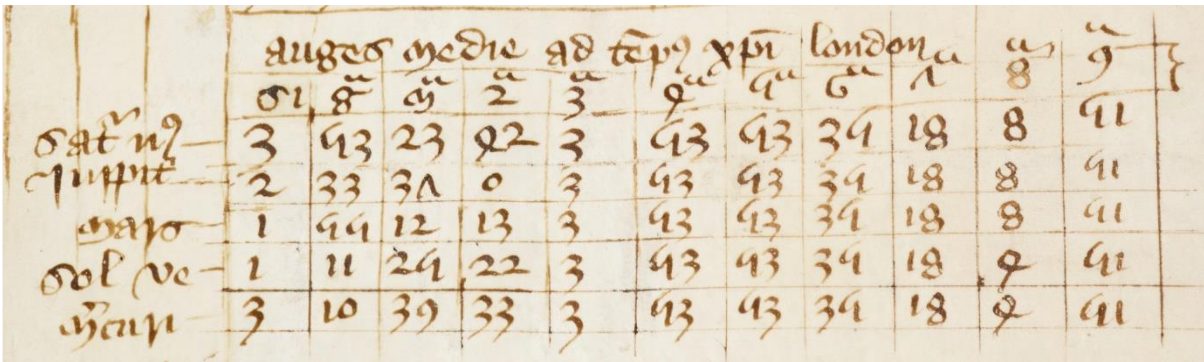
The quantity of these errors is not unusual for a table of this kind; any theory as to their origin must be speculative. The most likely cause is wavering concentration during the copying of so many seemingly random digits. In some cases, such as the confusion of 12 for 13 in the mean longitude of Caput Draconis, it may be suggested that the source text was misread by the copyist. In a few others, it is just possible that errors arose when the calculation was first carried

Table 2: Radices of mean longitude and mean argument 'ad eram Christi', adapted from Toledo values (f. 5r)

	Toledo values (°)	Westwyk's radix (f.5r) (°)	Value recomputed for meridian of 8;26° (°)
Argument of the 8th sphere	5,59;12;34	5,59;12,33,59,17,15,7,7,40	(as left)
Mean longitude of the Sun, Venus, Mercury	4,38;21,0,30,28	4,38;19,37,23,**6**,45,12,**37**,4,39	4,38;19,37,23,**5**,45,12,**38**,4,39
Mean longitude of the Moon	2,2;46,50,16,40	2,2;28,19,4,**8**,34,**9**,25,53,28	2,2;28,19,4,**6**,34,**19**,25,53,28
Mean anomaly of the Moon	3,19;0,14,31,17	3,18;41,52,42,26,30,20,23,4,24	(as left)
Mean longitude of Caput Draconis	1,31;55,52,41	1,31;55,48,**12**,3,5,8,50,13,37	1,31;55,48,**13**,3,5,8,50,13,37
Mean longitude of Saturn	1,14;5,20,12	1,14;5,17,22,30,23,29,37,9	(as left)
Mean longitude of Jupiter	3,0;37,20,44	3,0;37,13,43,22,36,52,36,10,3,20	(as left)
Mean longitude of Mars	0,41;25,29,43	0,41;24,45,31,12,**48**,59,38,20	0,41;24,45,31,12,**58**,59,38,20
Mean anomaly of Venus	2,9;22,2,36	2,9;21,10,**56**,**45**,49,16,40,45,40	2,9;21,10,**36**,**25**,49,16,40,45,40
Mean anomaly of Mercury	0,45;23,58,0	0,45;19,**32**,0,5,9,40,33,34,40	0,45;19,**36**,0,5,9,40,33,34,40

out, and its results transcribed from an abacus or set of counting stones. It would have been easy, for example, to miscount 7 for 8, as in the mean longitude of the Sun, Venus and Mercury. Whatever the cause of the errors, they need not have been made by John Westwyk: the fact that he is known to have been a careful copyist may make us suppose that he was copying an already faulty pre-existing table.[21]

