Chapter 37
Long-Term Timekeeping in the Clock of the Long Now

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Abstract We construct our systems of time for many different purposes: to measure intervals and events, to predict the future and solidify the past, and to align our activities with the cycles of the seasons and days. For most purposes, we can ignore the differences between the kinds of time that we need for these different purposes, but over long intervals, we cannot. This article describes the nine kinds of time that are used in the construction of the Clock of the Long Now, a mechanical clock that is designed to keep time continuously for 10,000 years.

Keywords Equation of time • Clock of the long now • Ten-thousand-year clock • 10,000-year clock • Mechanical timekeeping • Pendulum clocks • Solar sychronization

The purpose, design, and construction of the Clock of the Long Now is described elsewhere (Hillis 1995; Hillis 2013; http://www.longnow.org; Brand 1999; Hillis 2000). Besides being designed for an operation lifetime of 10,000 years, the clock has several other unusual features. Like many clocks, it displays the positions of the Sun, Moon, and stars, as well as the time of day and Gregorian calendar date. Unlike most clocks, it only updates these displays when the clock is wound. When the clock is visited (it is buried deep inside a mountain), it initially shows the date and time of the last visitor. Only when it is wound does the display advance to the current date and time. The clock must keep track of passing time even when the display is not visited. The small power required to keep the pendulum swinging is generated by temperature changes from night to day. Only the power required to advance the display is generated by human winding. This allows the visitor to watch the display being updated at an accelerated rate.

The clock has a set of chimes which ring in a different permutation each day, so that the order of sequence never repeats over the lifetime of the clock. The chime mechanism only operates at solar noon, and only if the clock is fully wound. This can occur either because someone has just recently wound the clock or because the

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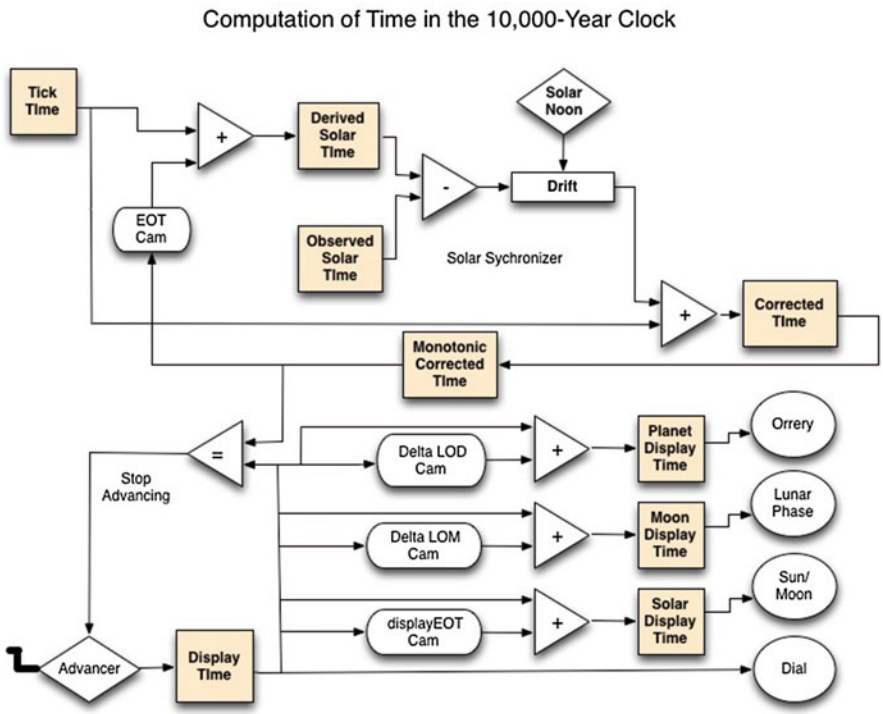

Fig. 37.1 Computation of time in the 10,000-year clock

self-winding mechanism that is powered by day-night temperature swings has accumulated extra power.

A second unusual feature of the clock is that it is phase synchronized to the Sun. Every summer solstice, light shines down the shaft at solar noon, so that a lens focuses the light on a trigger that detects thermal expansion. This solar trigger is used to adjust the time that is generated from the swinging pendulum, correcting any long-term drift relative to the timing of the Sun.

These functions require that the clock keep track of both solar and dynamical time,[1] as well as the interval between the displayed time and the current time,[2] and other rates required for operating the astronomical displays and the chimes. In all, there are nine kinds of time that are represented in the Clock of the Long Now. The relationship between them is show in Fig. 37.1 and explained below.

