TIME: A STRUGGLE FOR PRECISION

By

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Summary

The subject is one of general interest from an historical standpoint, yet becomes of engineering importance also as methods of controlling modern timepieces become more and more accurate.

This thesis deals first with the historical background of the subject, bringing out the very early date at which the fundamental concepts were brought forward. Secondly, the matter of maintaining a continuous standard of reference, and the method of checking this against the ultimate standard of celestial movement is sketched in some detail.

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Bibliography

Brearley, Harry C. ------------------------ "Time Telling Thru The Ages"

Proceedings Institute Radio Engineers ------ May, 1928

Proceedings Institute Radio Engineers ------ February, 1929

Proceedings Institute Radio Engineers ------ July, 1929

Proceedings Institute Radio Engineers ------ January, 1931

Consultants

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It was a moonless night in No Man's Land. A man in uniform stood silently waiting in a frontline trench. In the darkness, his eyes were drawn, fascinated, to the luminous figures on the watch-dial at his wrist. A splinter of pale light, which he knew to be the hour-hand, rested upon the figure eleven. A somewhat longer splinter crept steadily away from the figure twelve.

"Its gone past eleven," he muttered to himself. "There's less than twenty minutes now."

To the right and to the left of him, he now and then could see his waiting comrades in the blackness of the trench, their outlines vaguely appearing and disappearing with the intermittent flares of distant star-shells. He knew that they, too, were intent upon similar tiny figures in small luminous circles and upon the steady, relentless progress of gleaming minute-hands which moved in absolute unison with the one upon his own wrist. He knew, also, that far in the rear, clustered about their guns, were other comrades tensely counting off the passing minutes.

At twenty minutes past eleven, the artillery bombardment would begin and would continue until exactly midnight. Then would come a barrage, protecting curtain of exploding shells behind which the uniformed figure and his companions would advance upon the enemy's trenches, perhaps also upon eternity.

It seemed strangely silent after the crashing chaos of the daylight hours. There were moments when the rumble of distant guns almost died away, and he could hear the faint ticking of his timepiece or a whispered word out of the darkness near at hand. He knew, though, that the silence was misleading, but the lull before a storm.

Five minutes ticked away.

In another fifteen menutes, the fury of bombardment would begin, doubtless to draw equally furious fire from the enemy guns.

At twelve-ten plus forty-five seconds, he and his comrades were "going over", into the inferno of No Man's Land. That was the instant set for advance - when the barrage would lift and move forward, a protecting wall of fire to keep enemy pinned to the ground.

The slender hand on the glowing dial stole steadily onward. It was ten minutes after now. Ten minutes after eleven, an hour and forty-five seconds of eternity. His thoughts flew back to his home in the great city behind the lines.

Ten minutes after eleven. How plainly he could picture the familiar scenes of rushing, bustling life back there. How the millions of his native city and of other cities and towns, and even of the country districts, all moved upon schedule. Clocks and watches told them when to get up, when to eat their breakfasts, when to catch their trains, reach their work, eat their lunches, and return to their homes. Newspapers came out at certain hours; mails were delivered at definite moments; stores and mills and factories and schools all began their work at specified times.

What a tremendous activity there was back there, and how smoothly it all ran--smooth as clockwork. Indeed, one might almost say it ran <u>by</u> clockwork. The millions of watches in millions of pockets, the millions of clocks on millions of walls, all running steadily together - these were what kept the complicated machinery of modern life from becoming hopelessly entangled and confused.

Yes; but what did people do before they had such timepieces? For back in the very beginning, before they had invented or manufactured anything, far back in the days of the caveman, even those people must have had some method of telling time.

A bright star drew above the shadowy outline of a hill. At first the man in uniform thought that it might be a distant star-shell; but no, it was too steady and too still. Ah yes, the stars were there, even in the very beginning, and the moon and the sun, they were as regular then as now; perhaps these were the timepieces of his earliest ancestors.

A slight rustle of anticipation stirred through the waiting line and his thoughts flashed back to the present. His eyes fixed themselves again on the ghostly splinters of light at his wrist. The long hand had almost reached the figure four --- the moment when the bombardment of Paris would begin again.

He and his comrades braced themselves, and the night was shattered by the crash of artillery.

The story of the watch upon your wrist, the clock upon your wall, and Big Ben of London all began countless centuries ago, and is as long as the history of the human race. When our earliest ancestors, living in caves, noted the regular succession of day and night, and saw how the shadows changed regularly in length and direction as day grew on toward night, then was the first faint and feeble germ of the beginning of time-reckoning and time measurement.

No timepieces were available, but the great timepiece of nature, the sun, and a shadow falling upon a certain stone were all that the primitive cave-dweller needed in making and keeping an appointment.

The next step in planning ahead required that appointments should be made by a timepiece which could indicate more than a single day, since the daily position of lights and shadows was not sufficient. Next to the sun, the moon is the most conspicuous of the heavenly bodies, particurlarly arresting because of its peculiar property of changing shape. It was noticed that these phases of the moon occured in regular sequence, over and over again in the same way, so as a natural outgrowth of this the moon became added to the sun to serve as a timepiece.

Centuries later comes the date 4000 B.C., the beginning of recorded history. Mesopotamia was the cradle of one of the most ancient civilizations, and the home of a people who were learned in the movements of the stars. Without telescopes or other instruments, it is marvelous to see how many astronomical laws they deduced by observation alone.

First, they observed that the sun slowly changed the points at which it rose and set. During certain months, the place of sunrise traveled northward, and at the same time the sun rose higher in the sky, and at noon was more nearly overhead.

