How are Quantum Principles Used in GPS Systems and Atomic Clocks to Achieve High Precision?

Research Paper By **Ishan Jain**

Abstract

GPS systems guide airplanes, ships, phones, and emergency services, and all of these depend on very accurate time measurement. Even a small timing error can create a large position mistake. For example, a 1-nanosecond mistake can shift a GPS position by about 30 centimeters, and a 1-microsecond error can cause a 300-meter shift. Because of this, GPS satellites cannot rely on normal clocks. They require clocks that are stable, reliable, and do not drift. This is why GPS uses atomic clocks, which work on quantum principles.

Atomic clocks use the predictable behavior of atoms. In quantum physics, atoms change energy levels in fixed and measurable steps. These steps produce a very stable frequency. The Cesium-133 atom, for example, changes energy states at exactly 9,192,631,770 cycles per second, which defines one second according to international standards (NIST, 2024). This stable ―atomic heartbeat‖ allows satellites to keep extremely precise time even while traveling in space.

This paper explains how quantum transitions, laser cooling, and hyperfine splitting help atomic clocks stay accurate; how GPS satellites use these clocks; and why relativity corrections are needed. The study shows that quantum mechanics is the foundation that makes global navigation possible.

Keywords: GPS, atomic clocks, quantum mechanics, precision timing, satellite navigation.

Introduction

Modern society depends heavily on precise time measurement. Every day, billions of people use GPS systems for travel, delivery services, banking, science, aviation, and emergency response. All these systems work because GPS satellites can measure time with extreme accuracy. The basic idea behind GPS is simple: a receiver on Earth calculates its position by measuring how long it takes signals to travel from satellites to the ground.
Because these signals travel at the speed of light, even a very small timing error causes a large mistake/ chage in distance. According to the U.S. National Institute of Standards and Technology (NIST), an error of **1 nanosecond (one-billionth of a second)** can shift a GPS position by almost **30 centimeters**[1]. This level of sensitivity shows why GPS cannot rely on normal clocks[2] .

To achieve this accuracy, GPS satellites use **atomic clocks**, which are based on **quantum principles**. Quantum physics explains how atoms have fixed and predictable energy levels. When an atom moves between these levels, it absorbs or releases energy at a very specific frequency. These frequencies act like perfect ―ticks‖ of a clock. One of the best examples is the Cesium-133 atom. The international definition of one second is based on the frequency of its hyperfine transition: **9,192,631,770 cycles per second** (International Bureau of Weights and Measures, 2019). Because this frequency is extremely stable, atomic clocks drift far less than normal mechanical or quartz clocks.GPS satellites carry multiple atomic clocks—usually cesium or rubidium—because they must maintain precise time while traveling at high speeds in orbit. The accuracy of these clocks is so high that scientists must even apply **relativity corrections** to adjust for the effects of gravity and motion on time, as predicted by Einstein's theories. Without these corrections, GPS errors would grow by

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[1] Septentrio. (n.d.). How GPS brings time to the world. https://www.septentrio.com/en/learn-more/insights/how-

gps-brings-time-world , and a 1-microsecond error can create a 300-meter mistake (NIST, 2020)

[2] (National Institute of Standards and Technology. (2020). How do atomic clocks work? Retrieved November 17, 2025, from https://www.nist.gov/atomic-clocks/how-do-atomic-clocks-work

around **10 kilometers every day**[3]. This combination of quantum mechanics and relativity is what makes global navigation possible.

This research paper aims to explain how quantum principles allow atomic clocks to achieve extremely high precision, and how this precise timing forms the foundation of modern GPS systems. It focuses on three main questions. First, it explores the specific quantum properties—such as fixed energy levels and hyperfine transitions—that make atomic clocks far more stable and reliable than ordinary mechanical or quartz clocks. Second, it explains how GPS satellites use these atomic clocks to calculate distance and position accurately by measuring signal travel time with nanosecond precision. Finally, the paper examines how new scientific advancements, including laser cooling, atomic fountain clocks, and next-generation optical lattice clocks, can improve timing accuracy even further and support the future of global navigation, communication, and autonomous technologies.[4]

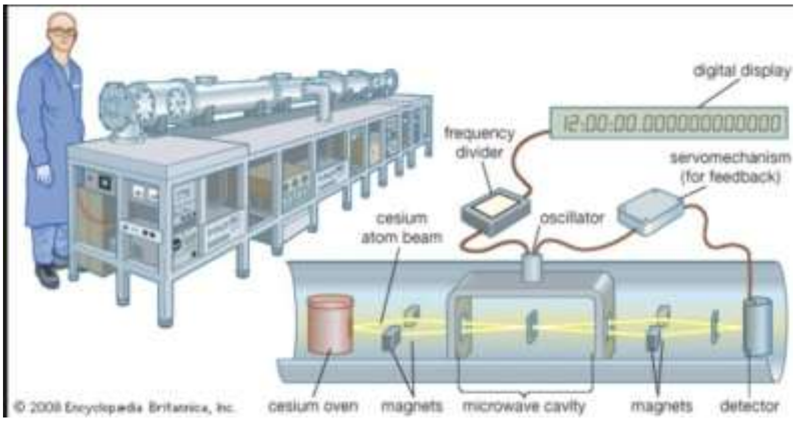
I chose this topic because GPS and atomic clocks are technologies we use every day without realizing how deeply they depend on quantum physics. Understanding the quantum principles behind these systems helps me appreciate how science, engineering, and mathematics come together to support modern life. This topic is helpful because accurate timing is important for navigation, telecom networks, banking, emergency services, and future technologies like self-driving cars. Learning about atomic clocks and GPS also builds

