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Surveying and Mapping Program

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Publication Review of

From Sundials to Atomic Clocks
Understanding Time and Frequency
Second Revised Edition

By James Jespersen and Jane Fitz-Randolph

(Mineola, New York: Dover Publications, Inc; 1999)
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From Sundials to Atomic Clocks by James Jespersen and Jane Fitz-Randolph is a fascinating and informative treatise on the subject of time. Time is a very broad subject to try to exhaust in a volume of only 300 pages, but the authors do a marvelous job, covering a multitude of aspects of time and leaving the reader with a greatly enhanced understanding of time and frequency. This book offers an unusually clear and accessible introduction to time—its measurement, dissemination, historic methods of timekeeping, the uses of time information, and the role of time in science and technology. Hundreds of drawings and cartoons (more than one per page) help illustrate the concepts and aid in understanding.

Beginning with a discussion of the nature of time, natural clocks, the relation of time and frequency, and the role of time in navigation, the authors then proceed to a fascinating treatment of man-made clocks and watches—from the sundials and water clocks of ancient Egypt to today's amazingly precise atomic clocks. Subsequent chapters offer detailed, yet accessible explanations of the continuing search for more uniform time; the application of time to energy, communication, and transportation; and the role of the world's official timekeepers. Finally, the authors look at time in the context of theoretical science and technology, showing how time has long been a crucial element in theories of the fundamental laws of nature and in astronomy, while improvements in the measurement of time have fostered major developments in the realm of physics.

The book is amazingly comprehensive and the authors capably explain esoteric concepts in language for laymen. The progression of the book is disjointed at times, skipping without apology from a discussion of radioactive dating to the topic of time as information, to a description of a television signal, all in three pages, but it is coherent generally in that the varied topics are well organized. The book is difficult to summarize, being so wide-ranging in its subject matter, but I shall attempt a summary and highlight the parts I found most useful and interesting.

All clocks, from ancient to modern, the authors posit, consist of three main parts. First, a clock needs to have some periodic phenomenon to regularly tick off equal amounts of time. This "ticker", more technically called a resonator, can take many forms, such as the daily rising of the Sun, water or sand leaking through a small hole, a pendulum, a vibrating quartz crystal, or a vibrating cesium atom. The resonator must be sustained by some power source, such as a spring, a weight, an electric current, etc. Finally, in addition to a resonator and a power source, a clock needs a counter with a display to accumulate the "ticks" of the resonator.

Throughout the ages, there has consistently been a need to find more uniform time scales and more stable clocks. In other words, the trend has been to find resonators that more evenly tick off uniform amounts of time, and do so even in adverse environmental conditions such as changing temperature, humidity, and atmospheric pressure or even on the rolling deck of a ship at sea. The authors introduce the concept of quality factor, or Q, which is a measure of how well a resonator stays oscillating at its resonant frequency, that is, how uniformly it ticks off the time. A quartz crystal oscillator has a higher Q than a pendulum, for example. The period of the pendulum is more variable than that of the crystal, being influenced by temperature changes, air currents, and other forces.

Undoubtedly the first and most natural clock employed by man is the Earth-Sun clock. The Sun rises every morning and sets every evening with unquestioned reliability, making the day an obvious choice for a unit of time. All of our units of time less than a day (hours, minutes, and seconds) are arbitrary divisions of this one standard. The Earth-Sun clock enjoys many advantages. It is universally available, reliable, and has great overall stability.

But though the "resonator" of the rotating earth has a high Q, in modern times resonators have been developed with still much higher Q. By today's precise standards, the Earth-Sun clock is not stable for several reasons. The Earth's axis is tilted to the plane containing its orbit around the Sun, causing sunrise-to-sunrise time intervals to vary throughout the year. The Earth's orbit is not a perfect circle, but is slightly elliptical, so the Earth travels faster when it is nearer the Sun than when it is farther away. Viewed from the Earth, as we see it, the Sun moves across the sky slower in January than in July. Furthermore, the Earth spins at an irregular rate around its axis of rotation. Not only is the Earth gradually slowing down because of tidal braking from the Sun and Moon, but there are also seasonal fluctuations in the Earth's rotation rate. In the spring, the Earth slows down, and in the fall it speeds up because of seasonal variations in the distribution of water on the surface of the earth. On top of all that, the Earth's axis of rotation wobbles slowly with respect to the stars, and even the positions of the North and South poles wander around by a few meters from year to year.

With the exception of the tilt of the Earth's axis with respect to the plane of rotation around the Sun, all of these phenomena are very slight and undetectable by casual observation. Even their accumulated effect over a lifetime is only detectable with great care and using precise instruments. But with the advent of more stable clocks, they have become important. For as long as mankind has been measuring time in seconds, the second has been defined as 1/60 of 1/60 of 1/24 of a day, and the length of a day has been defined astronomically by the positions of the Sun or the stars in their courses. But these astronomic observations are subject to the Earth's unstable rotation rate, so the length of a second must change as the Earth's rotation rate changes.