At this time the days were longer because the sun was above the horizon more of the time, and it was summer. During certain other months, the sun traveled south again, and all these conditions were reversed; the days grew shorter and it was winter. The Babylonian priests of Mesopotamia were the first to study these phenomena and make something of them. They were also the first to record their deductions. From the time which was consumed in the motion from furthest north to furthest south and return, they worked out their year.

In order to calculate time, they devised the zodiac, a sort of belt encircling the heavens and showing the course of the sun and the location of twelve constellations through which it would be seen to pass if its light did not blot out theirs. They divided the region of these twelve constellations into the same number of equal parts; consequently, the sun passing from any given point around the heavens to the same point, occupied in so doing an amount of time that was arbitrarily divided into twelfths.

They also divised another twelve part division of the year. They noticed that the moon went through her phases in about thirty days. So one moon, or one month, corresponded with the passage of the sun through one sign of the zodiac. Our word "month" might well be written "moonth", since that is really its derivation. This gave them a year of twelve months, each month having thirty days, or three hundred and sixty days in all.

Then from the seven heavenly bodies which they had identified with seven great gods they got the idea of a week of seven days, one day for special worship of each god and named for him.

In similar manner, they divided the day and the night each into twelve hours; and the hour into sixty minutes and these again into sixty seconds. The choice of "sixty" was not an accident, for no lower number can be divided by so many other numbers and still give an integer.

The early scientists who developed all this also devised a complex method by which they pretended to foretell future events and the destinies of men. This division of chicanery is now known as astrology, but does not detract from the very real contributions of the ancient wise men who practiced it.

Their year of three hundred and sixty days was five days too short, as they eventually discovered. In six years, however, the difference would amount to thirty days, which was exactly the length of one of their months. So, correction was easily made by doubling the month "Adar" once in six years. This "leap-year" principle, which we still use with refinements, originated then with the ancients.

The Babylonian calendar remained practically the same up to the time of Julius Caesar, only a few years before the Christian Epoch. The names of the months had naturally been changed into the Latin; and instead of doubling a whole month, the Romans had decided to add the extra five days to several months, one day to each. That is the reason for some of our months having thirty-one days.

When Caesar was Dictator of Rome it had become known that the year of exactly 365 days was still a little too short. It should have been 365 1/4. So Caesar in reforming the calendar provided that the first, third, fifth, seventh, ninth, and eleventh months should be given thirty-one days each, and that the others should have thirty days, except in the case of February which should have its thirtieth day only once in four years. A little later, his successor, the Emperor Augustus, after whom the month of August is named, decided that his month must be as long as July, which was Julius Caesar's month. Therefore, he stole a day from February and added one to August; then he changed the following months by making September and November thirty day months and giving thirty-one days to October and December.

The Julian calendar, with the changes by Augustus, remained in use until A.D. 1582, when it was learned that the average year of 365 1/4 days was still not exactly right according to the motion of the earth around the sun. The exact time is 365 days, 5 hours, 48 minutes, and 46 seconds. This is 11 minutes and 14 seconds less than 365 1/4 days. Therefore, when we add a day to the year every four years, as Caesar commanded, we are really adding too much. This excess was corrected by Pope Gregory XII in 1582 when he changed the calendar so that the last year of a century should be a leap year only when its number could be divided evenly by 400. Thus, 1700, 1800, and 1900 were not leap years, but the year 2000 will be. This new calendar, which is the one now generally in use in most of the world, is known as the Gregorian calendar.

So, the main plan and principle of the modern calendar has remained unchanged for 6000 years.

Astronomers today can figure out in advance what is to happen in the heavens with an exactness which would have seemed magical not many centuries ago, and is astonishing even yet. The accuracy is made possible by improved scientific instruments, more flexible and improved mathematics, and greater accuracy in the measurement of time.

Early humanity was dependant upon the clocks of nature, whose course controlled their existence as it does ours. We still depend upon these great primeval timepieces, although many times unconsciously, for it is hard to remember that our master clocks must still be set by the motion of the heavenly bodies. This will be discussed later.

Although the calendar which indicates the large divisions of time was developed at an early date, there has been only a slow evolution of methods for making hour and minute measurements.

The first and most primitive method has already been mentioned; namely the sun dial. At first it was only a stick placed upright in the ground, and the shadow was a measure of the hour. The first new development to come was that of making the shadow move over a hollow space such as a walled courtyard, going down one side, across, and up the other side as the sun went up, across and down the sky. If the courtyard be covered over with a dome and a narrow slit be cut therein, a shaft of light will mark the time instead of a shadow. The first written reference to a sun-dial of any type is to this latter design, and is found in Isaiah, Chapter thirty-eight, where reference is made to the Dial of Ahaz in telling of a miracle.

The next improvement came when it was realized that the sun's shadow could be accurately cast upon a flat surface at all times of the year only if the pointer was pointing to the north. Then it was found that the angles of division which represent the hours must be recomputed for each latitude, as there is appreciable error here also. This was first noted in Rome, where a captured dial from another latitude was discovered appreciably incorrect after being installed for one hundred years. The sun-dial marks apparent time, which differs from mean time (which we use) by plus or minus sixteen minutes at the greatest variation during the year, and is equal to mean time at four times during the year.

A considerable time after development of the calendar, the Egyptians devised a water clock or Clepsydra. This device comes much closer to being a machine than a stick in the sand, and therefore represents a fruther step in the evolution of time-pieces.