[3] Ashby, N. (2003). *Relativity in the Global Positioning System*. Physics Today, 55(5), 41–47. https://doi.org/10.12942/lrr-2003-1

[4] National Institute of Standards and Technology. (2020). Time and Frequency from A to Z. Am to B

https://www.nist.gov/pml/time-and-frequency-division/popular-links/time-frequency-z/time-and-frequency-z-am-b#atomicclock

strong knowledge in physics, which is useful for higher studies in science and engineering[5]. By understanding these ideas, we can see how deeply quantum physics supports the digital world we use every day—from mobile phones and banking systems to global transportation and scientific exploration. Overall, this research helps me understand a real-world application of quantum physics that affects billions of people every day.



cesium atomic clock

Source - Encyclopaedia Britannica. (n.d.). *Atomic clock*. In *Britannica*. Retrieved from https://www.britannica.com/technology/atomic-clock

Background -GPS Positioning and Time Synchronization

The Global Positioning System (GPS) finds a user's position using a mathematical process called trilateration. Trilateration means calculating location by measuring distances from three or more known points. In GPS, these known points are satellites that orbit Earth. Each satellite sends a signal that contains the exact time at which the signal was transmitted,
along with the satellite's position in space. The receiver on the ground compares the time the

[5] International Bureau of Weights and Measures. (2019). *The International System of Units (SI).*

https://www.bipm.org/en/publications/si-brochure

signal was sent with the time it was received. Because radio signals travel at the speed of light, the difference in time tells the receiver how far the satellite is.When a GPS receiver measures distance from at least four satellites, it can calculate latitude, longitude, altitude, and even correct its own internal clock. These distance measurements are called pseudoranges because they are not perfect; they depend heavily on precise time. If the time is wrong, the distance becomes wrong. This is why synchronization between satellite clocks and receiver clocks is essential.

A very small timing error leads to a very large position error. For example, a 1 microsecond (one-millionth of a second) error can cause around 300 meters of mistake in position because light travels about 300 meters in one microsecond. A 1 nanosecond (one- billionth of a second) error creates about 30 centimeters of position error (U.S. GPS.gov, 2023). This high sensitivity shows how tightly GPS performance is linked to time accuracy.[6] Because satellites move at high speeds and signals pass through the atmosphere, further corrections are needed. The GPS control stations on Earth constantly monitor each satellite clock and update timing corrections. This continuous monitoring keeps all satellites synchronized to a common time scale, coordinated with atomic clocks on Earth.

The Need for High-Precision Timing in GPS

GPS accuracy depends mainly on how stable and reliable the clock inside the satellite is. Everyday devices, like phones or computers, use **quartz clocks**, which work by vibrating a quartz crystal. Quartz clocks are useful for normal activities but not stable enough for GPS

[6] United Nations Statistics Division. (n.d.). Satellite navigation and GPS errors. https://unstats.un.org/unsd/geoinfo/ungegn/docs/_data_icacourses/_HtmlModules/_Selfstudy/S06/S06_05b.html

because they drift several microseconds every day. Even a small drift of **1 microsecond** is enough to cause hundreds of meters of position error. Therefore, quartz clocks cannot provide the precision needed for space-based navigation.

GPS signals depend on the constant and predictable speed of light. When signals travel from satellites to Earth, they take about 60–80 milliseconds. Any difference in timing between the satellite and receiver immediately affects the position calculation. Because satellites continuously orbit Earth, small timing errors accumulate over time. A quartz clock in a satellite would drift so quickly that GPS would stop working within minutes.Another issue is **oscillator stability**. A stable oscillator maintains the same frequency consistently. Quartz oscillators change frequency due to temperature changes, radiation, pressure, and acceleration in orbit. In contrast, atomic clocks drift only by about a **billionth of a second per day** (NIST, 2020). This stability is why satellites use atomic clocks rather than quartz clocks.

