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Dennis D. McCarthy , P. Kenneth Seidelmann
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1

Time Before the 20th Century

1.1 In the Beginning

The earliest people on the planet surely recognized the cycles of the most basic astronomical motions. The Sun and Moon rose and set each day, and moved through the sky with predictable patterns, and the weather followed a cycle related to the movement of the Sun with respect to the stars. The units of days, months, and years naturally followed. With further observations, those watching the sky could visualize patterns in the stars and distinguish comets and "stars" that "wandered" among the others. Dramatic events such as solar and lunar eclipses were seen, and, in some cases, they were recorded and predicted, and their "meanings" interpreted. The observation and measurement of these cycles were important for daily life, religious practices, and agriculture, and they became the bases for timekeeping and calendars. Apparently, some of these observations even affected the orientations of early constructions of tombs or stone circles, such as Stonehenge. Naturally different cultures developed different customs for both keeping time and developing calendars (Aveni, 2002). Variations in accuracy of observations and application led to changes in understanding of the motions and ability to make predictions. These improvements in knowledge and accuracy even continue to drive changes in our definition and use of time in the present and into the future.

1.2 Characterizing Time

Much has been written about the topic of time, and so it is necessary to acknowledge the distinctions between the concepts of time, idealized timescales, definitions of timescales, requirements for different timescales, practical realizations of timescales, and the applications of timescales. In addition, there are time units that we can measure, and nonmeasurable time units that can only be calculated.

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Traditionally, we have recognized the desirability of a kind of “uniform time” with basic units that always remain the same. Isaac Newton (Newton & Motte, 1934) distinguished between an idealized “absolute time” and the time provided by physical measurements. The use of the word “uniform,” however, implies the existence of a standard of comparison to establish that it is truly uniform. The failure of observations to agree with prevailing instrumentation and models based on established philosophy or theory crafted to provide that standard has led to changes in the theories as well as the means of determining time.

The search for a practically realized uniform time drives the hunt for an ideal unit of time and the means to access it. As measurement accuracies improve, it has been, and will continue to be, necessary to develop better concepts, definitions, and practical realizations of time. Today general and special relativity along with theories regarding the origin of the universe impose further considerations regarding time in the coordinate systems of the future.

1.3 Calendars

The development of calendars varied, depending largely on religion, culture, politics, and economics. Religious practices and holidays along with agriculture cycles have been defined in terms of lunar sightings, solar motion, and the appearance of the stars in the sky. Hence, calendars have been based on lunar or solar motions, or a combination of the two. Unfortunately, years, months, and days are not integral multiples of each other, and this has led to complications in creating calendars. For example, the year as measured by the length of time for the Sun to return to the same place along its path in the sky (ecliptic) is currently equal to 365.2421897 days of 86,400 seconds, and the length of the month measured by the Moon’s phases is 29.53059 days. The year cannot be composed of an integral number of months or days. Historically, the counting of years in different calendars has been based on the reigns of rulers, the lives of religious leaders, and the traditional beginnings of cultures.

Today, while a number of calendars remain in use for religious or national reasons, the Gregorian calendar, introduced by Pope Gregory XIII in 1582 and adopted by various countries over the next 340 years, is the calendar used internationally for civil purposes (*Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac*, 1961). It will be of satisfactory accuracy for thousands of years to come. A number of books and references on calendars have been published, and software has been developed to convert between them (Seidelmann, 1992; Richards, 1999; Urban & Seidelmann, 2013). A set of chronological “eras” exist based on the various calendars, and these along with current years of various calendars are tabulated annually (*The Astronomical Phenomena*).