On the other hand, if the second is defined as so many vibrations of a cesium atom, as it is today, we obtain a much more stable and uniform standard of time. But now the day is defined in terms of the second, not vice versa. A day measured by counting atomic vibrations (atomic time) differs from a day measured by solar or stellar observations (astronomic time). As the rotation of Earth gradually slows, the two would drift apart so that the Sun might eventually rise at midnight and set at noon, were it not for the occasional leap second added from time to time. Just as a leap day added every four years keeps Christmas from moving to the summertime, so leap seconds are added to atomic time to keep it matched to astronomic time. The result is Coordinated Universal Time (UTC) which "coordinates" the uniform ticks of atomic time with the observations of astronomic time.

The book gives a primer on atomic clocks, introducing ion traps, laser cooling, and some quantum mechanics. The inner workings of cesium and rubidium clocks as well as hydrogen masers are described in layman's terms. A discussion of how time is disseminated is also discussed in some detail. The book describes the time signals transmitted from station WWV in Fort Collins, Colorado on various short-wave frequencies. Each of the various radio frequencies propagates differently, some bouncing off the ionosphere and traveling great distances, and some traveling by line of sight, but all arriving at the user's receiver some short time after they were transmitted. The authors discuss various methods to estimate or measure the propagation delay, and discuss time transfer by satellites.

Having covered the precise measurement of time and methods of time dissemination, the authors next discuss several uses of precise timing information. Electric power generation and transmission requires precise timing to keep all of the alternating-current generators operating at the same frequency, 60 Hz. Navigation by air and by sea also uses precise timing. From the days of the first chronometers used to determine longitude, to the radio and satellite navigation aids of more modern times, time information is a necessity. The telecommunications industry uses time division multiplexing and frequency division multiplexing to increase data transmitted through an optical fiber or radio link, all of which requires precise synchronization.

The last section, Time Science and Technology, gives an interesting discussion of physics and metaphysics. Many widely diverse topics are considered in these chapters. A brief discussion of Einstein's general and special theories of relativity lead to the conclusion that time is relative. Next, the authors observe that time has a direction, and that our observation of time's direction is related to our observation of a change in entropy. If we watch an egg fall to the floor and break, and a movie of the same event played backwards, we can easily tell which shows the proper direction of time. But if we watch a movie of a fork stirring scrambled eggs played forward and backward, we may have difficulty determining which is correct. The unbroken egg represents a condition of greater organization and lower entropy and the broken and scrambled eggs, a state of higher entropy. Thus the way we can determine time's direction is by observing an increase in entropy. The discussion from this point gets more and more esoteric, dabbling in information theory, chaos theory, and theoretical physics. The authors strive to simplify the explanations, but clearly there is a host of details on these topics that are left untouched. The discussion ranges from symmetry to the big bang to black holes to paradoxes and curved space, to phase space, determinism and free will and the age of the universe.

To a prospective land surveyor, probably the most useful topic discussed in this section concerns measurement. Time is the most accurately measurable quantity, so other measurable quantities, such as mass, length, voltage, etc. are most accurately measured by measuring time or frequency. In 1983 in Paris, the General Conference on Weights and Measures adopted a new definition of the meter based on a time measurement: the meter was the distance that light travels in 1/299,792,458 of a second. At the time of the new definition, atomic clocks were accurate to about 1 part in 10^{13} while the accuracy of the krypton length standard was about 4 parts in 10^{9}, so the potential improvement was by a factor of about 5000.

One of the most delightful characteristics of the book is the way it causes the reader to think about time. Scattered throughout the book are self-evident but seldom-articulated truths about time, such as these.

- The standard second, unlike the kilogram, or meter, cannot be sent in an envelope or box and put on a shelf for future reference, but must be supplied constantly, ceaselessly from moment to moment.
- Time must be kept. A clock that winds down and stops may be wound up again. It may uniformly tick seconds, but it requires information from another clock before it will again show the correct time.
- Time has a direction, always moving from the past to the future. We know the past, but the future remains uncertain, and, to the extent that the future is uncertain, we have the option to exercise free will.
- Atomic time is the most uniform time scale known at the present, but there is no way to tell whether the atomic second itself is actually getting longer or shorter with time.

The book was not difficult to read, and it greatly aided my understanding of many concepts related to time and frequency. I recommend you read it when you find time.

Appendix A

Typographical Errors and Errors of Fact found in

<u>From Sundials to Atomic Clocks</u>

By James Jespersen and Jane Fitz-Randolph

In the first full paragraph on page 52, the word "oscillator" was omitted from this sentence: These two phenomena together are the oscillator.

In the first full paragraph on page 54, the word "can" should be replaced with "cannot" in this sentence: If the radiation field has no frequency that corresponds to the energy associated with an allowed jump, then energy can be absorbed."

On page 248, the parentheses are missing from this sentence: "He discovered that there are always some mathematical truths in any mathematical system of sufficient complexity, (algebra is an example) that can't be proved true within that system."

In the sidebar on page 295 entitled Particles Faster Than Light – An Aside, the example in the second paragraph should read, "tachyons gain speed as they lose energy."