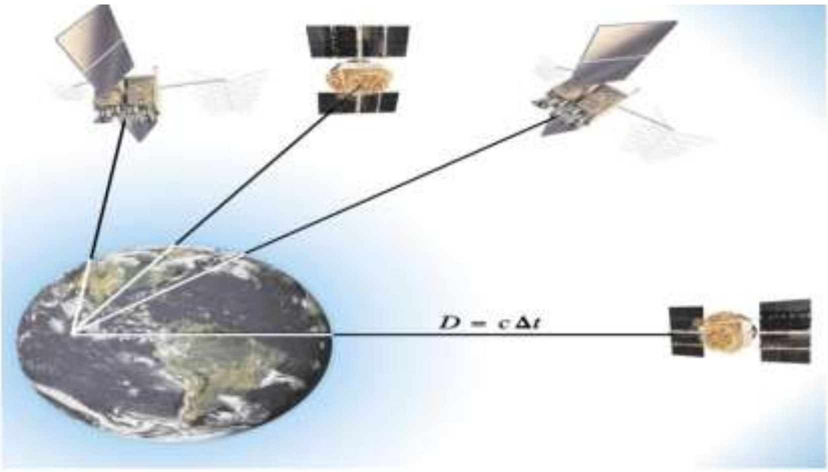


Figure - The Fundamental Principle of the global positioning system is the constancy of the speed of light *c* in an inertial frame. If a receiver on the ground simultaneously receives signals from four GPS satellites above its horizon, the distance *D* to each is given by $c\ \Delta t$, where Δt is the time interval between transmission and reception. But because the satellites and the receiver are moving through the local inertial frame and are at different gravitational potentials, their clocks cannot be synchronized without taking account of relativistic effects[7].

Also, satellites experience **time dilation**, a prediction of Einstein's relativity. Their onboard clocks tick differently because of high orbital speed and weaker gravity. Without correction, GPS errors would grow by almost **10 kilometers per day.**[8] Only highly stable clocks can be corrected for these relativistic effects. GPS needs clocks that never drift, work in space, and can be corrected using physics. Only atomic clocks meet these requirements.

Quantum Physics and Atomic Clocks

Atomic clocks rely on basic ideas from quantum physics. One of the most important principles is that atoms have discrete energy levels. This means electrons inside an atom can only exist at specific energy values, not in between. This idea comes from the Bohr model, which states that electrons jump from one energy level to another by absorbing or releasing a fixed amount of energy.[9] When an electron jumps between two energy levels, the atom emits or absorbs electromagnetic radiation at a very exact frequency. This frequency is the same for every atom of the same type anywhere in the universe. This is why atomic clocks are so

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[7] Source - Ashby, N. (2002). *Relativity and the Global Positioning System*. Physics Today, 55(5), 41–47. https://doi.org/10.1063/1.1485583

[8] (Ashby, N. (2002). *Relativity and the Global Positioning System*. Physics Today, 55(5), 41–47. https://doi.org/10.1063/1.1485583).

[9] (CK-12 Foundation. (n.d.). 5.6: Bohr's atomic model. In Introductory Chemistry (CK-12). LibreTexts. https://chem.libretexts.org/Bookshelves/Introductory_Chemistry/Introductory_Chemistry_(CK-12)/05%3A_Electrons_in_Atoms/5.06%3A_Bohr's_Atomic_Model)

reliable—atoms behave consistently and predictably.Quantum physics also explains that energy and frequency are related by Planck's relation:

$E = h\nu$,where E is energy, h is Planck's constant, and ν (nu) is frequency. This relation tells us that each quantum transition corresponds to one fixed frequency. Atomic clocks use this frequency as their ―tick.‖(2024, May 31). Copenhagen interpretation of quantum mechanics. In Stanford Encyclopedia of Philosophy.[10]

The most famous example is the cesium-133 atom, which has a hyperfine transition frequency of exactly 9,192,631,770 cycles per second. This value defines the international standard for one second (BIPM, 2019). No mechanical clock can produce such a stable frequency because mechanical systems wear down, change with temperature, or vibrate unevenly. Atoms do not.[11].Modern atomic clocks use additional quantum methods such as **laser cooling**, which slows down atoms using light. When atoms move slowly, their frequency becomes more stable. Some advanced clocks use optical transitions with far higher frequencies, allowing even greater precision. These ―optical lattice clocks‖ use frequencies nearly 100,000 times higher than microwave cesium clocks, improving accuracy dramatically[12].[13]

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[10] (E. N. Zalta & U. Nodelman, Eds.). Stanford University. https://plato.stanford.edu/entries/qm-copenhagen/)

[11] .(ScienceDirect. (n.d.). Atomic clock. In Medicine and Dentistry. Elsevier. https://www.sciencedirect.com/topics/medicine-and-dentistry/atomic-clock)

[12] .(Bureau International des Poids et Mesures (BIPM). (2019). The International System of Units (SI Brochure). https://www.bipm.org/en/publications/si-brochure)

[13] National Institute of Standards and Technology. (2020). Frequency Synthesis for Atomic Standardshttps://www.nist.gov/pml/time-and-frequency-division/time-and-frequency-metrology/frequency- synthesis-atomic-standards

Working Mechanism and Quantum Principles

An atomic clock is a special type of clock that keeps time using the natural vibrations of atoms rather than mechanical parts or electronic crystals. Normal clocks, such as wall clocks or quartz clocks, rely on physical objects that can expand, shrink, or wear out. These changes make their time-keeping less stable. In contrast, atoms behave the same way everywhere in the universe, and their energy transitions follow exact laws of quantum physics. This makes atoms

extremely reliable frequency sources.An atomic clock measures time by detecting the resonant frequency of an atom when it changes between two energy states. The most commonly used atom is cesium-133, which has a very stable hyperfine transition in its ground state. Because quantum transitions do not change with temperature, pressure, or age, they provide excellent stability.This is why atomic clocks are used in GPS satellites, scientific laboratories, and national standards institutes. They allow us to define the
―second‖ based on the natural behavior of atoms, making time measurement far more accurate than any mechanical method ever created. Inside a cesium atom, the nucleus and the electrons have a property called spin, similar to tiny magnets. When the magnetic moments of the nucleus and the electron interact, they create what is known as hyperfine energy splitting. This splitting means that the atom's ground state is divided into two closely spaced energy levels.