The original idea was very simple. At first, it was merely a vessel of water having a small hole in the bottom through which the liquid dripped out drop by drop. As the level within the jar was lowered, it showed the time upon a scale. Thus, if the hole were so small and the vessel were so large that it would require twenty-four hours for the water to drip away at an absolutely steady rate, the side of the vessel could be marked with twenty-four divisions to indicate the hours. One advantage of this device was that the water would naturally drip as rapidly at night or in shadow as in sunlight. Therefore, the clepsydra could be used indoors, whereas the sun-dial could not.

However, it had to be regularly refilled, the water had to be clean, and the orfice had to be cleaned out periodically. Another disadvantage was that a difference in barometric pressure due to a change in altitude, or day to day variations with weather would cause error. Also, as the level of the water in the vessel was lowered, the effective pressure forcing water through the ordice would change, necessitating a non-linear scale.

An interesting fact about the clepsedra's development is that it involved a new concept in the marking of time. It was not so much a question of "when" as of "how long," for the scale could not, for example, tell the observer when it was noon, but rather indicated how long since it had last been filled.

Ctesibus of Alexandra improved upon the contrivance by first supplying a double vessel to keep the scale linear, and second by attaching pulley mechanism to a float which rotated a clock hand. This happened about 140 B.C., a time when Roman culture was flourishing and captive peoples bent their arts toward increasing Imperial Greatness.

An interesting use of clepsydrae arose when Pompey commanded their use in law courts to limit length of arguments. Of course, there was always the possibility of bribing someone to put muddy water in the clock, but ordinarily the idea worked out quite well.

Developed simultaneously with the water clock was the hour-glass. The principle is the same, but sand replaced the liquid medium. This solid media flowed through the opening at an approximately even rate, no matter how great the weight above it, so it was really a technical improvement over the clepsydra. The hour-glass has largely degenerated to the egg-timer stage, and is no longer important except to Schiaparelli and Father Time.

See Figure (1) for examples of early time-pieces. The sundial was designed and placed in Cransbury Park, England, by Sir Isaac Newton. The Hourglass on left was designed for Pulpit use, approximate sermon length two hours. The glass on right is an example of French handiwork in the seventeenth century.

A medieval practice was to determine the length of time for a candle to burn, and then, having calibrated its lenght, make another of alternate colored rings. Although only approximate, it served quite well as a marker for the passage of hours in the rough age when it was used.

Our debt to the Ancients in the matter of recording time is typical of that in many others.

Sun Dial Designed and
Placed by Sir Isaac Newton
in Cranbury Park, Winchester,
England

Pulpit Two-Hour Glass
American, 1700-50
in the Essex Institute,
Salem, Mass.

Silver Gilt
French Hour Glass
Eighteenth Century
in the Metropolitan
Museum

TYPES OF THE EARLIEST TIME TELLING DEVICES

The sun dial is the first ancestor of all time tellers, and the sand glass was probably the first portable time telling device.

Fig. 1

We owe to them our whole fundamental system and conception of it; from the astronomy by which we measure our years and our seasons down to the arithmetic of our minutes and seconds and the names of our months and days.

However, in the modern application and practical use of their legacy, we owe nothing. Aristotle never made a clock or watch or any device more than ornamental today, although the general plan was so well worked out that in has never been bettered.

It seems difficult to understand the instinct which led men to keep their learning like a secret among the initiated of a mystic fraternity, feeling no impulse to make known that which they knew. The great men of bygone days thought and did tremendous things which are now everyone's common property. But the common people of that time lived in a fashion terribly primitive by comparison and in an ignorance which certainly was weakness and yet might somehow have been bliss.

The ancient world is gone - both the body and the spirit of it. But there remains along with their art and philosophy the hour-glass to symbolize the relentless flight of time which they feared but could not stop; and the sun-dial in front of Student-Center, a memory to the worldly-wise philosophy which counts only the shining hours.

The typical modern clock is powered from the pull of a weight or the pressure of a spring, unless it is operated by electricity or compressed air. The regulator of mechanical clocks is known as the escapement, the recording device generally consists of hands, dial, and a gear train, and there may perhaps be a striking mechanism.

The first direct forbear of Big Ben appeared in the eleventh century, coincidental with the appearence of William the Conqueror in England. This was the monastery clock, which struck the hour and told all people within hearing when it was time for prayers.

An example is the elaborate Clock of Strasbourg Cathedral in Lorraine, which was built in 1352. See Figure (2). This clock represents the extreme in medieval craftsmanship. It is three stories high and stands against the wall somewhat in the shape of a great altar with three towers. Among its movements are a celestial globe showing the positions of the sun, moon, and stars; a perpetual calendar; a device for predicting eclipses; and a procession of figures representing the pagan gods from whom the days of the week are named. There are also devices for showing the age and phases of the moon and other astronomical events. The hours are struck by a succession of automatic figures, and at the stroke of noon a cock perched upon the topmost tower flaps his wings and crows. Although it keeps no better time than a $.79 alarm clock, it is a mechanical monstrosity reminiscent of the age in which it was created, and beautiful in the eyes of all Cook's Tour guides.

The first pendulum clock was made about 1665 by Christian Huyghens, a Dutch astronomer and mathematician who discovered the rings of Saturn.

From that time on, the important improvements of clockwork were chiefly made in two directions - those of mechanical perfection of the escapement and the compensation for changes of temperature.

