Time Marks and Clock Corrections: A Century of Seismological Timekeeping

Duncan Carr Agnew
Institute of Geophysics and Planetary Physics,
Scripps Institution of Oceanography,
University of California San Diego,
La Jolla, California, USA 92093-0225

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Abstract

Accurate time measurement is a crucial element of seismic data collection. For data collected before the 1980's and especially before 1960, the technologies involved are no longer familiar to most researchers. I outline how reliable time has been obtained for seismology, and describe the histories of master clocks, local clocks, time transfer, time comparison, and uniform motion for visual recording. A compendium of station data for 1921 gives a snapshot of early seismological timekeeping. I present an overview of subsequent developments, with suggestions on how to weight observed times using descriptions of the timing system used.

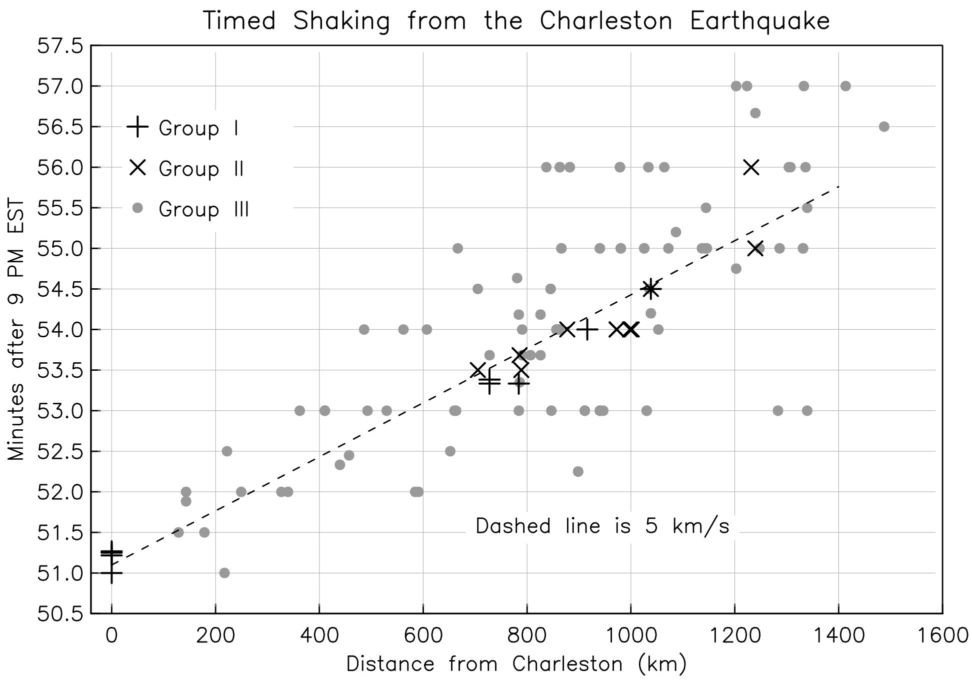

Figure 1: Times of the start of felt shaking from the Charleston earthquake. Different symbols are used for the three groups of observations used by Newcomb and Dutton (1888): group I were times deemed accurate and precise (given to the nearest second), group II were times deemed accurate but not precise (given to the nearest minute or half-minute) and group III were times deemed usable but not good.

Introduction

On the evening of August 31, 1886, Mr. M. C. Whitney of New York City was standing in front of a jeweler's shop, watching the pendulum clock in the display window and waiting for it to indicate the next minute, so that he could release the seconds hand on his pocket watch and have it show the correct time. As he waited, he felt the ground begin to move, recognized this as an earthquake, and noted the precise time: 9:54:35 PM, slightly more than three minutes after the start of the Charleston earthquake, over 1000 km away (Dutton, 1890).

Mr. Whitney's observation, with a few others equally precise and accurate, was used by Newcomb and Dutton (1888) to determine the wave speed from the earthquake as close to 5 km/s: much higher than earlier estimates, but also the first seismic wave speed found to agree with numbers that "theory indicates as belonging to the movement of elastic waves in an indefinitely extended solid mass of siliceous material" (Dutton, 1890). Figure 1 plots the times used.

Three years later, in June 1889, Dr. E. von Rebeur-Pachwitz, reading of an earthquake in Tokyo on April 18 of that year, correlated it with “singular disturbance” on his horizontal pendula at Potsdam and Wilhemshaven. Using, quite reasonably, the local time at Tokyo (converted to Greenwich Mean Time, or GMT) he deduced a travel time of 64.3 minutes, giving a wave speed along a straight path of 2.1 km/s (von Rebeur-Paschwitz, 1889).

Each result depended on a recent action. For the Charleston times, it was was the 1883 decision by the major railroads of the United States to adopt four “Standard Times” for their operations; these times were one hour apart, with the eastern one being the time 75° West of Greenwich (Bartky, 1989). The railroads did this to avoid state or local governments imposing time changes on them. They put these times into effect on November 11, 1883; on that day, or soon after, many cities adopted these standard times as their official time. So it was possible to assume that the reports for the Charleston earthquake were all on the same time system; Dutton (1890) is quite definite that this standardization was crucial to successfully measuring wave speed.

For the Tokyo earthquake, the important action was that taken by the International Meridian Conference in Washington in October 1884. This conference resolved that there should be a “universal day” whose time and date would be that of a particular meridian, which was chosen to be that of Greenwich Observatory (Bartky, 2007). This standardization of time only slowly replaced local times throughout the world (Milne, 1899; Ogle, 2015), but did have the immediate result that Japan adopted the meridian 135° East of Greenwich as its national time: perhaps an easier decision than for other countries because Japan had long assumed a uniform time system (Frumer, 2018). As Knott (1889) pointed out, this change in time reporting altered von Rebeur-Pachwitz’s computation, making the true travel time equal to 45 minutes.

Seismologists have always needed consistent, accurate, and precise times: a requirement shared (in the sciences) only with astronomy and geodesy. Even in a high-tech setting timekeeping can be poor: a 1988 survey of times on Internet servers found that 60% had errors of more than a minute (Mills, 1989); only 30% of the Charleston observers used by Newcomb and Dutton (1888) did this badly.

My aim here is to describe how seismologists could and did find the time over the 100 years from 1890 to about 1990: the end date is about when GPS time became readily available. Now, thanks to GPS and smartphones, highly accurate time is ubiquitously available and older timekeeping technology is disappearing. My title includes two now-vanished techniques: clocks that need to be corrected, and marks put on a visual record to indicate the time. Part of analysing earlier data is deciding how accurate the time is; this paper aims to provide information that can help in evaluating this accuracy.

After a short discussion of how to think about timekeeping, I provide narrative accounts of the different elements of accurate timekeeping from before 1900 to the late 1980’s, with special focus on the period before 1960; I then give some examples and summaries of how these methods were used by seismologists.

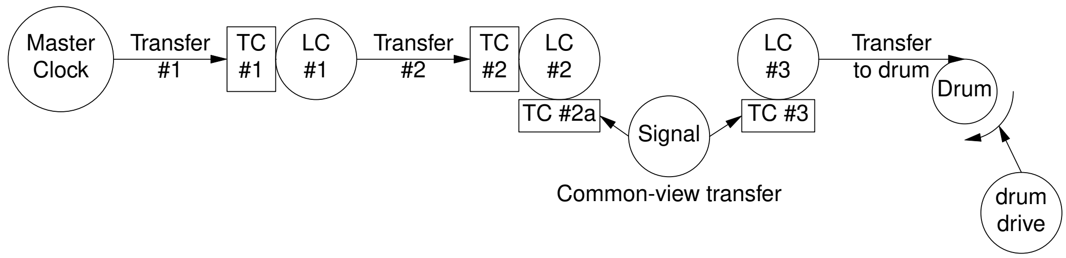

Figure 2: Schematic block diagram of the timekeeping chain for seismic recording. LC stands for Local Clock, TC for Time Comparison. The arrows from the ellipse labeled "Signal" show how common-view time transfer is done.

Advances in timekeeping and the transfer of time to different places were not done with seismologists in mind; rather, these served practical needs in navigation and communications. Also, as numerous historians have documented (O'Malley, 1996; Landes, 2000; Gay, 2003; Hashimoto, 2008; Glennie and Thrift, 2009; McCrossen, 2013; Ogle, 2015), one hallmark of modernity has been an ever-growing concern with having accurate time. We don't know why Mr. Whitney wanted to set his watch accurately to the second, but clearly he thought it worth the trouble – to the benefit of seismologists.

I have tried to make this article reasonably self-contained, though parts of it are unavoidably both compressed and somewhat simplified. I have not discussed effects (or methods) that are associated with timekeeping to better than 0.1 seconds; these, and many other details are fully discussed by Urban and Seidelmann (2013) and McCarthy and Seidelmann (2018).

The Timekeeping Chain

To see how complicated it can be to find the time, consider a hypothetical but realistic example: how did John Milne, after building his teleseismic observatory in 1895, set the watch used to put time marks on the record? A plausible story might begin with him setting his watch from the station clock at the Shide station of the Isle of Wight Railway. This railway might have determined its time by carrying a watch, set to the clock at the Southampton terminal of the London and South Western Railway (LSWR), to its own central station. The LSWR clock would have been set, whether by carrying a watch or by telegraph, to the time at its London terminus, Waterloo Station. The clock there was almost certainly set by a telegraph signal from Greenwich Observatory, actuated by the Greenwich solar mean time clock, which itself was adjusted by comparison with the Greenwich sidereal clock, whose rate and time were determined from the Earth's rotation using chronograph records of star transits observed with the Airy Transit Circle (Ellis, 1865; Anonymous, 1875; Ellis, 1876).

