The Quantum Leap
September 10, 2024

Why Should I Care About (Quantum) Clocks?

The first reason you should care is because it is approximately a **$500 million per year market and growing rapidly**[1]. The second reason is because ever more precise timing scales are spurring many important advances including increased network and cellular bandwidth, more resilient power grids, increased financial trading volumes and more precise and reliable GPS, among other things.

Throughout history, increases in the precision of time measurement have led to significant advances in science, commerce and world power. If you think this is an overstatement, consider that by the end of the 18th century the British Empire was the world's leading colonial power, with a global reach that included colonies in North America, the Caribbean, India, Africa, Asia and Australia. It was the largest empire (measured both by the fraction of the Earth covered and the percentage of the world's population under its rule) in the history of humanity. One of the core technologies that enabled Great Britian to wield this power, was its mastery of ocean navigation…and that mastery was due to the development of the most precise timekeeping device of its time. More on that below.

In December of 2022 I wrote a blog about time (*Does Anybody Really Know What Time It Is?*, which you can read here). As I continued to study recent advances in clocks, I became more fascinated, and my appreciation for how enmeshed timekeeping is with our modern world continued to grow.

A Bit of Timekeeping History

As I noted in the prior post, "time" is not some absolute and discrete "thing", it's a somewhat arbitrary convention that society agrees to agree on. [It's also "relative" as in Einstein's theory, which essentially means that time can differ based on conditions of the measurer]. In the very early days, it was measured by the earth's rotation, with a day being defined as one rotation. Ancient Egyptians defined a second by dividing the day by 24 into hours, then by 60 into minutes and then again by 60 into seconds (rooted in night cycles and decans), so a second was 1/86,400th of a day. In other words, our current "second" is a man-made construct.

Clocks work by counting a periodic event with a known frequency. In the above example, it is the daily rotation of the earth. When grandfather clocks were the standard time-keeping devices, they worked by having a pendulum swing back and forth with its gears counting the swings. The arm of the pendulum in that grandfather clock is typically adjusted to make each half-swing one second. One "cycle" per second is known as 1 Hertz (Hz).

[1] Perplexity AI. (2024, July 26) retrieved from Perplexity.ai and citing a June 2024 Coherent Market Insights report as well as a Mordor Intelligence report.

When electronic wrist watches were developed, they used a piece of quartz which vibrates at a certain frequency (32,768 Hz) so in this case a "second" is measured as 32,768 vibrations. The higher the base frequency, generally the more accurate the clock. For example, if that grandfather clock is off by 0.1 Hz, it will be off by one second in ten. If the quartz wristwatch is off by 0.1 Hz, it will be off by one second out of 327,689 or roughly 0.26 seconds per day.

Around 70 years ago, scientists realized that atoms could be used for clocks. When certain atoms are exposed to specific energies the outer electrons transition between orbits. Specifically, the electron jumps to a higher energy orbit (or takes a "quantum leap") and the time it takes to return to the original lower energy state is the measurement frequency, hence the "quantum" connection. Since 1967, The International System of Units (SI) has defined the "second" as the period equal to the radiation transition of Cesium-133. And "Universal Time Coordinated" or UTC is an aggregate of the data of more than 400 atomic clocks operated by over 80 laboratories around the world, averaging their "time" to create the world's "official" time.

The following chart shows how the precision of timekeeping has continued to rise over the ages:

