Time MEASUREMENT

by Douglas Clarkson

Time has increasingly become a key aspect of our modern times. Without a world-wide appreciation of its every passing instant, and the relativities of time in zones around the world, our modern society could not function. Also, as the link of telecommunications and computers increasingly integrates the world, so too, there are more clocks to synchronise.

A study of time measurement, however, reveals a vast history of human endeavour and application and encompasses understanding of physical science at many levels ranging from celestial mechanics, quantum physics and general relativity. The accurate measurement of time has been a lifelong dedication for a great many individuals and consequently, the amount of material that is touched upon in such a study is considerable. This is almost impossible to summarise in one article.

In the modern era, the importance of accurate time keeping was initially brought about by the requirements for navigation at sea – in particular, to know the longitude. The striving for an accurate time keeper or chronometer on board ships at sea was borne out of the need to navigate successfully around the world. At stake was the expansion of the British Colonies, the establishment of trade and being victorious in conflicts with rival maritime nations. Thus, the keeping of accurate time was not just a convenience to ensure that all guests arrived at a dinner party on time. The floors of the oceans are littered with wrecks of vessels whose navigators could not determine longitude accurately. In this regard, the keeping of time was relative to the solar day. It would be a great error, however, to consider that time was not important to much more distant cultures – far from it.

Ancient Keepers of Time

While the Greeks reflected an advanced knowledge of astronomy and geometry that gradually slipped from western culture, this appreciation of many of the subtler aspects of astronomy had certainly been a core of knowledge of even earlier cultures.

The builders of Stonehenge and Avebury in England, Callanish in the Outer Hebrides, the Ring of Brodgar in Orkney – not to mention the extensive systems of Carnac in Brittany, all reflect an understanding of the passage of the Earth around the sun and of the moon around the Earth. Linked also with this was consideration of various principal stars including Canopus, Capella and Sirius. Thus, using the features of the Earth (distant mountains, etc.), in association with man-made stone rings, avenues and ellipses, quite ancient societies were able to measure time, not in terms of seconds in a day, but in terms of days within a year for the solar calender and days within the 18·61 year cycle of the moon's orbit round the Earth. The moon has quite a complex orbit round the Earth, since not only is the orbit inclined to the ecliptic by about 5°, but the moon's orbit has an eccentricity of 0·0549.

There was also an appreciation in the Ancient World of the precession of the equinoxes, as in the cycle of around 25,920 years for the pole star to wander in a complete circle through the signs of the zodiac. The key point in this cycle is the point of the sky to which the Earth points at sunrise on the spring or vernal equinox. Recent speculation related to appreciations of the origins of the Sphinx in Egypt in the book *Keeper of Genesis* by Robert Bauval and Graham Hancock has provoked widespread interest. While conventional archaeologists point to the evidence of water-related erosion of the monument, it is quite revealing to determine that the giant lion-like edifice would have been looking directly on the horizon at the rising of the constellation of Leo in the year around 10500 BC – in fact, the date of claimed completion of the monument by these authors. This is, of course, the stuff that nightmares are made of for Egyptologists, who prefer to move the period of the building of the Sphinx to more like 2500 BC.

It is interesting to note that, according to Diodorus Siculus, book V of the first century BC:

'The disposition of the stars as well as their movements have always been the subject of careful observation among the Egyptians . . . they have preserved to this day, records concerning each of these stars over an incredible number of years, this study having been zealously preserved among them from ancient times.'

That point in time when records first began to be made is now being placed earlier and earlier by such new theories. Numerous cultures around the world shared this preoccupation with clocks in the sky. The book *In search of ancient astronomies,* edited by E. C. Krupp, provides a scholarly and well researched work on this topic.

There is no doubt, however, that the Egyptian civilisations have attracted the lion's share of archaeological interest. An interesting account of time keeping and in particular, calenders in the Mayan culture of South America, is given by Adrian G. Gilbert and Maurice M. Cotterell in the *Mayan Prophecies.*

Thus, in the past, the preoccupation with time was with how the Earth would interact with the cosmos – what external factors by way of alignments, oppositions, conjugations, etc. were or would be present with the inherent belief that such influences would influence the destiny of human affairs.

In the modern context, the preoccupation with time is with the 'instant' – the here and now. It turns out, however, that time is now one of those physical quantities that can be measured with excellent accuracy. An increasing number of physical parameters are being defined in

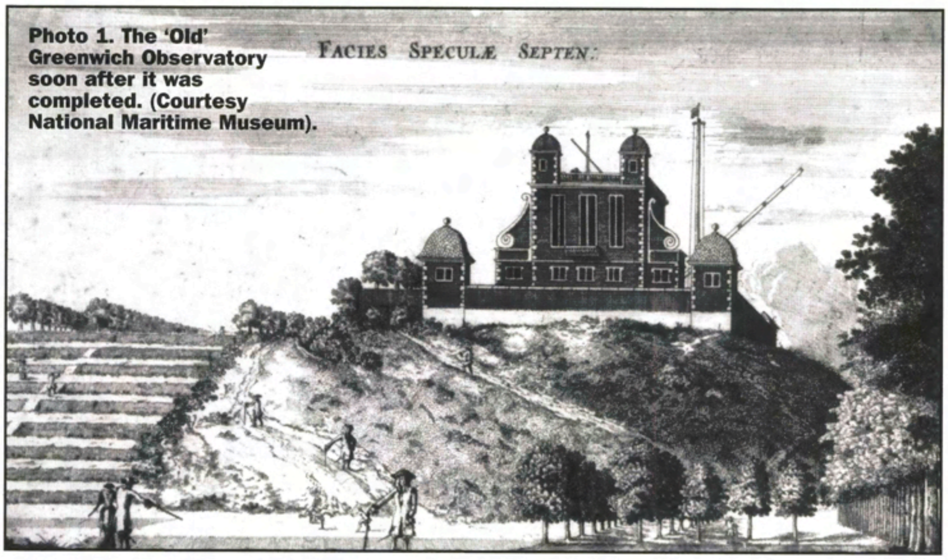


Photo 1. The 'Old' Greenwich Observatory soon after it was completed. (Courtesy National Maritime Museum).

terms of time as the defining standard. In fact, the history of the derivation of time as we know it is a fascinating tale. So much of what we take for granted in the way time is displayed and its value distributed has taken place only in the last 150 years.