On the other hand, another table adjusted for the longitude of London reveals how easily copying errors could slip in, even for a copyist as diligent as Westwyk. Figure 4 shows a small table of the radices of the mean apogees of the planets. Because the apogees moved at the same rate owing to precession, each radix was adjusted by the same amount: 8;26°/360° multiplied by the daily motion of 0;0,04,20,41,17,12,26,37°, which is given in a table on the same folio. Because they were adjusted to a greater level of precision than the original Toledo radices, the final seven columns in the table are the same for each planet. Yet in the penultimate column the final two rows show 4 instead of 8, which must have arisen from a lapse in concentration when copying. (An identical table on f. 5v repeats this error.) Such a copying error does not prove that the re-computation was not the work of John Westwyk: he could have miscopied from his own earlier calculations. But it does reveal how easily mistakes could be made. The fact that such a



Saturni	3	43	23	42	3	43	43	34	18	8	41
Jupiter	2	33	31	0	3	43	43	34	18	8	41
Mars	1	44	12	13	3	43	43	34	18	8	41
Sol Ve	1	11	24	22	3	43	43	34	18	4	41
Merc	3	10	39	33	3	43	43	34	18	4	41

Fig. 4: Table of mean apogees 'ad tempus Christi', adapted from Toledo values. Peterhouse, Cambridge MS 75.I, f. 13v. Reproduced by permission of the Master and Fellows of Peterhouse, Cambridge.

noticeable error was not corrected may suggest that Westwyk made little further use of this table, or that he did not care about the later sexagesimal places when using it.

Experimentation for learning

Westwyk did not always challenge himself to perform calculations; after all, his equatorium was designed to minimise the need for such tasks. What he did do was try out a range of instrumental and computational techniques for obtaining astronomical answers at different levels of precision. We have already seen that the set of tables he collected for his manuscript included not only precise tables of the linear and oscillating components of precession, but also a table in degrees and minutes, which functioned as a ready-reckoner to adjust the apogees. Westwyk clearly used both. Above the ready-reckoner, we find a signe-de-renvoi (the geomantic figure for Fortuna Major); the same sign appears eighteen folios earlier (45r), together with a note in Westwyk's hand instructing the reader to use the ready table of additions. (As Figure 5 shows, the reference to the eighteenth folio following has been emended in a different hand, suggesting that the tables may not have been in their current order when Westwyk wrote the canon.)

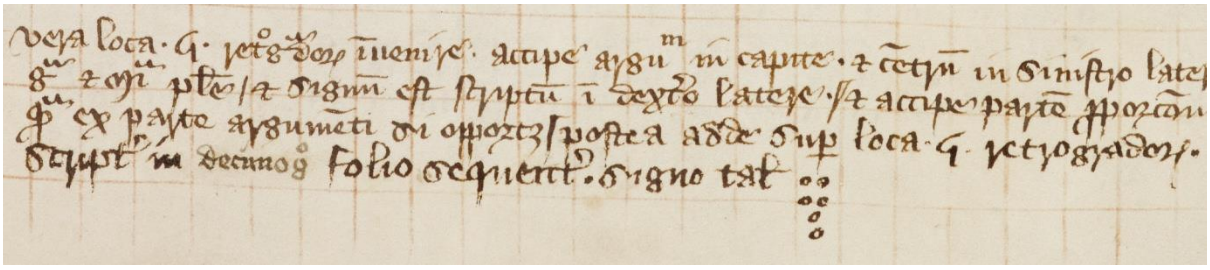


Fig. 5: Part of canon, with signe-de-renvoi and corrected folio reference. Peterhouse, Cambridge MS 75.I, f. 45r. Reproduced by permission of the Master and Fellows of Peterhouse, Cambridge.