A transition between these two hyperfine levels creates radiation at a very exact frequency:

9,192,631,770 cycles per second (Hz). This number is not estimated—it is measured with extremely high precision and is the same for every cesium atom in the universe. Because of this stability, the international definition of one second is based on this transition. The International Bureau of Weights and Measures (BIPM) defines one second as:

―the duration of 9,192,631,770 periods of the radiation from the transition between the two hyperfine states of the cesium-133 atom.‖[14]

Inside an atomic clock, cesium atoms are exposed to microwave radiation. When the microwave frequency matches the natural hyperfine transition frequency, the atoms absorb the energy and change states. This is called resonance. The clock continuously adjusts the microwave signal so that it stays perfectly tuned to this resonance frequency. Because the resonance occurs at exactly the same frequency every time, the clock ―ticks‖ with extraordinary accuracy.[15]

Hyperfine transitions never change because they depend only on fundamental quantum forces—not on temperature, humidity, mechanical wear, or material defects. This is the main reason why atomic clocks are so precise and why GPS systems rely on them for global navigation.

Laser Cooling & Atomic Fountains

Older atomic clocks had a limitation: atoms move quickly, and their motion changes the frequency slightly. This is due to the Doppler effect, the same effect that changes the pitch of a moving ambulance siren. When atoms move, the frequency of their absorbed radiation shifts. To reduce this problem, scientists developed laser cooling, a quantum technique that uses light to slow atoms down.Laser cooling works because photons (particles of light) have momentum. When a laser beam is tuned slightly below the resonant frequency

[14] Bureau International des Poids et Mesures. (n.d.). *SI base unit: Second (s)*. Retrieved November 17, 2025, from https://www.bipm.org/en/si-base-units/second)
[15] (National Physical Laboratory. (2010). The second [Video]. YouTube.
https://www.youtube.com/watch?v=Tc_tDVbjCQk)

of an atom, moving atoms absorb photons and lose momentum, which slows them. This process reduces atomic motion to extremely low speeds—just a few centimeters per second. Once the atoms are cold, the frequency shifts become much smaller, and the clock becomes more precise.Laser-cooled atoms are then tossed gently upward in a vertical vacuum tube to create an atomic fountain. As they rise and fall under gravity, lasers and microwaves measure their hyperfine transitions. These ―fountain clocks‖ keep atoms in the measurement zone for a longer time, which improves the precision of the frequency measurement. Two famous examples are the NIST-F1 and NIST-F2 clocks developed in the United States[16].

NIST-F1 has an uncertainty of about 1 second in 100 million years. NIST-F2 is even better, with lower environmental noise and improved cooling techniques (NIST, 2020, https://www.nist.gov/pml/atomic-standards). These clocks are used to maintain the U.S. civilian time standard.Laser cooling also improves the linewidth of the transition, meaning the frequency becomes sharper and easier to detect. A narrow linewidth means the clock can identify the resonance point more precisely, which reduces error and improves long-term stability.[17]Atomic fountain clocks represent one of the most important advancements in quantum time-keeping. They provide the accuracy needed for modern GPS systems and form the basis for future clocks, such as optical lattice clocks, which promise even higher stability and precision.

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[16] (National Institute of Standards and Technology. (1999, December 29). *NIST-F1 cesium fountain clock*. https://www.nist.gov/news-events/news/1999/12/nist-f1-cesium-fountain-clock)

[17] .(National Institute of Standards and Technology. (n.d.). *NIST's cesium fountain atomic clocks*. https://www.nist.gov/pml/time-and-frequency-division/time-realization/cesium-fountain-atomic-clocks)

Cesium, Rubidium, and Hydrogen Masers in GPS

GPS satellites carry different types of atomic clocks because each type has strengths and weaknesses. The three most common atomic clocks used are **cesium clocks**, **rubidium clocks**, and **hydrogen** masers.Cesium clocks serve as the primary frequency reference because the definition of the second is based on the cesium-133 hyperfine transition. They have excellent long-term stability and provide accurate frequency for years. However, they are larger, more expensive, and use more power than other clocks.Rubidium clocks are smaller, cheaper, and use less power than cesium clocks. They are widely used in GPS satellites because they can handle the harsh space environment and provide very stable performance. Although rubidium clocks drift more than cesium clocks over long periods, they are sufficient for short-term stability in orbit and are easier to maintain. The rubidium oscillator inside these clocks responds quickly to corrections sent from ground stations.Hydrogen masers offer the best short-term stability of all atomic clocks. They work by storing hydrogen atoms in a chamber where they emit microwave radiation at a very stable frequency. Hydrogen masers are used in ground stations, scientific research, and deep-space tracking systems. Their precision is excellent for short periods, but they drift more over long periods compared to cesium clocks.

