Chapter 19 **(Oechslin: 9.1)**

Johann's globe clock in Mainz (1796?)

This chapter is a work in progress and is not yet finalized. See the details in the introduction. It can be read independently from the other chapters, but for the notations, the general introduction should be read first. Newer versions will be put online from time to time.

19.1 Introduction

The clock described here was constructed in c1796 by Nicolaus Alexius Johann (1753-1826) and is located in Mainz. It is Johann's first big astronomical clock.

Johann was not a clockmaker, but a professor, musician and composer. He was born in Steinach an der Saale, now part of Bad Bocklet, about 10km from Bad Kissingen, in Germany. His father was mason. He entered the orders of the Augustinians in 1770 and became Pater Alexius in 1774. He then moved to Freiburg im Breisgau. After studying theology in Freiburg, he became priest in 1777. He has composed pieces of church music, including some operas. It was probably in Freiburg that Johann became acquainted with clockmaking. He remained in Freiburg until 1781 and he was then transferred to the Augustinian monastery in Mainz. It was there that he constructed his first great astronomical clock which was possibly completed in 1796 and is described here.[1]

From 1802 to 1809, Johann was priest in Mainz and during this time he built his second great astronomical clock for the pastor Josef Mangold. This clock was destroyed in 1942 (figure 19.1 and 19.2). It was described by Arentz and Kraetzer.[2]

[1] There is still some doubt about the date of completion of the clock and different dates have been given. I have therefore put a question mark in the title. See Gauly about this matter [5, p. 52-53].

[2] See [4], [7], as well as [2, 3] and [1, p. 200-201].

In 1809, Johann took the parish of Heidesheim, a few kilometers West of Mainz. He spent his last years again in Mainz.

His brother Baptist Johann (1765-1826) also entered the order of the Augustinians. He seems to have come to Mainz around 1794. The two brothers lived in the same place in 1825. After the death of Nicolaus Alexius Johann, Baptist Johann returned to Steinach and died there only a few months later.

The two brothers are in fact the authors of at least eight astronomical clocks, of which several survive in private collections.[3]

Abeler has tried to find out where the Johann brothers got their interest and knowledge in the construction of clocks. It is for instance possible that Alexius Johann was in touch with Thaddäus Rinderle in Freiburg, although Johann left Freiburg before Rinderle built his astronomical clock (Oechslin 7.1).[4] Abeler also assumes that Johann knew of the descriptions published by Pater Aurelius, Frater David and Philipp Matthäus Hahn, but concludes that Johann devised independent solutions and did not copy those of other clockmakers, although I believe that he was influenced by at least the external appearance of some clocks he knew of.

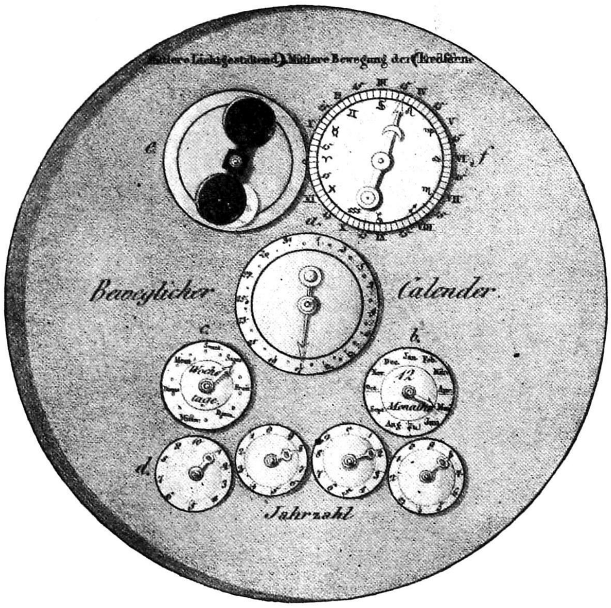

Figure 19.1: The calendar dial of Johann's second big astronomical clock, destroyed by fire in 1942. (source: [2], taken from [4])

[3]For more information on the Johann brothers, see Abeler's article [1] and Gauly's book [5]. On Johann's clocks, see also Maurice [8, v.1, p. 279-280] and King [6, p. 242, 244].

[4]See [1, p. 203].

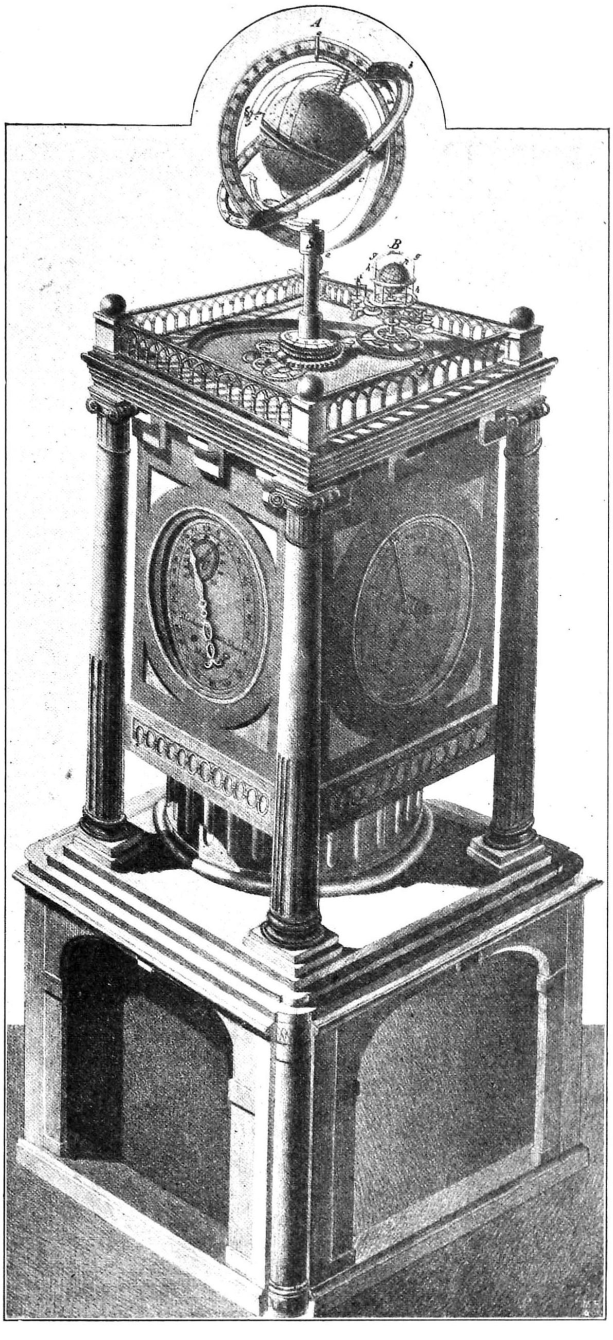

Figure 19.2: Johann's second big astronomical clock, destroyed by fire in 1942. (source: [2], taken from [4])

19.2 Description of the clock

The clock described here is a globe clock, having a cubic base topped by a celestial globe containing an intricate set of gears.[5] It bears similarities with some of Philipp Matthäus Hahn's globe clocks. Johann described this clock in a manuscript which has been transcribed by Abeler.[6]

The clock was donated by will to the priest seminar in Mainz. In 1857, this clock was damaged during an explosion in the bishop's palace in Mainz and was again put in working order by Clemens Kissel (1849-1911).[7] Then, during WWII, the clock was walled under a staircase of the palace, and thus survived the burning of the palace.