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1.4 Astronomical Observations

Astronomical observations throughout human history have led to catalogs of star positions and theories of motions, all for the purpose of being able to predict future phenomena. In order to catalog the positions of stars, planets, the Moon, and the Sun, it was necessary to develop a reference frame. A natural choice devised in antiquity was a set of measures based on the equator, defined by the apparent diurnal motion of the stars, and the ecliptic, which is the apparent path of the Sun in the sky. The intersection of these two "circles" provides a natural origin useful for making angular measurements. That origin was called the *equinox*, since days and nights are approximately equal when the Sun is located in that direction. *Declination*, measured north (positive) or south (negative) of the equator in degrees, minutes, and seconds of arc up to 90 degrees, provides one angular coordinate of the direction to a celestial object. The other is the measure along the equator from the equinox, designated as *right ascension* and measured in hours, minutes, and seconds of time up to 24 hours. The sexagesimal system of measure, currently in use, probably is of Babylonian origin. It was widely used for scientific purposes in antiquity and is retained today in angular measurements. Hipparchus discovered the motion of the equinox in about 129 BC from comparisons of his star positions with positions determined about 150 years earlier (Neugebauer, 1975). This motion is called *precession* and is about 50″ per year. Further contributions to our fundamental astronomical knowledge were made by Ptolemy and various Chinese, Mayan, Middle Eastern, and Indian astronomers. An inconvenience of this system is that both circles are in motion in space.

In the 17th century, the need for navigation and timekeeping led to the establishment of national observatories in Paris (1667), Greenwich (1675), Berlin (1701), and St. Petersburg (1725). As astronomers sought improvements in knowledge and accuracy from observations, star catalogs were prepared, and discoveries were made. Edmond Halley showed in 1718 that the positions of the bright stars, Aldebaran, Sirius, and Arcturus, had changed by minutes of arc from their positions in antiquity. This angular motion perpendicular to the line of sight was called *proper motion*. In 1728, James Bradley discovered that the Earth's orbital motion caused a change of the direction of an object by approximately 30″ due to the finite speed of light, and this was called *stellar aberration*. Bradley detected the periodic motion of the Earth's celestial pole with respect to the stars in 1748. This motion, called *nutation*, can reach an amplitude of about 18″. In 1781, William Herschel discovered the planet Uranus from its motion and his systematic observations of the sky. He also discovered the solar motion toward the constellation Hercules from an analysis of proper motions. Friedrich Wilhelm Bessel, Wilhelm von Struve, and Thomas Henderson independently detected in 1838–1849 that star positions shifted as the observer moved in the Earth's orbit. This confirmation of the Copernican theory and measurement of stellar distances, called *parallaxes*, required observations with a precision of a few tenths of an arcsecond (Kovalevsky & Seidelmann, 2004).

The inclusion of these effects, along with refraction, has contributed to the improvements in accuracies over the years. Improved instrumentation, including photography, led to accuracy improvements in observations. Hence, there was a succession of improved star catalogs from Washington and Germany, including the FK5 catalog in the 1980s and the current standard, the Hipparcos Catalogue (Perryman et al., 1997). These catalogs were the basis for the reference systems defined in terms of the equinox and equator.

Newton's law of universal gravitation demonstrated that Kepler's three laws of planetary motion were the consequences of a gravitational central force. From that development, general theories of the motions of the Sun, Moon, and planets were produced by a number of scientists in different countries. Improved accuracies of these theories, along with comparisons with steadily improving observations, led to many mathematical developments, improvements in the knowledge of astronomical quantities, and the discovery of Neptune in 1849. However, there was a lack of international agreement on astronomical quantities or ephemerides. At the end of the 19th century, agreement was reached with international acceptance of Newcomb's constants, and solar system ephemerides, based on general theories by Newcomb and Hill, which were introduced in 1900.

The lunar theories presented a more challenging situation. Since the motion of the Moon is so rapid and the perturbations so large, the development of a theory for the motion of the Moon has presented continuing problems. Many scientists have worked on the theory, and a number of different methods were employed in attempting to develop lunar theories that would successfully represent observations and predict the future motion of the Moon. In the process, a great empirical term (Newcomb, 1878) was introduced, and tidal friction, variable rotation of the Earth, and the secular acceleration of the Moon were discovered. Still the understanding and accurate calculation of the ephemeris of the Moon remained a challenge.