Atomic Clock Comparison

Characteristic	Strengths	Weaknesses
Cesium-133	Best long-term stability	Large, high power, expensive
Rubidium	Small, low power, low cost	Slightly worse long-term stability
Hydrogen Maser	Best short-term stability	Long-term drift, complex

GPS satellites often carry multiple clocks for redundancy. A satellite may include two rubidium clocks and one cesium clock. Ground control compares performance and switches clocks when needed. This combination ensures both short-term and long-term stability.To measure performance, scientists use the Allan deviation, which describes frequency stability over time. Lower Allan deviation means a better clock with less frequency drift.The use of these different atomic clocks ensures GPS works reliably 24 hours a day, providing accurate navigation to the entire world.

GPS Satellites and Quantum Timekeeping

GPS satellites depend on atomic clocks because precise time measurement is the foundation of global navigation. Each GPS satellite carries three to four atomic clocks, usually a mix of rubidium and cesium clocks. The reason for having multiple clocks is redundancy. If one clock fails or drifts, the satellite automatically switches to another clock. This ensures that the satellite always provides stable and accurate timing signals.These atomic clocks are part of the onboard timing units, which continuously produce precise time signals. The satellite broadcasts this time along with its position to receivers on Earth. If the time signal is even a few nanoseconds wrong, the calculated distance becomes incorrect, which affects the user's position accuracy.

GPS satellites cannot rely only on internal clocks. They work as part of a global timing network. Therefore, ground control stations constantly monitor and correct the clocks on each satellite. The U.S. GPS Control Segment operates monitoring stations around the world that check satellite clocks for drift and errors. When a correction is needed, the ground station sends an uplink control signal to the satellite. This updates the satellite clock parameters so that the timing remains synchronized with the GPS Time standard.According to the U.S. GPS.gov website, ground stations upload clock corrections every few hours, ensuring that satellites remain aligned with the master clocks on Earth, which also use atomic standards.[18]This combination of onboard atomic clocks and continuous ground-based corrections keeps GPS satellites reliable 24 hours a day. Without this careful monitoring and redundancy, GPS accuracy would quickly decrease.

Relativistic Corrections

In addition to quantum physics, GPS also depends on **Einstein's theory of relativity**.

Time on a satellite moves differently than time on Earth due to two main effects: **special relativity (SR)** and **general relativity (GR)**.

1. **Special Relativity – Speed Slows Clocks Down**

GPS satellites travel at about **14,000 km/h**. According to special relativity, moving clocks run **slower** compared to clocks at rest. This means the atomic clocks on satellites tick a bit slower than identical clocks on Earth.
This effect makes satellite clocks run **7 microseconds per day slower**.

2. **General Relativity – Weaker Gravity Speeds Clocks Up**

GPS satellites orbit at a height of 20,200 km above Earth. At this height, gravity is weaker than it is on the ground. According to general relativity, clocks in weaker gravity run **faster**.

[18] (GPS.gov, 2023, https://www.gps.gov/systems/gps/control/).

This effect makes satellite clocks run **45 microseconds per day faster**.

Net Relativistic Effect = +38 microseconds per day

When we combine both effects:

+45 microseconds (GR) −7 microseconds (SR) = +38 microseconds per day faster

This means that if no corrections were applied, every GPS satellite clock would get ahead by **38 microseconds every day**. Since light travels 300 meters in one microsecond, this results in a position error of **11.4 kilometers per day**.

Physicist Neil Ashby, in his famous paper ―Relativity and the Global Positioning System,‖ clearly showed that GPS would completely fail without applying relativity corrections[19].

How GPS Fixes Relativity

Relativity is corrected in two ways:

1. **The satellite clocks are pre-adjusted on Earth**

   Before launch, engineers set the atomic clocks to run slightly slower on the ground so that once in orbit, they run at the correct speed.

2. **Real-time corrections from ground stations**

   The control segment constantly checks for relativistic drift and broadcasts correction values in the satellite navigation message.

Together, these corrections make sure that GPS time stays consistent. Without applying relativity, the entire GPS network would become unusable within a matter of hours.