This example shows how many details have to be understood to learn how a time was found. Figure 2 illustrates the process more schematically, showing what could be called the timekeeping chain. The chain always begins with a master clock: some system which defines the time. The links of the chain can be many or few, but each involves the same elements:

1. A clock, called the local clock, which keeps its own time but is adjusted or corrected using the time from the clock in the previous link.
2. A method of time transfer, which takes the output of the clock in the previous link and provides it "close to" the local clock. Because the difference in local times between two places determines their difference in longitude, most methods of time transfer were developed to aid navigation.
3. A method of time comparison, which can be used to find the difference between the transferred time and the local clock.

Figure 2 also shows how local clocks can be connected indirectly, using what is called common-view time transfer. In this method a signal is observed at, and compared with, two local clocks that form different elements of the chain: the two times when the signal is received relates the local clocks to each other. The signal does not need to be from a clock: for example, in the oldest systematic use of the method (proposed by Galileo in 1616) it was the immersion or emersion of one of the moons of Jupiter (Heilbron, 2010).

If all we wanted was the time, this series of clocks, transfers, and comparisons would be enough. But, in the pre-digital era, seismic recording also needed a final timekeeper, adding time to an analog record by physically moving it. Providing a steady advancement at a constant rate, was not as simple as it might seem to be.

Master Clocks: The Earth and the Atom

For the first six decades of seismic recording, the master clock was, as it always had been, the rotation of the Earth. Because of the conservation of angular momentum, this rotation rate was constant, so time could be equated to the angular position of the Earth. But this position could only be defined with reference to other astronomical bodies, so precise time and astronomy were closely linked.

The astronomical phenomena are most easily discussed by using a geocentric frame, with the Sun and other stars moving around the Earth. A vertical plane running north-south and extended indefinitely is called the meridian, and when a celestial object crosses this plane it is said to transit. The time between successive transits of some celestial object defines the day, which then forms the basis of timescales both long (calendars) and short (hours, minutes, and seconds). If the celestial object is the Sun, the time between transits is a solar day; if a star, a sidereal day. The stars define an inertial frame, so the sidereal day is as invariant as the Earth's rate of rotation. Relative to the sidereal motion, the sun moves irregularly across the sky, so the solar day varies in length relative to the sidereal day. Time based on the observed solar day is called Apparent Solar Time. Correcting for the Sun's irregular motion gives a "mean Sun" which provides Mean Solar Time; the ratio between sidereal and mean solar days is fixed. The difference between the transit times of the Mean and actual Sun is called the equation of time.

While the Sun is the easiest star to observe, its large angular diameter means that shadows or light spots of sunlight are so broad that a sundial cannot give time to much better than a minute–unless that sundial is the size of a cathedral (Heilbron, 1999). For precise measurements, the usual astronomical observation was of the time of transit of stars, observed through a telescope (a transit telescope or meridian circle) designed to move only in the plane of the meridian. When a star crosses the center of the telescope's optical axis the local sidereal time is equal to the right ascension of the star. Stars with the most accurate right ascensions were therefore called clock stars. The local mean solar time can be found from the sidereal time, and, as a final step, converted to GMT by subtracting the longitude of the telescope, expressed in time units. Given a known longitude, and either a sundial and a table of the equation of time, or a transit telescope and a star catalog, any seismic observatory could find GMT on its own. Before convenient methods of time transfer were developed, there was no good alternative to this.

The quality of this sidereal time depended on how precisely the star's transit could be timed, something discussed in the "Time Transfer" section below. The accuracy of this time depended on how accurately the right ascension was known, and on how well the plane defined by the telescope matched the true meridian plane. For an exact match the telescope must rotate around an axis that is exactly level and oriented East-West. An angular error of $15''$ (7μradian) or a longitude error of 50 meters gave a time error of 0.1 second.

The Earth's rotation remained the definition of timekeeping until 1960, when it was replaced, until 1967, by a time standard based on conservation of angular momentum of the Earth and planets as they orbit the Sun. This standard, Ephemeris Time, had in practice only the effect of defining the length of the second to match the average rate of Earth rotation during the nineteenth century.

This time standard lasted so briefly because of the development of a time standard based on quantum effects in the energy levels of electrons orbiting cesium atoms. These effects made possible frequency standards much better than anything previously available; integrating this frequency gave time defined by an "atomic clock". Essen and Parry (1955) built the first cesium oscillator with the needed stability; their announcement of it was immediately followed by a short note by Bullard (1955), suggesting that the quality of this new system meant that it should replace astronomical measurements as the standard for measuring time.

While this redefinition did not occur until 1967, some time scales based on atomic clocks actually go back as far as 1955 (Guinot and Arias, 2005); since then (Levine, 2012, 2016) data from more and more such clocks have been combined to form high-quality time scales. The associated errors and uncertainties are far smaller than anything needed in seismology.

Because of their stability, and ability to quickly provide a time scale, atomic clocks became the effective master clocks before 1967: since the late 1950's time as used by seismologists has been derived from atomic time scales, with adjustments to keep the distributed time approximately in step with the Earth's rotation.

Local Clocks: Pendulums, Springs, and Crystals

In 1890 mechanical clocks were by far the most accurate way of keeping time; for general use they remained so until around 1980, when mass-produced quartz-controlled clocks and watches ended seven centuries of mechanical timekeeping (Landes, 2000). So I have kept in mind that many readers may never have seen, much less learned about, mechanical timekeepers, and have provided very basic descriptions. Mechanical and electronic clocks and watches share one characteristic: they both keep time by counting the oscillations of something that, ideally, approximates a simple harmonic oscillator. This oscillator must have a very stable frequency: a clock whose "rate of going" is stable to one second per day needs a frequency stability of 10^{-5}.

Pendulum Clocks

The oscillators in the earliest mechanical clocks lacked a natural frequency of oscillation, and a great advance was made by the introduction of a better oscillator, in the form of the pendulum, applied to clocks by Huygens in 1657. By 1900 pendulum clocks were a very mature technology, one discussed in detail by Rawlings (1993), Woodward (1995), and Roberts (2003a). Pendulum clocks came in a very wide range of prices and performance; only the highest-grade systems are relevant to seismological timing. The usual name for such a high-quality pendulum clock is "regulator", though this term has been used for certain designs whether or not they qualify as precision clocks. An "observatory regulator" can be taken to have very high quality. Three other signs of a clock designed for accurate timekeeping are a seconds-beating pendulum (frequency 0.5 Hz), the absence of bells, and a display in which seconds, minutes, and hours each have a separate dial. Roberts (2003a,b, 2004) provides a large number of examples.

The actual performance of a pendulum clock strongly depends on the quality of workmanship, most especially on reducing friction, often by using jewels as bearings. Any frictional irregularity can change the amplitude of the pendulum's swing; because a pendulum is a slightly nonlinear oscillator, with an amplitude-dependent frequency, amplitude changes affect timekeeping.

Good performance also requires that the effective length of the pendulum be insensitive to temperature changes: because of thermal expansion of the pendulum rod, even a few degrees of temperature change can easily change a clock's rate by 10 seconds per day. Any precision pendulum clock will be temperature-compensated. This was first done by Graham in 1715, using a jar full of mercury as the pendulum bob. An increase in temperature lengthens the pendulum rod but also expands the mercury so that the center of mass remains unchanged. This system remained the commonest form of temperature compensation until 1897, and the development of invar: an alloy of nickel and steel with a much smaller coefficient of thermal expansion.

From 1700 until about 1950 high-precision pendulum clocks were available from a number of clockmakers; even those who mostly produced lower-quality clocks could, with care, build a precision clock. For seismological use a clock usually needs to be able to briefly close a switch at intervals to place time marks on the record: two terms for this are contact clock and break-circuit clock. The Göttingen instrument firm Spindler & Hoyer included a contact clock “according to Prof. Dr. Wiechert” in their 1908 catalog of seismographs; they do not identify the actual maker (very common in horology), or describe performance or type of temperature compensation, but the illustration in their catalog suggests a fairly standard wall regulator.

The best-performing pendulum clocks were produced by a few makers who focused on clocks for the most demanding users. In Germany the firm of Clemens Riefler made pendulum clocks (and compensated pendulums for other makers) from 1891 until 1965 (Roberts, 2004). Almost any astronomical observatory aiming at high precision would own at least one Riefler. Another German maker of precision pendulum clocks was Strasser and Rohde (1875-1958). The very best performance for pendulum clocks came from the British Shortt-Synchronome (Hope-Jones, 1940), which used two pendulums, one swinging almost freely in a low-pressure chamber, connected electrically to another which both provided an infrequent impulse to the free pendulum and was reset by it. A French maker, Leroy et Cie, built high-precision pendulum clocks from 1912 until 1957, primarily for francophone observatories: most notably the Paris Observatory, which served as a de-facto world time standard for a number of years (Kershaw, 2019). No American clockmaker tried to compete in this market, though some, such as Seth Thomas, did make regulators for less demanding uses.

Spring-balance Clocks

Since pendulum clocks cannot keep time when moved, portable timekeepers (watches) needed another kind of oscillator, namely a spring-mass system just like an inertial seismometer. To make this oscillator insensitive to acceleration, the mass was a pivoted circular ring (balance wheel) and the spring a spiral or helix (balance spring): while such an oscillator is sensitive to rotation, this is usually smaller than accelerations.