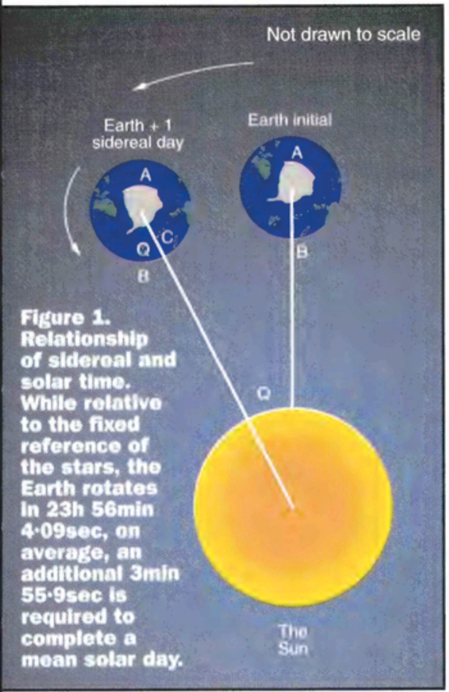


Figure 1. Relationship of sidereal and solar time. While relative to the fixed reference of the stars, the Earth rotates in 23h 56min 4·09sec, on average, an additional 3min 55·9sec is required to complete a mean solar day.

Solar and Sidearal Time

In the concept of sidereal time and solar time, sidereal time is that time referenced to the rotation of the Earth against the fixed background of the stars. Solar time relates to the apparent time interval of a day – e.g., the time between successive points in time when the sun is highest in the sky.

In Figure 1, the Earth is shown as revolving on its axis and with also moving to its present position one sidereal day later. Relative to Sidereal Time, one revolution of the Earth will translate point B to B. To complete a solar day, an extra time interval is required to bring the sun directly overhead at C – i.e., to complete a solar day. This additional time interval is, on average, 3 minutes and 56 seconds.

In Figure 1, the average angle, Q, is given by 360/365·25, being the total number of degrees in one revolution round the sun divided by the number of days of the year cycle.

$$\textit{Solar Day} = \textit{Sidereal Day} + \textit{Sidereal Day} \times \frac{Q}{360}$$

$$\textit{Solar Day} = \textit{Sidereal Day}\left(1 + \frac{1}{365{\cdot}25}\right)$$

$$\textit{Solar Day} - \textit{Sidereal Day} = \frac{\textit{Sidereal Day}}{365{\cdot}25}$$
$$= 3 \textit{ minutes, } 55{\cdot}9 \textit{ seconds.}$$

Between successive days, the transit time of a star to a point on the horizon is 23 hours, 56 minutes and 4·09 seconds (1990 data) and the mean solar day is, therefore, very close to 24 hours. This was one way for clock makers to test out the accuracy of their earthly mechanical clocks where they did not have available a highly accurate mechanical timepiece.

Thus, solar time is not just influenced by the rate of rotation of the Earth on its own axis – it is modified by the angular velocity of the orbit of the Earth round the sun.

The eccentricity of the orbit is 0·017, meaning that ratio of minor to major axis of the ellipse. While the mean distance to the sun is $1{\cdot}496\times10^8$km, the length of the solar day is not constant for the Earth in orbit round the sun. The variability of difference between solar day and a sidereal day ranges from 3 minutes, 35 seconds to 4 minutes, 26 seconds.

When the Earth is further away from the sun, the sidereal day is closer to the solar day and when the Earth is closer to the sun, it is moving faster and so the solar day is longer. The Earth is, in fact, at aphelion (furthest distance) at around 3rd July and at perihelion (closest distance) at around January 4th. The main effect of this is to make successive solar days – e.g., timed noon to noon on successive days of variable length. What is relevant in this regard, however, is the concept of the mean solar day – the average length of the day during the year.

This effect is indicated in Figure 2, where the so-called Equation of Time relates how local solar time as indicated on a sun dial is fast or slow relative to a mean time, where days are defined to be of equal length. Thus, the correction varies from +16 minutes fast to 14 minutes slow during the year. For many types of activity, however, this degree of accuracy – when the sun was available – was quite adequate. For scientific and subsequently commercial practice, it was very unsatisfactory. The transits of the stars provided a more accurate clock in the sky.

A Non-Constant Earth

Everyone is familiar with the demonstration of the spinning ice skater, who with arms outstretched, spins at one speed and then with arms drawn in, spins at a faster speed – a demonstration of the conservation of angular momentum. The Earth can also be considered to possess a finite amount of rotational energy. Every kg of mass at the equator has a rotational kinetic energy of around 100,000J.

Changes in density of material deep within the crust of the Earth or changes in distribution of dense and light air masses on the Earth's surface can cause detectable fluctuations in the speed of the Earth's rotation as its rotational inertia fluctuates.

In addition to the seasonal fluctuations and also unpredictable wobbles, the dissipation of energy through tidal cycles is causing the speed of rotation of the Earth to slow down, so that days are – ever so slowly – getting longer. In a few million years, there could be exactly 365 days in the year instead of the current 365·25, although it is difficult to project present observations into the far future.

These two effects are in a way complications, which have added complexity to the measurement of time. While the effect of the non-constant length of the solar day due to orbital velocity variation round the sun was known to the ancient Greeks, the effect of variation in speed of rotation of the Earth was only measurable with more accurate clocks from around 1920 onwards.

Ancient Clocks

The Moons of Jupiter and Pendulums

The ancient Egyptians around 700 BC used so called shadow clocks to tell the time. These consisted essentially of a raised rectangular block on top of which a horizontal rod was mounted. The day was marked into a mid day shadow line and five distinct hours that would apply to both morning and afternoon. In use the device was laid flat on the ground and pointed in the direction of the sun.

The Clepsydra or 'water thief' clock was used by the ancient Greeks and Egyptians – being essentially a vessel initially filled with water and which emptied in a set time. Presumably there would have been a slave whose duty it would have been to refill it and keep a tally of the refills during the day.