Westwyk's canon describes the adjustment of the apogees as the final stage in a computation of planetary positions that was a complete alternative to the use of his equatorium. Instead, this technique used the tables on ff. 45r-61r, written in 'Hand S'. Entitled 'Equatio [name of planet]', they are double-argument tables at intervals of 6°, allowing the user to find the true longitude directly from the mean centre (down the left hand side of the table) and the mean anomaly (along the top). The longitude is given in degrees and minutes, with the names of the signs written down the right hand side and demarcated by lines across the table; annotations underneath indicate phases of direct and retrograde motion, stations and conjunctions. The tables are the '1348' tables associated with Oxford (North, 1977, pp. 279-284; North, 1988, p. 188); the only significant difference is that the Oxford tables, following John of Lignières, were given with signs of 30°, whereas Westwyk's tables use signs of 60° for the mean centre and mean anomaly.[22]

Although Westwyk's canon details the procedure for use of these tables, he does not explain how the mean centre, which is not tabulated anywhere in the codex, was to be found. Although this could be calculated simply by subtracting the apogee from the mean longitude, it represents an added step in the process and an inconsistency in the tables: the mean longitudes provided elsewhere in the codex are perfect for use with his equatorium design, as we have seen, but are not ideally suited for the use of these Oxford-style tables of equations. However, once the mean centre was obtained, the tables of equations could be used to give an approximation of the longitude of the planets in a single step. However, that would only be a very rough approximation, since the tables, like the Oxford tables from which they were presumably copied, give mean centres and mean anomalies in 6° increments. Westwyk does not specify how or when he thought interpolation should be used to obtain more precise results: his canon merely advises the reader to 'take the proportional part corresponding to the centre or corresponding to the argument if necessary'; a suitable table of proportions appears on the preceding few folios (38v-44v).[23] We cannot be certain how often Westwyk would have deemed it necessary to use the table of proportions, but its use had the potential to add significant labour to the procedure of computing the longitude. If, as is most likely, both the mean centre and mean anomaly fell between 6° values, the table of proportions would have had to be used for two sets of sexagesimal multiplication; for each, the table would have to be consulted four times and the resulting four figures added together, taking care to ensure that they were kept in the correct sexagesimal column. Including the addition of the final interpolated figure to the rounded value drawn from the table of equations, interpolation could involve up to eight multiplications using the tables of proportion and three additions: a time-consuming and error-prone process. There is evidence in the manuscript that Westwyk attempted, and experienced difficulties with, these interpolations: a note in ciphered Middle English on the first page of the table of proportions (f. 38v) emphasizes that for the planets, the proportions of 6° should be used (the table also permits working with proportions of 3°). On the same page Westwyk corrected a note made (in Latin) by an earlier user of the 'Hand S' tables, reminding the user that degrees multiplied by degrees yield degrees (rather than minutes as originally stated), minutes multiplied by minutes yield seconds, and so on. A similar reminder is conveyed by the small multiplication tables that Westwyk added to ff. 1v, 5v and 7r. A note on the last of these folios, concerning the adaptation of planetary longitudes to account for the equation of days, refers to the tables of equations, suggesting that Westwyk used the tables he had compiled and those in 'Hand S'together.

It is clear, then, that even if Westwyk originally obtained the 'Hand S' tables to facilitate calculation with his equatorium – and his note 'pro instrumento equatorii' on a calendar of the daily motion of the Moon's deferent centre (f. 20r) is evidence that he did use them in that way – he also took advantage of the opportunity they provided to compute positions without the equatorium, using interpolation techniques on some occasions to obtain more precise results. The fact that Westwyk used both methods indicates that he was learning, or trying out, different techniques, perhaps at different times or for different purposes. For a very rough approximation the tables could be used more quickly than the instrument, and were more portable; on the other hand, they could perhaps give greater precision, but only via complex and time-consuming calculations. As we have seen, the equatorium provided for a good balance of speed and precision, and although it needed instructions for use, so did the tables of equations, as demonstrated by the canons that Westwyk added to them. And of course they could be used to learn different techniques, or to emphasise different theoretical points.