The ultimate in perfection of modern clocks used for maintainence of time standards uses one more refinement, a "slave clock". This is simply a device which removes the friction of the escapement at the end of each pendulum swing. Clocks of this type were developed around the turn of the century by Riefler and by Shortt, three each of which are sealed in the vaults of the Naval Observatory in Washington, D.C.

See illustrations for examples of jeweled watches, developed at a

A Time Piece of the Middle Ages

The huge and elaborate Clock of Strasbourg Cathedral, in Lorraine, was built in 1352 and is an example of the first clocks.

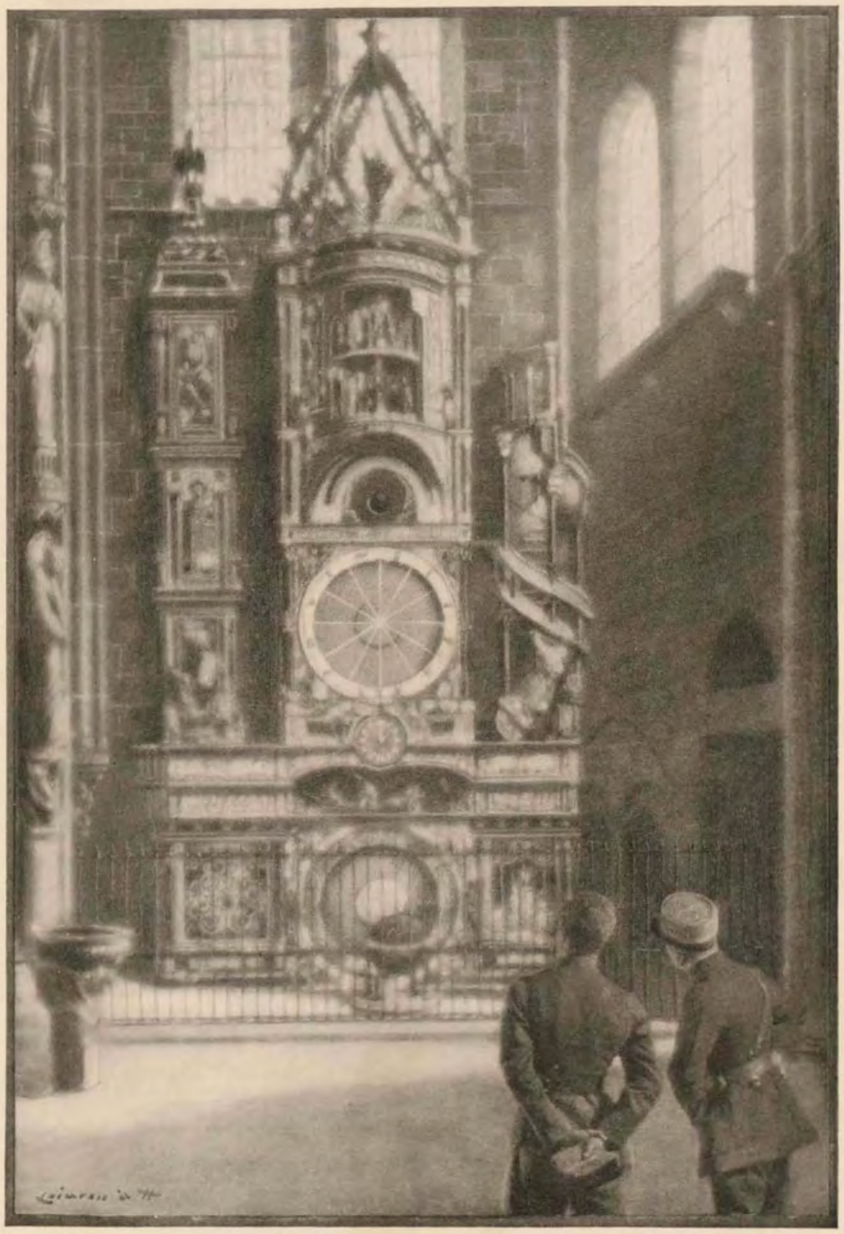

Fig. 2

London
about 1600

Octagonal Rock
Crystal Watch
French, 1560-90

Square
French Watch
Late Sixteenth Century

Oval
French Watch
1590

Shell Shaped
Rock Crystal Watch
French

Cross Shaped
Rock Crystal Watch
French

Book Shaped
Swiss Watch
1560-1600

WHEN WATCHES WERE JEWELS

Watches of the Sixteenth Century, with but one hand, and pierced metal or rock crystal cases. In the collections of the Metropolitan Museum.

Fig. 3

Limoges Enamel
Watch
English 1610-25

English Repeater
about 1650

Silver
Skull Watch, French.
Intended to remind the
wearer that each second
brought death nearer

Gold Enamel
Watch—French

French Watch
intended for the
head of a cane,
1645-70

Agate Case
French

SEVENTEENTH CENTURY WATCHES

Grew more elaborate and ornamental, but scarcely more useful.
In the collections of the Metropolitan Museum.

Fig. 4

time when beauty was everything and accuracy didn't make much difference. Figure three shows typical watches of the fifteenth and early sixteenth centuries, and figure four watches of the late sixteenth century.

The evolution of timepieces having been briefly reviewed, it becomes important to consider in detail the methods of establishing the accuracy and precision of modern clocks, watches, and noon whistles.