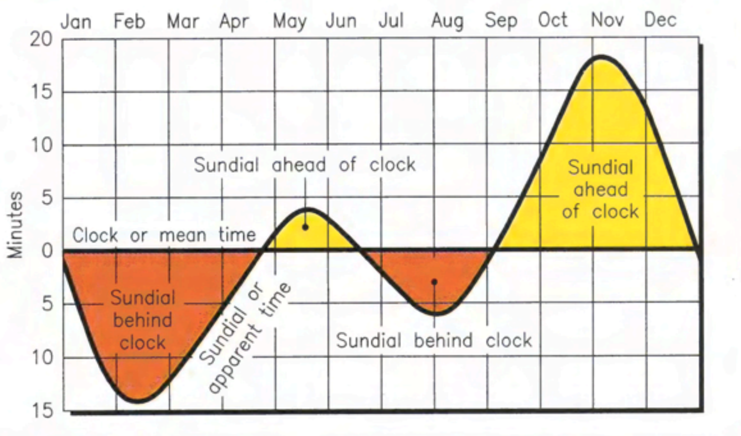
The ancient Chinese water clock consisted of a series of around six vertically mounted vessels which slowly drained into each other. Water was initially added at the top and the time noted for the level in the lowest collecting vessel to change by set amounts.

Sand clocks were later developed in Europe, typically in units of 15, 30, 45 and 60 minutes. In the reign of King Alfred, time at court was kept using candle clocks marked in hour extents. For most of the population, however, activity was essentially regulated by the sun. It was only around 1335 onwards that there are reports of mechanical clocks with these being developed initially in Italy.

The Greenwich Connection

The Greenwich Old Observatory has played a pivotal part in the determination of time for the whole world. This role relates both to the measurement of time in terms of high accuracy from timekeeping and also to

Figure 2. The Equation of Time of the difference of apparent solar time from mean solar time.



setting Greenwich as the zero meridian of longitude. In our current modern age when the importance of our maritime role is significantly reduced, the legacy of setting the standards for time serves as a major memorial of the age when Britannia did rule the waves.

In one sense, the origin of the Observatory at Greenwich is quite clear. King Charles II signed a royal warrant for its establishment on the 4th March 1675. The actual set of events that led to this result, however, are rather more obscure, and involve the king's mistress, Louise de Kerouaille and a Frenchman, St. Pierre, who proposed a method of lunar measurements and predictions to calculate longitude. The observatory was basically initiated in order to establish a core of observational data that could lead to the successful implementation of such a scheme. It is perhaps no coincidence that some years previously, Louis XIV had established in 1666, the French Academie Royale des Sciences, principally to solve the problem of longitude through astronomical observation.

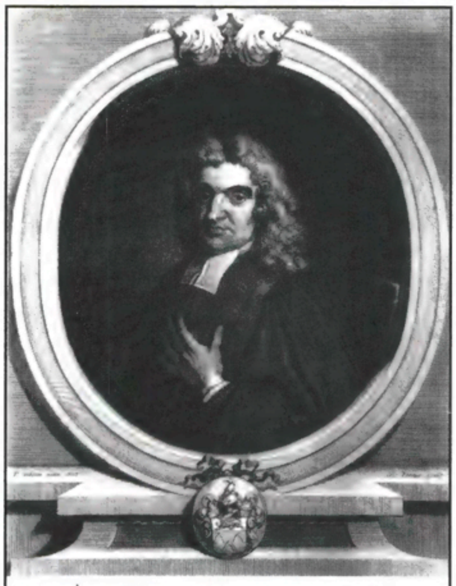


Photo 2. Illustration of John Flamsteed, the first Astronomer Royal. (Courtesy National Maritime Museum).

The Royal Observatory at Greenwich was designed by Sir Christopher Wren and with observations beginning by John Flamsteed – the first Astronomer Royal – in around October 1676. Flamsteed's star catalogue, which had taken around 40 years to compile, was published posthumously in 1725. Photo 1 shows the Old Greenwich Observatory soon after it was completed and Photo 2 depicts John Flamsteed.

Two so-called 'great clocks' were ordered to be made for the observatory by Thomas Tompion, a leading London clockmaker, and were set going satisfactorily together on 24th September 1676. These clocks had a 13ft. long pendulum for a 2 second period, used a new pin-wheel escapement and used very heavy weights in order that the clock would only have to be wound once per year. This was really the first instance of determination of Mean Solar Time at Greenwich. Flamsteed in fact used the transit of the bright star Sirius as a time reference for monitoring Mean Solar Time as kept by the 'great clocks'. The reliability of these clocks was around seven seconds per day. Flamsteed's work was indeed an uphill struggle, based on the meagre allowance he had been allocated to undertake his work.

One of the key parameters measured was the time at which the sun was highest overhead – at noon. From 1676 to 1725, the method used was that of Double Altitude or Equal Altitude, when the time that the sun attained a fixed altitude a set time before noon was compared with a corresponding set time after noon. The time of apparent noon (by sun's position) was then calculated. Applying the correction of the Equation of Time then gave the Mean Solar Time.

The invention of the transit instrument by Ole Romer led to the introduction of such an instrument by Edmond Halley in 1721 at Greenwich. This telescope device had essentially only one degree of freedom, with the axis of telescope in east west direction fixed. This was in time replaced by Airy's transit circle in 1851, and which continued to be used until 1927.

John 'Longitude' Harrison

The loss of five warships off the Scilly Isles on the foggy night of October 22nd 1707 with the loss of 2,000 troops focused attention on the need to improve navigation methods. This resulted in the passing of the Longitude Act of 1714, which offered a prize of £20,000 for solving the problem of finding longitude at sea. In this method, there were two main rivals – that of astronomy and that of accurate time keeping. As time progressed and mechanical invention developed, so did the science of astronomy.