The main side of the base shows the time on a 24-hour dial and the year on four small horizontally aligned dials, one per digit. This is reminiscent of Hahn's clock in Aschaffenburg constructed in 1776/1777 (Oechslin 8.4). A second dial shows the motions of Mercury, Venus and the Earth. A third dial shows the motions of the Earth, Mars, Jupiter and Satur. A small tellurium is also fitted on top of the base, but below the celestial sphere.

I will first describe the going work, then the two parts of the orrery, then the tellurium, then the celestial globe.

19.2.1 The going work

The clock is a weight-driven pendulum clock. The arbor 3 makes one turn in two hours, and we can therefore deduce that the drum wheel on arbor 1 makes one turn clockwise (from the front of the time dials) in $\frac{95}{28}$ days, hence about 81.4 hours:

$$\mathrm{T}_3^0 = 12 \tag{19.1}$$

$$\mathrm{T}_1^0 = \mathrm{T}_3^0 \times \left(-\frac{12}{76}\right) \times \left(-\frac{14}{90}\right) = \frac{28}{95} \tag{19.2}$$

The motion of arbor 3 is transferred to the escape wheel on arbor 5:

$$\mathrm{T}_5^0 = \mathrm{T}_3^0 \times \left(-\frac{72}{6}\right) \times \left(-\frac{60}{6}\right) = \mathrm{T}_3^0 \times 120 = 12 \times 120 = 1440 \tag{19.3}$$

Consequently, the escape wheel makes one turn in 60 seconds. It carries 30 pins or teeth and the pendulum must therefore make a half-swing in one second and be about one meter long.

The motion of arbor 3 is transferred to arbor 6:

$$\mathrm{T}_6^0 = \mathrm{T}_3^0 \times \left(-\frac{72}{72}\right) = -12 \tag{19.4}$$

[5] This clock was exhibited in the 1989 Hahn exhibition catalogue [11, p. 68].

[6] [1, p. 198-200]

[7] See [10, p. 107] and [5, p. 52, 56].

It is used to obtain the motion of the minute hand on arbor 7:

$$T_7^0 = T_6^0 \times \left(-\frac{40}{20}\right) = 24 \tag{19.5}$$

It is also used to obtain the motion of tube 8 which is that of the hour hand on the 24-hour dial:

$$T_8^0 = T_6^0 \times \left(-\frac{8}{96}\right) = (-12) \times \left(-\frac{1}{12}\right) = 1 \tag{19.6}$$

This tube makes one turn clockwise in 24 hours. It is coupled with the central arbor 9 whose motion is used to drive the calendar work which is not described here. It is also used to derive the motion of the vertical arbor 22 which drives the celestial globe, here seen from above:

$$V_{22}^0 = T_9^0 \times \left(-\frac{76}{79}\right) \times \left(-\frac{76}{58}\right) \times \left(-\frac{35}{44}\right) = T_9^0 \times \left(-\frac{25270}{25201}\right) = -\frac{25270}{25201} \tag{19.7}$$

$$P_{22}^0 = -\frac{25201}{25270} = -23 \text{ h } 56 \text{ mn } 4.08\ldots \text{ s.} \tag{19.8}$$

The same value is given by Oechslin.

This, interestingly, is the same ratio as the one used by Hahn for the sidereal day velocity.

19.2.2 The two orreries

The orrery on Johann's clock is divided in two separate orreries. There is the inner orrery for Mercury, Venus, and the Earth, and there is the outer orrery for the Earth, Mars, Jupiter and Saturn.

In the inner orrery, the motion of arbor 22 is used to derive that of arbor 24, here also seen from above:

$$V_{24}^0 = V_{22}^0 \times \left(-\frac{19}{47}\right) \times \left(-\frac{6}{65}\right) = V_{22}^0 \times \frac{114}{3055} = -\frac{25270}{25201} \times \frac{114}{3055} \tag{19.9}$$

$$= -\frac{576156}{15397811} \tag{19.10}$$

$$P_{24}^0 = -\frac{15397811}{576156} = -26.7250\ldots \text{ days} \tag{19.11}$$

The same ratio is given by Oechslin. The motion of this arbor is used to drive the tellurium described below.

But it is also used to derive the motion of arbor 101 which links the two orreries. Here we measure the velocity of arbor 101 from the side of the *outer* orrery:

$$V_{101}^0 = V_{24}^0 \times \left(-\frac{6}{41}\right) = \left(-\frac{576156}{15397811}\right) \times \left(-\frac{6}{41}\right) = \frac{3456936}{631310251} \tag{19.12}$$

The same ratio is given by Oechslin.

19.2.2.1 The inner orrery

The input of the inner orrery is arbor 108, whose velocity is measured from the side of the *inner* orrery:

$$\mathrm{V}^0_{108} = \mathrm{V}^0_{101} \times \frac{24}{24} = \frac{3456936}{631310251} \tag{19.13}$$

$$\mathrm{P}^0_{108} = \frac{631310251}{3456936} = 182.6213\ldots \text{ days} \tag{19.14}$$

The same ratio is given by Oechslin. The period of this arbor is in fact exactly half of the tropical year, as we will see shortly.

The motion of arbor 108 is used to obtain the motion of tube 113 which drives Mercury:

$$\mathrm{V}^0_{113} = \mathrm{V}^0_{108} \times \left(-\frac{45}{11}\right) \times \left(-\frac{34}{67}\right) = \mathrm{V}^0_{108} \times \frac{1530}{737} \tag{19.15}$$

$$= \frac{3456936}{631310251} \times \frac{1530}{737} = \frac{5289112080}{465275654987} \tag{19.16}$$

$$\mathrm{P}^0_{113} = \frac{465275654987}{5289112080} = 87.9685\ldots \text{ days} \tag{19.17}$$

This is the mean orbital period of Mercury. The same value is given by Oechslin.