The spiral spring and balance wheel combination was introduced by Huygens in 1672, and became the usual oscillator in portable timekeepers for the next 300 years. Again, temperature compensation was needed, though for a different reason, namely the thermal coefficient of Young's modulus of the spring. The first practical temperature compensation for this oscillator was built by Harrison in 1761, the temperature sensor being the now-familiar bimetallic strip, with brass and steel fused together to form a metal strip that would bend with temperature changes. The best temperature compensation for spring balances came from making the balance wheel bimetallic, so that temperature changes would change its moment of inertia to offset the change in the spring's elasticity. The introduction of invar improved this compensation, and other nickel-steel alloys were developed that had a very low thermal coefficient of elasticity.

All of these refinements, and others, were included in the highest quality of spring-balance timekeepers, namely marine chronometers (Gould *et al.*, 2013; Davies, 1978; Betts, 2018), often referred to as box chronometers because they were usually mounted in gimbals in a box. As is well known, these timekeepers vastly improved marine navigation by making it possible to find an accurate longitude out of sight of land; they were also the choice of anyone who needed the best available time but could not use a pendulum clock. The nineteenth century saw a continuous refinement of chronometers, and they were widely available from a number of makers (the name on the dial may not relate at all to who made the movement). As with pendulum clocks, "contact chronometers" included a switch to provide timed electrical impulses.

Normal-Mode Frequency Standards

Another timekeeping method eventually replaced both pendulums and spring balances. It was based on something very familiar to seismologists: the normal modes of an elastic body, or more properly, a single mode used as a frequency standard, which when integrated provided a measure of time. For a homogeneous body the modes could have a very stable frequency, and this, along with a higher quiality factor Q, created an excellent clock. (Bateman (1977) provides typical Q values for a horological oscillators: 100 to 300 for spring balances, 10^3 to 10^4 for most pendulums and tuning forks.) The mode frequencies would be, roughly, a typical S-wave speed divided by the length of the body being used: for materials with the appropriate stability this ratio leads (for conveniently-sized objects) to frequencies from 10^2 to 10^7 Hz. Counting these rapid oscillations was not really feasible until electronic systems were introduced; only with the 1950's development of the transistor did such systems become widely used.

The first normal-mode oscillator was the tuning fork, which provided a standard musical pitch. In the nineteenth century some electrically-maintained forks were developed. Around 1920 much superior systems were developed that used electronics to make both the sensing and driving noncontact: these arrived just in time to provide something badly needed for radio, a stable frequency standard (Marrison, 1948). Considerable effort went into developing ways to relate tuning fork frequencies to time intervals (Katzir, 2015), and forks have had some, though limited, use as timekeepers and frequency standards through to the present. A related device is the reed oscillator (named by analogy with reed musical instruments), in which the oscillating body is like a one-prong tuning fork whose prongs are made very thin and have mass added to the end, with mode frequencies as low as 10 Hz. Reed oscillators were little used for timekeeping, but have served as frequency standards for driving recording drums.

Tuning forks saw limited use because the period around 1920 was also when quartz crystals began to be developed as frequency standards (Marrison, 1948; McGahey, 2009; Katzir, 2008, 2016a,b, 2017). As frequency standards crystals had three advantages over tuning forks. The much higher frequency of the modes made a quartz oscillator more suitable for measuring radio frequencies; the crystal had a higher Q (10^5 for early examples, later 10^6); and the piezoelectric nature of quartz made the modes easy to excite and sense. For a clock the crystal's high frequency was actually a handicap, since electronics had to be developed to divide the frequency to small enough values that it could drive a motor that, by integrating the oscillations, would provide a measure of time. Such a "quartz clock" was first built by Marrison in 1927, soon after by other laboratories.

These clocks all used vacuum tube electronics, so they were large and power-hungry, and had relatively frequent failure rates: to overcome the last problem, they were often run in threes. Quartz clocks did not move out of the laboratory for some time, though the high stability they offered meant that they soon replaced mechanical clocks at some leading observatories: Greenwich time, for example, was based on quartz clocks as early as 1942 (Rooney, 2016). Only with transistor electronics did quartz oscillators become part of general horology; for example, the first marine chronometers with quartz oscillators were introduced in the 1960's (Read, 2015). The development of CMOS integrated circuits so lowered the power requirements for the electronics that a quartz-based wristwatch became possible, with the first models introduced in 1970 (Stephens and Dennis, 2000). The section "An Overview" describes the consequences for seismological timekeeping.

Time Transfer

Carrying a clock from one place to another has twice been the only way to precisely transfer time. From 1790 to about 1860 the procedure was to carry chronometers, sometimes more than 100, from one place to another and back again. For example, when the survey ship *Beagle* circumnavigated the Earth from 1831 through 1836, she carried, in addition to Charles Darwin, 22 chronometers (Davidson and Linstead-Smith, 2016). The second period of precise transfer using clocks was from 1965 to 1992, when the best way to transfer time from one atomic clock to another was to fly a rubidium standard clock back and forth between them (Dick, 2003). For short distances and from 1790 on, carrying a clock was the most flexible and simple method of time transfer; an example is the chronometer-based London time service maintained by John, Maria, and Ruth Belville from 1834 through 1940 (Rooney, 2006).

But almost all precise time transfer since about 1850 has used electrical signals. Only two weeks after the first Morse telegraph line was opened from Washington to Baltimore in 1844, it was used to compare clock times for finding longitude. By 1850 a toolkit had been developed for accurately and precisely recording the times of star transits (see the "Time Comparison" section) and for sending clock signals by telegraph (Bartky, 2000; Stachurski, 2009). These tools were almost immediately used for time distribution by astronomical observatories; as a service (sometimes paid), the time would be provided to local governments, railroads, or telegraph companies. Three notable examples were Harvard College Observatory, for New England; Greenwich Observatory, for England, Scotland, and Wales; and, with the largest areal coverage, the US Naval Observatory, which sent a "noon signal" to the Western Union Telegraph Company, which in turn sent it to all its stations to the south and west of Washington (Saff, 2019; Ellis, 1865; Gay, 2003; Bartky, 2000; Dick, 2003). Along with standard times, Dutton (1890) stated that a key to the quality of times for the Charleston earthquake was that " once each day a signal is telegraphed from an astronomical clock to every telegraph station in the country at an appointed hour, minute, and second". And it was only the determination of longitude by telegraphy over deep-sea cables that make it possible for Tokyo time to be exactly nine hours different from GMT. Comparisons of time signals from different American observatories, made privately by Western Union (Bartky, 2000, p. 117) showed that the overall accuracy was usually within two seconds. So when instrumental seismology began in the 1890's, precisely coordinated time over the whole Earth was something actually available.

But this time was only available where there was a telegraph wire, a restriction removed by time transfer using radio waves. As a practical form of communication, radio (then, and now again, called wireless) was first demonstrated in the late 1890's and over the following decades saw very rapid growth; Aitken (1985), Hong (2001), and Belrose (2006) are useful guides to the complexities, financial and technological, of the first two decades of development. Only radio could communicate with ships at sea, so the initial growth was fastest there. Providing time for better navigation was an obvious step; the first known time signals were broadcast by a US Navy station in 1904 (Howeth, 1963).

Both experience and what theory there was for radio propagation (Yeang, 2013) indicated that distant communication was best done by transmitting at high power (10^5 W) and at, in today's terms, low or very low frequencies (LF or VLF). With radio wavelengths of kilometers, transmitting stations also needed very large antennas. One place where such antennas could be erected close to an astronomical observatory was Paris, which already had an unintended radio mast in the form of the Eiffel tower, only 3.5 km from the Paris Observatory (Figure 3). The first consistent broadcast of precise time signals was from there, beginning in 1910; by 1912 these broadcasts included a "rhythmic" signal that made it possible to transfer time with high precision, as described in "Time Comparison" below (Bureau of Longitudes, 1915). Early comparisons between two independent transmissions initially showed scatter of 1-2 seconds (Bartky, 2007, p. 154), but those published by the International Seismological Association for the two years 1912-1914 usually show differences less than 0.5 seconds.

Starting in 1912 the US Navy built high-powered VLF radio transmitters in the continental US, Hawaii, Panama, and the Philippines, providing global coverage. U.S. Naval Hydrographic Office (1922) lists 34 radio stations emitting time signals, though many of these were relatively local. Not all time signals were accurate at the one-second level, but the better stations were consistent to within a few hundred milliseconds (Sampson, 1922). Figure 4 shows the frequencies of time-signal broadcasts at several dates, indicating the next big advance in radio: the discovery, initially by radio amateurs (Yeang, 2013) that much higher frequencies ("short waves") and much lower powers could also provide widespread coverage. By 1930 13 of the 73 time signals listed in U.S. Naval Hydrographic Office (1930) were short-wave ones.

All these stations transmitted time signals once to a few times per day, using a large variety of telegraphic codes. The most precise rhythmic signals were sent only by a few stations. Time signals were first broadcast continuously by the US National Bureau of Standards (NBS) station WWV in 1944, transmitting at short-wave frequencies. The simple time code used (with voice announcements from 1950 on) made it possible for anyone with a shortwave receiver to access accurate time without having to read Morse code (Nelson, 2019).

