Chapter 15 **(Oechslin: 8.6)**

Hahn's globe clock in Darmstadt (1785)

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.

15.1 Introduction

The clock described here was constructed in 1785 by Philipp Matthäus Hahn (1739-1790)[1] and is located in Darmstadt. It is a cubic case with four sides, three of which have dials, one showing the time, another one giving calendar data, and the third given the years in Johann Albrecht Bengel's chronology of the world.[2]

On top of the base, the Earth-Moon system rotates around the Sun. Over them, a globe represents the motion of the sky, and over it there is another lunar sphere.

15.2 The going work

The clock is driven by a spring and regulated by a pendulum.

One face of the base shows the hours and minutes. These are shown on arbors/tubes 7 and 2. (Note that the central arbor 2 must in fact be linked to

[1]For biographical details on Hahn, I refer the reader to the chapter on the Ludwigsburg *Weltmaschine* (Oechslin 8.1).

[2]See especially the 1989 exhibition catalogue [10, p. 399-401, pl .14], and Oechslin [9, p. 46]. This clock is also mentioned by Zinner [11, p. 354]. There are several similar clocks by Hahn, one of which was described by Hahn in 1770 [6]. At least two such clocks are kept in the *Landesmuseum* in Stuttgart, including a clock described in this book (Oechslin 8.5). A similar clock was also described by Hahn in 1774 [5]. Another similar clock was also reconstructed by Alfred Leiter [7].

the 40-teeth wheel which seems to be part of an independent tube. Or perhaps Oechslin meant to show that the two are only connected by friction.) In any case, we have

$$\mathrm{T}_2^0 = \frac{1}{24} \text{ (one rotation in an hour)} \tag{15.1}$$

And given that velocity, we can obtain the half-period of the pendulum:

$$T = 3600 \times \frac{8}{72} \times \frac{8}{56} \times \frac{6}{36} \times \frac{1}{22} = \frac{100}{231} \tag{15.2}$$

Hence the pendulum must be about 60 cm.

$$\tag{15.3}$$

The motion of the hour hand, that is a rotation in 12 hours, is transmitted to the other parts of the clock. The rotation in 12 hours is first converted in a rotation in 24 hours on arbors 9, 10, 11 and 12. The arbors 10 and 11 are probably tied by friction.

$$\mathrm{T}_{11}^0 = 1 \tag{15.4}$$

This motion is used for the display of the weeks and months on one side of the base. I will not describe this part in detail, first because I want to focus on the regular astronomical motions, and second because I do not have all the details of that part of the gears. The motion is also used to display the year in Johann Albrecht Bengel's chronology of the world.[3] A similar dial is shown on the Ludwigsburg *Weltmaschine* (Oechslin 8.1).

After that, the motion or arbor 11 is transfered on another side of the base, on arbor 20:

$$\mathrm{T}_{20}^0 = \mathrm{T}_{11}^0 \times \left(-\frac{57}{58}\right) \times \left(-\frac{35}{33}\right) \times \left(-\frac{76}{79}\right) \times \left(-\frac{79}{79}\right) = \frac{25270}{25201} \tag{15.5}$$

In certain cases, it may be necessary to change the sign of the result. This is not necessary here, because the wheels on arbor 11 and 20 could be considered flipped to vertical axes and all the rotations seen from above.

$$\mathrm{P}_{20}^0 = \frac{25201}{25270} = 0.9972\ldots \text{ days} = 86164.0838\ldots \text{ seconds} \tag{15.6}$$

This is the sidereal day. The same motion is transfered to the vertical arbor 29 going through the Sun:

$$\mathrm{V}_{29}^0 = -\frac{25270}{25201} \tag{15.7}$$

[3] See in particular Bengel's works [1, 2, 3, 4] and Marini [8].

Notice that this motion is clockwise as seen from above, hence the negative sign.