Tube 113 is actually excentered from that of Mercury, so that the motion of Mercury is made irregular, although it describes a circular path. Johann has however drawn excentric circles, so that one has to find the intersection between the hand of the planet and the corresponding circle.

The motion of tube 108 is also used to derive those of tube 111 (Venus) and 110 (Earth):

$$\mathrm{V}^0_{111} = \mathrm{V}^0_{108} \times \left(-\frac{47}{22}\right) \times \left(-\frac{35}{92}\right) = \mathrm{V}^0_{108} \times \frac{1645}{2024} = \frac{15124095}{3398329649} \tag{19.18}$$

$$\mathrm{P}^0_{111} = \frac{3398329649}{15124095} = 224.6963\ldots \text{ days} \tag{19.19}$$

$$\mathrm{V}^0_{110} = \mathrm{V}^0_{108} \times \left(-\frac{47}{22}\right) \times \left(-\frac{22}{94}\right) = \mathrm{V}^0_{108} \times \frac{1}{2} = \frac{3456936}{631310251} \times \frac{1}{2} \tag{19.20}$$

$$= \frac{1728468}{631310251} \tag{19.21}$$

$$\mathrm{P}^0_{110} = \frac{631310251}{1728468} = 365.2426\ldots \text{ days} \tag{19.22}$$

We thus have obtained the orbital periods of Venus and the Earth. The same two values are given by Oechslin.

In the case of the Earth, we have the same construction as for Mercury and the tube 110 is in fact offset from the center of the Earth hand. Likewise, the drawn orbit is an eccentric one.[8]

[8] See Oechslin on these eccentric orbits [9, p. 142-143, 155].

19.2.2.2 The outer orrery

The input of the outer orrery is arbor 101, whose period is

$$\mathrm{P}^0_{101} = \mathrm{P}^0_{108} = \frac{631310251}{3456936} = 182.6213\ldots \text{ days} \tag{19.23}$$

which is half a tropical year.

This arbor is used to obtain the motion of tube 106 which carries the Earth:

$$\mathrm{V}^0_{106} = \mathrm{V}^0_{101} \times \left(-\frac{29}{34}\right) \times \left(-\frac{34}{58}\right) = \mathrm{V}^0_{108} \times \frac{1}{2} = \frac{3456936}{631310251} \times \frac{1}{2} \tag{19.24}$$

$$= \frac{1728468}{631310251} \tag{19.25}$$

$$\mathrm{P}^0_{106} = \frac{631310251}{1728468} = 365.2426\ldots \text{ days} \tag{19.26}$$

We find again the tropical year. The same value is given by Oechslin.

The arbor 101 is also used to obtain the motion of tube 107 which carries Mars:

$$\mathrm{V}^0_{107} = \mathrm{V}^0_{101} \times \left(-\frac{29}{34}\right) \times \left(-\frac{24}{77}\right) = \mathrm{V}^0_{101} \times \frac{348}{1309} \tag{19.27}$$

$$= \frac{3456936}{631310251} \times \frac{348}{1309} = \frac{5926176}{4070862653} \tag{19.28}$$

$$\mathrm{P}^0_{107} = \frac{4070862653}{5926176} = 686.9290\ldots \text{ days} \tag{19.29}$$

The same value is given by Oechslin. This is a good approximation of the orbital period of Mars. The same value is used in the celestial sphere.

The arbor 101 is also used to obtain the motion of tube 104 which carries Jupiter:

$$\mathrm{V}^0_{104}? = \mathrm{V}^0_{101} \times \left(-\frac{12}{48}\right) \times \left(-\frac{14}{74}\right) = \mathrm{V}^0_{101} \times \frac{7}{148} \tag{19.30}$$

$$= \frac{3456936}{631310251} \times \frac{7}{148} = \frac{6049638}{23358479287} \tag{19.31}$$

$$\mathrm{P}^0_{104}? = \frac{23358479287}{6049638} = 3861.1366\ldots \text{ days} \tag{19.32}$$

However, this period (also given by Oechslin) is obviously wrong, since the correct orbital period of Jupiter is about 4330 days. Oechslin does not fix the gears in the drawing (and neither in his calculations), but it is likely that the 74-teeth wheel should actually have had 83 teeth.[9] In that case, we have

$$\mathrm{V}^0_{104} = \mathrm{V}^0_{101} \times \left(-\frac{12}{48}\right) \times \left(-\frac{14}{83}\right) = \mathrm{V}^0_{101} \times \frac{7}{166} \tag{19.33}$$

$$= \frac{3456936}{631310251} \times \frac{7}{166} = \frac{12099276}{52398750833} \tag{19.34}$$

$$\mathrm{P}^0_{104} = \frac{52398750833}{12099276} = 4330.7344\ldots \text{ days} \tag{19.35}$$

[9] See [9, p. 205] on this error.

which is much better. And moreover, the same value is used in the celestial sphere.

Finally, the arbor 101 is used to obtain the motion of tube 103 which carries Saturn:

$$V^0_{103} = V^0_{101} \times \left(-\frac{12}{48}\right) \times \left(-\frac{7}{103}\right) = V^0_{101} \times \frac{7}{412} \tag{19.36}$$

$$= \frac{3456936}{631310251} \times \frac{7}{412} = \frac{6049638}{65024955853} \tag{19.37}$$

$$P^0_{103} = \frac{65024955853}{6049638} = 10748.5697\ldots \text{ days} \tag{19.38}$$

The same value is given by Oechslin. This is an approximation of the orbital period of Saturn. And again, the same value is used in the celestial sphere.

Mars, Jupiter and Saturn are also having an irregular motion, like Mercury and the Earth in the inner orrery.

19.2.3 The tellurium

The tellurium is located above the base of the clock, but below the celestial globe. It shows the motion of the Earth around the Sun (not pictured, but on the central vertical axis), and of the Moon around the Earth. The horizontal plane is the plane of the ecliptic. The Earth rotates around a tilted axis which always keeps the same orientation. The Moon also has an irregular motion and moves up and down in order to account for its tilted orbital plane.

19.2.3.1 Main motion

The main motion of the tellurium is obtained from the motion of arbor 24 described above. A 9-leaves pinion on arbor 24 drives the main frame of the tellurium on tube 25:

$$V^0_{25} = V^0_{24} \times \left(-\frac{9}{123}\right) = V^0_{24} \times \left(-\frac{3}{41}\right) \tag{19.39}$$

$$= \left(-\frac{576156}{15397811}\right) \times \left(-\frac{3}{41}\right) = \frac{1728468}{631310251} \tag{19.40}$$

$$P^0_{25} = \frac{631310251}{1728468} = 365.2426\ldots \text{ days} \tag{19.41}$$

The same value is given by Oechslin. This is the same approximation of the tropical year as in the orreries. The frame supporting the Earth and the Moon makes one turn counterclockwise (seen from above) in one tropical year.