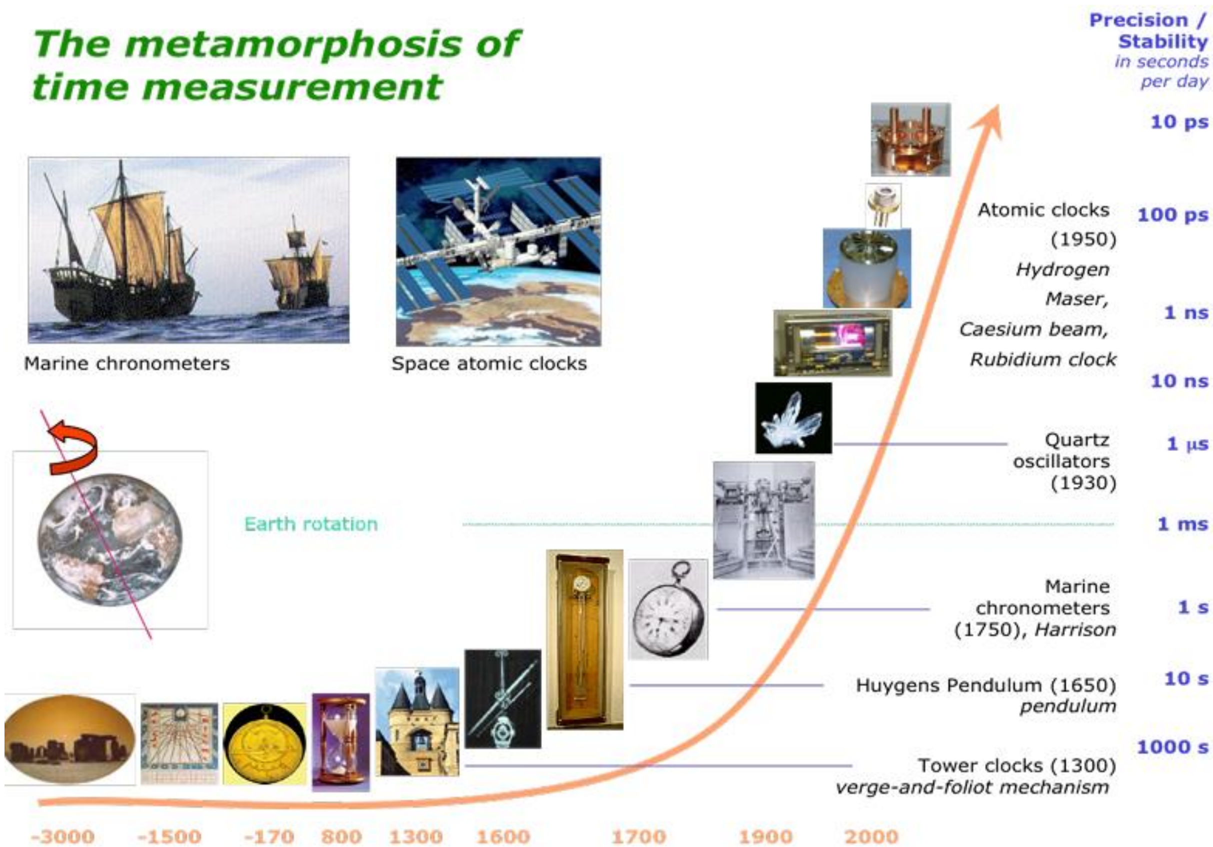


Image from Prof. G. Mileti, University of Neuchatel, Switzerland, as shown in "A Comprehensive Overview of Atomic Clocks and their Applications.

To help illustrate why accurate timekeeping is so important, imagine that you oversee a single-track train tunnel that brings goods in and out of a city. If the trains that run on the track are accurate to within 5 minutes of their schedule, that means you must allow a 10-minute window for that train to have access to the tunnel (+/- the five minutes) and therefore you can only schedule 6 trains per hour to use the tunnel. If those trains were more accurate and arrived within 2 minutes of their schedule, you could schedule 15 trains per hour (60 minutes divided by the 4-minute window). So, the throughput of the tunnel is directly proportional to the accuracy of the trains.

This same concept impacts many critical infrastructure elements of our modern society, including:

- Telecommunications systems
- Computer networks
- Position and navigation
- Stock exchanges
- Power grids
- Defense applications (e.g., ballistics accuracy)

So, with more precise clocks, we can have more stock trades, expanded and synchronized network bandwidth and more precise navigation (see Optical Clock Applications on page 4 for more examples).

A Bit More Context Regarding the British Empire and its Surge in Power Due to Better Maritime Navigation (Driven by Accurate Timekeeping)

Recognizing that the above sub-header may seem a bit out of context, if you bear with me, you'll see why it's included in this post. We are all familiar with GPS and most of us have GPS enabled maps on our smart phone. However, we may not realize that GPS is inseparable from time, in fact it is the time beamed down from the GPS satellites that our phones use to calculate location. However, a time error as small as 1 billionth of a second translates into almost 1 foot of distance/positional error, and it is largely the reason why today's GPS is only accurate to about 3 feet, which is fine for determining your route but not sufficient for fully autonomous vehicles.

With that context, consider the dilemma that sailors faced in the heyday of global exploration from the time of Magellan and Columbus through the mid 1700's. When navigating the seas, they could readily determine their latitude (north/south) by various measurements of the sun or stars. However, they could not use the sun or stars to determine longitude (east/west), and many a ship and fleet was lost or crashed on rocks and reefs because of an unknown longitude. To determine longitude, the ship's captain needs to know what time it is on the ship (which could readily be done by setting noon to the high point of the sun) AND what time it is at a known point on land. By calculating the difference in time, the captain could determine how many degrees East or West he was from that known point on land. This was such a difficult challenge that the British government came up with a contest (The Longitude Act of 1714) with a reward of 20,000 pounds (about $2 million today) for anyone who could solve this problem by creating a timekeeping device that could withstand the motion and large temperature changes that a ship experiences at sea and enable longitude calculation to within ½ a degree of actual position. The best clocks at that time were pendulum clocks, but their swinging oscillators could not function properly on seabound ships. At the time, a typical voyage from England to the West Indies took about 6 weeks and just ½ of a degree of uncertainty in longitude equated to about 65 miles. To be more accurate than that, the clock on the ship had to be within 2 minutes of the actual time back in London, equivalent to less than 3 seconds of imprecision per day - quite a feat at the time. John Harrison, an English carpenter, created several portable clocks, or chronometers and his H4 chronometer created in 1755, was able to achieve that level of precision[2].