The ultimate standards of reference are the celestial bodies, which, although they may slowly change position, nevertheless do so at rates which may be allowed for with great exactitude. This checking is carried on at a great many observatories throughout the world, but as the method is almost exactly similar everywhere, the arrangements at the Naval Observatory, Washington, D.C. will be considered as typical. A factor in the choice of this Observatory additional to its proximity is that work there is continued on a twenty-four hour basis, and the time measurements resulting are broadcast throughout the world, being considered the ultimate standard for at least the Western Hemisphere.

The standard time transmissions are available to anyone who either uses a radio or desires to run a wire to the observatory proper. No charges are made, the work being carried on gratuitously by government funds under auspices of the Navy department.

At the present time transmissions go to the Time Central, Navy Department; Postal Telegraph; American Telephone And Telegraph Co.; Western Union; and the District Fire Alarm lines. Western Union uses the transmissions to keep their numerous clocks on leased service correct, while the Fire Department uses the service to insure that their employees do not work more than eleven thousandths of a second overtime. The Navy Department is responsible for sending the transmissions over the air via its official station NAA.

Transmission there is on several frequencies and many times throughout the day.

The growth and usefulness of the Naval Observatory after 1842 resulted in the purchase of its present site of seventy-two acres on Massachusetts Avenue in Northwest Washington. The location is circular in shape, having a radius of exactly one thousand feet with the standard clock vault at the center.

The Observatory is the United States' source of data required for navagational astronomy as well as its official time standard.

In 1844 a time ball was dropped from the staff of the building every day. This has long since been discontinued.

In 1865 the Western Union service to its telegraph offices was begun, and has since been gradually expanded.

In 1904 the Naval radio station NAA, located in Arlington, Virginia sent out the first signal ever broadcast.

In 1905 the NAA regular time transmissions were begun and have been continued ever since.

In 1931 the broadcasts were increased from one per day to six per day.

In 1934 twenty daily broadcasts were initiated, and automatic transmission to the transmitter was begun through Time Central, Navy Department.

The directors of the Observatory are justly proud that the average error of all transmissions during the last year was less than 0.011 seconds, a fact which will be further enlarged upon a bit later.

One of two instruments must be used in making accurate time determinations. At the Observatory is a six inch Transit Circle, or Meridian

Transit telescope, made in 1897, which is still in continuous use for observing sun, moon, and planets and selected stars. The purpose of the observations is to determine their fundamental position by noting their position at time of transit over the meridian. Having determined their position, the time of transit across the meridian may be very accurately computed from other data. About seventy-five hundred observations are made each year.

The other instrument which may be used in a Photographic Zenith Tube. The instrument at the Observatory was built in 1911, has an aperture of eight inches, and a focal length of seventeen feet. It is mounted vertically, and is immovable. It is used to photograph the stars as they pass near the zenith in order to determine the variation of latitude due to the earth wobbling on its axis. This variation of latitude is used in the correction of all observations for declinations.

In addition these photographic observations are used to determine time to the nearest 1000th of a second. The Naval Observatory is the only one to use the method. Since human error is eliminated, accuracy is greatly increased.

The accepted basis of time measurement is the earth's rotation on its axis. The rate of this rotation is usually considered uniform, although it is doubtless affected by both progressive and other variations. This rotation causes the sun and stars to appear to cross the sky from east to west. If a person located on the earth's equator measured the time interval between true successive passages overhead of a very distant star, he would thereby measure the period of the earth's rotation. If he then made similar measurements on the sun instead of a star, he would obtain a result about four minutes longer than before. This difference is due to the earth's motion around the sun, which continuously changes the apparent place of the sun among the stars. The effect is the same as that noted when traveling in an automobile; the near objects appear to move backward when judged by the more distant ones. Thus during the course of a day the sun appears to move a little to the east among the stars, so that the earth must rotate on its own axis more than 360° in order to bring the sun overhead again.

Even if the earth did not rotate at all on its own axis, the sun would rise and set once during the year, because of the earth's journey around the sun. The stars, however, are not within the earth's orbit. Since they are generally more than a million times as distant as the sun, their apparent positions are only very slightly affected by the earth's orbital motion. The apparent positions of the stars in the sky are commonly reckoned with reference to an immaginary point called the vernal equinox, which is the intersection of the celestial equator and the ecliptic. The sun is at the vernal equinox at the beginning of spring, when it passes over the earth's equator on its journey northward. The period of the earth's rotation measured with respect to the vernal equinox is called a sidereal day, although it might better be named an apparent equinoctial day. The period with respect to the sun is called an apparent solar day. Unfortunately, both the sun and the equinox move at variable rates among the stars, so consequently the apparent solar and sidereal days are of variable length. In order to overcome this irregularity, mean time has been devised. Mean solar time, which is generally used in ordinary life, is sometimes ahead of and sometimes behind apparent solar time, but on the average it is the same. The difference between these two different kinds of time is called the equation of time. Its maximum value is a little over sixteen minutes. The difference between apparent equinoctial (sidereal) time and mean equinoctial (sometimes called uniform sidereal) time is due to the mutation or nodding of the earth's axis. Its greatest value is only a little over a second, and its greatest daily change is a little over a hundredth of a second. Because this difference is so small, sidereal time has generally been used by astronomers.

In recent years, a few observatories, including the Naval Observatory, have begun to employ mean equinoctial time in computing the rates of precision clocks.

Since the sun does not rise and set in different parts of the world simultaneously, it is evident that the various parts of the world have different solar times. In order to reduce confusion, standard time zones have been adopted. All the points in each zone use one uniform time which is generally different from their local times by not much over half an hour, and in some places, of course, is exactly the same.