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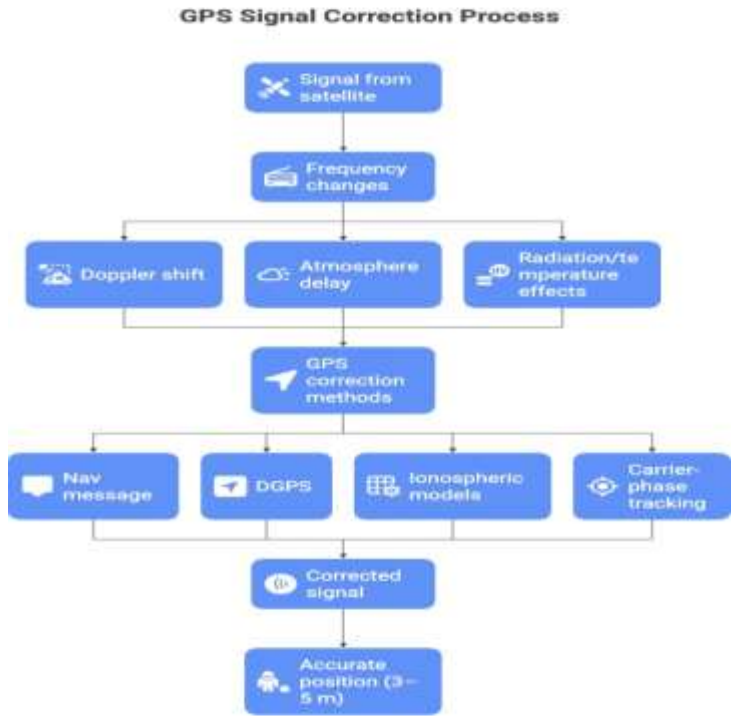
[19] Ashby, N. (2003). *Relativity in the Global Positioning System*. Physics Today, 55(5), 41–47. https://doi.org/10.12942/lrr-2003-1

Frequency Shifts & Real-Time Corrections

Even with atomic clocks and relativity corrections, GPS signals face several challenges that can change their frequency by the time they reach Earth. Because satellites move very fast, the signal received on the ground is not the same as the signal transmitted in space. This happens due to the Doppler shift, which is the change in frequency caused by motion. When a satellite moves toward a GPS receiver, the signal frequency slightly increases; when it moves away, the frequency decreases. GPS receivers must constantly correct this shift to calculate distance accurately. In addition to movement, environmental factors also affect the signal. As GPS signals travel through the ionosphere and troposphere, they slow down in different ways depending on weather conditions, atmospheric density, and solar activity. The ionospheric delay alone can cause 5–15 meters of positional error if left uncorrected. Magnetic fields, temperature changes, and space radiation can also influence the satellite's internal oscillators, creating small timing errors. Engineers must consider all these factors in real time to keep GPS signals stable and accurate for users on Earth.

GPS systems use several real-time correction methods to maintain high accuracy.

Each satellite continuously sends navigation messages that include information about clock drift, orbital position errors, and atmospheric conditions, allowing GPS receivers to adjust their calculations. In addition to satellite data, Differential GPS (DGPS) uses ground reference stations that know their exact location. These stations compare the signals they receive with their true position and broadcast correction data to nearby users, reducing errors even further. GPS receivers also apply ionospheric models, which are developed by government agencies to estimate and correct the delay caused by the Earth's atmosphere. For high-precision applications, such as surveying or autonomous machines, receivers use carrier- phase tracking, a method that measures the phase of the radio signal wave to achieve accuracy at the centimeter level. All these correction methods are necessary because GPS relies on perfectly synchronized and stable signals. When signal integrity is affected by the environment, satellite motion, or timing errors, real-time corrections help ensure the system remains accurate and reliable.According to GPS.gov, continuous monitoring and correction help keep GPS accuracy within 3–5 meters for civilian users and much better for military and scientific applications[20]).



Quantum Advancements Improving GPS Precision

Optical Lattice Clocks

Optical lattice clocks represent one of the biggest advancements in modern time- keeping. These clocks use atoms such as strontium or ytterbium instead of cesium. The reason they are more accurate is that they operate at optical frequencies, which are much

[20] (GPS.gov, 2023, https://www.gps.gov/systems/gps/performance/accuracy/

higher than microwave frequencies used in traditional atomic clocks. A strontium optical clock operates at around 430 terahertz (THz), meaning the atom ―ticks‖ much faster. A faster tick allows scientists to measure time more precisely, reducing uncertainty.

According to the U.S. National Institute of Standards and Technology (NIST), optical lattice clocks are about 100 times more precise than the best cesium clocks used today.[21] These clocks trap thousands of atoms in a pattern of laser light called an optical lattice. This lattice holds the atoms still, preventing movement that would otherwise disturb the frequency. The clock then uses a femtosecond laser and a frequency comb to measure the optical transitions with great precision.

Because these clocks are so accurate, they could help future GPS systems achieve centimeter-level global accuracy. Current civilian GPS accuracy is about 3–5 meters, and improvement to just a few centimeters would support advanced technologies such as self- driving cars, drone delivery systems, and precision agriculture.

Optical lattice clocks are still too large and complex to place on satellites, but research is progressing quickly. Countries such as the United States, Japan, Germany, and France are working on creating compact optical clocks suitable for space missions. These clocks may form the backbone of a future ―GPS 2.0,‖ where time measurement is far more stable than today.

