Tick-Tock Atomic Clock

Scientists are building atomic clocks that keep time with mind-boggling precision. Such devices will help farmers, physicists, and interstellar travelers alike.

"I must go down to the seas again, to the lonely sea and the sky
And all I ask is a tall ship and a star to steer her by;" from *Sea Fever* by John Masefield, 1900.

April 8, 2002: In John Masefield's poem, "Sea Fever," all he needs to roam the seas is "a tall ship and a star to steer her by." In fact, a good clock was just as important. Mariners who navigated by the stars needed to know *when* they were looking at the sky. Otherwise their charts and tables would be useless.

At the time Masefield wrote his poem, at the beginning of the 20th century, navigating by the stars had been made much more accurate by the invention of maritime chronometers. They were spring-driven clocks that, once set, kept the time within a fraction of a second each day.

In the 21st century, our ships travel much greater distances -- not only from London to New York, but from Earth to Mars and beyond. As a result, the accuracy of our time pieces must be greater as well.

Modern navigators rely on atomic clocks. Instead of old-style springs or pendulums, the natural resonances of atoms -- usually cesium or rubidium -- provide the steady "tick" of an atomic clock. The best ones on Earth lose no more than one second in millions of years.

That's impressive, but scientists working in NASA's Fundamental Physics Program would like to do better. For those of us who mutter "just a minute" when we mean "half-an-hour," improved precision might seem overboard. Yet there are many uses for it: to test theories of gravity, for example, to guide spaceships, and to solve a surprising variety of down-to-Earth problems.

Sailers, truck drivers, soldiers, hikers, and pilots ... they all rely on atomic clocks, even if they don't know it. Anyone who uses the Global Positioning System (GPS) benefits from atomic time. Each of the 24 GPS satellites carries 4 atomic clocks on board. By triangulating time signals broadcast from orbit, GPS receivers on the ground can pinpoint their own location.

Tiny instabilities in those orbiting clocks contribute at least a few meters of error to singlereceiver GPS measurements. Making the clocks smaller (so that more of them can fit on each satellite) and increasing their stability could reduce such errors to fractions of a meter.

Pilots landing on narrow airstrips at night would appreciate the improvement. So would surveyors, prospectors, search and rescue teams ... and farmers. "Precision farmers" already use GPS-guided tractors to dispense custom-doses of water, fertilizer and pesticides over garden-sized plots. Better GPS data could guide those tractors to individual rows or perhaps even to individual plants for special care.

"One day, we'll want to have GPS satellites around other planets, too," notes Don Strayer of NASA's Fundamental Physics Program at JPL. For example, a Martian Global Positioning System could guide explorers -- both robot and human -- across the Red Planet. Less likely but possible: Future farmers on Mars might want GPS to help them tend crops as their cousins on Earth do. Martian fields will definitely need special care.

Atomic clocks on board GPS satellites are stable "within 1 part in 10^{12}," says Lute Maleki who supervises JPL's Quantum Sciences and Technology Group. That means an observer would have to watch a GPS clock for 10^{12} seconds (32,000 years) to see it gain or lose a single second. "To guide spacecraft from planet to planet we use clocks that are even better -- good to 1 part in 10^{14}," he added.

Recently scientists have built atomic clocks that are better still -- "stable to about one part in 10^{15}," notes Maleki. They did it using a new technique called "laser cooling." In the 1990's several groups of researchers made a counter-intuitive discovery: Shining lasers on atoms can cool them to temperatures only a millionth of a degree above absolute zero. Such cold atoms make excellent "pendulums" for atomic clocks, explains Strayer, "because lower temperatures allow the natural frequency of the atom to be measured more accurately."

If cold atoms are good, then *floating* cold atoms are even better.

"The International Space Station is a great place for atomic clocks because the station is freely falling around the Earth," Strayer continued. Slow-moving atoms in a cooled weightless clock can be observed for a longer time, and they're less likely to hit the walls of their container in mid-oscillation.

If all goes as planned, a laser-cooled clock named PARCS will be installed on the ISS in late 2004 or 2005. Experts expect it to be the most stable clock ever, keeping time within 1 second every 300 million years (1 part in 10^{16}).

According to Einstein's theory of gravity and space-time -- called "general relativity" -- clocks in strong gravity tick slower than clocks in weak gravity. Because gravity is weaker on the ISS than at Earth's surface, PARCS should accumulate an extra second every 10,000 years compared to clocks ticking on the planet below. PARCS won't be there that long, but the clock is so stable that it will reveal this effect in less than one year. (Strayer notes that clocks on GPS satellites experience this relativistic phenomenon, too, and that onboard systems must correct for it.)

"Putting atomic clocks in orbit is a good way to test general relativity," says Maleki. "General relativity has passed every test so far, but no theory is perfect -- not even Einstein's. Eventually, as we extend the precision of our experiments, we expect to find flaws in it, and that will dramatically change what we know about the nature of the Universe."

The stretching of time by relativity has been felt and measured by other orbiting clocks -- GPS, for example -- but PARCS will measure the effect with errors one hundred times smaller than its predecessors did. Furthermore, PARCS will test technologies to be used in a next-generation clock named RACE slated for installation on the ISS in 2006. Stable within 1 part in 10^{17}, RACE will keep time so well that if it ran for three billion years it would lose less than 1 second.

Clocks like RACE will test physics like never before. They will improve telecommunications on Earth -- "in ways we can't imagine yet" says Maleki -- and do wondrous things for navigation. Indeed, with RACE on board, a mariner could navigate not only *by* the stars, but *between* them as well.

Perhaps if Masefield were alive today, he would craft his poem differently: "I must RACE down to the launch pad, to my craft so sleek and true; All I need is a stable clock and a star to steer her to...."