In general, these time zones differ from Greenwich, or zero meridian time, by some whole number of hours. In the continental United States, there are four time zones. Eastern Standard Time is the local time of the seventy-fifth meridian, and five hours less advanced than Greenwich time. Central Standard Time is the local time of the ninetyth meridian, and six hours less advanced than Greenwich time. Mountain Standard for the one-hundred fifth, and Pacific Standard for the one-hundred twentyth meridian

The Naval Observatory is thus able to furnish one time signal which will provide time for all zones.

Since the object of the time zones is mainly one of convenience, the boundaries between the zones have been placed where they will be the source of least inconvenience, rather than along the exact meridians.

For instance, if the lines were straight, the people in one part of a small town might be using different time from their neighbors, and the railroads might have to make time changes at inconvenient points rather than at terminals. The Interstate Commerce Commission holds hearings concerning the placing of these divisions.

In order to determine time with high precision, it is necessary to observe stars, or other celestial objects, with a telescope. Such observations are most conveniently and accurately made when the stars are passing over the meridian at the place of observation. The meridian is an imaginary line in the sky, passing through the zenith and the north and south points. The most commonly used instruments for time determination at fixed stations are called meridian transit telescopes. They are pivoted so that they may be pointed anywhere along the meridian, but not elsewhere. The observations are usually made visually, and the times of transit are recorded by a mechanism which is either operated or regulated by the observer.

Recently, a new type of instrument has been put into service for work at the Naval Observatory. The telescope, called a Photographic Zenith Tube as already described, is rigidly fixed in a vertical position and therefore cannot photograph any objects except those which pass very near the zenith. At the lower end of the tube is a basin filled with mercury. The light from a star passes through a lens at the upper end of the instrument, continues down through the tube, is reflected from the mercury surface, and comes to focus on a small photographic plate located just under the lens. The location of the plate and the curves of the lens are such that the lens and plate may be tilted as a unit, through a small angle, without sensibly altering the position of the image on the plate. If the plate and lens, both are rotated through 180°, then the distance on the plate between the image of the star before and after reversal corresponds to twice the zenith distance of the star. Were it possible to take both photographs at the same instant, when a star was exactly at the zenith, the two images would coincide, and the time of meridian transit for that particular star would be the time when the photograph was taken. In actual practice, the plate is driven from west to east so as to keep pace with the motion of the star's image, and the clock time at which the plate is in certain positions is automatically recorded. The images obtained before and after reversal do not coincide, but by measurement of the distances of the images it is possible to determine the positions of the stars during exposure and so to deduce the times of transit.

By observing the time of meridian transit of the sun, the time of local apparent solar noon is acertained without further calculation. Sun observations are not so precise as those of stars, owing to the size of the sun's disk, and the unsteadiness of the atmosphere at midday.

It is possible to observe a number of stars during one night, thereby increasing accuracy. To make the star observations useful, the positions of the stars in the sky, as measured from the vernal equinox, must be known. As the relative motions of the sun and earth fix the position of the equinox, solar observations are a necessity. Observations of the sun and stars regularly over a period of several years, show their relation very accurately. The results of this long series of observations are utilized in making the calculations for the valuation of a single night's observation.

By use of data contained in Naval publication "The American Ephemeris and Nautical Almanac", the correct sidereal and mean solar times of star transits are derived.

During the exposures with the photographic zenith tube, the clock times at which the photographic plate is in certain positions are automatically recorded by an electric chronograph which records graphically both the clock ticks and the signals from the photographic telescope. Thus the clock time is determined within 0.001 second. By comparing these clock times with the theoretical times, computed as already indicated, the clock error is determined.

As the times of the star transits are most readily computed using sidereal time, the standard clocks are rated to run on sidereal time also. These clocks are maintained under constant temperature and pressure. They are specially designed and manufactured for precision purposes.

They are never disturbed, never reset, never interfered with in any way except for repairs. The actual rates of the clocks are not so important, provided they are nearly constant. They are checked by the astronomical observations, and their errors predicted for any time in the near future on the basis of past performance. The short period variations in the rates of the clocks permit the clock rates to be predicted within a few thousandths of a second per day.

Although sidereal time is convenient for star observations, it is not suitable for the general public. The mechanism for the transmission of time signals is therefore rated to mean solar time. The transmission of signals begins at 55 minutes 0 seconds of each hour and continues for five minutes.

Signals are transmitted every second during that time, except that there is no signal on the twenty-ninth second, nor on certain seconds at the ends of minutes, as shown on the following diagram:

Minute	Second	50	51	52	53	54	55	56	57	58	59	60
55		X		X	X	X	X					X
56		X	X		X	X	X					X
57		X	X	X		X	X					X
58		X	X	X	X		X					X
59		X										X

The "X" indicates the seconds on which signals are transmitted. The seconds marked "60" are the zero seconds of the following minute. All seconds from zero to fifty are transmitted except the twenty-ninth, but are not shown for convenience. The dash on the beginning of the hour (59-60 above) is much longer than the others. In all cases the beginnings of the dash indicate the beginnings of the second.

The number of dashes sounded in the group at the end of any minute indicate the number of minutes yet to be broadcast.

During the broadcast, the signal is recorded automatically at the observatory, showing signal ticks in the observatory, ticks of one standard clock, and the signal received back by radio from the sending station.

A sample of the record of this electric chronograph is appended as Figure (5).

Line number one is that signal sent by NAA. It is received at the observatory with one receiver for each transmitted frequency, and compared to the other clocks by reading either total time or the time difference in corresponding groups. In all cases each dot represents 0.005 seconds

Line number two is the record of sidereal clock standard number one in the sealed vault.