19.2.3.2 The internal motions

For the internal motions within the moving frame 25, two trains are used. One is based on a fixed 80-teeth wheel on the frame 30 supporting the vertical arbor

22 leading to the globe. The other train is based on the motion of tube 27 which is derived from the motion of the central vertical arbor 22. We have

$$\mathrm{V}^0_{27} = \mathrm{V}^0_{22} \times \left(-\frac{44}{68}\right) \times \left(-\frac{68}{44}\right) = \mathrm{V}^0_{22} \tag{19.42}$$

In other words, tube 27 merely replicates the motion of the internal arbor 22 and makes one turn clockwise in a sidereal day.

$$\mathrm{V}^0_{27} = -\frac{25270}{25201} \tag{19.43}$$

19.2.3.3 The tilt of the axis of the Earth

The tilted arbor 49 around which the Earth rotates pivots on frame 32. This frame is linked to a 80-teeth wheel which is the last wheel of the first train mentioned above. Consequently, we have (with respect to the moving frame 25)

$$\mathrm{V}^{25}_{32} = \mathrm{V}^{25}_{30} \times \left(-\frac{80}{38}\right) \times \left(-\frac{38}{80}\right) = \mathrm{V}^{25}_{30} \tag{19.44}$$

and

$$\mathrm{V}^0_{32} = \mathrm{V}^0_{30} = 0 \tag{19.45}$$

The frame 32 has a fixed orientation in space, and therefore the axis of the Earth always keeps the same orientation.

19.2.3.4 The rotation of the Earth around its axis

The central arbor proving the rotation of the Earth is arbor 29. The train of wheels going from tube 27 to arbor 29 is such that arbor 29 replicates the motion of tube 27:

$$\mathrm{V}^{25}_{29} = \mathrm{V}^{25}_{27} \times \left(-\frac{80}{38}\right) \times \left(-\frac{38}{80}\right) = \mathrm{V}^{25}_{27} \tag{19.46}$$

and therefore also

$$\mathrm{V}^0_{29} = \mathrm{V}^0_{27} \tag{19.47}$$

The velocity of arbor 29 with respect to a fixed frame is that of the sidereal day, but clockwise. This motion is transferred to the tilted arbor 49, which has a fixed orientation, as mentioned above. Consequently, we also have

$$\mathrm{V}^0_{49} = \mathrm{V}^0_{29} \times \left(-\frac{19}{19}\right) = -\mathrm{V}^0_{29} = -\mathrm{V}^0_{27} = \frac{25270}{25201} \tag{19.48}$$

The axis of the Earth rotates counterclockwise in one sidereal day, as it should.

19.2.3.5 The day/night boundary

There is a frame 35 around the Earth and the motion of this frame replicates that of tube 33 which is fixed on the main rotating frame 25. Therefore:

$$\mathrm{V}_{35}^{25} = \mathrm{V}_{33}^{25} \times \left(-\frac{27}{27}\right) \times \left(-\frac{27}{27}\right) = \mathrm{V}_{33}^{25} \tag{19.49}$$

This frame 35 does therefore always keep the same orientation with respect to the Sun, and it is used to show the day/night boundary.

19.2.3.6 The mean motion of the Moon

The central arbor 29 leading to the Earth also carries a small 6-leaves pinion. This pinion is used to produce the mean motion of the Moon on tube 38, using a train located on frame 32. This frame has a fixed orientation in space. Therefore

$$\mathrm{V}_{38}^{32} = \mathrm{V}_{38}^{0} = \mathrm{V}_{29}^{0} \times \left(-\frac{6}{69}\right) \times \left(-\frac{71}{32}\right) \times \left(-\frac{14}{74}\right) = \mathrm{V}_{29}^{0} \times \left(-\frac{497}{13616}\right) \tag{19.50}$$

$$= -\frac{25270}{25201} \times \left(-\frac{497}{13616}\right) = \frac{6279595}{171568408} \tag{19.51}$$

$$\mathrm{P}_{38}^{0} = \frac{171568408}{6279595} = 27.3215\ldots \text{ days} \tag{19.52}$$

The same value is given by Oechslin, also in sidereal days (but with a slightly incorrect decimal value). This is a good approximation of the tropical month, the period of the motion of the Moon in the zodiac. The same period is used in the celestial sphere.

19.2.3.7 The orientation of the Moon and the lunar nodes

The Moon is fixed on the arbor going through tube 46 and pivots on a frame (numbered 38 by Oechslin, but I will number it 38′ as it is not identical with the mean motion of the Moon) containing a number of other gears. This frame is set at the *corrected* position of the Moon. The gears that are contained in it are used for the orientation of the lit part of the Moon towards the Sun, and for the vertical motion of the arbor holding the Moon, to account for the tilt of the lunar orbit.

The orientation of the Moon with respect to the Sun is obtained very easily. The frame 35 which, as we have seen above, keeps the same orientation towards the Sun, carries a 52-teeth wheel which meshes with an intermediate wheel on arbor 45, which in turn meshes with another 52-teeth wheel on tube 46. This wheel therefore has the same orientation as the first 52-teeth wheel and it keeps the same orientation with respect to the Sun. The arbor holding the Moon moves up and down through tube 46, but the orientation of the Moon is determined by the tube.

Within frame 38′, a gear train causes an oscillation of a plate for the inclination of the lunar orbit. The velocity of this oscillation is that of arbor 48:

$$V_{48}^{38'} = V_{35}^{38'} \times \left(-\frac{52}{66}\right) \times \left(-\frac{73}{35}\right) \times \left(-\frac{35}{53}\right) = V_{35}^{38'} \times \frac{1898}{1749} \tag{19.53}$$

$$= \left(V_{35}^{0} - V_{38'}^{0}\right) \times \frac{1898}{1749} = \left(V_{25}^{0} - V_{38'}^{0}\right) \times \frac{1898}{1749} \tag{19.54}$$

$$\approx \left(V_{25}^{0} - V_{38}^{0}\right) \times \frac{1898}{1749} \approx \left(\frac{1728468}{631310251} - \frac{6279595}{171568408}\right) \times \frac{1898}{1749} \tag{19.55}$$

$$\approx \left(-\frac{145542724201}{4297960188808}\right) \times \frac{1898}{1749} = -\frac{10624618866673}{289120475777892} \tag{19.56}$$

$$P_{48}^{38'} \approx -\frac{289120475777892}{10624618866673} = -27.2123\ldots \text{ days} \tag{19.57}$$

This value is not given by Oechslin. It is an approximation of the draconic month. The sign of the period is irrelevant here, because we have a periodic and symmetric motion. The ratio used here is slightly different from the one used in the celestial globe.