Significant progress towards the development of an accurate chronometer for sea navigation was to come not from the more famous clock makers of London such as Thomas Tompion and George Graham, but rather, from a certain John Harrison from Barrow-on-Humber in Linconshire. Having been apprenticed as a carpenter, John Harrison soon migrated to making clocks. Not apparently having received formal training in such a craft, Harrison revisited many of the problems of accurate time keeping and came up with highly original and advanced solutions. He found it possible to use special types of self-lubricating wood for key elements of his clock movements, which allowed clocks to operate without lubrication. Also, in the design of pendulum clocks, Harrison combined brass and steel in pendulums to ensure that the pendulum had a length essentially independent of temperature. Also, he developed the 'going ratchet' to keep the clock ticking while it was being wound.

Harrison visited London in 1730 and was well received by Astronomer Royal, Halley and George Graham a famous London watchmaker – giving encouragement in the quest for the development of an accurate timepiece to win the coveted Longitude Prize established by Act of Parliament.

In order to win the prize, however, Harrison had to evolve completely new designs. At sea, pendulums had a nasty habit of stopping due to the violent motion of ships in rough seas. He would spend the next 40 years of his life both perfecting the mechanisms with the aim of claiming in full the payments assigned by the Longitude Act. Dava Sobel's book gives a good account of this innovative period of timepiece design. It is a fascinating story.

Table 1 gives a summary of the main events in the saga of John 'Longitude' Harrison's uphill struggle. One of the major difficulties that Harrison was to experience was that highly influential astronomers wanted their methods of astronomical observation to win the Longitude Prize. By all accounts, Harrison should have been awarded the prize in 1762, but he was to have to wait until 1773 following intervention by the King, until some redress was made.

Date	Event
1730	Received in London
1735	Completes H1 clock
1736	Successful trials onboard HMS Centurion
1741	H2 presented to Board of Longitude
1757	H3 essentially complete
1759	H4 completed
1761	Sea trial of H4 on HMS Depford
1762	H4 accuracy verified but not credited
1765	Parliament changes rules of Longitude Act
1766	H1, H2, H3 and H4 removed to Greenwich
1770	H5 completed
1772	Captain Cook uses K1 copy of H4
1773	Belated payment of L8750 to Harrison
1775	Captain Cook vindicates K1 accuracy
1776	Death of John Harrison

Table 1. Key events in saga of John 'Longitude' Harrison.

The accuracy of H4, had been verified in 1762 as losing only five seconds after 81 days at sea. H4 was a very exceptional watch – a miraculous watch in some respects. Lesser watches were subsequently made as official copies but they omitted various key features of the original mechanism design.

John Harrison's timepieces not only improved the accuracy of clocks and watches in general, it allowed safer navigation of the sea with all the implications for trade and establishment of colonies overseas.

The London watchmaker, Lacrum Kendell, was given H4 to copy, making the famous timepiece K1 and later, a less accurate K2. K1 was used with great success on Captain Cook's second voyage, from which he returned in 1775. K2 was used by the mutineers on board HMS Bounty to find Pitcairn Island. During this period of horological history, necessity was very much the mother of invention.

Before long, chronometers of acceptable quality were widely available. It was common, however, for reliance not to be placed on a single timepiece. Thus, when HMS Beagle set out in 1831 with Charles Darwin on board, a total of 22 chronometers were in use.

The End of Local Solar Time

In the early 1800s, while there were a great many clocks in the land, it was the custom for them to show local solar time. Thus, clocks in Norwich could be 6 minutes ahead of Greenwich and clocks in Plymouth, 16 minutes behind. This caused the greatest problem for the operation of Railway Timetables. It was however, not until 1840 that the Great Western Railway established Greenwich Mean Time at all of its stations. Gradually, over a period of ten years, other railway companies also began to use Greenwich time.

With the implementation of telegraph ines, Greenwich from around 1850 onwards began to act as the source of time synchronisation signals across the UK. The adoption of Greenwich Mean Time (GMT), however, was more progressive than universal, with some 98% of public clocks in Great Britain being set to GMT by 1855. It was not until 1880 that GMT became the egal time also for commerce and industry n Britain.

Towards Global Time Standards

It was one thing for one country to adopt a national time standard – quite another for there to be global agreement regarding time. It was only at the International Meridian Conference in Washington DC in 1884 that a consensus was adopted for the definition of the length of the day, viz: 'That the universal day is to be mean solar day; is to begin for all the world at the moment of mean midnight of the initial meridian, coinciding with the beginning of the civil day and date of that meridian; and to be counted from zero up to twenty-four hours'.

This conference also accepted 'the adoption of the meridian passing through the centre of the transit instrument at the Observatory at Greenwich as the initial meridian for longitude'.

Up until this point in time, there were at least eleven other contenders for other points of origin for the meridian – with Paris the main rival. It was the fact, however, that some 72% of global shipping were using maps with the Greenwich meridian for navigation that led to the choice of Greenwich as the prime meridian.

This subsequently allowed the formalisation of time zones around the world, with generally zones of one hour corresponding to 15° of longitude. Since then in many respects, time has seen some subtle refinements but no major re-definitions.

The New Time Machines

The accuracy of clocks used for astronomical purposes and time reference improved during the 19th century. In 1870, the Dent number 1906 of Airy kept time to an accuracy of 0·1 seconds per day. Around the turn of the century, significantly more accurate clocks produced by Sigmund Riefler of Munich became available. In the 1920s, so-called free pendulum clocks produced by W. H. Shortt in the UK became available with an accuracy of 10 seconds per year. In the free pendulum clock, the time is maintained by a free pendulum in an evacuated chamber and synchronised to time with a slave pendulum in a normal atmosphere.

The development of quartz as a resonator material provided a superior means of measuring time compared with mechanical clocks. Quartz, however, was sensitive to environmental conditions of temperature and vibration. Also, quartz crystal underwent a gradual ageing process which gradually altered its resonant frequency with time. Initially, resonant frequencies around 100kHz were used at Greenwich between 1939 and 1964, though subsequently higher frequencies were used. Typical accuracies of high precision quartz clocks was of the order of 0·1ms per day.

For the modern wristwatch, the accuracy of quartz to a few seconds per week is entirely adequate. Photo 3 shows the component parts of the Seiko Kinetic movement with quartz oscillator.