Line number three is not used, and runs uncontrolled.

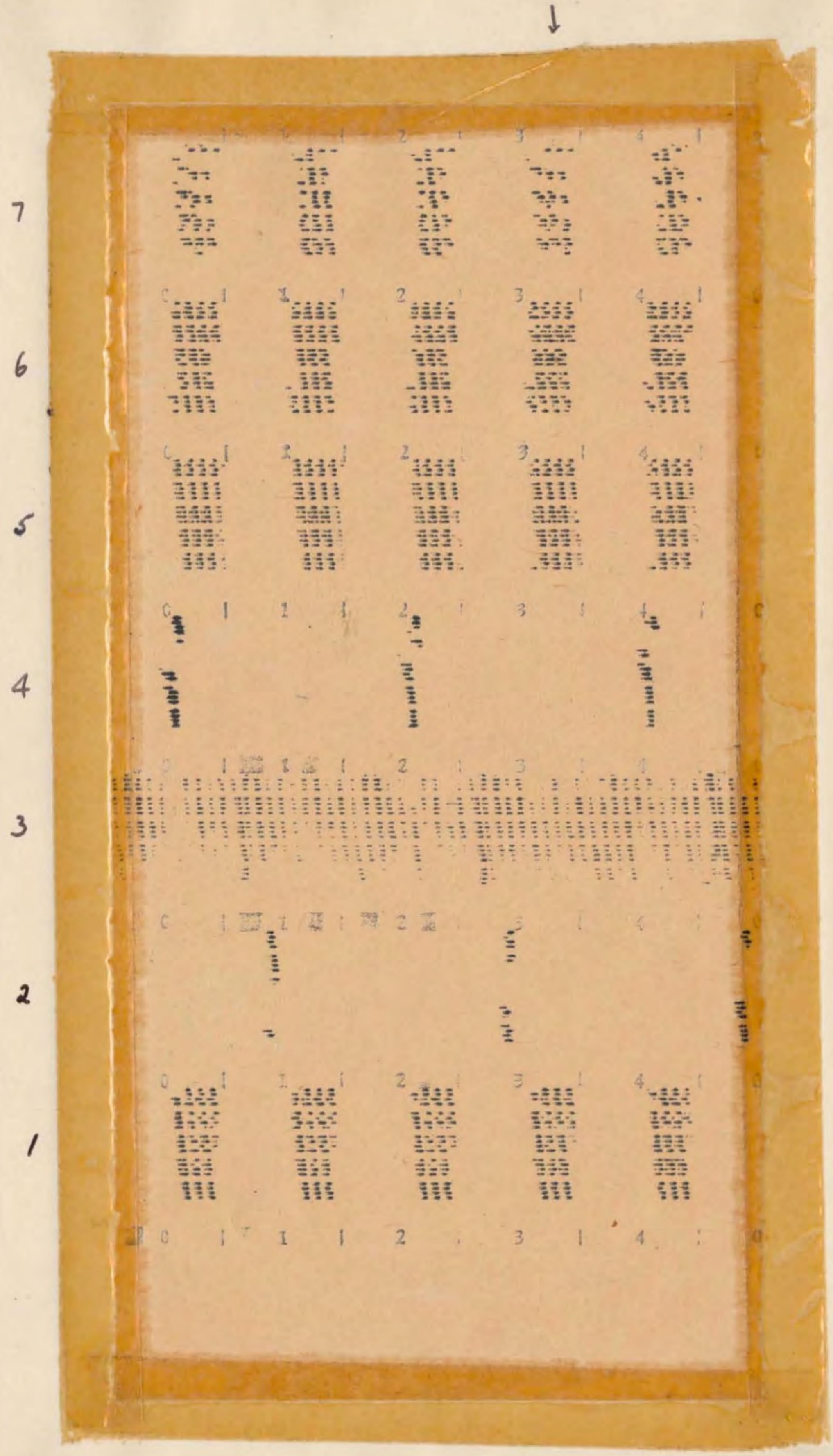

Fig. 5

Line number four is the record of sidereal clock number two, also in the sealed vault. The other four sidereal clocks are not connected on this particular day. Those two which previous record shows will probably be the most accurate are the only ones used at any one time.

Line number five is a record of standby transmitting clock number one.

Line number six is a record of the primary transmitting clock, of which more later.

Line number seven is the record of the standby transmitting clock number two.

By comparing the number of dots or spaces beneath corresponding columns, it is possible to determine the error.

For example, let it be desired to determine the lag of the transmitted signal from the radio station (NAA) behind the signal put on the wires from the Observatory. The record is taken for every second, and to keep columns numbered for comparison they run: 0, 1, 2, 3, and 4. The immediate problem is to find the time difference between lines one and six in the third column. Then the time after 3.000 at which the indicator starts to record line six is the time interval per dot multiplied by the number of spaces. This is (0.005)(15), or 0.075 second. variation. On line number one, the transmitted signal from the observatory, there is a full column and one space lag. Then the lag behind 3.000 is (0.005)(21) or 0.105 second. The difference between the two readings is then the difference between 0.105 and 0.075 or 0.030 second, the required lag.

Knowing the lag to be expected, the transmitting clock can then be set that amount ahead of the standard, and so make the signal transmitted to the public exact within the limits of the primary's accuracy.

In similar fashion, corrections can be applied to the other clocks, and then corrections may be made to the standard itself on the basis of star observations.