Another development in radio time transfer came with a return to low frequencies, which allow much more accurate frequency dissemination than short waves do. Adding a time-code modulation to the carrier produced a widely available signal from which clocks could set themselves. The NBS station WWVB began time-code transmissions in July 1965, as did the Swiss station HBG in January 1966, and the German DCF in 1973 (Read, 2007; Lombardi and Nelson, 2014). The signals from the European stations covered enough population to encourage the manufacture of consumer-level radio-controlled clocks; partly to make this possible in the US, WWVB was upgraded to higher power in 1999 with similar mass-market results. Global coverage by low-frequency signals was provided by the OMEGA radionavigation system, which saw some use for timing (Schneider *et al.*, 1987) before it was shut down in 1997. Another source of time-code signals was the GOES satellite system, which covered most of the Pacific Ocean and North and South America from 1974 to 2004 (Lombardi and Hanson, 2005).

Time Comparison

For the period we are considering, the comparison of clocks depended on human senses, sometimes aided by methods that allowed time to be stretched out in some way.

The first step in finding Earth-rotation time is an example: while observing a star an astronomer would listen to the beats (ticking) of a clock; when he saw the star passing the

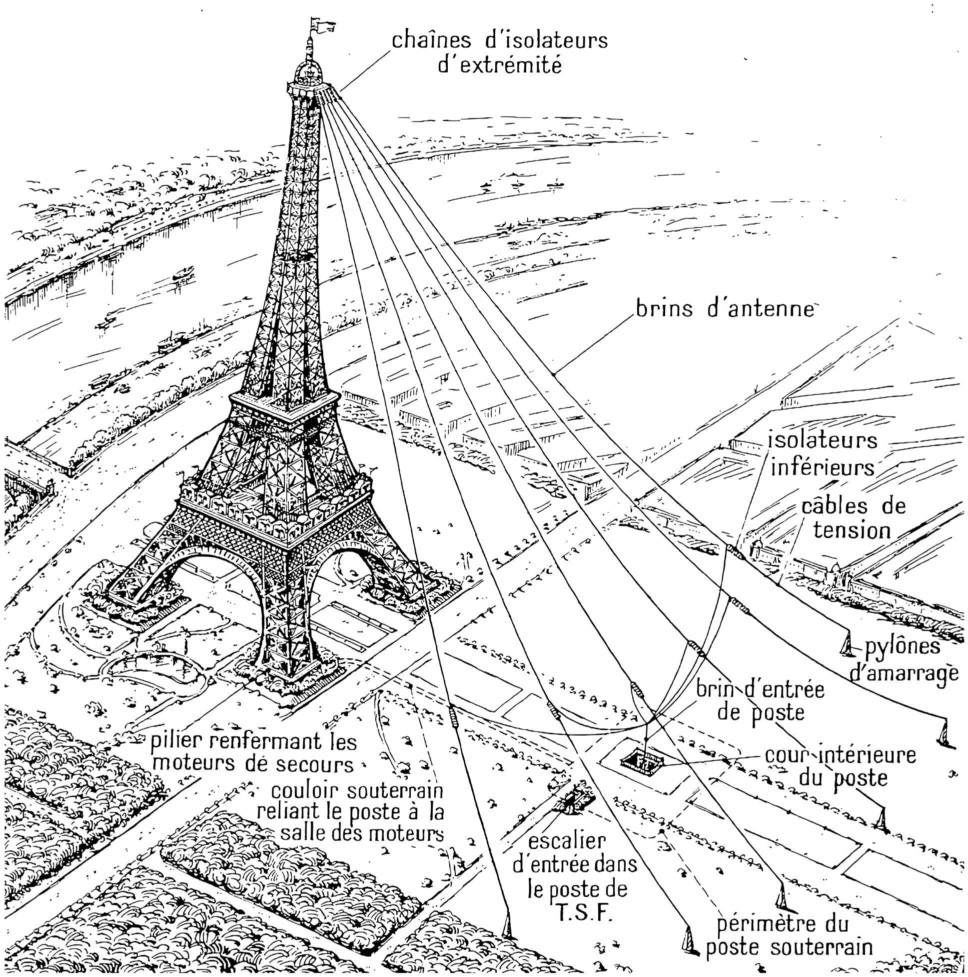

Figure 3: Radio antenna used for the Eiffel Tower time-signal. The radiating portion, *brins d'antenne*, run from the upper insulators at the top of the Tower, to tne lower insuators, *isolators inferieurs*. (Modified from Wikimedia Commons image, file https://commons.wikimedia.org/wiki/File:Antenne_tour_Eiffel_1914.jpg, last accessed November 2019).

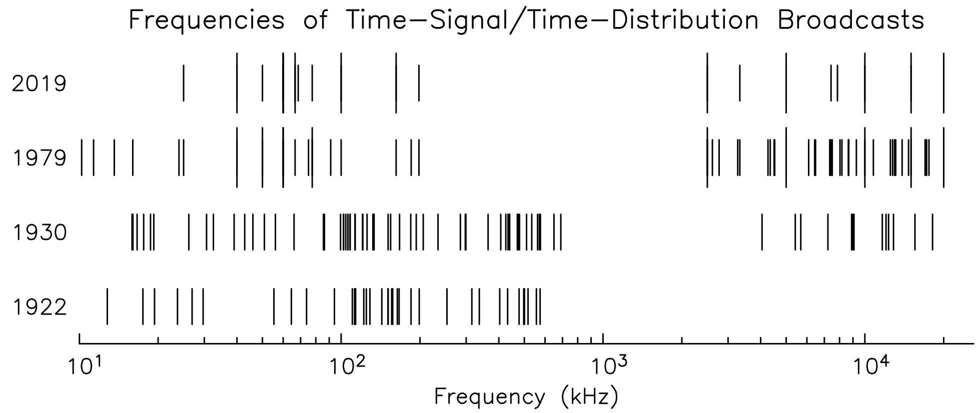

Figure 4: Frequencies of broadcast time signals at four different dates. The data from 1922 come from U.S. Naval Hydrographic Office (1922), for 1930 from U.S. Naval Hydrographic Office (1930), for 1979 from the Annual Report of the Bureau International de l'Heure for that year, and for 2019 from the Annual Report on Time Activites of the Bureau International des Poides et Measures for that year. Longer vertical lines indicate broadcasts with continuous time codes or signals.

meridian he would estimate the time by mentally subdividing the interval between beats. This "eye and ear method" was taken to have a nominal precision of 0.1 seconds, though its accuracy was less than this because different observers would make different judgements. So each observer was assigned a correction, known as the personal equation, to be applied to his time estimates (Schaffer, 1988). Eventually procedures were developed (Kershaw, 2014, 2019) to observe meridian transits with much less uncertainty. But the eye-and-ear method has lived on for low-accuracy clock comparison, for example in comparing audible time signals to a visible change in a clock display, such as the second hand passing the minute mark.

Better comparisons used the same sense to observe both clocks. One method was to listen to two clocks ticking at different rates: the ticks would slowly come to coincide and then separate. Getting the time at which they seemed to coincide allowed the relative time between them to be determined more precisely and accurately. The earliest application of this "method of coincidences" was when one clock (used to time star transits) was running at a sidereal rate, and another at mean time: the interval between coincidences was then about six minutes. The "scientific" or "rhythmic" signal sent from the Eiffel Tower was explicitly designed for this procedure, with 59 ticks per minute, the coincidence interval was about one minute. Timing several coincidences over a few minutes of listening could give a precision better than 0.1 seconds (Sampson, 1914).

But in 1900 the best general method of clock comparison was one familiar to any

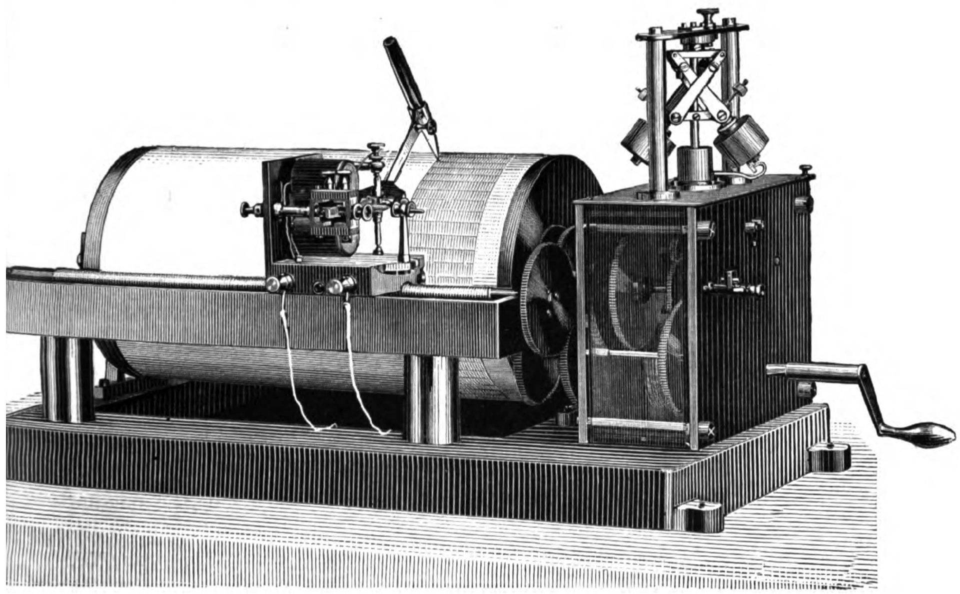

Figure 5: Typical drum chronograph, from (Ambronn, 1899, Fig. 978). The driving system, on the right, includes a precise flyball governor (on the top). Note that the time marks on the drum are seconds.

seismologist who works with older data: a visual comparison between different signals drawn on moving paper. Sometimes this would be a long strip of paper with a pen actuated by both clocks, but more commonly the recording was on a drum, running at a high enough speed (a few cm/s) that measurements between seconds marks could give time intervals to 0.01 seconds. Such a recorder (Figure 5) was called a drum chronograph, or quite often just a chronograph: an ambiguous usage, because in horology "chronograph" is used for any system for measuring short time intervals, including stop watches. The drum chronograph was developed around 1850 (Bartky, 2000; Saff, 2019), and usually recorded both the beats of a contact clock, and star transits, registered by an observer pressing a key. This technique was a such an improvement over the eye-and-ear method that it was rapidly became the standard for recording star transits, and remained so for almost 100 years.