The diversity of methods and content is most obvious in the manuscript's final set of tables, written in Westwyk's own hand. Few of these tables are closely related to the equatorium, because they are not planetary; some, indeed, are more suited to use with an astrolabe, an instrument with which Westwyk was clearly familiar. They are, however, squarely astrological and are thus related to the planetary tables. Most obvious in this regard is the horoscope of Māshā'allāh that appears on f. 64v (Kennedy, 1959), but the tables of right and oblique ascensions on ff. 65r-70v should also be noted. The latter are based on John Walter's tables of astrological houses (North, 1986, pp. 128-130; North, 1988, p. 191), and this set of tables gives the strong impression of having been compiled from a wide variety of sources that caught Westwyk's eye. Their variety, and discrepancy with tables earlier in the manuscript, is striking. Most obvious is the fact that the majority of this set were explicitly produced for Oxford, in contrast with Westwyk's first set of tables where it is stated that the radices are for London. Yet this discrepancy is not new: it exists even within the first set, where on f. 3v we see that the table of revolutions of years is for latitude 51;34° (suitable for London), while the facing page has a table of ascensions of signs for latitude 51;50°, which was probably Oxford. (St Albans, Westwyk's sometime home, was ascribed a latitude of 51;38°.[24]) But other inconsistencies are new. The table on f. 63v, which gives the differences in half the length of the day between the equinox and solstice for latitudes from 0 to 60°, incorporates an ecliptic obliquity of 23;35°, which contrasts with the figure that appears directly on f. 64r, which is 23;33,30°.[25] Finally, a list of radices on f. 64r, computed for 28 February 1394, at London, incorporates a longitude of 8° east of Toledo. This contrasts with Westwyk's first set of tables which, as we saw, were adapted from Toledo tables by the subtraction of an arc equivalent to 8;26° of time. It is likely, therefore, that rather than updating his own radices by the addition of a year's (or in this case a year and two months') motion to previous radices, Westwyk took these radices ready-prepared from another source.

The source of Westwyk's radices is significant because the (now settled) arguments about Chaucer's possible authorship of the manuscript pivoted around the 'Radix Chaucer' note on f. 5v. That note expresses 1392 years sexagesimally and remarks that it is 'deffe^{a} xpi & R^{x}a chaucer' – the difference between [the era of] Christ and the radix of Chaucer. John North argued that this was Chaucer writing his own name, because no astronomer would cite another for such a simple radix; it was, North stated, 'a trifling matter for anyone who was capable of calculating with such a set of tables as we have here, to produce fresh radices for each year's end' (North, 1988, p. 173). But the evidence we have already seen suggests that, for an amateur astronomer such as John Westwyk, that was not the case. Westwyk was not as capable as North supposed; on the other hand, he was keen to draw on a wide range of material, and to cite his sources. A small table of planetary positions for the end of 1393 (f. 63v) is headed 'J. Somer, oxonia', undoubtedly the same John Somer whose calendar inspired Chaucer (Chaucer, 1988, p. 663; Mooney, 1998; O'Boyle, 2005). On the facing page (f. 64r) is the comment, above a table of declinations, that 'istae sunt declinationes arsachelis ut estimo // verum est quod R.B.'[26] Arzachel (or al-Zarqālī) was and is well known as a leading contributor to the Toledan Tables; R.B. may refer to Roger Bacon, who was known to have drawn up tables, and is cited in identical terms in other scientific manuscripts of this period (Bacon, 1897, pp. 208-210; Millás Vallicrosa, 1943; Voigts, 1990).[27] Finally, on the penultimate page of the table of ascensions, itself the penultimate table of the codex, a note appears referring to the Jewish astronomer Jacob ben Makhir Ibn Tibbon (d. 1304), known to Westwyk as Profatius (f. 70r). The note (shown in Figure 6) gives the maximum and minimum values for the equation of days, which is related to the modern equation of time (North, 1986, p. 128-29). The maximum equation is stated to be when the Sun is at Scorpio 8-9°, and it cannot be coincidental that the note appears beneath the section of the table for an ascendant in Scorpio, where the maximum value is indeed at 8-9°. However, the two maximal values for the equation are different: the note says 7;57°, while the table gives 7;54°.[28] Judging by its appearance before a wedge paragraphus and to the left of an