19.2.3.8 The corrected motion of the Moon

The frame 38 carries a tube 40 whose velocity with respect to frame 38 is

$$V_{40}^{38} = V_{35}^{38} \times \left(-\frac{40}{27}\right) \times \left(-\frac{34}{47}\right) = V_{35}^{38} \times \frac{1360}{1269} \tag{19.58}$$

$$= \left(V_{35}^{0} - V_{38}^{0}\right) \times \frac{1360}{1269} = \left(-\frac{145542724201}{4297960188808}\right) \times \frac{1360}{1269} \tag{19.59}$$

$$= -\frac{24742263114170}{681763934949669} \tag{19.60}$$

$$P_{40}^{38} = -\frac{681763934949669}{24742263114170} = -27.5546\ldots \text{ days} \tag{19.61}$$

This value is not given by Oechslin. It is the anomalistic month. This causes the main oscillation of the lunar motion, namely the equation of center. The ratio used in the celestial sphere is slightly different.

If we compute the velocity of tube 40 in an absolute frame, we obtain

$$V_{40}^{0} = V_{40}^{38} + V_{38}^{0} = -\frac{24742263114170}{681763934949669} + \frac{6279595}{171568408} \tag{19.62}$$

$$= \frac{16884555704445}{5454111479597352} \tag{19.63}$$

$$P_{40}^{0} = \frac{5454111479597352}{16884555704445} = 3230.2368\ldots \text{ days} \tag{19.64}$$

The same value is given by Oechslin. It is the period of precession of the lunar apsides.

However, Johann added a second correction to the motion of the Moon. This second oscillation is that of arbor 44.

The 47-teeth wheel on tube 40 carries an excentric pin. The position of this pin is that of the Moon corrected for the anomaly. But the 47-teeth wheel carries the arbor 44 which also carries a wheel with an eccentric pin, which is used to add a second correction. We have

$$\mathrm{V}_{44}^{40}? = \mathrm{V}_{41}^{40} \times \left(-\frac{17}{18}\right) \times \left(-\frac{10}{19}\right) \times \left(-\frac{7}{26}\right) = \mathrm{V}_{41}^{40} \times \left(-\frac{595}{4446}\right) \tag{19.65}$$

$$= -\mathrm{V}_{40}^{38} \times \left(-\frac{595}{4446}\right) = \frac{24742263114170}{681763934949669} \times \left(-\frac{595}{4446}\right) \tag{19.66}$$

$$= -\frac{387411751392925}{79766380389111273} \tag{19.67}$$

$$\mathrm{P}_{44}^{40}? = -\frac{79766380389111273}{387411751392925} = -205.8956\ldots \text{ days} \tag{19.68}$$

and

$$\mathrm{V}_{44}^{38}? = \mathrm{V}_{44}^{40}? + \mathrm{V}_{40}^{38} = -\frac{387411751392925}{79766380389111273} - \frac{24742263114170}{681763934949669} \tag{19.69}$$

$$= -\frac{3282256535750815}{79766380389111273} \tag{19.70}$$

$$\mathrm{P}_{44}^{38}? = -\frac{79766380389111273}{3282256535750815} = -24.3022\ldots \text{ days} \tag{19.71}$$

All these values are obviously meaningless and do not correspond to any well known lunar anomaly. Oechslin has also had to gripple with similar mysterious values, but he did not compute the same ratios as above.[10] He computed for instance V_{44}^{0}, although this is of little use, and found the value $\mathrm{P}_{44}^{0} = -219.9128$ which he could not interpret.

There is however a simple explanation to these erroneous values. If we change the rotation of arbor 44 by adding another set of wheels, we obtain

$$\mathrm{V}_{44}^{40} = \mathrm{V}_{41}^{40} \times \left(-\frac{17}{18}\right) \times \left(-\frac{10}{19}\right) \times \left(-\frac{7}{26}\right) \times \left(-\frac{x}{x}\right) = \mathrm{V}_{41}^{40} \times \frac{595}{4446} \tag{19.72}$$

$$= -\mathrm{V}_{40}^{38} \times \frac{595}{4446} = \frac{24742263114170}{681763934949669} \times \frac{595}{4446} \tag{19.73}$$

$$= \frac{387411751392925}{79766380389111273} \tag{19.74}$$

$$\mathrm{P}_{44}^{40} = \frac{79766380389111273}{387411751392925} = 205.8956\ldots \text{ days} \tag{19.75}$$

and

$$\mathrm{V}_{44}^{38} = \mathrm{V}_{44}^{40} + \mathrm{V}_{40}^{38} = \frac{387411751392925}{79766380389111273} - \frac{24742263114170}{681763934949669} \tag{19.76}$$

$$= -\frac{2507433032964965}{79766380389111273} \tag{19.77}$$

$$\mathrm{P}_{44}^{38} = -\frac{79766380389111273}{2507433032964965} = -31.8119\ldots \text{ days} \tag{19.78}$$

[10]See [9, p. 208-209].

The first period hasn't changed, but the period of arbor 44 with respect to frame 38 is now about 31.8 days, which is exactly the period of the second lunar anomaly, the evection.

The same problem occurs (but not with the exact same ratios) in the celestial globe, and the same solution applies. This is obviously a construction error by Johann.

These two corrections, the anomaly and the evection, are added, and their sum is used to produce the oscillation of frame $38'$ with respect to frame 38.

19.2.4 The celestial sphere

The celestial globe rotates about a vertical axis representing the axis of the Earth, and the planets, the Moon and the Sun rotate around the globe. However, Johann does not have all the tubes come out of the poles of the ecliptic, like in Hahn's globe clocks. Instead, Johann's globe is constructed as two hemispheres and the planets, the Sun and the Moon move on disks that protrude at the junction of the two hemispheres. The gears inside the globe are divided in two groups, those in the Northern hemisphere (Mars, Jupiter and Saturn), and those in the Southern hemisphere (Moon, Sun, Mercury and Venus).

We have seen above that the input to the celestial globe is arbor 22 and that it makes one turn clockwise (seen from above) in one sidereal day. This arbor moves the entire globe. The motions within the globe are obtained using two wheels fixed on the outer (non moving) frame, one with 41 teeth at the bottom of the globe, and another with 10 teeth at the top of the globe.