Atomic Clocks

It seems that although time is being measured with ever increasing accuracy, there is always the perception that even greater accuracy is required. The advent of quartz clocks in the 1940s provided an accuracy of around 0·1ms per day. This was not, however, of sufficient resolution to investigate specific tests relating to relativity. Some pioneering work was undertaken with atomic beam resonance at Columbia University in the 1930s. The first atomic clock to be used in earnest was one at NPL in 1955 and developed by John VL Parry. In 1967, the second was defined as 9,192,631,770 periods of the resonance of Cs 133 atom. The Q of such a resonator, the ratio of the frequency divided by the line's frequency spread, is of the order of 100 million. For such clocks, the reproducibilities are of the order of 1 in 10^{14}.

The atomic beam frequency standard is indicated in Figure 3. A source of atoms is obtained by heating Caesium atoms by a filament lamp. Atoms of appropriate energy state selected by magnet A pass into a resonant microwave cavity where their energy is changed to a second level and with magnet B deflecting these to a detector. The system incorporates a servo mechanism to optimise the current of Caesium atoms detected and hence to resonant frequency of the microwave cavity.

Recently, atomic hydrogen masers have been developed, which allow improved performance at a lower frequency of around 1,420MHz. Initial problems with the poorer stability of the resonant cavity have been overcome to make atomic hydrogen masers the atomic clock of choice for several national laboratories, including that of the NPL in the UK. The Q of such a resonator is of the order of 10^9 and with a frequency stability better than one part in 10^{15}.

Another clock which is commercially available is that of Rubidium 87 at a frequency of 6,836MHz. While such sources are less expensive, their reproducibly is only of the order of one part in 10^{10}.

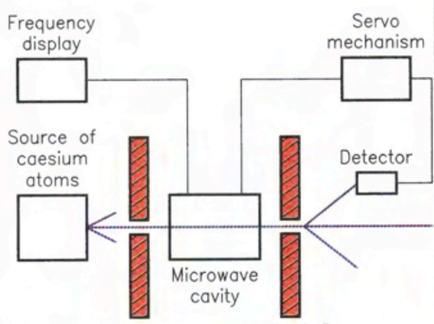


Figure 3. Schematic diagram of Caesium beam atomic clock.

Lonely Cold Ions

Investigations, however, continue in the search for even more accurate methods of measuring time. Trapped atoms suspended in a vacuum and isolated from disturbing influences have been made to resonate with stabilities comparable or equal to that of the hydrogen maser. In the so-called atomic fountain, atoms are nudged into a resonant microwave cavity by a series of laser beams so that the atoms suffer no spectral broadening through collisions with containment walls. A resonant Q of such systems of 1013 has been observed in work at NIST in the USA. The problem with such systems, however, is that they have not been operated over extended periods. Perhaps, however, this technology will provide a natural end point for the accuracy of time measurement.

Recent work at the NPL has reported on using trapped Ytterbium ions cooled to within 0·5mK as a means of obtaining an ultra-stable 467nm clock transition. While the best Caesium clocks give a stability of 3 parts in 10^{15} per day, this ion trap technique could provide an additional factor of a thousand in line stability. Figure 4 summarises the details of the sequence of ions cooling, energy absorption and recycling of ion energy system.

Initially, the Ytterbium ion is in a reference state. The ion is irradiated by a laser beam at around 369nm, just below an absorption transition of the ion. If the ion moves toward the photons, the doppler effect increases the energy of the photon and the ion absorbs it – absorbing momentum and in effect slowing it down. This continues until the ion is more or less stopped. If another laser is tuned around

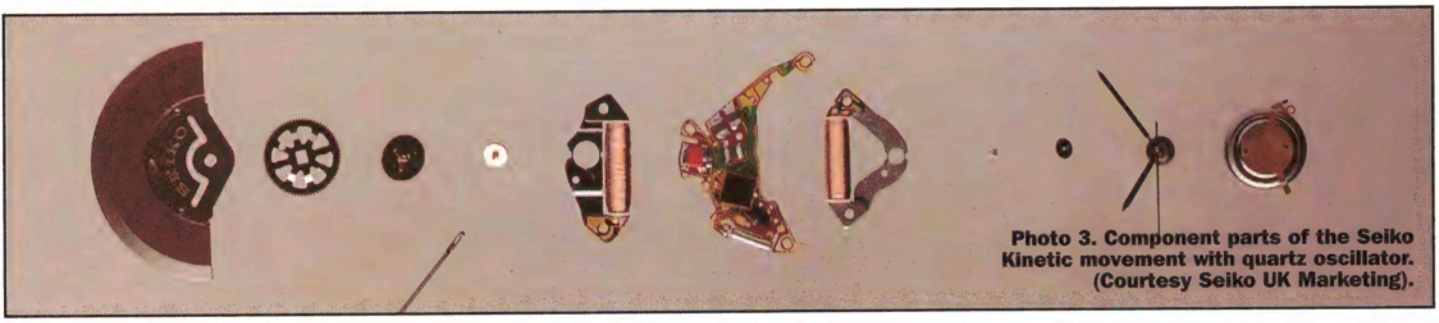


Photo 3. Component parts of the Seiko Kinetic movement with quartz oscillator. (Courtesy Seiko UK Marketing).

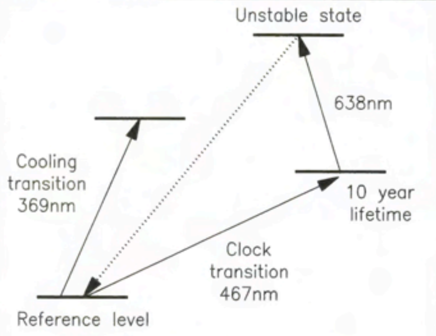


Figure 4. The ultra-stable 467nm absorption is achieved by cooling the ion to close to absolute zero. The ion is 'recycled' by raising it to a higher level which in turn decays rapidly to the reference level.