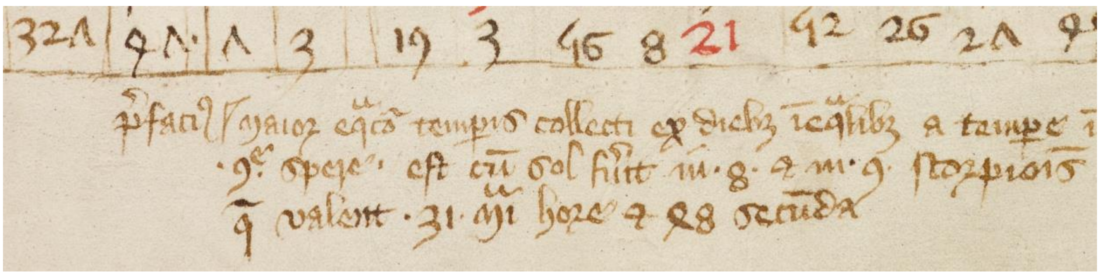


Fig. 6: Note on referring to Profatius. Peterhouse, Cambridge MS 75.I, f. 70r. Reproduced by permission of the Master and Fellows of Peterhouse, Cambridge.

otherwise aligned body of text, the reference to Profatius as an authority appears to have been added later. It is possible that Westwyk computed his own value and called upon Profatius as an authority, but this seems unlikely to have been within his astronomical capabilities.[29] More likely is that, as a diligent student and copyist, he had spotted a discrepancy in two sources he was using. He maintained the value he found in John Walter's tables, but noted that 'Profatius' had used a different value. The tables commonly misattributed to Profatius are now known to be by Peter of St. Omer, but Westwyk was not alone in this confusion, which arises in several British copies of Peter's *Tractatus de semissis* (Pedersen, 1983-84, p. 43.)

Westwyk's diligence as a copyist and table-maker is demonstrated by a curious duplication that occurs on f. 62v. This is the first table of Westwyk's latter set, and the only one of this group that could be used – albeit indirectly – with the equatorium: it is a division table allowing the user to interpolate hourly values for the longitude of the Moon. This table, which was useful for the prediction of eclipses, has no equivalent in Westwyk's first set of tables, and it seems that he may have chosen to add it later. A note in Latin instructs the user to first calculate the daily motion of the Moon from two successive noon positions 'in almenac'. The user then looks for this 24-hour difference (in degrees and minutes) on the far right of the table, and can then interpolate the motion in 1-12 hours within the table. Although it is unusual to find a table whose entry is on the right, its content is straightforward; however, what is strange is that the table appears to be missing every fourth row.[30] Such regular omissions are unlikely to be inadvertent; nonetheless it was probably dissatisfaction with those gaps that motivated Westwyk to redraw the table immediately beneath, identical but for the insertion of the missing rows, and a slightly different range.[31]

It is clear from this table, as well as from the radix Westwyk added to the 'Hand S' calendar of the double elongation of the Moon (f. 30v), that he was particularly interested in lunar positions and eclipses. We should not be surprised, therefore, that his equatorium included a tool to compute the latitude of the Moon. He explained this tool in staggering detail, covering three-and-a-half pages of the manuscript, with emphatic repetitions and three worked examples (ff. 77r-78v, for 17 December and 19 and 23 February 1391). The level of worked detail indicates that Westwyk lacked confidence with these techniques, and this is supported by some errors in his explanation. He states that Caput and Cauda Draconis are each confined to one half of the zodiac, when in fact they both rotate through the zodiac, always opposite each other. There is also a mistake in the last of his three worked examples: he gives the latitude as 1;22° N, when it was in fact southerly. This is an understandable error caused, perhaps, by the fact that northerly and southerly latitudes were read on the same ±0-5° scale on the equatorium.[32]

Overall, it is hard to escape the conclusion that Westwyk was himself learning these methods as he was carefully teaching them to his reader, perhaps inspired by Seneca's dictum 'homines dum docent discunt'.[33]

The sense of learning through experimentation, at the same time as providing instruction for future readers, is perhaps most apparent in the comments in cipher that appear in five places within the later sets of tables (ff. 14r, 30v, 38v, 62v, 63v; Price, 1955, pp. 182-187). Not only is the fairly basic substitution cipher itself evidence of experimentation with different techniques and ideas; the contents of the ciphered passages suggest incipient understanding of the tables being copied and commented on. For example, the ciphered comment on the table of half-day lengths on f. 63v (Figure 7) reads 'this is how mochel the half ark of the lengest dai is more than six houris', which is a straightforward description of a fairly simple table.[34] We thus have a glimpse of Westwyk's enjoyment of the parallel process of learning the use of the tables and of cipher. In cipher, in Latin and in plain English he makes notes on what he sees and copies, cites authorities whose achievements he respects, and comments on the results of his computations.