The two inputs *on* the globe are then those of tube 50 at the bottom, and of tube 82 at the top. We have

$$\mathrm{V}_{50}^{22} = \mathrm{V}_{30}^{22} \times \left(-\frac{41}{74}\right) = -\mathrm{V}_{22}^{30} \times \left(-\frac{41}{74}\right) \tag{19.79}$$

$$= \frac{25270}{25201} \times \left(-\frac{41}{74}\right) = -\frac{518035}{932437} \tag{19.80}$$

$$\mathrm{V}_{82}^{22} = \mathrm{V}_{30}^{22} \times \left(-\frac{10}{20}\right) \times \left(-\frac{6}{65}\right) = -\mathrm{V}_{22}^{30} \times \frac{3}{65} = \frac{25270}{25201} \times \frac{3}{65} \tag{19.81}$$

$$= \frac{15162}{327613} \tag{19.82}$$

where 22 is the globe frame.

19.2.4.1 The mean motion of the Moon

The mean motion of the Moon is obtained on tube 53:

$$\mathrm{V}_{53}^{22} = \mathrm{V}_{50}^{22} \times \left(-\frac{71}{23}\right) \times \left(-\frac{8}{32}\right) \times \left(-\frac{7}{82}\right) = \mathrm{V}_{50}^{22} \times \left(-\frac{497}{7544}\right) \tag{19.83}$$

$$= \frac{518035}{932437} \times \frac{497}{7544} = \frac{6279595}{171568408} \tag{19.84}$$

$$\mathrm{P}_{53}^{22} = \frac{171568408}{6279595} = 27.3215\ldots \text{ days} \tag{19.85}$$

The same value is given by Oechslin. It is the tropical month, the period of the mean motion of the Moon with respect to the zodiac. It is the same period as the one used in the tellurium.

19.2.4.2 The lunar nodes

The motion of tube 53 is then used to obtain that of tube 58:

$$\mathrm{V}_{58}^{22} = \mathrm{V}_{53}^{22} \times \left(-\frac{82}{26}\right) \times \left(-\frac{6}{30}\right) \times \left(-\frac{6}{36}\right) \times \left(-\frac{6}{42}\right) \times \left(-\frac{19}{71}\right) \tag{19.86}$$

$$= \mathrm{V}_{53}^{22} \times \left(-\frac{779}{193830}\right) = -\frac{6279595}{171568408} \times \frac{779}{193830} \tag{19.87}$$

$$= -\frac{1968533}{13382335824} \tag{19.88}$$

$$\mathrm{P}_{58}^{22} = -\frac{13382335824}{1968533} = -6798.1262\ldots \text{ days} \tag{19.89}$$

The same value is given by Oechslin. It is the period of precession of the lunar nodes in the zodiac. The period is negative, because there is a retrogradation of the nodes.

We can also compute the motion of tube 53 with respect to tube 58:

$$\mathrm{V}_{53}^{58} = \mathrm{V}_{53}^{22} - \mathrm{V}_{58}^{22} = \frac{6279595}{171568408} + \frac{1968533}{13382335824} \tag{19.90}$$

$$= \frac{491776943}{13382335824} \tag{19.91}$$

$$\mathrm{P}_{53}^{58} = \frac{13382335824}{491776943} = 27.2122\ldots \text{ days} \tag{19.92}$$

This value is not given by Oechslin. It is the draconic month. This ratio is slightly different from the one used in the tellurium.

Johann moreover added an arbor 66 which is used to shift the Moon vertically with the period of the draconic month. Since arbor 66 is located on the frame of the mean Moon (or almost), the period of that motion is the above one of tube 53 with respect to tube 58.

19.2.4.3 The corrected motion of the Moon

The frame attached to tube 53 carries a number of gears aimed at obtaining the corrected motion of the Moon. When that frame rotates, a wheel on arbor 60 meshes with a fixed wheel on the central arbor 59 of the globe. This causes the rotation of a plate 62′ which is that of the main correction to the Moon.[11] We have

$$\begin{aligned}
\mathrm{V}_{62'}^{53} &= \mathrm{V}_{59}^{53} \times \left(-\frac{67}{22}\right) \times \left(-\frac{14}{43}\right) = \mathrm{V}_{59}^{53} \times \frac{469}{473} = -\mathrm{V}_{53}^{22} \times \frac{469}{473} && (19.93)\\
&= -\frac{6279595}{171568408} \times \frac{469}{473} = -\frac{2945130055}{81151856984} && (19.94)\\
\mathrm{P}_{62'}^{53} &= -\frac{81151856984}{2945130055} = -27.5545\ldots \text{ days} && (19.95)
\end{aligned}$$

This value is not given by Oechslin. It is the anomalistic month. The ratio is not the same as the one used in the tellurium. Like above, the negative sign has no significance here.

The 43-teeth wheel on tube 62′ carries an excentric arbor 65. The position of this arbor is that of the Moon corrected for the anomaly. But this arbor carries another wheel which also carries an eccentric pin, which is used to add a second correction. We have

$$\begin{aligned}
\mathrm{V}_{65}^{62'}? &= \mathrm{V}_{62}^{62'} \times \left(-\frac{17}{18}\right) \times \left(-\frac{10}{26}\right) \times \left(-\frac{7}{19}\right) = \mathrm{V}_{62}^{62'} \times \left(-\frac{595}{4446}\right) && (19.96)\\
&= -\mathrm{V}_{62'}^{53} \times \left(-\frac{595}{4446}\right) = \frac{2945130055}{81151856984} \times \left(-\frac{595}{4446}\right) && (19.97)\\
&= -\frac{92229072775}{18989534534256} && (19.98)
\end{aligned}$$

and

$$\begin{aligned}
\mathrm{V}_{65}^{53}? &= \mathrm{V}_{65}^{62'}? + \mathrm{V}_{62'}^{53} = -\frac{92229072775}{18989534534256} - \frac{2945130055}{81151856984} && (19.99)\\
&= -\frac{781389505645}{18989534534256} && (19.100)\\
\mathrm{P}_{65}^{53}? &= -\frac{18989534534256}{781389505645} = -24.3022\ldots \text{ days} && (19.101)
\end{aligned}$$

These values are incorrect, as they were in the tellurium, although the tellurium has slightly different ratios. Here too, Oechslin noticed that something was wrong, but he did not come up with an explanation. The most likely reason is that Johann forgot a pair of gears to implement the second lunar anomaly. The solution is the same as the one given in the tellurium. With

[11] Oechslin names the arbor 62, but does not give a name to the rotating plate, which I thus call 62′.

that fix, we have

$$\mathrm{V}_{65}^{62'} = \mathrm{V}_{62}^{62'} \times \left(-\frac{17}{18}\right) \times \left(-\frac{10}{26}\right) \times \left(-\frac{7}{19}\right) \times \left(-\frac{x}{x}\right) = \mathrm{V}_{62}^{62'} \times \frac{595}{4446} \tag{19.102}$$

$$= -\mathrm{V}_{62'}^{53} \times \frac{595}{4446} = \frac{2945130055}{81151856984} \times \frac{595}{4446} \tag{19.103}$$

$$= \frac{92229072775}{18989534534256} \tag{19.104}$$

and

$$\mathrm{V}_{65}^{53} = \mathrm{V}_{65}^{62'} + \mathrm{V}_{62'}^{53} = \frac{92229072775}{18989534534256} - \frac{2945130055}{81151856984} \tag{19.105}$$

$$= -\frac{596931360095}{18989534534256} \tag{19.106}$$

$$\mathrm{P}_{65}^{53} = -\frac{18989534534256}{596931360095} = -31.8119\ldots \text{ days} \tag{19.107}$$

We now have the period of the evection, the second lunar anomaly.