The Harrison H4

With such nautical precision, the British Navy was able to navigate the seven seas and build the most powerful navy of its day, leading to one of the largest and strongest empires ever created.

Optical Clock Applications

The world has benefited from the increased precision of atomic clocks since the 1950's, but until recently, optical atomic clocks were not practical. However, today an increasing number of optical clocks are being built and are in the early stages of commercialization. Precision timing is a large and rapidly growing market and as the precision of optical atomic clocks surpasses that of standard atomic clocks, it will continue to impact nearly every aspect of our lives. The table below highlights some key applications seeking increased timing performance such as that provided by optical clocks.

Commercial	Defense	Aerospace	Science
• Data Center synchronization • Cellular throughput (esp. coming 6G) • More precise GPS • Fintech and high-speed trading • Metaverse latency reduction	• Telemetry • Precision radar (i.e., to detect drones and balloons) • Sensor fusion • Missile guidance • GPS denied navigation	• Deep space navigation • Free space communications • Telemetry • Sensor fusion	• High energy physics • Maser replacement • UTC (universal time) • Synthetic aperture (ultra detailed optics) • Precision length measurement at sub-nanoscale

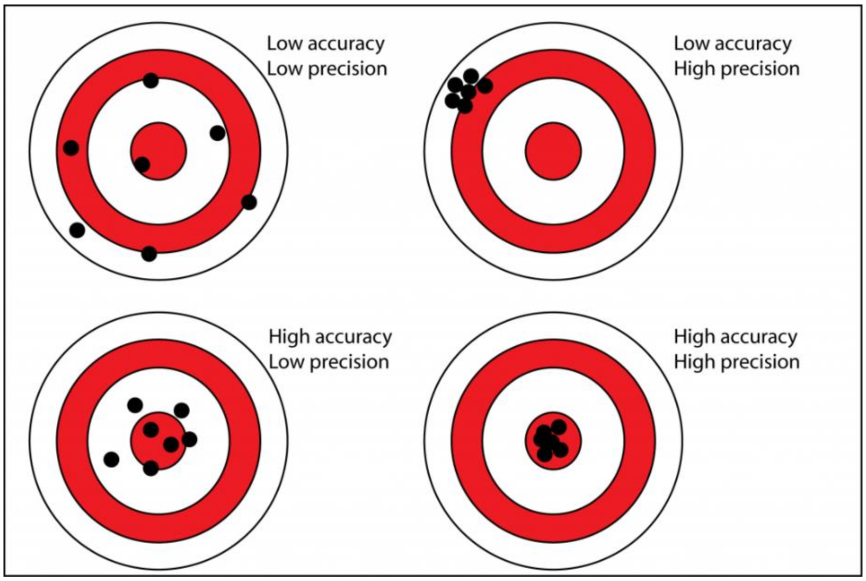
As can be seen, the applications for precision timekeeping are broad and growing, ranging from

[2] For a fascinating account of this longitude challenge, including details about John Harrison and his chronometers, I highly recommend the book *Longitude* by Dava Sobel.

deep science to more precise GPS. As the amount of data we generate and consume continues to increase, especially driven by AI, and as existing GPS continues to be vulnerable, the needs for more precise timekeeping will continue to grow.

Measuring and Comparing Clock Performance

"Accuracy" and "precision" are often used interchangeably, but they are different and understanding that difference is important when considering clock performance or comparing two clocks. "Accuracy" essentially means how close to the target you are, while "precision" means how consistent your results are. The graphic below helps showcase this difference:



When describing a clock's accuracy, its "system uncertainty" is generally used, which is a measurement of how well the clock represents the true natural frequency of its reference. So, for atomic clocks such as the cesium clock noted on page 2, system uncertainty measures how closely the clock oscillates versus the 9,192,631,770 cycles of cesium that is its reference. When describing a clock's precision, we refer to its "frequency stability", or how its oscillation changes over a period. This metric is commonly measured as "Allan deviation" (ADEV) or "Time deviation" (TDEV). The lower the figure the better the clock.

Another important measurement standard is known as "holdover" which measures how long a clock can remain accurate. It is typically specified as a time error accumulation, such as nanoseconds per week. This is a vital metric for things like positioning when a GPS signal is unavailable or is interfered with, so high holdover is crucial for GPS-denied navigation or for long space voyages. Again, the lower the figure the better the clock.