Three times a week comparative corrections are published, and once a week absolute corrections on the basis of the astronomical data are published. The weekly report lags from two to three weeks behind the time of transmission of a given signal. This allows time for the complex computation required to determine the absolute time at time of transmission.

Star sights both of the day before and after are used in the absolute determinations. These computations indicate that the average error of the time signals as sent from Arlington is about 0.02 second.

Comparison with signals emitted from fourteen different observatories indicates further correction of 0.01 for a National average.

No method of transmitting has been found to decrease the error. However, for persons wishing more accurate data, the above-mentioned tables of correction may be applied, sending accuracy up to a few thousandths of a second.

Signals were first sent out so that navigators might check and readjust their chronometers before leaving the harbor. Now they are also used directly by navigators at sea.

The signals are also used for Longitude determination in precise surveying and map making.

Still another use in in gravity determination by means of which minerals and oil are located, and geodetic questions investigated.

Radio monitoring stations use the signals in checking their substandards, which are in turn used in checking the frequencies of transmitting stations.

Seismologists use the signals to coordinate records of various stations throughout the world.

It is now of interest to outline briefly the physical set-up at the Naval Observatory which accomplishes such precise determinations and comparisons as described above.

The transmitting clock is run at a frequency of 1000 cycles. To obtain this continuous frequency, and maintain it accurately, a crystal oscillator operating on thirty kilocycles is used. The piezo-electric crystal which controls actually measures three inches long, one-half an inch wide, and one quarter of an inch thick. The output of this electronically operated circuit is put into a six kilocycle multivibrator unit which transforms the frequency to five thousand cycles, one-sixth the original. This in turn is fed into a five kilocycle multivibrator which reduces to the desired frequency of one thousand cycles, or one kilocycle. The output of this circuit is not very strong, although of the correct frequency, so it is therefore amplified until sufficiently strong to run the clock motor.

The transmitting clock itself consists of a small motor which drives a disc about seven inches in diameter at exactly one revolution per second. The disc is divided into one thousand divisions, and a stroboscope set up within the case allows reading of the disc's position to within a tenth of a division, or one ten-thousandth of a second. The motor shaft is also connected through electric contactors to a switchboard, where it automatically controls magnets, chronograph, power, time transmitter, and sidereal switches, in fact everything necessary to make the service automatic.

The chronograph contains seven cylinders, each driven, or set up so that it may be driven, by a different clock. Each cylinder has a number of printing fingers, brought into printing position by energy from its driving clock. The record used as Figure (5) was taken from this machine.

Standby transmitting clock number one is similar to the regularly used transmitting clock in construction, and is available for emergency use.

Standby number two is a pendulum clock which is not controlled by the crystal oscillator as are the other two. In case of failure of the oscillator, this would be used for transmission of the time signals. An interesting feature of this clock is the provision made for making small adjustments. A magnet coil is placed directly beneath the swinging pendulum. An oscillating current of the same frequency as the pendulum's period is supplied through a reversing switch so that the force field of the magnet may be made either to oppose or aid the swing of the pendulum. A means is provided for comparing the output of this clock with that of the primary transmitting standard so that the speed-retard control of the standby can be used to visually adjust the two clocks within one ten-thousandth of a second. Unfortunately, the standby will not stay in step for periods over an hour, so ~~this~~ resetting is necessary quite frequently.

A single pen chronograph is used in the observatory proper to record the one second ticks of the sidereal standard clock (in the vault) being used for the day's primary standard, and the time at which photographs are taken. These two records show up on the same line by means of a small control magnet which acts on the pen to push it off normal position in one direction for the standard ticks, and in the other direction for photographic exposure.

The photographic zenith tube has already been described with one exception. The photographic plate must be exposed for approximately twenty seconds. Therefore, the mercury pool which acts as a reflecting mirror in the bottom of the tube, and the lens which concentrates the light, and also the plate and plate holding mechanism are all driven by an astronomical clock which keeps the units pointed to the same spot in the heavens as the earth rotates.

The star photographed is generally not exactly at the zenith. Therefore, the plate is examined under a Traversing Microscope. This instrument is set up to measure small angles with extreme precision. The resulting measured angle is applied as a correction to the single pen chronograph's record of the time at which the photograph was taken. The corrected time then gives the exact time of the star's transit across the meridian and zenith as shown by the record of the standard clock down in the vaults. (Record of second ticks of clock as shown on chronograph) Knowing the apparent time of the star's transit, and having already calculated the exact time at which that particular star may be expected to cross the zenith, the variation of the number one sidereal clock is the difference between the two values.

The complex astronomical computations required to obtain accuracy are performed upon a mechanical computing machine of standard design, but modified to give a greater number of significant figures.

Power used at the observatory is taken from the regular lines, but standby units are installed which will take over automatically in case of line failure.

The stages of mankind's struggle towards precision measurement of time would in retrospect seem to split into four main divisions. The first is the long prehistoric era, extending back into the distant past far beyond the memory of man. The only measures of the passage of time during this interval were the sun and moon, and the passage of the seasons. The second period heralded the first rude devices for less rough measurement, including the sundial, water clock, and hour-glass. Setting up of a calendar might also be included here. Next is the medieval period, which has seen the development of a mechanical instrument which keeps fairly accurate time. This merges into the modern period where split second accuracy is the order of the day, and very precise astronomical measurements are used to check the accuracy.

It seems safe to say that modern time-pieces of one type or another now exist ready to meet all requirements. If history be any indication, then any future need for greater precision will as in the past in some way be met.