Using the sidereal motion of arbor 20, Hahn obtains the motion of arbor 24:

$$\mathrm{T}^0_{24} = \mathrm{T}^0_{20} \times \left(-\frac{32}{32}\right) \times \left(-\frac{32}{32}\right) \times \left(-\frac{6}{64}\right) \times \left(-\frac{3}{103}\right) = \frac{113715}{41531248} \quad (15.8)$$

$$\mathrm{P}^0_{24} = \frac{41531248}{113715} = 365.22224\ldots \text{ days} \quad (15.9)$$

This is the tropical year. The 103-teeth wheel making one turn in one tropical year then advances another 10-teeth wheel on arbor 25 once a year. The latter therefore makes one turn in 10 years, but intermittently. That motion is yet transfered to a wheel on arbor 26 making one turn in 100 years. And finally, it is transfered to a wheel making one turn in 8000 years. Supposedly, the year can be read on this dial as a combination of a value between 0 and 99 (the units and tens), and of another one between 0 and 79 (the hundreds and thousands).

15.3 The tellurium

The part above the base is a tellurium, namely a rendering of the motions of the Earth and the Moon around the Sun. The input of this tellurium is the motion of arbor 29 in one sidereal day mentioned above. This motion is used to produce the motion of the rotating frame 34 of the Earth-Moon system:

$$\mathrm{V}^0_{34} = \mathrm{V}^0_{29} \times \left(-\frac{41}{41}\right) \times \left(-\frac{41}{41}\right) \times \left(-\frac{41}{41}\right) \times \left(-\frac{6}{64}\right) \times \left(-\frac{3}{103}\right) \quad (15.10)$$

$$= \mathrm{T}^0_{24} = \frac{113715}{41531248} \quad (15.11)$$

$$\mathrm{P}^0_{34} = 365.22224\ldots \text{ days} \quad (15.12)$$

The same value is given by Oechslin.

Hence, the velocity of frame 34 is the same as that of arbor 24 seen earlier, but in the opposite direction. The Earth-Moon frame rotates in the direct direction (counterclockwise) in one tropical year.

Now, the moving frame 34 has two inputs. First, there is arbor 35 which is actually tied to the reference frame. This arbor carries a 65-teeth wheel. Second, there is the central arbor 29 whose motion is that of the sidereal day, but clockwise as seen from above:

$$\mathrm{V}^0_{35} = 0 \quad (15.13)$$

$$\mathrm{V}^0_{29} = -\frac{25270}{25201} \quad (15.14)$$

The tilted axis of the Earth is on tube 39 and its orientation is determined from the wheel on tube 35. The velocity of the tilted axis is

$$\mathrm{V}_{39}^{34} = \mathrm{V}_{35}^{34} \times \left(-\frac{65}{65}\right) \times \left(-\frac{65}{65}\right) \times \left(-\frac{65}{65}\right) \times \left(-\frac{65}{65}\right) = \mathrm{V}_{35}^{34} \tag{15.15}$$

$$\mathrm{V}_{39}^{0} = \mathrm{V}_{39}^{34} + \mathrm{V}_{34}^{0} = \mathrm{V}_{35}^{34} + \mathrm{V}_{34}^{0} = \mathrm{V}_{35}^{0} + \mathrm{V}_{0}^{34} + \mathrm{V}_{34}^{0} = \mathrm{V}_{35}^{0} = 0 \tag{15.16}$$

In other words, the Earth's axis is still in the reference frame and always keeps the same orientation.