A seismic drum was used as a somewhat unusual chronograph in the early years of the Southern California network that was established by the Carnegie Institution of Washington in the 1920's under the leadership of H. O. Wood; this network was taken over by Caltech in the 1930's, and so represents the start of today's Southern California Seismic Network (Goodstein, 1984; Hutton *et al.*, 2010). A goal of this network was to locate nearby earthquakes to within a few kilometers, so the target for time accuracy was 0.1 seconds (Day, 1928). Setting up a dedicated radio transmitter for time signals was considered but rejected on

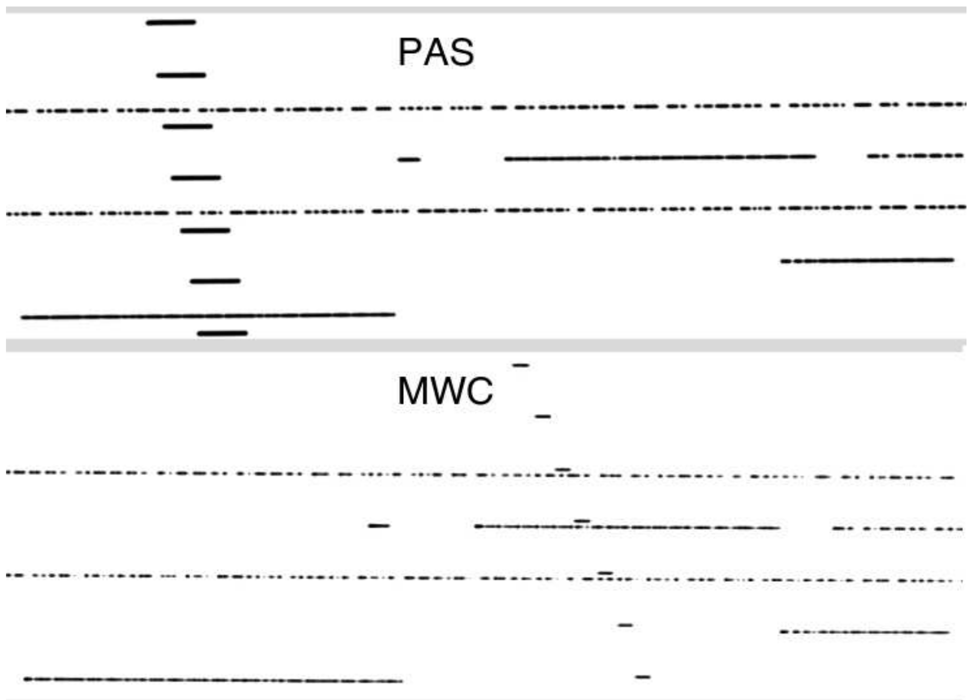

Figure 6: A small part of the records from the time drums at stations MWC and PAS, of what is now the Southern California Seismic Network. The complete records are for January 20-21, 1932. The interrupted lines are signals from radiotelegraph stations, the offset lines are timing marks from the station clock.

grounds of cost and reliability. Instead, each station included a “time drum”, on which were recorded both the time marks from the local clock and the signal from a radiotelegraph station. The record from this signal would be identical at all stations, allowing the relative times of the local clock to be found: another early example of the common-view method of time transfer. Good absolute time was needed only at the central station in Pasadena. This method required a fair amount of measurement and computation to get relative times – though only around the times of earthquakes. Figure 6 shows an example of two such timing records: the common radiotelegraph signal is easily identified on each record.

Uniform Recording

For the method just described to work, the drums need to rotate at a uniform rate. Eventually this could be done using a motor synchronized to the alternating-current (AC) line power,

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with gearing to reduce the speed down to (often) 15 minutes per revolution, which gave a record speed of 1 mm/s for a drum with a diameter of 28.6 cm. The motor design needed was invented by H. A. Warren in 1916, specifically to be used for electric clocks (Warren, 1932). But for acceptable timekeeping this required the powerline frequency to be stable to at 10^{-4} of its nominal value, much more stability than was needed for power distribution. So Warren also developed a master clock (Telechron Types A and B), in which a precision pendulum clock drove one second hand, and a synchronous motor another: the power-station operator could then adjust the generator speed to keep these coincident (Holcomb and Webb, 1985). Larger power networks, with many generating stations, also required precise frequency control; by the 1950's it was usually reasonable to rely on an AC synchronous motor to produce uniform rotation.

But what about earlier? Clocks and watches had a sufficiently steady rate, but produced intermittent rather than uniform motion. Drum chronographs and telescope drives both required very uniform rotation, and many speed governors were developed to provide this (Darius and Thomas, 1989; Caplan, 2012; Saff, 2019). The simplest was a vane designed so that air friction, opposing the driving force, would keep the rotation rate steady; Figure 7 shows this speed control applied to the early Wiechert seismographs. Much better performance came from using a conical pendulum arranged so that a small change in speed would produce a large variation in frictional resistance; such flyball governors used on telescopes and chronographs (Figure 5) into the early twentieth century.

Here again the needs of the southern California seismic network required additional development; in the sections of Day (1925, 1929, 1930) devoted to instrumentation drum drives often get more discussion than anything else. By the report of Day (1930) four different systems had been developed, the one finally used at most stations being a low-power synchronous motor driven by impulses from a temperature-controlled battery-powered 10 Hz reed oscillator. Time marks were put on the records by an electrically-wound contact chronometer, and at the central station by a tuning-fork clock (Pasadena Seismological Laboratory, 1939).

This drum-drive system was viewed by others as too expensive to construct and operate (Nelson, 1941). Spring-balance clocks were used, though these could give very poor performance (Blake and McComb, 1933; Ruge and McComb, 1937), so other methods were developed that used a pendulum clock to control an electric motor to produce more uniform rotation.

The State of the Art in 1921

So how were the different elements of the time chain combined for seismological timekeeping? Wood (1921) provides a very useful overview, since seismograph station operators were asked for information about their timing systems. The 312 station reports in

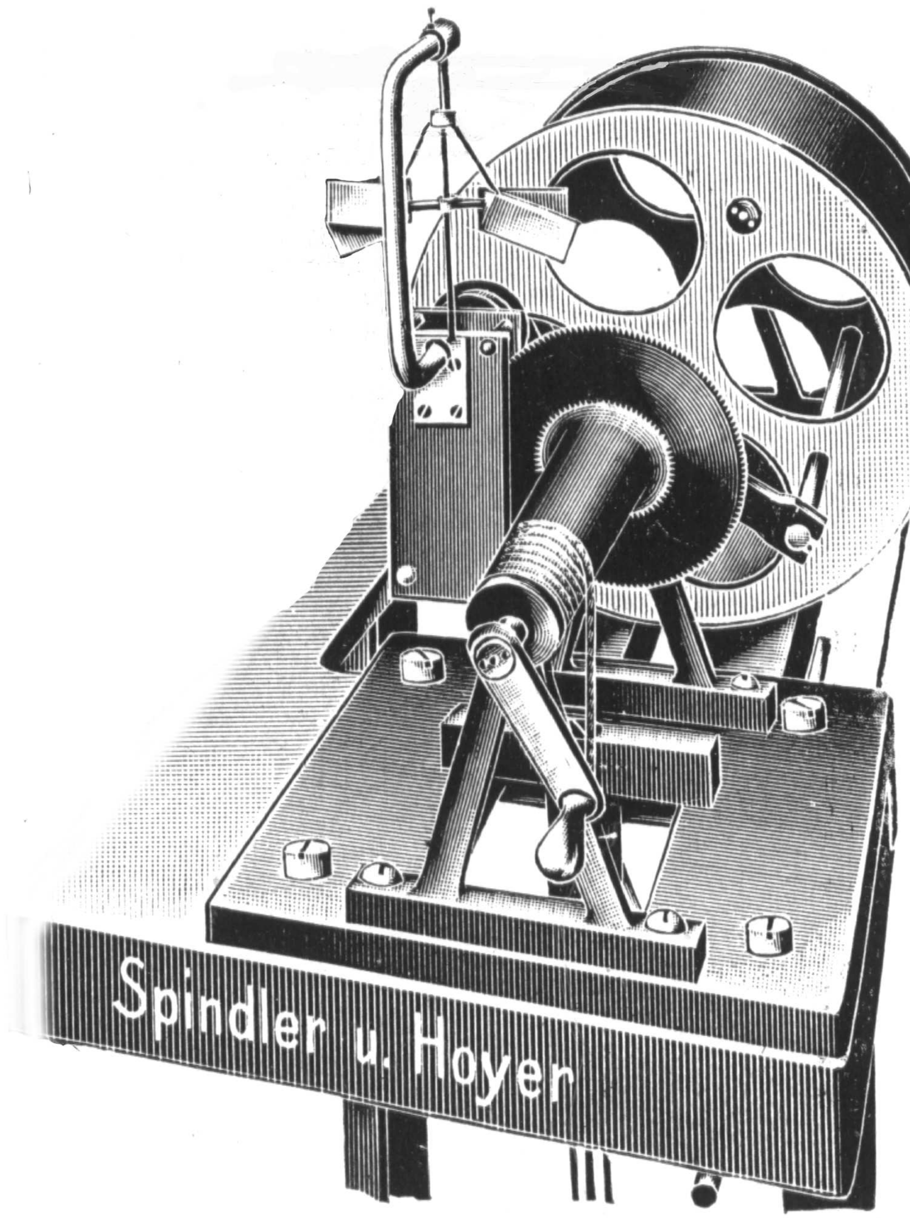

Figure 7: Drum recorder for a Wiechert two-component horizontal seismograph, with driving weight and air-vane (fly) speed regulator. Modified from engraving in the 1908 Spindler and Hoyer catalog.

this compendium show, as might be expected, wide variation. Some (21%) reported nothing about timing: many of these were from an earlier survey which did not ask about this. Others (7%) stated only what kind of local clock they used. Of the 223 stations that provided more information, 66% stated that their time came from an astronomical observatory (sometimes at the same institution), while 20% used their own transit (or in a few cases sundial) observations. Thirty-three stations (15%) obtained their time from sources as diverse as the local railway station, a local time ball, or the noon cannon from a meteorological observatory, and 10% did not specify where their time ultimately came from.