1.5 Timekeeping

The Sun's position in the sky has always been an obvious means to keep track of time. The use of shadows cast by the Sun of sticks and sundials was a natural means of telling time. These tools could indicate the time of day by the direction of the shadow, and the time of year by the length of the shadow. The astrolabe first appeared in the third or second century BC and provided further improvement. Examples range from simple devices for measuring the angular separation between two directions, to quite sophisticated instruments. They could be used to measure

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the altitude of the Sun, Moon, planets, and stars, determine the hour of day or night, the latitude of the observer, and solve other astronomical problems without numerical calculations (Fraser, 1982; Dohrn-van Rossum, 1996).

The use of controlled flow of water produced alternative means of measuring time in Egypt, India, China, and Babylonia before 1500 BC. In the third century BC, water clocks were being used for scientific observations (Dohrn-van Rossum, 1996). In the 8th to 11th centuries AD, water was used to drive mechanical wheel clocks in China. Sand clocks were introduced in the late 14th century AD (Dohrn-van Rossum, 1996). In the late 13th or early 14th century, weight-driven mechanical clocks were developed, but their actual origin is uncertain. Initially, they were more decorative than accurate, and did not have minute hands. In the 17th century, Galileo recognized the value of the pendulum as a timekeeping device, but it was Huygens who built the first pendulum clock in 1656. It had an accuracy of 10 seconds per day, providing reasonably accurate, but not highly reliable timekeeping. It was the late 18th century when clocks were improved enough to provide reliable, accurate time (Jespersen, Fitz-Randolph, Robb, & Miner, 1999). Later, pendulum clocks were improved by various refinements to provide accurate sources of time for national timekeeping and for astronomy.

The challenge of safe navigation and the means of determining longitude at sea was a strong motivator for the development of robust, accurate mechanical clocks. This challenge was met by John Harrison with his H4 chronometer, made in 1759. In sea tests in 1762, it only lost five seconds in 81 days (Sobel, 1995).

In the 1800s, providing accurate time for civil purposes became an important function of local observatories. Typically, they made transit observations of the Sun by day and stars at night to determine local solar time for their location. Hence, each locality or region had its own time based on the location of the Sun in the sky.

1.6 Time Epochs

Throughout history there have been different choices for beginning the day. The ancient Egyptians began the day at dawn, but the Babylonians and Jews chose sunset. The ancient Romans switched to midnight after first using sunrise to mark the day's beginning. Sunrise was the most common choice in Western Europe before the general use of clock time. Time was counted in units of 12 hours of day and 12 hours of night. The ancient origin of 12-hour days and nights is lost, but they were transmitted from ancient Greece, Egypt, and Babylonia. A probable developmental explanation is given by Neugebauer (1957).

Since the periods of day and night varied during the year, the length of the hours differed from day to night and during the year. For astronomical purposes, these seasonal hours were replaced by a subdivision of the complete period of daylight and darkness into 24 equal and constant parts, known as *equinoctial hours*. Apparently Hipparchus was the first to adopt the equinoctial hours in place of the unequal and varying seasonal hours. The seasonal hours spread throughout the Greco-Roman world during the Hellenistic period, and until mechanical clocks became common during the Middle Ages, they remained in use for civil purposes. The equinoctial hours were used only in astronomical and calendrical works, or for other special purposes.

According to Pliny, Hipparchus reckoned the day from midnight, but Ptolemy reckoned it from noon at Alexandria, and in his *Handy Tables* (Neugebauer, 1975) divided the day and night into 24 equal hours, each hour subdivided into minutes and seconds. For astronomers and navigators observing the stars at night, it was convenient to avoid a change of days during the night, so they used days counted from noon to noon. This practice was established in astronomical tables and ephemerides within the Greek, Latin, and Arabic civilizations. For this reason the Julian day numbers, a continuous count of days from 4713 BC, continue to start each day at noon. Until 1925, the day in Greenwich Mean Time began at noon. In 1925, Greenwich Mean Civil Time was introduced as starting at midnight, and eventually Greenwich Mean Time came to be accepted as beginning at midnight. Thus, care must be taken when using observations from before 1930 as to what time system was used.

