Tick-Tock, Tick-Tock: Studying Time with Ever More Precise Clocks

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The International Space Station (ISS) is equipped with special clocks. These atomic clocks measure how time in outer space flows differently than time on Earth, or to say it with Einstein, how our planet's gravity slows down time. The experiment sprang from an idea developed by Christophe Salomon, laureate of the 2025 Balzan Prize.

In today's world, precise timekeeping is essential. One application that we use every day and that simply cannot function without extremely accurate clocks is GPS. We rarely think about it while navigating, but if the clocks in GPS satellites were off by even a fraction of a second, we would be hopelessly lost.

Satellite navigation – GPS – relies on signals sent by satellites orbiting Earth at an altitude of about 20,000 kilometers. A GPS receiver determines its position by measuring the travel time of signals from multiple satellites, determining its location through a geometric calculation that depends not only on the satellites' positions but also on the exact moment each signal was transmitted. This is why the satellites provide each signal with a timestamp, which means that the clocks inside our GPS devices must be synchronized with the clocks in the satellites. If not, the calculation yields an incorrect location.

Synchronizing clocks in space is not just a technical challenge; it requires cutting-edge fundamental physics. Since the seminal work of Albert Einstein, we know that time is not absolute, but relative. Time runs faster or slower depending on how observers move relative to each other – this effect, known as time dilation, is a core element of Einstein's theory of special relativity. But gravity also affects time. In a place where there is more gravitational pull, time passes more slowly (relatively) than in a place where gravity is weaker – part of Einstein's theory of general relativity. These time differences are far too small to notice in our daily lives, but GPS is one of the rare technologies where they matter crucially.

That is why the clocks aboard GPS satellites are corrected for both their motion, as they race around Earth at speeds of around 14,000 km/h, and for the weaker gravity they experience. Without these relativistic corrections, the satellites would constantly transmit inaccurate timestamps, causing positioning errors in the GPS receivers that could grow by several kilometres per day. To summarize: without Einstein's relativity, modern satellite navigation would not work.

Einstein's theories of relativity are more than a century old, but they still stand firm. Yet physicists continue to search for mismatches between theory and experiment – which in a certain sense is their job. With ever more precise clocks, they test the time differences caused by gravity (gravitational time dilation). And what is a better place to do that than in space?

Here ACES, the Atomic Clock Ensemble in Space, enters the scene. This European space mission was launched in April 2025 and brought an ultra-precise atomic clock to the ISS. There it measures time, and physicists compare the measurements with clocks on Earth. It is an extremely accurate test of gravitational time dilation. Where GPS is an application of relativity, ACES is a test of it. If the results were to deviate from predictions, physicists would know that our current understanding of the theory of gravity and spacetime is incomplete – potentially triggering another revolution in physics, more than a century after the theory was developed.

The idea of the mission dates back to 1997, when French physicist Christophe Salomon – laureate of the 2025 Balzan Prize for Atoms and Ultra-Precise Measurement of Time – launched his proposal to the

European and French space agencies. The heart of ACES is a cesium atomic clock, the gold standard of atomic clocks. The clock has a precision of 1 in 10 quadrillion (10^{16}), which means that it would take 300 million years for it to drift by one second. It took more than two decades to develop the ACES clock and its support systems, as they had to be made suitable for operation in outer space: not too large, compact, shock-resistant and able to withstand high-energy radiation. Since April 2025, the equipment has been operating aboard the ISS. Scientific coordination is handled by the Laboratory for Space Time (LTE) at the Paris Observatory. The mission will run until 2030. Salomon used half of his Balzan Prize money to support three young physicists working on ACES data analysis.

Meanwhile, comparable experiments are being carried out on Earth, using even more precise atomic clocks based on strontium atoms. The most advanced of these is housed at the Joint Institute for Laboratory Astrophysics (JILA) at the University of Colorado Boulder in the United States. A massive, room-sized apparatus forms the strontium clock, which is so precise that it would take billions of years to gain or lose a single second.

The strontium clock is far too large and complex to send into space, but physicists have used it to measure the effect of gravity on the passage of time. A few years ago, they raised the clock by (only!) one millimeter. However, that tiny increase in height reduced Earth's gravitational pull on the clock ever so slightly, causing the clock to run a little faster. The resulting time difference was minuscule but measurable. One millimeter higher, the clock gained about a hundred-quadrillionth of a second (10^{-17} seconds), exactly as Einstein's theory predicts.

Over the past seventy years, the precision of clocks has improved by a factor of one billion, as pointed out by Christophe Salomon during the Balzan Prizewinners Interdisciplinary Forum in November 2025. But where will this end? Is there a fundamental limit to how precisely we can measure time? And if such a limit exists, what does it imply for that other great triumph of 20th-century physics: quantum mechanics, a theory that has yet to be reconciled with relativity?

Time will tell, whether we study it in outer space or on the ground.