The rotation of the Earth around its axis 44 is obtained from the sidereal day:

$$\mathrm{V}_{44}^{0} = \mathrm{V}_{44}^{39} = \mathrm{V}_{43}^{39} \times \left(-\frac{30}{30}\right) \tag{15.17}$$

And

$$\mathrm{V}_{43}^{39} = \mathrm{V}_{43}^{34} + \mathrm{V}_{34}^{39} = \mathrm{V}_{29}^{34} \times \left(-\frac{65}{65}\right) \times \left(-\frac{65}{65}\right) \times \left(-\frac{65}{65}\right) \times \left(-\frac{65}{65}\right) + \mathrm{V}_{34}^{39} \tag{15.18}$$

$$= \mathrm{V}_{29}^{34} + \mathrm{V}_{34}^{39} = \mathrm{V}_{29}^{34} - \mathrm{V}_{39}^{34} = \mathrm{V}_{29}^{34} - \mathrm{V}_{35}^{34} = \mathrm{V}_{29}^{34} + \mathrm{V}_{34}^{35} = \mathrm{V}_{29}^{35} \tag{15.19}$$

$$= \mathrm{V}_{29}^{0} = -\frac{25270}{25201} \tag{15.20}$$

$$\mathrm{V}_{44}^{0} = \frac{25270}{25201} \tag{15.21}$$

As expected, the Earth performs a rotation around its axis in one sidereal day. This motion is counterclockwise as seen from above.

However, we should also notice that the tropical year is inconsistent with the sidereal day. Normally, after one day, the angular motion of the Earth with respect to the Sun should be the difference of its motion with respect to the zodiac and the motion of the Earth around the Sun. We have therefore

$$\frac{1 \text{ day}}{1 \text{ sidereal day}} - \frac{1}{1 \text{ tropical year}} = 1 \tag{15.22}$$

and the tropical year and sidereal day are related.

This translates to

$$\mathrm{V}_{44}^{34} = \mathrm{V}_{44}^{39} + \mathrm{V}_{39}^{34} = \frac{25270}{25201} + \mathrm{V}_{0}^{34} = \frac{25270}{25201} - \mathrm{V}_{34}^{0} \tag{15.23}$$

$$= \frac{25270}{25201} - \frac{113715}{41531248} = \frac{41531245}{41531248} \tag{15.24}$$

This is the mean velocity of wheel/arbor 44, as it is wobbling in frame 34. But most importantly, we can observe that the value of V_{44}^{34} is not 1.

With the modern values, the above corresponds to

$$\frac{86400}{86164.0905} - \frac{1}{365.2422} \approx 1 \tag{15.25}$$

In Hahn's gears, we should normally have had

$$\frac{25270}{25201} - \frac{25270}{25201} \times \frac{6}{64} \times \frac{3}{103} = 1 \text{ (False)} \tag{15.26}$$

but this is not exactly the case. It is quite possible that Hahn wasn't able to find adequate gears to ensure this equality. On the other hand, if he had used the ratios $\frac{23}{57} \times \frac{6}{76} \times \frac{6}{70}$ instead of $\frac{6}{64} \times \frac{3}{103}$ (and with an additional direction reversal), Hahn would have been able to ensure the above equality.

Hahn's approximation of the tropical year is in fact better than his approximation of the sidereal day. This is easy to see when computing the tropical year from the sidereal year. We then find a tropical year of $\frac{25201}{69} = 365.2318\ldots$ days. In fact, the ratio $\frac{6}{64} \times \frac{3}{103}$ used for the tropical year is quite good, and Hahn should have replaced his ratio $\frac{57}{58} \times \frac{35}{33} \times \frac{76}{79}$ for the sidereal day by the ratio $\frac{3296}{3287} = \frac{32}{173} \times \frac{103}{19}$.

The Moon is located on frame 46. We can compute the velocity of this frame with respect to the rotating frame 34. This motion is derived from the train producing the rotation of the Earth:

$$\mathrm{V}_{46}^{34} = \mathrm{V}_{42}^{34} \times \left(-\frac{12}{41}\right) \times \left(-\frac{12}{104}\right) \tag{15.27}$$

$$\mathrm{V}_{42}^{34} = -\mathrm{V}_{43}^{34} = -\left(\mathrm{V}_{43}^{0} + \mathrm{V}_{0}^{34}\right) = -\mathrm{V}_{43}^{0} - \mathrm{V}_{0}^{34} = -\mathrm{V}_{43}^{0} + \mathrm{V}_{34}^{0} \tag{15.28}$$

$$= -\mathrm{V}_{43}^{39} + \frac{113715}{41531248} \tag{15.29}$$

$$= \frac{25270}{25201} + \frac{113715}{41531248} = \frac{41758675}{41531248} \tag{15.30}$$