Many stations (41%) did not specify how time was transmitted to them; some of these were at astronomical observatories where transmission was not needed. Of the 132 stations that described how time was transmitted, 62 (47%) used telegraphic signals, and 60 (45%) radio; most of the radio signals were from the Paris Observatory via the Eiffel Tower, the US Naval Observatory via a Navy transmitter in Arlington (Virginia), or the Tokyo Observatory signals. Finally, 8% of the stations received time signals by telephone.

A few years after this report, Mohorovičcić: (1924) presented a critical review of the different instruments and timing procedures described in this report. Given that he expected times to be accurate to one second, it is not surprising that he stated that good timekeeping required a "first-class time clock", without which "it would be better to abandon the station". Furthermore, he said that clock corrections should be made "as often as possible, or needed, by astronomic observations, wireless time signals, or through a very careful exchange from an observatory." The reference to exchange is that the best telegraphic time transfer required that transmission and reception be done in both directions; he states that in telegraphic transfers "an error is very easily introduced", and that stations getting "their time from the nearest telegraph station...cannot be spoken of as seismic stations at all." But beyond this "the weak point in most seismographs is the regulator of paper speed" because of the use of "the cheapest clocks" or an air-governor (as in Figure 7); his preferred drum system is a flyball governor. Many, perhaps most, seismic stations did not meet his standards.

An Overview

The previous sections show that there cannot really be a single history of seismological timekeeping: every seismic station will have its own history, often documented only locally. What was used depended both on what was possible and what could be afforded in first cost and maintenance: the latter depended on system reliability.

There is almost always a tradeoff between quality and cost; even stations that used their own astronomical observations could choose between high-quality and expensive transit instruments, or small and inexpensive instruments (Stott and Hughes, 1987).

At the inception of instrumental seismology the only tools available for precise timekeeping were telescopes, telegraphs, pendulum clocks, and chronometers. Any

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seismologist not prepared to find the time astronomically needed telegraphic communication with someplace else that could. All seismologists needed some expertise in the management of clocks so as to have the time available between occasional determinations. The introduction of radio from 1910 onwards made accurate time much more widely available: a seismic observatory with a radio and a timekeeper was adequately supplied, given careful and ongoing attention to the care and use of both.

From the 1920's onwards the most obvious change was the increase in time signals broadcast at high frequencies, which made it easier to receive them; otherwise the technology of time determination for seismologists remained little altered at least through 1950. Few could afford to get extremely high-precision clocks for their observatories, though in 1928 the station at Florissant, Missouri, was equipped with Shortt-Synchronome clock number 15 (Macelwane, 1950; Miles, 2019).

The seismological community was aware of and interested in better methods. Katzir (2016a, footnote 99) states that in 1930 Bell Labs declined to build a quartz clock for "a group of California scientists"; since the reference is to a letter from A. Day, this is very likely the Carnegie seismological network. Bell Labs gave the same response 19 years later when the US Air Force asked them to build quartz clocks for their seismic monitoring network (Melton, 1981); directing them instead to a maker of timing machines for watchmakers. This company, American Time Products, used a thermostatted tuning fork to produce 60 Hz alternating current which drove synchronous motors for the time marking and the drums. Even with a large budget, in 1949 the best backup the Air Force could find was still precise pendulum clocks (Synchronome, though not the Shortt-Synchronome). In 1953 Texas Instruments did build a quartz clock for Air Force use: a full rack of equipment drawing 325 W of power.

Soon after, transistor electronics made quartz clocks feasible, and in 1958 a quartz system was chosen over an originally-planned tuning-fork one (Melton, 1981). This system became the clock for the World Wide Seismograph Network (WWSSN) (Geotechnical Corporation, 1961). The 30.27 kHz output of a thermostatted quartz oscillator was divided by 2^9 to produce 60 Hz AC that drove the drums and a time programmer to mark the seismic record. The quartz systems seem to have been hand-crafted, since the components of each oscillator were "individually selected, matched, and aged".

For time comparison, a neon lamp on a wheel rotating once per second (a "stroboscope") could be made to flash from the WWV time ticks; the location of this flash on a circle allowed the offset between clock time and radio time to be found to within 0.01 s. The clock frequency was adjusted to keep the time offset less than 0.05 s (Peterson and Hutt, 2014).

Also, time codes from radio stations other than WWV were added to the output on the NS short-period four times per day; as Figure 8 shows, these codes remained quite varied. Non-WWSSN stations might also use other time signals: for example, the southern California network used time signals from the Navy station NPG (Mare Island, California) from before 1929 (Day, 1929) to 1965 (Miller, 1963; Lehner and Press, 1966).

For the western United States, the WWVB time code provided a convenient and direct

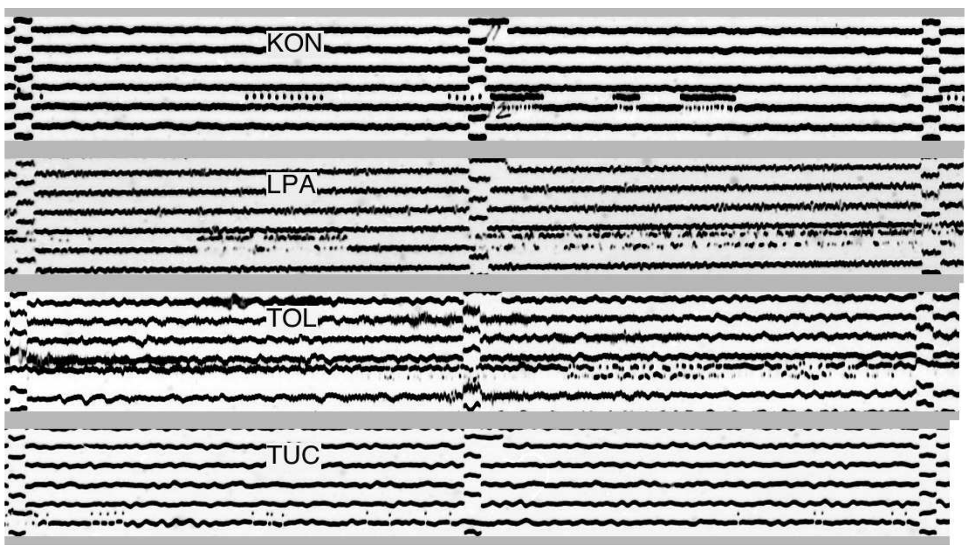

Figure 8: Records from four WWSSN stations for January 10, 1962, showing a two-minute span. The long dash at the top is the 1100 hour mark; the three short dashes below it are minute marks for 1115, 1130, 1145; there is no mark on the next line (1200), but time codes are visible. Stations are KON (Kongsberg, Norway), LPA (La Paz, Bolivia), TOL (Toledo, Spain), and TUC (Tucson, Arizona).

source of accurate time, even if sometimes lost because of attenuation (Hutton *et al.*, 2010). Only a year after this was introduced, Eaton *et al.* (1970) deployed recorders using WWVB after the 1966 Parkfield earthquake. The survey of Poppe (1979) showed most US seismic stations to be using quartz-clock systems, most of them (like the Wiechert pendulum clocks) made by the companies who provided seismic sensors. The ability to miniaturize such clocks, soon to upend the global watch industry, was shown in seismology by the "suitcase" system of Prothero and Brune (1971), with a quartz clock requiring less than 0.1 W of power. By 1980 advances in electronics were making analog seismic recording obsolete; a discussion of timing for digital systems is beyond the scope of this paper.

Conclusion

The information presented here suggests some rules for judging the quality of timing at a seismic observatory. Before the advent of radio time signals the quality will almost certainly be very good for seismic measurements made at an astronomical observatory; otherwise timing should be regarded as more problematic.

From 1920 through the 1960's the main measure of timing quality is what radio signals were used to set the time-marking clock. Sources such as U.S. Naval Hydrographic Office (1930) and the *Bulletin Horaire* of the Bureau International de l'Heure can be used to determine the quality of the time signals from particular radio transmitters, and after 1950 the WWV transmissions can be taken as high-quality. After 1930 at the latest, the timing of any station not using radio time should be given lower weight. For earlier time periods variations in the drum speed should be checked if possible – though for every rule there is an exception: the report from Marseilles in Wood (1921) states that the local AC power frequency was stable to better than 0.2 s/day.