19.2.4.4 The mean motion of the Sun

The mean motion of the Moon is then used to obtain the mean motion of the Sun on tube 68:

$$\mathrm{V}_{68}^{22} = \mathrm{V}_{53}^{22} \times \left(-\frac{82}{63}\right) \times \left(-\frac{10}{174}\right) = \mathrm{V}_{53}^{22} \times \frac{410}{5481} \tag{19.108}$$

$$= \frac{6279595}{171568408} \times \frac{410}{5481} = \frac{183902425}{67169031732} \tag{19.109}$$

$$\mathrm{P}_{68}^{22} = \frac{67169031732}{183902425} = 365.2427\ldots \text{ days} \tag{19.110}$$

The same value is given by Oechslin. It is an approximation of the tropical year.

An eccentric pin on arbor 70 is used to produce the corrected motion of the Sun. We have

$$\mathrm{V}_{70}^{68} = \mathrm{V}_{59}^{68} \times \left(-\frac{64}{32}\right) \times \left(-\frac{16}{32}\right) = \mathrm{V}_{59}^{68} \tag{19.111}$$

Consequently, the arbor 70 replicates the central arbor of the globe, and is thus still. The pin therefore has a fixed direction with respect to the stars, and this direction is at right angle with the line of apsides.

The frame corresponding to the corrected motion of the Sun is not named by Oechslin, but I will name it 68′. This frame carries the gear trains of Mercury and Venus.

19.2.4.5 The motion of Venus

For Venus, Johann assumes that its orbit is circular and he only considers the retrogradations due to the revolution of the Earth. In his astronomical clocks, Hahn also considered Venus' orbit as circular.

Johann merely implemented an oscillation of Venus around the Sun. The pin causing this oscillation is located excentrically on tube 75. This oscillation should have the period of the synodic revolution of Venus. We can compute the velocity of tube 75 with respect to the frame 68′ which is that of the corrected Sun. But since the gear train involves an arbor which is set on frame 72 which is not fixed on frame 68′, we first compute the velocity of tube 75 with respect to frame 72. Note that frame 72 actually replicates the motion of the entire globe.

$$\mathrm{V}_{75}^{72} = \mathrm{V}_{73}^{72} \times \left(-\frac{47}{23}\right) \times \left(-\frac{35}{44}\right) = \mathrm{V}_{73}^{72} \times \frac{1645}{1012} \tag{19.112}$$

$$= -\mathrm{V}_{72}^{73} \times \frac{1645}{1012} = -\mathrm{V}_{72}^{68'} \times \frac{1645}{1012} \tag{19.113}$$

Then

$$\mathrm{V}_{75}^{68'} = \mathrm{V}_{75}^{72} + \mathrm{V}_{72}^{68'} = \mathrm{V}_{72}^{68'} \times \left(1 - \frac{1645}{1012}\right) = -\mathrm{V}_{72}^{68'} \times \frac{633}{1012} \tag{19.114}$$

$$= -\mathrm{V}_{59}^{68'} \times \left(-\frac{64}{24}\right) \times \left(-\frac{24}{64}\right) \times \frac{633}{1012} = -\mathrm{V}_{59}^{68'} \times \frac{633}{1012} \tag{19.115}$$

$$\approx -\mathrm{V}_{59}^{68} \times \frac{633}{1012} = \mathrm{V}_{68}^{59} \times \frac{633}{1012} = \mathrm{V}_{68}^{22} \times \frac{633}{1012} \tag{19.116}$$

$$\approx \frac{183902425}{67169031732} \times \frac{633}{1012} = \frac{38803411675}{22658353370928} \tag{19.117}$$

$$\mathrm{P}_{75}^{68'} \approx \frac{22658353370928}{38803411675} = 583.9268\ldots \text{ days} \tag{19.118}$$

This is indeed a good approximation of the synodic period of Venus. The value is not given by Oechslin.

We can also compute the motion of Venus with respect to the globe:

$$\mathrm{V}_{75}^{22} = \mathrm{V}_{75}^{68'} + \mathrm{V}_{68'}^{22} \approx \mathrm{V}_{75}^{68'} + \mathrm{V}_{68}^{22} \approx \frac{38803411675}{22658353370928} + \frac{183902425}{67169031732} \tag{19.119}$$

$$\approx \frac{302519489125}{67975060112784} \tag{19.120}$$

$$\mathrm{P}_{75}^{22} \approx \frac{67975060112784}{302519489125} = 224.6964\ldots \text{ days} \tag{19.121}$$

The same value is given by Oechslin, also in sidereal days.

19.2.4.6 The motion of Mercury

The motion of Mercury is more complex, because Johann not only took into account its retrogradations, but also the fact that its orbit is highly elliptical.

For the retrogradation of Mercury, Johann's construction is similar to that used for Venus. There is an eccentric pin on tube 80, which rotates on the frame 68′ of the corrected sun. In this case, tube 77 plays a similar role to tube 72 and also replicates the motion of the entire globe. We have

$$\mathrm{V}_{80}^{77} = \mathrm{V}_{78}^{77} \times \left(-\frac{77}{17}\right) \times \left(-\frac{44}{48}\right) = \mathrm{V}_{78}^{77} \times \frac{847}{204} \tag{19.122}$$

$$= -\mathrm{V}_{77}^{78} \times \frac{847}{204} = -\mathrm{V}_{77}^{68'} \times \frac{847}{204} \tag{19.123}$$

Then

$$\mathrm{V}_{80}^{68'} = \mathrm{V}_{80}^{77} + \mathrm{V}_{77}^{68'} = \mathrm{V}_{77}^{68'} \times \left(1 - \frac{847}{204}\right) = -\mathrm{V}_{77}^{68'} \times \frac{643}{204} \tag{19.124}$$

$$= -\mathrm{V}_{59}^{68'} \times \left(-\frac{64}{24}\right) \times \left(-\frac{24}{64}\right) \times \frac{643}{204} = -\mathrm{V}_{59}^{68'} \times \frac{643}{204} \tag{19.125}$$

$$\approx -\mathrm{V}_{59}^{68} \times \frac{643}{204} = \mathrm{V}_{68}^{59} \times \frac{643}{204} = \mathrm{V}_{68}^{22} \times \frac{643}{204} \tag{19.126}$$

$$\approx \frac{183902425}{67169031732} \times \frac{643}{204} = \frac{118249259275}{13702482473328} \tag{19.127}$$

$$\mathrm{P}_{80}^{68'} \approx \frac{13702482473328}{118249259275} = 115.8779\ldots \text{ days} \tag{19.128}$$

This is indeed a good approximation of the synodic period of Mercury. This value is not given by Oechslin.