We now have

$$\mathrm{V}_{46}^{34} = \frac{375828075}{11068077592} \tag{15.31}$$

And

$$\mathrm{P}_{46}^{34} = \frac{11068077592}{375828075} = 29.4498\ldots \text{ days} \tag{15.32}$$

This value of the synodic month is not very accurate, because the ratios used to compute V_{46}^{34} could have been better.

$$\mathrm{V}_{46}^{0} = \mathrm{V}_{46}^{34} + \mathrm{V}_{34}^{0} = \frac{375828075}{11068077592} + \frac{113715}{41531248} = \frac{812266245}{22136155184} \tag{15.33}$$

$$\mathrm{P}_{46}^{0} = \frac{22136155184}{812266245} = 27.2523\ldots \text{ days} \tag{15.34}$$

This value of the tropical month is also not very accurate, for the same reason. The same value is given by Oechslin, but he didn't give the value of the synodic month.

The orientation of the lit part of the Moon depends on the relative position of tube 47 with respect to frame 46. The Moon has a permanent lit part whose orientation is defined by the axis 49. We therefore must compute the velocity of axis 49 with respect to frame 34. This velocity is expected to be 0:

$$\mathrm{V}_{49}^{34} = \mathrm{V}_{49}^{46} + \mathrm{V}_{46}^{34} = \mathrm{V}_{47}^{46} \times \left(-\frac{44}{44}\right) \times \left(-\frac{44}{44}\right) + \mathrm{V}_{46}^{34} \quad (15.35)$$

$$= \mathrm{V}_{47}^{46} + \mathrm{V}_{46}^{34} = \mathrm{V}_{47}^{34} = 0 \quad (15.36)$$

15.4 The celestial globe

The celestial globe is located above the base and within a fixed frame. It shows the motions of the Sun, the Moon, the lunar nodes and Venus from a geocentric perspective. It is thus similar to the celestial globe in the globe clock in Stuttgart (Oechslin 8.5) from 1770, although the construction differs. This globe takes as only input the motion of arbor 29 in one sidereal day (clockwise from above). This arbor goes through the Sun which is actually fixed on the moving Earth frame 34. The Sun rotates with this frame.

The virtual vertical axis going through the celestial globe represents Earth's rotation axis. Consequently, the celestial sphere rotates around this axis. It does however do so indirectly. The celestial has its main axis tilted and this axis goes through the poles of the ecliptic. The ecliptic is shown by a strip and the Moon, the Sun, Venus and the lunar nodes are shown by curved hands rotating around these poles. The meridian and the equator planes are shown through the outside frame. The motions of the Sun, the Moon, and Venus are shown as seen from the Earth. For instance, the retrogradations of Venus are shown, but they are artefacts of the motion of the Earth around the Sun. The globe does not show the motion of Venus around the Sun.

The input motion of one turn in a sidereal day causes the tilted axis of the celestial globe to spin clockwise (from above) around the vertical axis. In fact, the entire globe is carried in this motion, and this corresponds to the observable motion of the sky.

At the base of celestial sphere, there is a fixed 41-teeth wheel. This wheel meshes with a similar wheel on which arbor another such wheel meshes with yet a similar wheel on the axis of the poles. The consequence is that the fixed reference frame is transfered inside the celestial globe. We will examine the inside of this globe in a moment, but first, we can study the small lunar globe located over the celestial sphere.