It should be clear from all of the above that timing in seismology has always been difficult to get right; while it has certainly gotten easier, it can still be challenging, particularly as the expectations and requirements for accurate time have become more stringent, and equipment failures can still lead to timing errors (Gibbons, 2006; Syracuse *et al.*, 2017). But at least the rest of society has come to depend on much more accurate levels of timekeeping than seismologists need: global timing infrastructure should be more than adequate for timing seismic waves.

Data and Resources

Figures 6 and 8 are from scans of seismograms held at the IRIS DMC collection of Historical Seismograms.

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I owe the saying “Only seismologists and astronomers really care about good timing” to Frank Vernon. I thank Jim Dewey, Michael Lombardi, Johannes Schweitzer, and Bob Hutt for comments. Johannes alerted me to the time-signal comparisons in the reports of the International Seismological Association, which are available at ftp://ftp.iaspei.org/pub/newsletters/1910-1919/ (accessed November 10, 2019).

References

Aitken, H. G. J. (1985), *The Continuous Wave: Technology and American Radio, 1900-1932*, 588 pp., Princeton University Press, Princeton, NJ.

Ambronn, L. (1899), *Handbuch der Astronomischen Instrumentenkunde*, 1276 pp., J. Springer, Berlin.

Anonymous (1875), The new sidereal standard clock of the Royal Observatory, Greenwich, *Nature*, **11**, 431–433.

Bartky, I. R. (1989), The adoption of standard time, *Tech. Cult.*, **30**, 25–56, doi:10.2307/3105430.

Bartky, I. R. (2000), *Selling the True Time: Nineteenth-Century Timekeeping in America*, 310 pp., Stanford University Press, Stanford, Calif.

Bartky, I. R. (2007), *One Time Fits All: The Campaigns for Global Uniformity*, 292 pp., Stanford University Press, Stanford, Calif.

Bateman, D. A. (1977), Vibration theory and clocks, Part 3: Q and the practical performance of clocks, *Horol. J.*, **120(3)**, 48–55.

Belrose, J. S. (2006), The development of wireless telegraphy and telephony and pioneering attempts to achieve transatlantic communications, in *History of wireless*, edited by T. K. Sarkar, R. Mailloux, A. A. Oliner, M. Salazar-Palma, and D. L. Sengupta, pp. 349–420, John Wiley & Sons, New York.

Betts, J. (2018), *Marine Chronometers at Greenwich: A Catalogue of Marine Chronometers at the National Maritime Museum, Greenwich*, 848 pp., Oxford University Press, Oxford.

Blake, A., and H. E. McComb (1933), Analyses of rates of rotation of recording-drums, *Trans. AGU*, **14**, 324–329, doi:10.1029/TR014i001p00324.

Bullard, E. C. (1955), Definition of the second of time, *Nature*, **176**, 282–282, doi:10.1038/176282a0.

Bureau of Longitudes (1915), *Wireless Time Signals: Radio-Telegraphic Time and Weather Signals Transmitted from the Eiffel Tower, and Their Reception*, 132 pp., E. & F. Spon, London.

Caplan, J. (2012), Following the stars: Clockwork for telescopes in the nineteenth century, in *From Earth-bound to Satellite: Telescopes, Skills, and Networks*, edited by A. D. Morrison-Low, S. Dupré, S. Johnston, and G. Strano, p. 265, Brill, Leiden.

Darius, J., and P. K. Thomas (1989), French innovation in clockwork telescope drives, in *Studies in the History of Scientific Instruments: Papers Presented at the 7th Symposium of the Scientific Instruments Commission of the Union Internationale d'Histoire et de Philosophie des Sciences*, edited by C. Blondel, F. Parot, A. Turner, and M. Williams, Rogers Turner Books, London.

Davidson, S. C., and P. Linstead-Smith (2016), W.E. Frodsham No. 1: Another chronometer identified from HMS Beagle's second voyage, *Antiq. Horol.*, **37**, 366–376.

Davies, A. C. (1978), The life and death of a scientific instrument: The marine chronometer, 1770-1920, *Ann. Sci.*, **35**, 509–525, doi:10.1080/00033797800200391.

Day, A. L. (1925), Report of the advisory committee for seismology, *Yearbook Carnegie Inst. Wash.*, **24**, 370–380.

Day, A. L. (1928), Report of the advisory committee for seismology, *Yearbook Carnegie Inst. Wash.*, **27**, 410–421.

Day, A. L. (1929), Report of the advisory committee for seismology, *Yearbook Carnegie Inst. Wash.*, **28**, 416–424.

Day, A. L. (1930), Report of the advisory committee for seismology, *Yearbook Carnegie Inst. Wash.*, **29**, 422–437.

Dick, S. J. (2003), *Sky and Ocean Joined: the U.S. Naval Observatory, 1830-2000*, 608 pp., Cambridge University Press, New York.

Dutton, C. E. (1890), The Charleston earthquake of August 23, 1886, *U.S. Geolog. Survey Ann. Rep.*, **10**, 203–528.

Eaton, J. P., M. E. O'Neill, and J. N. Murdock (1970), Aftershocks of the 1966 Parkfield-Cholame, California, earthquake: A detailed study, *Bull. Seismol. Soc. Am.*, **60**, 1151–1197.

Ellis, W. (1865), Lecture on the Greenwich system of time signals, *Horol. J.*, **7**, 85–91, 97–102, 109–114, 121–124.

Ellis, W. (1876), The Greenwich time signal system, *Nature*, **14**, 50–52.

Essen, L., and J. V. L. Parry (1955), An atomic standard of frequency and time interval: a cesium resonator, *Nature*, **176**, 280–282, doi:10.1038/176280a0.

Frumer, Y. (2018), *Making Time: Astronomical Time Measurement in Tokugawa Japan*, 270 pp., The University of Chicago Press, Chicago.

Gay, H. (2003), Clock synchrony, time distribution and electrical timekeeping in Britain 1880-1925, *Past Present*, **181**, 107–140, doi:10.1093/past/181.1.107.

Geotechnical Corporation (1961), *Operation and Maintenance Manual, World-Wide Seismograph System, Model 10700*, Geotechnical Corporation, Garland, TX.

Gibbons, S. J. (2006), On the identification and documentation of timing errors: An example at the KBS station, Spitsbergen, *Seismological Research Letters*, **77**, 559–571, doi:10.1785/gssrl.77.5.559.

Glennie, P., and N. Thrift (2009), *Shaping the Day: A History of Timekeeping in England and Wales 1300-1800*, 456 pp., Oxford University Press, New York.

Goodstein, J. R. (1984), Waves in the earth: Seismology comes to southern California, *Hist. Stud. Phys. Sci.*, **14**, 201–230.

Gould, R. T., J. Betts, and S. Hecht (2013), *The Marine Chronometer: Its History and Development: Incorporating Gould's own Amendments and Additions from his Original Annotated Manuscripts*, 287 pp., Antique Collectors' Club, Woodbridge, Suffolk.

Guinot, B., and E. F. Arias (2005), Atomic time-keeping from 1955 to the present, *Metrologia*, **42**, S20–S30, doi:10.1088/0026-1394/42/3/s04.

Hashimoto, T. (2008), Japanese clocks and the history of punctuality in modern Japan, *Asian Sci. Tech. Soc. Internat. J.*, **2**, 123–133.

Heilbron, J. L. (1999), *The Sun in the Church: Cathedrals as Solar Observatories*, 366 pp., Harvard Univerisity Press, Cambridge, Mass.

Heilbron, J. L. (2010), *Galileo*, 508 pp., Oxford University Press, New York.

Holcomb, H. S., III, and R. Webb (1985), The Warren Telechron Master Clock Type A, *Bull. Nation. Assoc. Watch Clock Collec.*, **27:1**, 35–37.

Hong, S. (2001), *Wireless: from Marconi's Black Box to the Audion*, 248 pp., MIT Press, Cambridge, Mass.

Hope-Jones, F. (1940), *Electrical Timekeeping*, 275 pp., N.A.G. Press, London.

Howeth, L. S. (1963), *Communications-Electronics in the United States Navy*, 657 pp., Government Printing Office, Washington, DC.

Hutton, K., J. Woessner, and E. Hauksson (2010), Earthquake monitoring in Southern California for seventy-seven years (1932-2008), *Bull. Seismol. Soc. Am.*, **100**, 423–446, doi:10.1785/0120090130.

Katzir, S. (2008), From ultrasonic to frequency standards: Walter Cady's discovery of the sharp resonance of crystals, *Arch. Hist. Exact Sci.*, **62**, 469–487, doi:10.1007/s00407-008-0020-3.

Katzir, S. (2015), Time standards from acoustic to radio: The first electronic clock, in *Standardization in Measurement: Philosophical, Historical and Sociological Issues*, edited by L. Huber and O. Schlaudt, pp. 111–124, Pickering and Chatto, London.

Katzir, S. (2016a), Pursuing frequency standards and control: the invention of quartz clock technologies, *Ann. Sci.*, **73**, 1–39, doi:10.1080/00033790.2015.1008044.

Katzir, S. (2016b), Variations and combinations: Invention and development of quartz clock technologies at AT&T, *Icon*, **22**, 78–114.

Katzir, S. (2017), Time standards for the twentieth century: Telecommunication, physics, and the quartz clock, *J. Mod. Hist.*, **89**, 119–150, doi:10.1086/690282.