Another major advancement in quantum technology that may improve GPS precision is quantum entanglement. Entanglement is a phenomenon in which two or more particles share a connection so strong that a change in one instantly affects the other, even if they are far apart. Albert Einstein famously called this ―spooky action at a distance.‖When applied to

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[21] (NIST, 2022, https://www.nist.gov/news-events/news/2022/02/new-record-precision-optical-lattice-clock.

clocks, entanglement allows multiple atomic clocks to work together as if they were a single, unified clock. In a network of distributed entangled clocks, the phase and frequency can be shared across long distances. This reduces frequency drift, which is one of the biggest challenges in satellite timing systems.[22]

A group of researchers demonstrated that entangled atoms can measure time more precisely than independent atoms because entanglement improves the signal-to-noise ratio. This method increases **phase coherence**, meaning the clocks stay synchronized more tightly.

The U.S. Defense Advanced Research Projects Agency (**DARPA**) is currently working on a ―Quantum Network Synchronization‖ project to explore how entangled clocks can be used for defense navigation systems and future satellite networks.[23] If successful, this technology could allow satellites to maintain perfect time synchronization even with fewer ground updates.

This kind of quantum clock network could help build a new system where satellites support each other instead of relying heavily on corrections from Earth. It may even prevent GPS outages caused by signal interference, space weather, or cyberattacks. Many experts

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[22] (Clavin, W. (2024, October 9). Merging atomic clocks with quantum computers could lead to ultraprecise measurements of laws of nature. Phys.org. https://phys.org/news/2024-10-merging-atomic-clocks-quantum-ultraprecise.html

[23] (Koberlein, B. (2020, December 18). *A new type of atomic clock uses entangled atoms. At most, it would be off by 100 milliseconds since the beginning of the universe*. Universe Today. https://www.universetoday.com/149413/a-new-type-of-atomic-clock-uses-entangled-atoms-at-most-it-would-be-off-by-100-milliseconds-since-the-beginning-of-the-universe/).

believe that entanglement-based networks will be essential in the future for **sub-centimeter precision**, deep-space positioning, and next-generation autonomous systems.[24]

Chip-Scale Atomic Clocks (CSAC)

While optical clocks and entanglement improve long-term accuracy, another important advancement focuses on making atomic clocks smaller and portable. Chip-Scale Atomic Clocks (CSACs) are tiny atomic clocks that fit on a small electronic chip. They use miniature vapor cells and microfabrication techniques, similar to how smartphone chips are made.A CSAC uses less than 150 milliwatts of power, which is thousands of times less than traditional atomic clocks[25].This extremely low power consumption makes them useful for battery-powered devices such as smartphones, sensors, and Internet of Things (IoT) devices.CSACs improve timing stability in environments where GPS signals are weak or unavailable. For example, underground mines, tunnels, forests, and inside buildings often block GPS signals. A CSAC allows a device to maintain accurate time and position even when satellite signals are lost for several minutes or hours.In the future, CSACs may play a major role in autonomous vehicles, military navigation, and emergency systems. Self-driving cars need very precise timing to fuse data from cameras, radar, and lidar. Small atomic clocks could also improve drone navigation and reduce errors in robotic systems.

Although CSACs are not as accurate as large optical or cesium clocks, they are accurate enough for many practical uses. Their combination of small size, low power, and

[24] (Massachusetts Institute of Technology. (2020, December 16). Newly-designed atomic clock uses entangled atoms to keep time even more precisely. ScienceDaily. https://www.sciencedaily.com/releases/2020/12/201216113301.htm)
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[25] (NIST, 2020, https://www.nist.gov/pml/time-and-frequency-division/chip-scale-atomic-devices).

good stability makes them one of the most promising technologies for next-generation navigation systems on Earth and in space.

Applications Enabled by Quantum Precision

Quantum-based atomic clocks do not just make GPS possible; they quietly support many important systems in modern life. In **engineering and surveying**, very accurate GPS allows builders and civil engineers to measure land, align bridges, lay pipelines, and design roads with errors as small as a few centimeters. This level of accuracy is only possible because satellite time signals are extremely precise.In telecom and 5G networks, mobile towers must be synchronized so that signals do not overlap and calls or data are not dropped. Precise timing from GPS atomic clocks is widely used to keep base stations in step across large areas (ITU, 2020). Without this synchronization, high-speed data and low-latency 5G services would be much less reliable.

Financial systems also depend on accurate time. Stock exchanges and banks use time stamps to record trades in the correct order. In some countries, regulators even require time stamps with accuracy better than one microsecond, often provided by GPS-based time . This helps prevent fraud and allows fair trading.In military navigation, quantum-precise GPS supports guided missiles, aircraft, ships, and soldiers in the field. Secure, accurate timing is also vital for encrypted communications and radar systems.Finally, future autonomous vehicles and drones will need even better position accuracy to move safely in busy cities.
Centimeter-level GPS, supported by advanced atomic and optical clocks, will help self- driving cars stay in the correct lane, avoid collisions, and follow detailed digital maps. In all these areas, quantum precision in timekeeping is not just a scientific achievement; it is a practical tool that keeps modern society working smoothly[26].