467nm, the ion absorbs this energy and the ion remains in a higher stable state. It would probably remain in this state for 10 years through natural lifetime processes. A laser at 638nm, however, is used to raise the energy to a higher state which rapidly decays to the starting level. The uncertainty in the frequency of the 467nm transition is only 0·5nHz which in turn provides an uncertainty of 1 in 1018. This is typically better by a factor of 10 million compared to state-of-the-art stabilised He-Ne reference lasers. Such a technique could well be the basis for future design of atomic clocks for resonance at the ultra-stable transition wavelength. Figure 5 summarises the increasing accuracy of achieved by clocks through history.

Towards Universal Time

There is a perception that there can only be one time for everybody. Allowing for time zones, then the minutes and seconds tick all over the world the same (except in time zones with 0·5 hour divisions). Current time is described as Coordinated Universal Time (UTC). There have been various key initiatives, however, in establishing UTC.

Date	Event
1884	Greenwich Mean Time adopted as Universal Time (UT)
1952	Ephemeris Time (ET) Introduced
1956	UT0, UT1, UT2 defined as sub-divisions of UT
1956	Ephemeris Second defined
Jan 1, 1958	TA1 (Atomic Time) commences
1967	Second defined in terms of Cs periods of radiation
Jan 1, 1972	Coordinated Universal Time (UTC) established

Table 2. Key events in determining time standards.

While time as Universal Time had been defined as established by Greenwich Mean Time in 1884, the advent of radio which allowed time signals to be sent rapidly round the world revealed that various stations could be several seconds adrift. It was the French who, in 1912, established the Bureau International de l'Heure (BIH) to co-ordinate accuracy in time keeping. This group did not formally function until around 1920.

From more accurate measurements of the Earth's rotation using more accurate clocks, it became apparent that the value of the mean solar day was changing very slowly. It became desirable to use instead the year as the measure of time scales. Even though the year is slowly decreasing by about 0·5 seconds per century, this would provide a more stable reference. Thus, in 1952, the so-called Ephemeris second was defined as the fraction 1/315,569,25·9747 of the tropical year for 1900 January 0d 12h ephemeris time.

While this provided a more stable basis for time measurement, and the second had been defined in terms of a time period that had occurred and, therefore, had a finite value, the problem of lack of accessibility remained. No one could produce, for example, a traceable pulse of signal exactly one second long.

The adoption of the atomic clock standard was to solve this with the formal adoption of the atomic second in 1967. Prior to this, the atomic clock had started ticking on January 1st 1958 and defined within TA1 (Atomic Time). The UTo (Earth time) was gradually losing seconds by this time. On January 1st 1972, a new time, Coordinated Universal Time (UTC), was defined as 10 seconds slow on TA1 (Atomic Time). The BIH in Paris currently coordinates the world 'mean' atomic clocks based on the time held by around 200 high precision atomic clocks. Thus, time as we know it is still subject to the vagaries of statistics. Table 2 summarises the main sequence of events in establishing time standards.

The point about the scales of time is that absolute accuracy is required for astronomy and modern communications technology. At the same time, it is required that the noon 'pip' of UT1 (close equivalent of Greenwich Mean Time) occurs within 0·9 seconds of noon according to the average transit of the sun. At present, leap seconds are being added at the rate of typically one per year – reflecting the fact that compared to the Ephemeris day of 1900 – the mean solar day of that year, the Earth is now rotating more slowly. The formal year as we know it is only reducing by around 0·5 seconds per century. Figure 6 indicates how leap seconds have been added to the UTC since 1972. Planned leap seconds are notified well in advance by the BIH in Paris.

Awareness in Time: The Türler Cosmic Clock

While time is something that is being charted with increasing accuracy, the awareness of where we are in time – its expression, as it were, of its passing is still subject to human inventiveness. The Türler Swiss watch company, founded in 1883, has

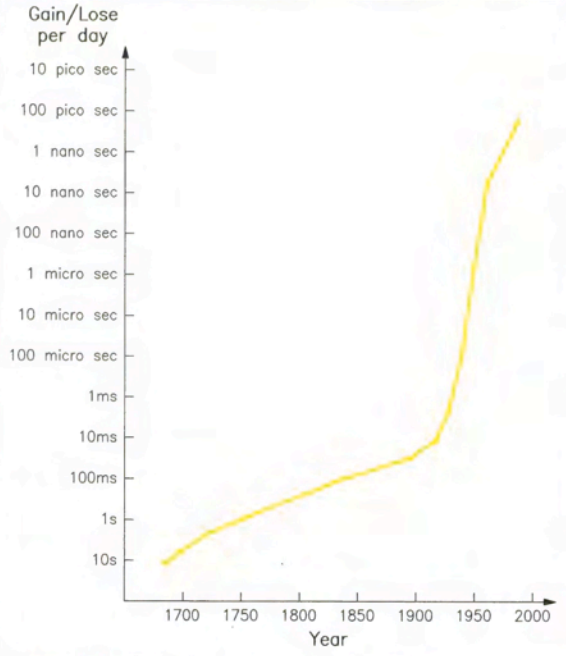


Figure 5. Sequence of increasing accuracy achieved by clocks through history.

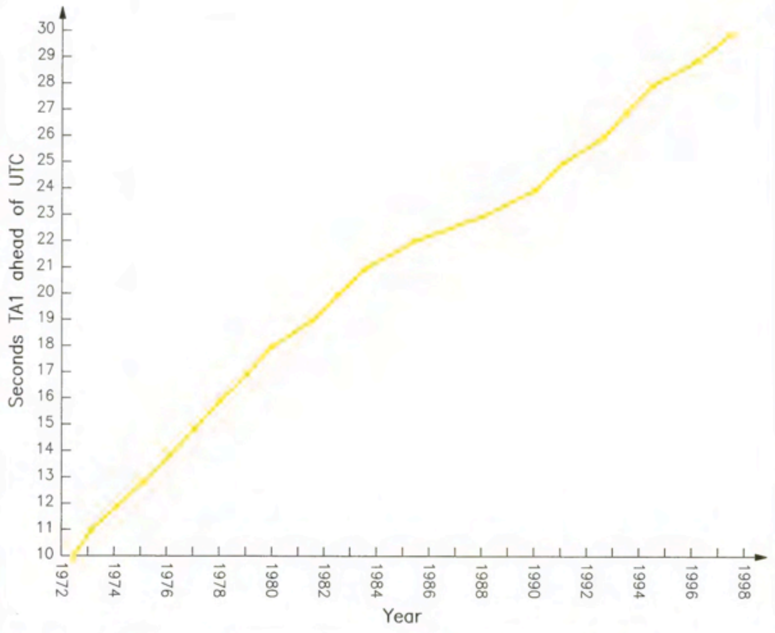


Figure 6. Incidence of adding leap seconds to UTC since 1972.