Kershaw, M. (2014), 'A thorn in the side of European geodesy': Measuring Paris-Greenwich longitude by electric telegraph, *British J. History Sci.*, **47**, 637–660, doi:10.1017/S0007087413000988.

Kershaw, M. (2019), Twentieth-Century longitude: When Greenwich moved, *J. History Astronomy*, **50**, 221–248, doi:10.1177/0021828619848180.

Knott, C. G. (1889), The earthquake of Tokio, April 18, 1889, *Nature*, **41**, 32.

Landes, D. S. (2000), *Revolution in Time: Clocks and the Making of the Modern World*, 415 pp., Harvard University Press, Cambridge, Mass.

Lehner, F. E., and F. Press (1966), A mobile seismograph array, *Bull. Seismol. Soc. Am.*, **56**, 889–897.

Levine, J. (2012), The statistical modeling of atomic clocks and the design of time scales, *Rev. Sci. Instr.*, **83**, 021,101, doi:10.1063/1.3681448.

Levine, J. (2016), The history of time and frequency from antiquity to the present day, *European Physical J. H*, **41**, 1–67, doi:10.1140/epjh/e2016-70004-3.

Lombardi, M. A., and D. W. Hanson (2005), The GOES time code service, 1974-2004: A retrospective., *J. Res. Natl. Inst. Stand. Technol.*, **110**, 79–96, doi:10.6028/jres.110.008.

Lombardi, M. A., and G. K. Nelson (2014), WWVB: A half century of delivering accurate frequency and time by radio, *J. Res. Natl. Inst. Stand. Technol.*, **119**, 25–54, doi:10.6028/jres.119.004.

Macelwane, J. B. (1950), *Jesuit Seismological Association: 1925-1950*, 346 pp., St. Louis University, St. Louis.

Marrison, W. A. (1948), The evolution of the quartz crystal clock, *Bell Sys. Tech. J.*, **27**, 510–588, doi:10.1002/j.1538-7305.1948.tb01343.x.

McCarthy, D. D., and P. K. Seidelmann (2018), *Time: From Earth Rotation to Atomic Physics*, Cambridge Univerisity Press, New York, doi:10.1017/9781108178365.

McCrossen, A. (2013), *Marking Modern Times: a History of Clocks, Watches, and Other Timekeepers in American Life*, 255 pp., The University of Chicago Press, Chicago.

McGahey, C. S. (2009), Harnessing nature's timekeeper: A history of the piezoelectric quartz crystal technological community (1880-1959), Ph.D. thesis, Georgia Institute of Technology., Atlanta.

Melton, B. (1981), Earthquake seismograph development, a modern history, *EOS Trans. Am. Geophys. Union*, **62**, 505–510, 545–547.

Miles, R. A. K. (2019), *Synchronome: Masters of Electrical Timekeeping*, 274 pp., Antiquarian Horological Society, London.

Miller, W. F. (1963), The Caltech digital seismograph, *J. Geophys. Res.*, **68**, 841–847, doi:10.1029/JZ068i003p00841.

Mills, D. L. (1989), On the accuracy and stablility of clocks synchronized by the Network Time Protocol in the internet system, *SIGCOMM Comput. Commun. Rev.*, **20**, 65–75, doi:10.1145/86587.86591.

Milne, J. (1899), Civil time, *Geograph. J.*, **13**, 173–194, doi:10.2307/1774359.

Mohorovičcić:, A. (1924), A critical review of the seismic instruments used today and of the organization of seismic service, *Bull. Seismol. Soc. Am.*, **14**, 38–59.

Nelson, G. K. (2019), A century of WWV, *J. Res. Natl. Inst. Stand. Technol.*, **124**, 124,025, doi:10.6028/jres.124.025.

Nelson, J. H. (1941), A "synchronous direct-current motor" for seismograph recorders, *Bull. Seismol. Soc. Am.*, **31**, 129–137.

Newcomb, S., and C. E. Dutton (1888), The speed of propagation of the Charleston earthquake, *Am. J. Sci.*, **35 (Ser. 3)**, 1–15, doi:10.2475/ajs.s3-35.205.1.

Ogle, V. (2015), *The Global Transformation of Time: 1870-1950*, 279 pp., Harvard University Press, Cambridge, Massachusetts.

O'Malley, M. (1996), *Keeping watch: A History of American Time*, 384 pp., Smithsonian Institution Press, Washington.

Pasadena Seismological Laboratory (1939), Quadrennial Report, *Pub. Bur. Cent. Seismol. Internat. Ser A*, **16**, 114–117.

Peterson, J. R., and C. R. Hutt (2014), World-Wide Standardized Seismograph Network: A Data Users Guide, *U. S. Geolog. Survey Open-File Report*, **2014-1218**, 82, doi:10.3133/ofr20141218.

Poppe, B. B. (1979), Historical survey of U.S. seismograph stations, *U. S. Geol. Surv. Prof. Pap.*, **1096**, 389.

Prothero, W. A., and J. N. Brune (1971), A suitcase seismic recording system, *Bull. Seismol. Soc. Am.*, **61**, 1849–1852.

Rawlings, A. L. (1993), *The Science of Clocks and Watches*, British Horological Institute, London.

Read, D. (2007), Observatory time by radio, 1901 to 1970: from the Eiffel Tower to UTC and the arrival of radio-controlled clocks, *Antiq. Horol.*, **31**, 65–87.

Read, D. (2015), The marine chronometer in the age of electricity, *Antiq. Horol.*, **36**, 343–360.

Roberts, D. (2003a), *Precision Pendulum Clocks: The Quest for Accurate Timekeeping*, 288 pp., Schiffer Publishing, Atglen, PA.

Roberts, D. (2003b), *English Precision Pendulum Clocks*, 296 pp., Schiffer Publishing, Atglen, PA.

Roberts, D. (2004), *Precision Pendulum Clocks: France, Germany, America, and Recent Advancements*, 224 pp., Schiffer Publishing, Atglen, PA.

Rooney, D. (2006), Maria and Ruth Belville: Competition for Greenwich time supply, *Antiq. Horol.*, **29**, 614–628.

Rooney, D. (2016), Quartz clocks and the public in Britain, 1930-60, *Antiq. Horol.*, **37**, 237–246.

Ruge, A. C., and H. E. McComb (1937), Preliminary report on a photoelectric pendulum control for recorder clocks, *Bull. Seismol. Soc. Am.*, **27**, 331–335.

Saff, D. (2019), *From Celestial to Terrestrial Timekeeping: Clockmaking in the Bond Family*, 424 pp., Antiquarian Horological Society, London.

Sampson, R. A. (1914), Note on the method of reduction of the Paris wireless rhythmic signals, *Mon. Not. Roy. Astron. Soc.*, **74**, 545–549, doi:10.1093/mnras/74.6.545.

Sampson, R. A. (1922), On the determination of time at different observatories, *Mon. Not. Roy. Astron. Soc.*, **82**, 215–225, doi:10.1093/mnras/82.3.215.

Schaffer, S. (1988), Astronomers mark time: Discipline and the personal equation, *Sci. Context*, **2**, 115–145, doi:10.1017/S026988970000051X.

Schneider, J. F., R. C. Aster, L. A. Powell, and R. P. Meyer (1987), Timing of portable seismographs from Omega navigation signals, *Bulletin of the Seismological Society of America*, **77**, 1457–1478.

Stachurski, R. (2009), *Longitude by Wire: Finding North America*, 239 pp., University of South Carolina Press, Columbia, S.C.

Stephens, C., and M. Dennis (2000), Engineering time: inventing the electronic wristwatch, *Brit. J. Hist. Sci.*, **33**, 477–497, doi:10.1017/S0007087400004167.

Stott, C., and D. W. Hughes (1987), The amateur's small transit instrument of the 19th century, *Quart. J. Roy. Astron. Soc.*, **28**, 30–45.

Syracuse, E. M., W. S. Phillips, M. Maceira, and M. L. Begnaud (2017), Identifying and correcting timing errors at seismic stations in and around Iran, *Seism. Res. Let.*, **88**, 1472–1479, doi:10.1785/0220170113.

Urban, S. E., and P. K. Seidelmann (Eds.) (2013), *Explanatory Supplement to the Astronomical Almanac*, University Science Books, Inc., Herndon, VA.

U.S. Naval Hydrographic Office (1922), *List of Lights, With Fog Signals and Visible Time Signals; Including Uniform Time System, Radio Time Signals, Radio Weather Bulletins, and Radio Compass Stations of the World*, 519 pp., Government Printing Office, Washington, D.C.

U.S. Naval Hydrographic Office (1930), *Radio Aids to Navigation*, 487 pp., Government Printing Office, Washington, D.C.

von Rebeur-Paschwitz, E. (1889), The earthquake of Tokio, April 18,1889, *Nature*, **40**, 294–295.

Warren, H. E. (1932), Synchronous electric time service, *Trans. Am. Inst. Elec. Eng.*, **51**, 546–550, doi:10.1109/T-AIEE.1932.5056117.

Wood, H. O. (1921), A list of seismologic stations of the world, *Bull. National Res. Council*, **2**, 397–538.

Woodward, P. (1995), *My Own Right Time: An Exploration of Clockwork Design*, 164 pp., Oxford University Press, New York.

Yeang, C.-P. (2013), *Probing the Sky with Radio Waves: From Wireless Technology to the Development of Atmospheric Science*, 361 pp., University of Chicago Press, Chicago.