We can also compute the motion of Mercury with respect to the globe:

$$\mathrm{V}_{80}^{22} = \mathrm{V}_{80}^{68'} + \mathrm{V}_{68'}^{22} \approx \mathrm{V}_{80}^{68'} + \mathrm{V}_{68}^{22} \approx \frac{118249259275}{13702482473328} + \frac{183902425}{67169031732} \tag{19.129}$$

$$\approx \frac{14160486725}{1245680224848} \tag{19.130}$$

$$\mathrm{P}_{80}^{22} \approx \frac{1245680224848}{14160486725} = 87.9687\ldots \text{ days} \tag{19.131}$$

The same value is given by Oechslin, also in sidereal days.

In addition, the fixed arbor 78 carries an eccentric pin whose purpose seems to be to take into account the elliptical orbit of Mercury. However, this pin seems to be at a fixed position with respect to the corrected Sun, and it isn't clear how this correction can be working.

19.2.4.7 The motion of the Sun in the upper part

In the upper part of the globe, the motion of the Sun is obtained on tube 84 which is part of the upper inner frame fixed to the globe:[12]

$$V^{22}_{84} = V^{22}_{82} \times \left(-\frac{38}{47}\right) \times \left(-\frac{6}{82}\right) = V^{22}_{82} \times \frac{114}{1927} \tag{19.132}$$

$$= \frac{15162}{327613} \times \frac{114}{1927} = \frac{1728468}{631310251} \tag{19.133}$$

$$P^{22}_{84} = \frac{631310251}{1728468} = 365.2426\ldots \text{ days} \tag{19.134}$$

This is the same value of the tropical year that we have met earlier. It is also given by Oechslin, also in sidereal days.

The corrected motion of the Sun is obtained by a wheel on a frame I will name 84′ (Oechslin also names it 84). A pin on the wheel on frame 84 drives the corrected motion of the Sun, but this motion is irregular because the axes of the two frames are offset.

This corrected motion of the Sun is replicated on frames 86 and 87 using the intermediate arbor 85 and identical ratios.

19.2.4.8 The mean motions of Mars, Jupiter and Saturn

The mean motion of the Sun in the upper part is also used to obtain the mean motions of Mars (tube 98), Jupiter (tube 94) and Saturn (tube 90). We have

$$V^{22}_{98} = V^{22}_{84} \times \left(-\frac{82}{6}\right) \times \left(-\frac{6}{41}\right) \times \left(-\frac{29}{22}\right) \times \left(-\frac{24}{119}\right) \tag{19.135}$$

$$= V^{22}_{84} \times \frac{696}{1309} = \frac{1728468}{631310251} \times \frac{696}{1309} = \frac{5926176}{4070862653} \tag{19.136}$$

$$P^{22}_{98} = \frac{4070862653}{5926176} = 686.9290\ldots \text{ days} \tag{19.137}$$

$$V^{22}_{94} = V^{22}_{84} \times \left(-\frac{82}{6}\right) \times \left(-\frac{6}{41}\right) \times \left(-\frac{6}{24}\right) \times \left(-\frac{14}{83}\right) \tag{19.138}$$

$$= V^{22}_{84} \times \frac{7}{83} = \frac{1728468}{631310251} \times \frac{7}{83} = \frac{12099276}{52398750833} \tag{19.139}$$

$$P^{22}_{94} = \frac{52398750833}{12099276} = 4330.7344\ldots \text{ days} \tag{19.140}$$

$$V^{22}_{90} = V^{22}_{84} \times \left(-\frac{82}{6}\right) \times \left(-\frac{6}{41}\right) \times \left(-\frac{6}{24}\right) \times \left(-\frac{7}{103}\right) \tag{19.141}$$

$$= V^{22}_{84} \times \frac{7}{206} = \frac{1728468}{631310251} \times \frac{7}{206} = \frac{6049638}{65024955853} \tag{19.142}$$

$$P^{22}_{90} = \frac{65024955853}{6049638} = 10748.5697\ldots \text{ days} \tag{19.143}$$

The same values are given by Oechslin.

[12] The fact that this frame is fixed is not readily apparent in Oechslin's drawing.

We can see here that Johann took the ratios of the orbital periods of Mars, Jupiter and Saturn to the Earth to be $\frac{1309}{696}$, $\frac{83}{7}$ and $\frac{206}{7}$ and he obtained excellent approximations of the orbital periods. The exact same orbital periods were used in the outer orrery on the base of the clock.

19.2.4.9 The eccentric motions of Mars, Jupiter and Saturn

The eccentric motions of Mars, Jupiter and Saturn are obtained like in the orreries on the base of the clock. Each "base" wheel has its axis offset from the axis of the globe. The base wheels are those on tube 98 (Mars), 94 (Jupiter) and 90 (Saturn), which move according to the mean motions of the planets. Each of these wheels has a pin driving another wheel immediately below it and which is not offset. I am naming these wheels 98′, 94′ and 90′. These three wheels therefore have an irregular motion which approximates that of the elliptic motion of the planet with respect to the stars.

19.2.4.10 The retrogradations of Mars, Jupiter and Saturn

Johann superposes the retrogradations of the planets to the motions of the corrected wheels 98′, 94′ and 90′. This is done in the same way for the three planets. Consider for instance the case of Saturn. Wheel 90′ carries a 40-teeth wheel which meshes with a 24-teeth wheel, which itself meshes with a 40-teeth wheel on the central tube 84′. That tube (named 84 by Oechslin) has the motion of the corrected Sun. Consequently, the first 40-teeth wheel on arbor 92 replicates the motion of the corrected Sun. This wheel carries an eccentric pin which drives the tube 90″ which is linked to the Saturn hand. This tube moves back and forth depending on the angle between the longitude of Saturn (given by tube 90′) and that of the Sun (given by tube 84′). In other words, this back-and-forth motion has the period of the synodic revolution of Saturn, which is what it should be.

In the case of Mars, the design is the same, but the intermediate wheel is an horizontal pinion and the two extreme wheels are contrate wheels.

19.3 References

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