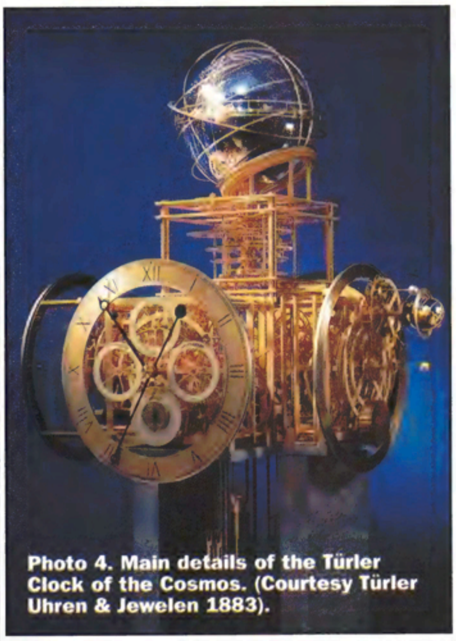


Photo 4. Main details of the Türler Clock of the Cosmos. (Courtesy Türler Uhren & Jewelen 1883).

always maintained a high standard of quality in watch design and manufacture. It was fascination with the aura surrounding time that inspired the present head of the company, Franz Türler, to create a clock 'of unique perfection' – and 'a work of art, timeless and of lasting value'.

To turn these aspirations into reality was to take nine years of planning and development. The end result is the Türler Clock – a model of the cosmos. This clock, whose main details are shown in Photo 4, combines in a way all the previous clocks that man has tried to build to describe sidereal time, solar time, rotation of the moon and the Platonic year of 25,794 years as the Earth completes one cycle of precession about its axis. The four components of the clock comprise the Globe, the Perpetual Calendar, the Planetarium, the Tellurion and the Horizon.

The Globe, shown in more detail in Photo 5, provides a snapshot of the relative rotation of the Earth, moon, sun and stars as perceived from an outside observer gazing in from the solar system. The Perpetual Calendar provides the time in hours and minutes and with four smaller inner dials indicating the day of the week, the day number in month, the month and the year in decade century and millennium. Full corrections are implemented for leap days on 29th February and with dropping leap day every 100 years and adding it again every 400 years, in accordance with full Gregorian calender.

The Planetarium encompasses the nine planets of the solar system, from Mercury with an orbit of 87 days, to that of Pluto of 247 years. It provides, therefore, a mechanical view of cosmic reality.

The Tellurion indicates with reference to a model globe of the Earth, the positions of the sun and moon and on the outer rim, the position of the sun in terms of the ecliptic, zodiac and month is displayed.

The Horizon is a novel representation of the paths of the sun and the moon, as visible at the location of the clock on the physical horizon. Events are indicated in terms of a 24-hour clock showing local mean solar time.

The Swiss Watch Industry

After suffering the destabilisation of the era of the dollar quartz watch, the Swiss watch industry, emphasising its skills in craftsmanship and quality, is still a major industry. In 1994, for example, exports totalled some SF 8 billion. While companies like Swatch have tried to recapture the mass production market, a core of companies in the famous Joux Valley, including Audemans Piguet, Blancpain, Jaeger-LeCoultre, Daniel Roth, Nouvelle Lemania, Dubois-Depraz and Fila, maintain the highest standards of quality and tradition. The focus of economic activity to high value products tends, therefore, to produce an economy which is inherently stronger. The Gross Domestic Product of Switzerland per person at around $35,000 is over twice that of the UK.

The NPL Time Services

MSF 60kHz Time and Date Code (Rugby clock)

This radio transmission is the principal means of communicating time within the UK, and broadcasts effectively UTC Coordinated Universal Time, which is always within one second of Greenwich Mean Time. With a transmitter power of 27kW, the signal can also be received widely in western and northern Europe. The carrier frequency is maintained at 60kHz within one part in 10^{12}.

Data from the clock is presented second-by-second with identification of details of seconds within minutes. The modulation used is simple on/off modulation. Figure 7 indicates the normal appearance of the identification of the second 00 – effectively a minute marker and appearance of subsequent seconds. The modulation is typically switched off for an interval of 500ms. In addition, however, other modulated information can fill this slot – presumably, test data of some kind. In each of the following seconds, the first 100ms is always OFF and with the next two intervals of modulation of 100ms, either ON or OFF, thus assigning values to bits A and B within the specific second. Data is primarily contained with bits 17A to 51A of the time signal within each second. Thus, from switch on, as it were, the clock needs a complete minute to recover all the data from the transmission regarding time, date, etc. Thereafter, the signal is principally updating the second details of the time. Table 3 indicates the year coding utilised and Table 4, the month, day in month and day of week.

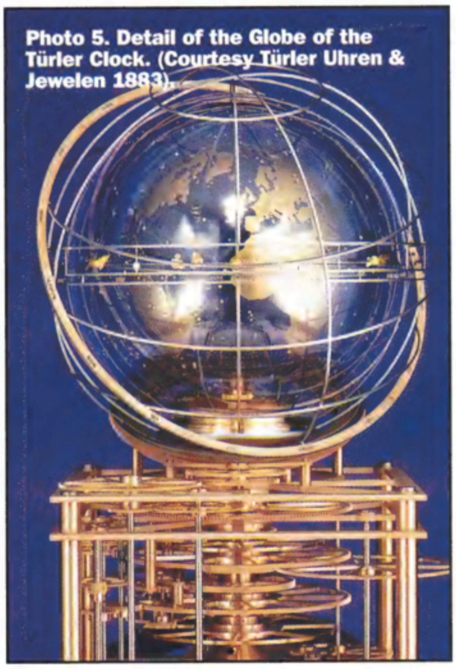


Photo 5. Detail of the Globe of the Türler Clock. (Courtesy Türler Uhren & Jewelen 1883).