Challenges, Limitations, and Ethical Considerations

Even though quantum-based atomic clocks make GPS extremely accurate, they also bring several challenges and limitations. The first major challenge is cost and complexity. High-precision atomic clocks—especially optical clocks—require advanced lasers, vacuum systems, and cooling equipment. These clocks can cost hundreds of thousands of dollars, and maintaining them requires skilled scientists and engineers. Because of this, only large organizations such as government agencies, research labs, and advanced industries can use the most accurate quantum clocks.Another important challenge is security. GPS signals are very weak when they reach Earth, which makes them easy targets for jamming (blocking the signal) or spoofing (sending fake GPS signals). Spoofing attacks have already been reported in many countries, where ships or aircraft suddenly show fake locations on GPS maps [27] These attacks can create dangerous situations and show that relying too much on satellite signals is risky.

There are also ethical concerns, especially because GPS and quantum timing are heavily used in military systems. Precision-guided weapons, drones, and surveillance systems depend on accurate timing. This raises questions about how these technologies should be

[26]Hedrick, J. (2018, July). PNT for autonomous vehicles and transportation systems. Inside GNSS. https://insidegnss.com/pnt-for-autonomous-vehicles-and-transportation-systems/)

[27] (U.S. Department of Homeland Security. (2021). *GLOBAL POSITIONING SYSTEM (GPS) INTERFERENCE December 2022* https://www.cisa.gov/sites/default/files/2023-02/CISA-Insights_GPS-Interference_508.pdf

used, who controls them, and how to ensure they do not harm civilians or increase global tensions.Finally, there is the issue of quantum technology inequality. Many developing countries do not have access to advanced atomic clocks or quantum research facilities. This creates a gap between nations that can build high-precision technological systems and those that cannot. Such inequality may affect economic development, national security, and participation in global scientific progress.These challenges show that while quantum precision greatly benefits society, it must be handled with responsibility, strong security systems, and fair access.

Future Possibilities

Quantum timekeeping and GPS are still evolving, and future systems may look very different from today. One important direction is the idea of a quantum internet, where clocks in different places are synchronized using entangled photons rather than only classical radio signals. Recent research has shown that satellite-based quantum clock synchronization could link ground stations around the world with picosecond-level timing accuracy, far better than what current GPS alone can provide[28].

Another major possibility is a kind of ―GPS 2.0‖ based on optical lattice clocks in space. Optical clocks, which can reach fractional uncertainties around 10^{-18}, are roughly 100 times more precise than today's cesium clocks[29].Studies suggest that if such clocks were used

[28] .(Haldar, S., et al. (2022). Global time distribution via satellite-based sources of entangled photons. arXiv. https://arxiv.org/abs/2209.15071)

[29] .(Shinkai, H., Takamoto, M., & Katori, H. (2025). Transportable optical lattice clocks and general relativity [Preprint]. arXiv. https://arxiv.org/pdf/2502.06104,)

in global navigation satellite systems, ordinary users could get centimeter or even millimeter- level positioning, instead of a few meters[30]. These advances would strongly support autonomous vehicles, robotics, precision farming, earthquake monitoring, and space exploration. At the same time, they will require new standards, new satellite designs, and careful thinking about security and fair access. Overall, the future of quantum timekeeping points toward a world where navigation and timing are far more precise, and deeply integrated into both ground and space networks[31].

Conclusion

Quantum principles are at the heart of the high precision that GPS systems and atomic clocks provide. The entire GPS network works only because atomic clocks use quantum energy transitions, which are fixed and repeatable for every atom. These transitions create extremely stable frequencies that define the second and allow satellites to measure time with nanosecond accuracy. Since even a 1-nanosecond error can shift a GPS position by about 30 centimeters, the reliability of quantum-based clocks is essential for navigation, science, communication, and safety across the world.[32] This paper shows that quantum physics not only helps measure time but also allows GPS to function as a **global infrastructure system**. Industries such as aviation, telecom, emergency services, banking, surveying, and military

[30] (Tang, B. Y., et al. (2023). Demonstration of 75 km-fiber quantum clock synchronization. EPJ Quantum Technology, 10(1), 20. https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-023-00207-9)

[31] (Boldbaatar, E., et al. (2023). Evaluating optical clock performance for GNSS positioning. GPS Solutions, 27,

58. https://pmc.ncbi.nlm.nih.gov/articles/PMC10347235/) .

[32] .(National Institute of Standards and Technology. (2020). Time and Frequency Division – Atomic Clocks. https://www.nist.gov/pml/time-and-frequency-division

navigation all depend on the accurate time signals produced by atomic clocks in satellites. Without quantum precision, none of these systems could operate smoothly or safely.Looking ahead, quantum technology will make GPS even more accurate. Optical lattice clocks, quantum-linked clock networks, and chip-scale atomic clocks may lead to GPS systems with centimeter- or even millimeter-level accuracy. These improvements will support future technologies like autonomous vehicles, drone networks, smart cities, and deep-space missions.quantum principles are not just theoretical concepts—they are practical tools that keep the modern world connected. As new quantum technologies continue to develop, global navigation and timing will become even more precise, stable, and reliable.

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