Types of Atomic/Optical/Quantum Clocks

The early atomic clocks oscillated in the microwave spectrum, and most existing measurement devices operate at that frequency. It wasn't until optical frequency combs (a Nobel winning technology) were commercialized that we could take advantage of the optical frequencies of certain atoms which are much higher/faster than those in the microwave spectrum and use them as timekeeping oscillators. Generally, the faster the oscillator (in this case the frequency resonation of the underlying atom), the more precise the clock. Interestingly, some of the technologies developed for qubits (i.e., ion traps) have applications in timing. The following chart highlights some of the different types of atomic clocks along with certain advantages and disadvantages. [Please note - for this post I have not differentiated between types of optical atomic clocks (i.e., ion, optical lattice, 2-photon, etc.), have not included every known element being used for timekeeping, nor have I included chip-scale atomic clocks (CSACs).]

	Clock Atom/ Approx Cost	Precision (ADEV)	~ Stability (Time until off by 1 second)	Advantages	Disadvantages
Microwave	**Rubidium** (Rb) $3k-$10k	10^{-12}	300,000 years	- High short-term stability - Smaller/cheaper than Cs	- Less accurate long-term - Environmental sensitivity - Drift
	Cesium (Cs) $30k-$100k	10^{-13}	3 million years	- High accuracy - Stability - Long history of usage	- Large & Complex - Needs high power - More expensive than Rb - Tubes need replacement
	Hydrogen (H) Maser $200k-$500k	10^{-15}	300 million years	- Very high short-term stability - "Gold Standard" for decades	- Very expensive - Environmental sensitivity - Large and difficult to operate
Optical	**Iodine** (I)	10^{-15}	300 million years	- Narrow/precise spectral lines - High accuracy	- Less stable
	Magnesium (Mg)	10^{-16}	3 billion years	- High accuracy - Low sensitivity to blackbody radiation	- Still being developed; not mature tech
	Aluminum (Al)	10^{-18}	300 billion years	- Narrow/precise spectral lines - Low environmental sensitivity	- Highly complex
	Ytterbium (Yb)	10^{-18}	300 billion years	- High accuracy - Stability	- Highly complex - Environmental sensitivity - Sophisticated laser trapping and cooling
	Indium (In)	10^{-18}	300 billion years	- Low environmental sensitivity	- Highly complex
	Strontium (Sr)	10^{-19}	3 trillion years	- High accuracy - Stability	- Highly complex - Environmental sensitivity - Sophisticated laser trapping and cooling

As you'll note, the optical atomic clocks are 100x or more precise (as measured by ADEV) than cesium atomic clocks. While we are still in the early stages of development and commercialization of optical clocks (hence the lack of pricing information), their precision and stability are generally orders of magnitude better than that of microwave clocks. Because these are relatively new technologies which are pushing the boundaries of current physics, they are still generally complex and expensive. The challenge is to create and produce commercial versions at similar price points to microwave clocks, but with 100x or better performance metrics.

For the past 30 years or so, the general standard for precision timekeeping has been Microsemi's 5071, a cesium based atomic clock with an average sales price (ASP) of about $100,000. At the upper limits of non-optical atomic clock performance is the hydrogen maser which has ~100x the precision of the 5071 but has an ASP nearing $400,000 and generally requires an isolated environment and needs to be operated and maintained by highly technical personnel. There is a major market opportunity for a company that can provide "maser-like" performance at 5071 or better pricing.

Optical Clock Manufacturers

There are a variety of players participating in this market with some making optical clocks, some focused on components and others focused on distributing time remotely. The following is a partial list of some of these companies.

Conclusion

The surging attention and resources dedicated to quantum mechanics has yielded amazing technological advances. Much of the *Quantum Leap* blog has focused on applications in Quantum Computing (QC), but other related technologies are also pushing the frontiers of technology and knowledge, and many are "today" developments as opposed to "5-10 year" developments which is often the quoted QC timeline. More accurate clocks, leveraging certain advances developed for broader quantum information sciences, are already beginning to have practical applications beyond QC including fundamental advances in physics, more accurate sensors and more precise time keeping. As NIST Fellow Jun Ye noted to me "Atomic clocks…represent some of the most exquisitely sensitive and accurate scientific instruments that humankind has built to explore the unknows of nature." It's an exciting time to be following quantum science and I look forward to tracking and reporting on evolving breakthroughs.

Disclosure: The author is a venture investor with investment interests in quantum and may have an interest in companies discussed in this post. The views expressed herein are solely the views of the author and are not necessarily the views of Corporate Fuel Partners or any of its affiliates or any companies it has investment interests in. Views are not intended to provide and should not be relied upon for investment advice.

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