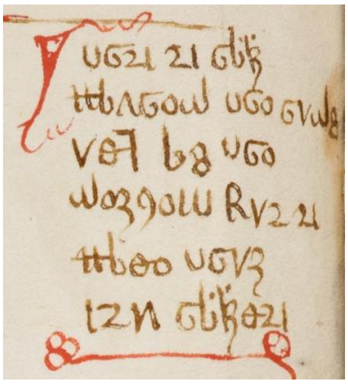


Fig. 7: Ciphered Middle English text. Peterhouse, Cambridge MS 75.I, f. 63v. Reproduced by permission of the Master and Fellows of Peterhouse, Cambridge.

Conclusion

Peterhouse MS 75.I is not an astronomer's rough workbook. Although his equatorium treatise is a draft, and some of his calculations contain errors, John Westwyk clearly took pride in his compilation. His diagrams are carefully drawn, and the radices he compiled (apparently at the same time) for 1392 and 1400 (f. 6v) demonstrate his intention to continue using the tables for years into the future. He surely realized that he still had techniques to learn; the absence of his annotations on some of the more complex 'Hand S' tables, such as the double-argument tables of latitudes, suggest the limitations of his abilities or interests. And although he perhaps lacked the sophistication to realize that great precision did not equate to 'the trowthe of conclusiouns', and his treatise contains some errors, he was far from incompetent, capable of explaining the construction and use of an equatorium in clear prose.

More significant than his mistakes is his malleability. He was willing to try different forms of presentation such as signs of 60° and 30°, and years ending on 31 December and 28 February; different layouts such as tables of numbered days and calendars grouped by months; even entirely different calculation techniques, using tables as well as the equatorium he had designed or adapted. Such variety may have been forced on him by the sources available for his compilation, but he was quite willing to use, and perhaps learn from, them. His suggestibility extends to language, where he adopts Latin and Arabic terms from his source texts and incorporates them into his own Middle English (whether plain or ciphered). Sometimes this was for lack of an existing term in the vernacular; but in other cases, such as his use of 'retrogradorum' when he could easily have written 'planetis' (f. 38v), we again have the sense of a keen learner trying out new ideas and techniques as he computes, compiles and composes a new treatise.[35] This willingness to experiment was not, perhaps, common to university scholars in this period. Rather, it is the hallmark of the amateur: a monk producing an idiosyncratic compilation, perhaps for use in his community.[36]

If the mistakes and inconsistencies that do occur in Westwyk's work diminish the astronomical value of the treatise and tables very slightly, they enhance its historical value hugely. Such imperfections, as is often the case, tell us far more than a faultless document or object would do. In the first place, they remind us of the their author's humanity and individuality. We still know little about John Westwyk: his life after he returned from crusade against Flanders in 1383, why he produced tables computed for London, and for whom he was writing. Such questions cannot be answered solely with reference to the astronomical content of Peterhouse MS 75.I. But an analysis of this manuscript has told us much about his abilities, interests and the methods through which he learned the science of astronomy. More broadly, mathematical analysis of Westwyk's tables has revealed important details of the processes of transmission, compilation and computation that went into this manuscript and others like it. Westwyk was an individual monk, but one learning the tools and techniques of a mathematical astronomy that extended across medieval Christendom, and beyond. And we too can learn through these tables, as such computational case studies offer new insights into the practices of the non-elites who learned, developed and communicated the ideas and instruments of medieval astronomy.

[1] 'The fifth part will be an introduction according to the rules of our experts, in which you may learn a great part of the general rules of astrological models. In this fifth part you will find tables of equations of houses for the latitude of Oxford, and tables of planetary dignities, and other useful things.'