Tick time is the time generated by counting the swings of the pendulum, which has a period of 7.5 s. This is used to derive the apparent solar time by adding a correction for the equation of time, that is, the difference between apparent solar and mean solar time, which is generated by a cam. This cam is different from the

[1]That is, time responsive to the slowing Earth versus the steady cadence of the pendulum.

[2]The precision of the clock is 5 min (in whatever time scale) allowing us a certain latitude of expression in this paper.

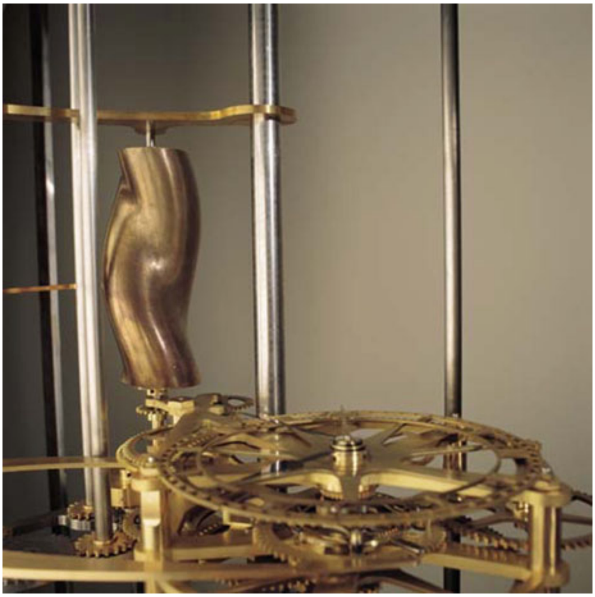

Fig. 37.2 An early prototype of the equation of time cam

equation of time cam in other clocks, because it must take into account the way that the equation of time changes slowly over the course of millennia, due to the factors such as precession of the Earth's axis, the slowing of its rotation, and the precession of the Earth's orbit around the Sun. A prototype cam is shown in Fig. 37.2. The cam rotates roughly once a year, and the cam follower rises along the length of the cam over the course of 10,000 years. Computing the shape of this cam required extending the JPL Ephemerides (Folkner et al. 1994; Hillis et al. 2011), 10,000 years into the future.

The correction from the equation of time cam is added to tick time to generate *derived solar time*. Since derived solar time is used to rotate the cam, this creates a circularity in its definition. This is not a problem since the correction to the "gain" around the control loop is small.

Observed solar time is based on the observation of the Sun. It is only valid on clear days at solar noon near the time of the summer solstice. This raises the question of how often such conditions may fail to occur, given the possibility of weather patterns changing substantially over the design lifetime of the clock. Based on the predicted accuracy of the pendulum, the clock may require a synchronization event as often as once every 22 years. This is not currently a danger in West Texas, where the clock is located, but the weather patterns may change. An investigation was performed to see if a shift in weather patterns was likely to cause such a gap (Grossman et al. 2014). This was accomplished by using historical weather data from all over the globe and asking if there is any place in the current world where the clock would have a significant chance of failing to synchronize often enough. For example, Fig. 37.3 shows locations where an inferior clock would not work, if it required a synchronization event every 8 years. The historical data showed no place on Earth where current weather patterns would produce more than a 1% probability