15.4.1 The lunar sphere at the top

The rotation of the celestial sphere is transfered at the top to 12-teeth wheel on an arbor which is actually the continuation of the input arbor 29. The velocity of the lunar sphere is

$$\mathrm{V}_{71}^{0} = \mathrm{V}_{29}^{0} \times \left(-\frac{12}{26}\right) \times \left(-\frac{3}{41}\right) = \mathrm{V}_{29}^{0} \times \frac{18}{533} \tag{15.37}$$

$$= \left(-\frac{25270}{25201}\right) \times \frac{18}{533} = -\frac{454860}{13432133} \tag{15.38}$$

$$\mathrm{P}_{71}^{0} = -\frac{13432133}{454860} = -29.5302\ldots \text{ days} \tag{15.39}$$

This value is not given by Oechslin.

This globe makes one turn clockwise (from above) in a synodic month. It is half golden, half black, and half of that globe is hidden. Through its rotation it can show the approximate phases of the Moon, in a similar way as the display of the lunar phases in the current astronomical clock in the Strasbourg cathedral.

This sphere is similar to the one on top of the globe clock in Stuttgart (Oechslin 8.5) from 1770. The same ratio $\frac{18}{533}$ is used in both clocks. However, in Stuttgart the lunar globe turns counterclockwise, which seems incorrect.

15.4.2 The inner workings of the celestial sphere

We now assume as a reference frame that of the celestial globe itself. The only input is that of tube 51 which has the opposite motion as that of arbor 29 with reference to the fixed frame:

$$\mathrm{V}_{51}^{29} = -\mathrm{V}_{29}^{0} = \frac{25270}{25201} \tag{15.40}$$

This is first used to obtain the mean motion of the Moon on tube 60. We first compute the velocity of the arbor 52, as it will be used in other parts of the globe.

$$\mathrm{V}_{52}^{29} = \mathrm{V}_{51}^{29} \times \left(-\frac{60}{60}\right) = -\mathrm{V}_{51}^{29} \tag{15.41}$$

$$\mathrm{V}_{60}^{29} = \mathrm{V}_{52}^{29} \times \left(-\frac{60}{61}\right) \times \left(-\frac{24}{89}\right) \times \left(-\frac{15}{109}\right) \tag{15.42}$$

$$= \mathrm{V}_{51}^{29} \times \frac{21600}{591761} = \frac{545832000}{14912968961} \tag{15.43}$$

$$\mathrm{P}_{60}^{29} = \frac{14912968961}{545832000} = 27.3215\ldots \text{ days} \tag{15.44}$$

This is an approximation of the tropical month. The same value is given by Oechslin, also in sidereal days.

The motion of the lunar nodes is obtained as follows:

$$V^{29}_{56} = V^{29}_{52} \times \left(-\frac{3}{30}\right) \times \left(-\frac{3}{36}\right) \times \left(-\frac{3}{48}\right) \times \left(-\frac{20}{71}\right) = V^{29}_{52} \times \frac{1}{6816} \quad (15.45)$$

$$= \left(-\frac{25270}{25201}\right) \times \frac{1}{6816} = -\frac{12635}{85885008} \quad (15.46)$$

$$P^{29}_{56} = -\frac{85885008}{12635} = -6797.3888\ldots \text{ days} \quad (15.47)$$

The same value is given by Oechslin, also in sidereal days. The actual value of the draconic period is 6798.3 days, this is therefore an excellent approximation. This period is negative, because the motion of the nodes is clockwise.

The motion of arbor 52 is also used to produce the apsidal precession of the Moon on tube 57:

$$V^{29}_{57} = V^{29}_{52} \times \left(-\frac{3}{30}\right) \times \left(-\frac{3}{36}\right) \times \left(-\frac{3}{81}\right) \quad (15.48)$$

$$= \left(-\frac{25270}{25201}\right) \times \left(-\frac{1}{3240}\right) = \frac{2527}{8165124} \quad (15.49)$$

$$P^{29}_{57} = \frac{8165124}{2527} = 3231.1531\ldots \text{ days} \quad (15.50)$$

The same value is given by Oechslin, also in sidereal days. The actual value of the apsidal precession is about 3233 days and the motion of the apsides is counterclockwise, hence the positive value.