[2] The explicit and potential audiences of the *Astrolabe* have been discussed by many scholars: see, for example, Laird (2007); Mead (2006).

[3] See particularly the 'General Introduction' and contribution by Alain Bernard (2014).
[4] The only other examination of the manuscript from a technical perspective is that of Emmanuel Poulle (1980, pp. 161-165), but this is limited to an analysis of the equatorium design.
[5] This dual approach is influenced by Soler et al. (2014). See especially the contribution by Karine Chemla.
[6] The manuscript has been fully digitised and is freely accessible at http://cudl.lib.cam.ac.uk/view/MS-PETERHOUSE-00075-00001.
[7] Medieval planetary theory (based on models set out in Ptolemy's *Almagest*) mapped the motion of the planets in the plane of the ecliptic. Mean motions in this theory are the mean anomaly (also known as mean argument), which gives the position of the planet on its epicycle; and the mean longitude (or mean motus), which gives the position of the epicycle centre on its path around the deferent circle, measured from the vernal point (head of Aries). Tables supplied daily and annual increments of the mean motions, which were added to the radix (the value at some epoch, such as the Incarnation of Christ) to give the mean motions at the desired date. See Chabás and Goldstein (2012).
[8] 'the smallest fractions will not be shown [as well] on such a small instrument as in ingenious tables calculated for a cause'.
[9] 'The larger you make this instrument, the larger your main divisions will be. The larger those divisions, the smaller the fractions into which they can be divided; and the smaller these fractions, the nearer the truth of your calculations.'
[10] On the importance of convenience to table-makers, see Chabás and Goldstein (2013).
[11] On the forms and contents of the Parisian Alfonsine Tables, see Chabás and Goldstein (2012), pp. 53-61.
[12] Price (1955), p. 75, designated the two main hands of the manuscript as Hand C and Hand S. Subsequent scholars have followed this usage, but Hand C has now been identified as that of John Westwyk. 'Hand A', a hand roughly contemporary with Hand S, added canons on two folios; Westwyk subsequently annotated one of those. Rand Schmidt (1993), pp. 111-112.
[13] The fact that f. 63r is blank may suggest that the table on f. 62v is incomplete: it does not contain values for 13-24 hours. However, the canon on f. 62v explains how to use the table as it stands to find the motion in 13-24 hours.
[14] The *argumentum medium* tabulated in the Parisian Alfonsine Tables corresponds to arcs of small circles which, in the theory of accession and recession attributed to Thābit ibn Qurra and incorporated into the Toledan Tables, carried the Aries and Libra points of the eighth sphere back and forth, causing the oscillating precession. See Dobrzycki, 1965; Chabás and Goldstein (2012), pp. 43-52.
[15] 'the line that goes from centre *aryn* [the centre of the equatorium] to the head of Capricorn, which line is called the Midnight Line in the *Treatise of the Astrolabe* ... the nine divisions of the midnight line just mentioned will serve for the equation of the eighth sphere.'
[16] The combination of linear and oscillating precession led to a total correction of 1° in about 65 years; the oscillating term accounted for around half of this. See Price (1955), pp. 104-107.
[17] The Moon's latitude (β) can be computed from the Moon's distance in longitude (L) from its node, where its orbit crosses the ecliptic, by the relationship $\beta = 5\sin L$ (North (1988), pp. 165-168), which was easily modelled on the face of the equatorium. Westwyk described a tool to perform this function, on the upper half of the instrument, in great detail (ff. 77r-78v). The relationship between the equation of accession and recession of the eighth sphere (ψ) and the mean argument of the eighth sphere (θ) was of the form $\sin\psi = \sin 9.\sin\theta$ (Chabás and Goldstein (2012), p. 51). Nevertheless, an astronomer working to a precision of minutes could use the approximation $\psi = 9\sin\theta$ to satisfactory effect.
[18] Westwyk made additions to the Hand A notes on ff. 31v and 38v.
[19] The word 'amateur', although sometimes used by historians of medieval science (quoted, for example, in the introduction to this article), is problematic. Here I am using it to denote lesser expertise, along with the freedom to pursue personal interests and satisfaction. For a discussion of the difficulties of defining professional and amateur status, see Berman (1975). Berman's definition focuses on the early nineteenth century, when these categories became contentious.
[20] These are taken from the first printed edition of the Alfonsine Tables (Alfonso, 1483). It is highly likely that these very common Toledo values were used, but even if not, it would not make any difference to most of the results, as most columns in the table were evidently subtracted from zero (because the correction was carried out to a greater number of sexagesimal places than the initial Toledo radix).
[21] Westwyk's copy of the tables in Richard of Wallingford's *Tractatus albionis* (Bodleian Library MS Laud Misc. 657, ff. 32r-45r, is remarkably free from errors.
[22] An example of the more usual 30° presentation is in Cambridge University Library MS Ii.1.27, ff. 23r-33v. This manuscript (dated 1424) also contains canons ascribed to Lignières.
[23] 'accipe partem proporcionalem tam ex parte centri quam ex parte argumenti si oportet.' The table allows the user to multiply two numbers from 1 to 60, with the results given as a proportion of 6°. For example, 5 x 5 gives the result 4,10.
[24] Bodleian Library MS Laud Misc. 674, f. 74r
[25] North (1986), pp. 128-30, discusses the table of differences in half-day length.
[26] 'These are the declinations of Arzachel, I believe. Correct, according to R.B.'