1.7 Time Transfer

Without widespread and comparatively rapid commerce, the distribution of a common time reference held little importance. Portable sundials were adequate tools to obtain the local time. In the early 14th century, European communities began to install weight-driven mechanical clocks in association with bells, either in town halls or in churches. These served as local time references and provided a means to notify people of the time for prayers, services, assemblies, and markets. Time balls on the top of buildings, which were visible by ships in ports, were used to signal the time on a daily basis for navigators. At the US Naval Observatory (USNO), for example, this service started in 1845. Well-calibrated portable mechanical clocks provided a means to distribute precise time. Local observatories made time available in various cities, based on their astronomical observations and mechanical clocks.

With the invention of the telegraph, time signals could be distributed over long distances. In 1865, the USNO started sending signals at 7:00 AM, noon, and 6:00

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PM over the fire alarm system in Washington. That signal went to the State Department, which also had a Western Union telegraph signal, so by 1867, the time signal from the USNO was transferred there and sent throughout the country. In 1869, the signals were going across the country for the railroads and by 1871, the US Signal Service was distributing the signal to weather stations. In 1886, synchronized clocks in public offices were kept on USNO time via the signals. Telegraph signals, in conjunction with astronomical determinations of local time, were also used to measure the time difference between distant points and, thus, determine their relative positions (Bartky, 2000; Dick, 2003).

1.8 Rotation of the Earth

Solar time determined from astronomical observations was the independent argument used to calculate ephemerides of the solar system until the mid-20th century. This was done with the understanding that solar time provided a uniform measure of time. Discrepancies between observed and calculated positions of solar system objects appeared and were most evident for the Moon, because its motion is most rapid and complex. J. C. Adams showed that the observed secular acceleration of the Moon's mean motion could not be due to gravitational perturbations (Adams, 1853). That the tides exert a retarding action on the rotation of the Earth, along with a variation in the orbital velocity of the Moon, according to the conservation of momentum, was shown independently by W. Ferrel and C.-E. Delaunay (Ferrel, 1864; Delaunay, 1865). Newcomb considered an irregular rotation rate of the Earth as the explanation for lunar residuals, but he could not find corroboration from planetary observations (1878). The correlation of the irregularities of the motions of the inner planets and the Moon to prove the irregularity of the rotation of the Earth is described in detail in Chapter 4.

In 1765, Euler predicted that, if the axis of rotation were not coincident with the principal axis of inertia, the axis of rotation would have a circular motion with respect to the Earth's crust (1765). Using historical transit circle observations, Seth Chandler (1891a, 1891b, 1892) detected this effect, called *polar motion*, which can displace the direction of the rotation axis by angles of the order of 0.5″. However, the observed period of 433 days did not agree with Euler's theoretical prediction of 305 days. Newcomb explained the difference as due to the non-rigid Earth (1891). In the 1890s the International Latitude Service (ILS), with several stations at 39 degrees north latitude, was established to make optical observations to measure polar motion. That service continued until more accurate methods were developed in the 1970s. Actually, the axis of maximum moment of inertia moves around the axis of rotation with a complicated pattern made up largely of an annual component and a 14-month (Chandler) component.

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1.9 Beginning the 20th Century

As the 20th century began, official time in each country was based on pendulum clock time standards. There was no international exchange of time. There were some accurate longitude measures by trans-oceanographic telegraph signals. The international monitoring of polar motion had just begun. Variations in the Earth rotation were suspected, but not proven. Mean solar time was based on Newcomb's theory of the Sun. Astronomical observations were improving based on photography, better instrumentation, recognition of the personal equation in observation timings, and the adoption of more accurate astronomical constants. The 19th century had experienced significant improvements in accuracy and knowledge, but the next century was to be more impressive.

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