The angular difference between tube 60 (mean motion of the Moon) and tube 57 (apsides) is the mean anomaly of the Moon. In the reference frame of the mean Moon, tube 60, we have

$$V^{60}_{62} = V^{60}_{57} \times \left(-\frac{44}{44}\right) \times \left(-\frac{44}{44}\right) = V^{60}_{57} \quad (15.51)$$

$$= V^{29}_{57} - V^{29}_{60} = \frac{2527}{8165124} - \frac{545832000}{14912968961} \quad (15.52)$$

$$= -\frac{175354187953}{4831801943364} \quad (15.53)$$

$$P^{60}_{62} = -\frac{4831801943364}{175354187953} = -27.5545\ldots \text{ days} \quad (15.54)$$

The period of this angular difference is the anomalistic month. This value is not given by Oechslin.

Using an excentric pin, the motion of arbor 62 is used to add the equation of center to the mean anomaly, so as to obtain (an approximation of) the true anomaly of the Moon.

The motions of the Sun and Venus are obtained from arbor 63. Its velocity is

$$V^{29}_{63} = V^{29}_{52} \times \left(-\frac{3}{33}\right) = \left(-\frac{25270}{25201}\right) \times \left(-\frac{3}{33}\right) = \frac{25270}{277211} \quad (15.55)$$

The velocity of the Sun on arbor 65 is then

$$\mathrm{V}_{65}^{29} = \mathrm{V}_{63}^{29} \times \left(-\frac{16}{33}\right) \times \left(-\frac{7}{113}\right) = \frac{25270}{277211} \times \frac{112}{3729} = \frac{2830240}{1033719819} \quad (15.56)$$

and the revolution period is

$$\mathrm{P}_{65}^{29} = \frac{1033719819}{2830240} = 365.2410\ldots \text{ days} \quad (15.57)$$

which is yet another value for the tropical year. The same value is given by Oechslin. This value was also used in the double-globe clock in Karlsruhe (Oechslin 8.8), also constructed in 1785, and in that of Villingen (Oechslin 8.9), dated 1770-1783.

The mean motion of Venus on the ecliptic, that is its orbital period, is obtained as follows on arbor 67, from arbor 63:

$$\mathrm{V}_{67}^{29} = \mathrm{V}_{63}^{29} \times \left(-\frac{11}{35}\right) \times \left(-\frac{16}{103}\right) \quad (15.58)$$

$$= \frac{25270}{277211} \times \frac{176}{3605} = \frac{11552}{2595703} \quad (15.59)$$

$$\mathrm{P}_{67}^{29} = \frac{2595703}{11552} = 224.6972\ldots \text{ days} \quad (15.60)$$

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

The actual orbital period of Venus is about 224.701 days.

Finally, the irregular motion of Venus depends on its elongation to the Sun. The mean elongation is the angular difference between the mean position of Venus and the (mean) position of the Sun (Hahn didn't take into account the equation of center for the Sun), that is between tubes 67 and 65. This elongation is translated into the relative motion of arbor 69 on frame 65:

$$\mathrm{V}_{69}^{65} = \mathrm{V}_{67}^{65} \times \left(-\frac{52}{52}\right) \times \left(-\frac{52}{52}\right) = \mathrm{V}_{67}^{65} = \mathrm{V}_{67}^{29} - \mathrm{V}_{65}^{29} \quad (15.61)$$

$$= \frac{11552}{2595703} - \frac{2830240}{1033719819} = \frac{182336768}{106473141357} \quad (15.62)$$

$$\mathrm{P}_{69}^{65} = \frac{106473141357}{182336768} = 583.9367\ldots \text{ days} \quad (15.63)$$

and its period is that of the synodic revolution of Venus. This period is not given by Oechslin.

The wheel on arbor 69 moves an excentric pin which accelerates or slows down the motion of Venus, producing the well-known retrogradations.

15.5 References

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