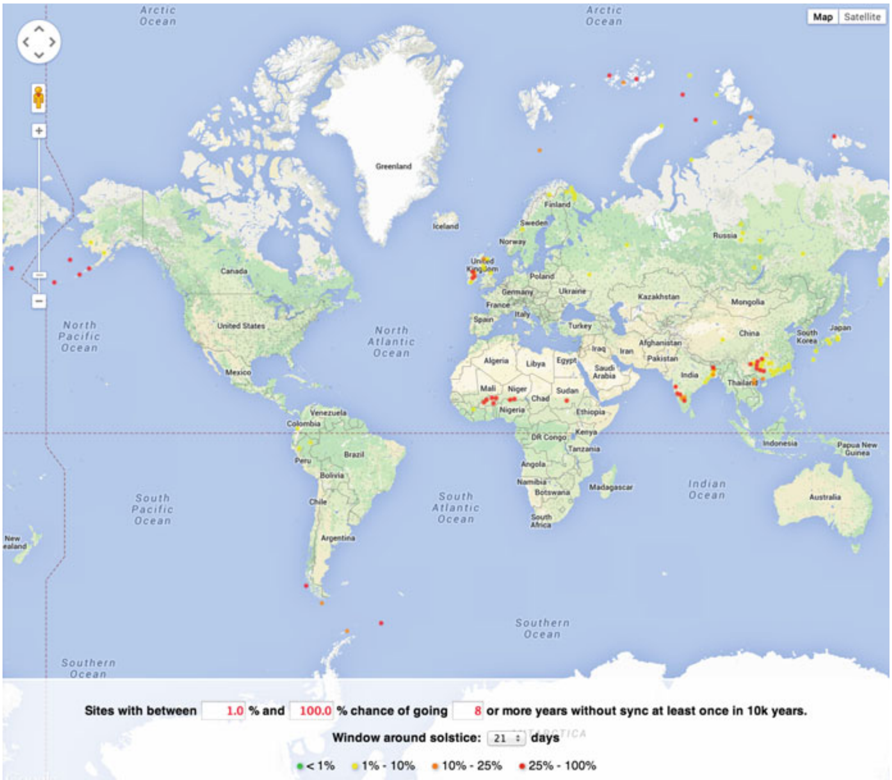

Fig. 37.3 Locations where synchronization of a hypothetical inferior clock would fail because of 8 consecutive years of blocked summer solstice Sun with >1% probability, sometime in 10,000 years

of 22 consecutive years of blocked summer solstice Sun in 10,000 years. Our conclusion is that shifting weather problems are not likely to cause a problem.

Whenever observed solar time is valid (the Sun is observed), the difference between it and derived solar time is used to correct the drift of tick time to produce *corrected time*. If the pendulum was perfectly accurate, corrected time would be the same as tick time. In reality, it is likely to occasionally jump forward or backward. Thus, corrected time is not necessarily monotonic and can repeat.

The non-monotonicity would be a problem for triggering events such as the chimes, since it might cause them to be re-triggered. For this reason, *monotonic corrected time* is generated from corrected time. Monotonic corrected time tracks corrected time, but pauses whenever corrected time reverses, until it catches up.

Display time is used to generate the time shown on the dial as well as the displays of the Sun, Moon and stars and the Gregorian calendar date. This time is only accurate immediately after the clock has been wound. It is updated by keeping track of the interval since the last winding, as measured by monotonic corrected time.

Table 37.1 Time periods displayed by the clock

	Julian days	Solar days	Clock	Time	Gear ratio
Sun/moon position	1.000000984	1	1	Solar	144 288 12 12
Moon phase	0.966136786	0.966136786	0.966136789	Lunar	220 263 19 197 16
Sidereal day	0.997270651	0.997269669	0.997269669	Solar	235 342 220 263 343 227 19 197 16
Precession	9412982.24	9412972.980	9412882.619	Planet	329 282 225 220 317 121 9 9 10 19 19 64
Tropical year	365.242189	365.2415227	365.2415166	Planet	220 317 121 19 19 64
Sidereal year	365.2563554	365.2559961	365.2564103	Planet	56 111 220 16 18 13
Mercury	87.96925718	87.96917062	87.96914701	Planet	321 151 19 29
Calendar year	365.2428594	365.2425000	365.2425000	Planet	321 151 235
Venus	224.7007992	224.7005781	224.7005862	Planet	19 29 92 56111 220
Earth	365.2563554	365.2559960	365.2564103	Planet	16 18 13 219 23 61 121 97 111 220
Mars	686.9796466	686.9789706	686.978544	Display	43 241 236 14 16 18 13 187 121 97 111 220
Jupiter	4332.820129	4332.815866	4332.798497	Planet	236 14 16 18 13 238 97 111 220
Saturn	10755.69864	10755.68806	10755.49679	Planet	14 16 18 13 321 151

The "gear ratio" column shows the ratio of the gear train connecting the display to the indicated time base, approximating the number of the predicted solar days

The display for the position of the Sun requires the recomputation of apparent local solar time from displays through the addition of a correction generated by a second equation of time cam, similar to the first. This generates *solar display time*.

The display for the phase and position of the Moon requires a correction for the predicted changes in both the Earth's and the Moon's orbital rate. This generates the addition of a length of month correction cam. This generates *moon display time*.

The display for the planets' relative positions requires only a correction for the predicted changes in the Earth's rotation. This generates the addition of a length of day correction cam. This generates *planet display time*, which is the closest long-term approximation in the clock to Barycentric Dynamical Time. Without this correction, the computed position of Mercury would be significantly inaccurate in 10,000 years. The periods and the rational approximations by which they are calculated are shown in Table 37.1.

Thus, the Clock of the Long Now needs to generate nine versions of time to meet different requirements. Given that nine versions of time are required in a single clock, perhaps it is less surprising that so many different time standards are maintained by timekeepers throughout the world.

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