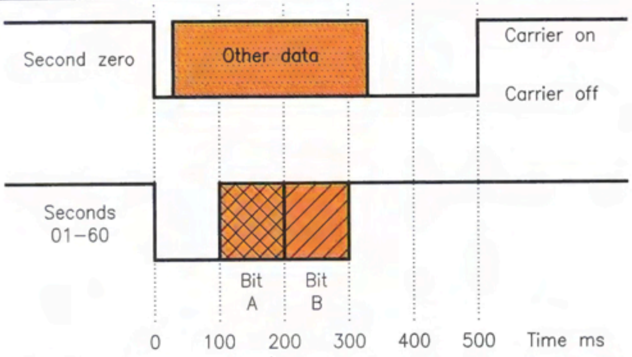
Last but not least, the time in hours and minutes is given by details as presented in Table 5.

Bits 9B to 16B are used to indicate the difference between UTC and UT1 (closely equivalent to GMT) to the nearest 100ms in range +800ms to -800ms.

NPL Truetime

NPL Truetime is a recently introduced time service that allows computer clocks to be set within one fiftieth of a second by direct telephone connection to the national time scale maintained by NPL. This time reference at NPL is itself based on an atomic clock which is itself maintained within one millionth of a second of Coordinated Universal Time (UTC). Data is currently set using V22 1,200-baud standard with eight data bits, no parity and one stop bits. Data is sent in strings of characters which are numbered 01, 02, ...77. More complete details are included in NPL information sheet reference CETM h 099. Table 6 summarises key parameters communicated by NPL Truetime.

Figure 7. Waveform of Rugby clock signals in the first and subsequent seconds.



Code	Function
17A	Year × 80
18A	Year × 40
19A	Year × 20
20A	Year × 10
21A	Year × 8
22A	Year × 4
23A	Year × 2
24A	Year × 1

Table 3. Year value decoding.

Code	Function
25A	Month × 10
26A	Month × 8
27A	Month × 4
28A	Month × 2
29A	Month × 1
30A	Day of Month × 20
31A	Day of Month × 10
32A	Day of Month × 8
33A	Day of month × 4
34A	Day of month × 2
35A	Day of month × 1
36A	Day of week × 4
37A	Day of week × 2
38A	Day of week × 1

Table 4. Month, day of month, day of week decoding (0 = Sunday).

Code	Function
39A	Hour × 20
40A	Hour × 10
41A	Hour × 8
42A	Hour × 4
43A	Hour × 2
44A	Hour × 1
45A	Minute × 40
46A	Minute × 20
47A	Minute × 10
48A	Minute × 8
49A	Minute × 4
50A	Minute × 2
51A	Minute × 1

Table 5. Month, day of month, day of week decoding.

Parameter	Details
Date	YYYY-MM-DD format
Time	hh:mm:ss format
local time	e.g., UTC+0 during GMT and UTC+1 during BST
day of week	Monday = 1 – 7 = Sunday
Week of year	week 01 contains first Thursday of year
DUT1	difference in 0·1 sec UT1 and UTC
LEAP SECONDS	announcement of pending leap seconds
Julian Date	Modified Julian Date – day value

Table 6. Key parameters communicated by NPL Truetime from 0891 number.

More complete details are given in NPL data sheet CETM h098. The number of NPL Truetime is (0891) 516 333 and can only be dialled from inside the UK. NPL Truetime provides direct traceability to the National Time Standard. There are a range of clocks that detect Rugby time. One interesting system provided by Timenet Ltd. serves as an add-in card to a PC to enable on line time keeping to be achieved.

Interconnected Units

The definition of the metre is related to 1/299,792,458 part of a second and the volt is defined in terms of the characteristic frequency associated with a voltage that appears across a Josephson junction in a superconducting circuit. Thus, improving the accuracy of time allows more accurate measurement of a range of related physical parameters.

Relativistic Effects

Just as it required clocks of improved accuracy to detect the variations in the rate of rotation of the Earth, so too, it required the development of clocks like the atomic clock to detect relativistic effects. One such effect relates to the relationship between the frequency of a photon of energy and the gravitational field in which it is emitted. If, at the surface of the Earth, a photon of light is emitted with a frequency fo, then at a height one metre higher, the frequency will be higher by one part in 10^{16}. This is part of the general effect of gravity lowering the energy of a quantum state. Thus, there is implied in this effect, the reference height at which standard measurements are made for the world's set of atomic clocks. This effect is a necessary correction to apply for atomic clocks held onboard Global Positioning Satellites in geostationary orbits round the world.

Also, there is an effect in respect of the non-uniformity of the velocity of the Earth round the sun – the very variation in orbital speed that resulted in the Equation of Days which corrected mean time against apparent solar time. This, coupled with the variation in sun's gravitational potential, makes TA1 run faster by about 6·6 parts in 10^{10} at aphelion around July 3rd compared to that at perihelion – around January 4th. The effect of this in a whole year is around 3·3ms. These relativistic effects probably are detectable and have to be corrected for in GPS technology.

Greenwich Meridian 2000

In the words of the 1884 International Meridian Conference, the universal day 'is to begin for all the world at the moment of mean midnight of the initial meridian'. This is taken as meaning that the prime Meridian at Greenwich is the point from which the new millennium will begin.

The 1000 Day Countdown to the new millennium began on Friday 4 th of April 1997 as indicated by unveiling of the Accurist Millennium Countdown Clock at Greenwich.

Summary

In the efforts of the individuals to investigate and measure time can be traced also the rise of the once supreme maritime nation of Great Britain. The confusion over the relevance of Greenwich in terms of the celebration of the Millennium is no more than an indication of the ignorance of the greatness of past days. Can you think what the French would do in terms of Millennium celebrations if the zero of longitude ran through Paris?

Also, in response to the age old question, 'What time is it?' – as after-dinner conversation, the reply could very well be long in the extreme.

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