[27] The tables that survive with the *Opus Maius* (Bacon, 1897, pp. 208-210) are for calculating the date of Easter; however, Bacon refers to other tables which are not extant.
[28] A maximal value of 7;57 does indeed appear in work commonly attributed by medieval astronomers to Profatius (in fact it is by Peter of St Omer (fl. 1289-1308)); see Pedersen (1983-84), pp. 42-43, 702; Pedersen (2002), pp. 984-985. John of Lignières also uses 7;57. 7;54 is the figure used by al-Battani, the Toledan Tables and Parisian Alfonsine Tables. See Chabás and Goldstein (2012), p. 40.
[29] In order to check his result, we would need to know what value he was using for the solar eccentricity, which is not certain; the value incorporated into the equatorium design was 1/30th of the solar radius, but this was quite different from the value common to authorities in this period. See Chabás and Goldstein (2012), p. 66.
[30] The leftmost column gives 24 hours' motion in minutes; since the maximum value given is 1080', there may be some relation with the common division of one hour into 1080 points (*ḥelaqim*). *Helaqim* are used in some tables of Jewish origin, and this, as well as the fact that the table is entered on the right, may suggest a Hebrew source. See Chabás and Goldstein (2012), p. 141.
[31] The rows are at intervals of 24'. The range of the first table is 10;0-17;12°/day; the second is 11;12-18;0. Both ranges exceed anything possible according to Ptolemaic lunar theory. Values for maximum and minimum daily lunar motion varied, but on the equatorium the range of achievable values was certainly no greater than 11;36-14;48°/day, so in that sense either table would have been quite sufficient. See Goldstein (1992).
[32] In Westwyk's defence, we may note that errors which Price claimed to have identified in his explanation were, in fact, correct; Price mixed up figures for the retrograde motion of Caput Draconis and the resulting position, which was obtained by subtracting the motion from 360°. We may therefore reasonably conclude that no scholar is immune to such errors, and we should not judge Westwyk's performance too harshly.

It is also worth noting that Westwyk had almost certainly not computed these exceptionally accurate (barring his one cardinal error) positions on the equatorium, but rather taken them from tables for use in his worked examples. See arguments in Price (1955), pp. 72-3, and North (1988), pp. 168-9.
[33] This is an impression sustained throughout the treatise, which is a model of pedagogical writing while still containing significant theoretical errors. Seneca (1917), VII:8. Seneca's writings were very popular in this period, and his influence on Chaucer has been noted (Wilson (1993)).
[34] 'This is the amount by which the half-arc [half the daylight hours] of the longest day is more than six hours.'
[35] On this use of 'retrogradorum', which may be influenced by John Somer, see North (1988), p. 188.
[36] Westwyk's use of the vernacular for the *Equatorie* treatise may well have been an act of devotionally inspired charity. See Getz (1990).

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