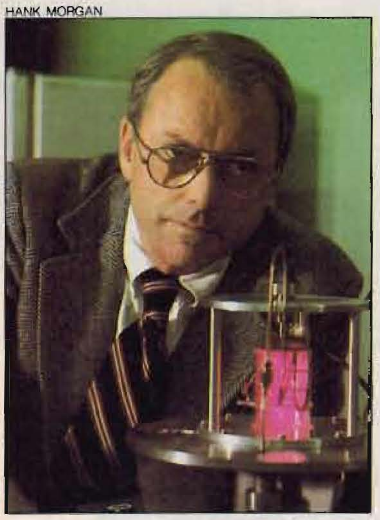
PHYSICS

# THE ULTIMATE TIMEPIECE

A clock that keeps time to trillionths of a second is measuring continental drift and the distance to deep-space probes

by MARCIA BARTUSIAK

HANK MORGAN



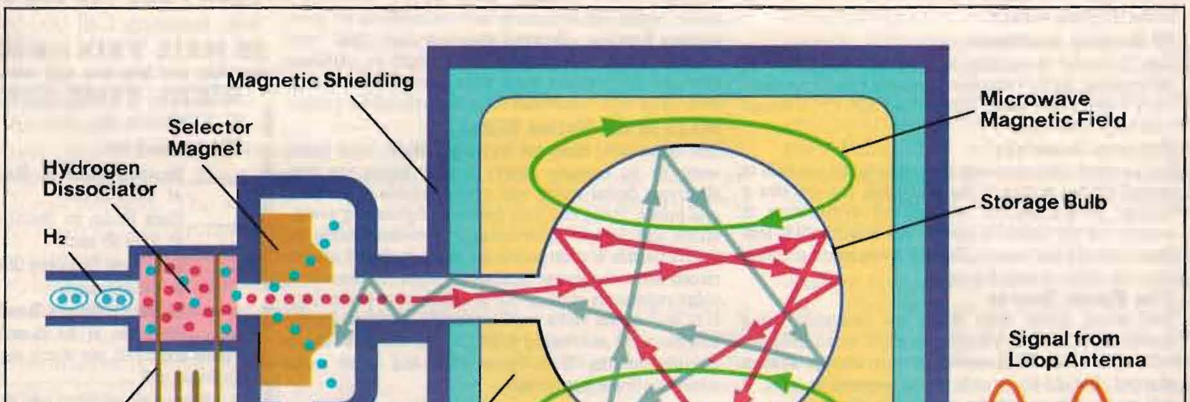
**Robert Vessot with dissociator; in the diagram, hydrogen atoms from the dissociator race into a bulb and generate a magnetic field that oscillates more than a billion times a second. Signal becomes a "pendulum" that ticks off infinitesimal units of time**

To Bostonians in the late 18th century, the stately clock atop Old South Meeting House was the ultimate timepiece. The Boston *Gazette* was so impressed by its accuracy that in April 1770 it wrote, "The great Clock at Dr. Sewall's Meeting House made by Gawen Brown of this Town goes with such Regularity and Exactness, that for this 14 weeks it has not lost by two minutes of Time." If master clockmaker Gawen Brown were alive today, he would be facing some formidable competition.

At the Harvard-Smithsonian Center for Astrophysics just a few miles northwest of that historic meetinghouse, physicist Robert Vessot and his colleagues are building the world's most advanced atomic clocks—clocks so regular and exact that they vary by only 50 trillionths of a second a day. "That's equivalent to one second every fifty million years," says Vessot, "though obviously our clocks aren't expected to run that long." That stability has important implications. Atomic clocks play a crucial role in measuring the barely perceptible but inexorable movements of the earth's crust, in navigating space probes through the swarm of moons circling Jupiter and Saturn, and in discerning the subtle structures of astronomical objects billions of light-years away.

All these endeavors call for more precise measurements of time than have ever before been needed. The cyclic swings of a balance wheel, or even the finely spaced vibrations of a quartz crystal, are much too irregular. What is required is a pure, extremely stable microwave signal that oscillates more than a billion times a second. And that is what is produced by a hydrogen maser, a microwave version of the light-generating laser.

"When we first started out in the early sixties to turn hydrogen masers into clocks," says Vessot, "we made this wild machine that weighed a thousand pounds and looked like a desk with a garbage can on top." Today he and his associates are meticulously constructing a $355,000 version that weighs half as much and looks like a small refrigerator filled



ILLUSTRATIONS BY GEORGE NICHOLSON

with circuit boards, electromagnetic coils, and vacuum pumps. Although better materials and improved electronics have led to ever more accurate maser clocks, the principle behind them has not changed since the physicists Norman Ramsey, Daniel Kleppner, and H. Mark Goldenberg made the first hydrogen maser at Harvard in 1960.

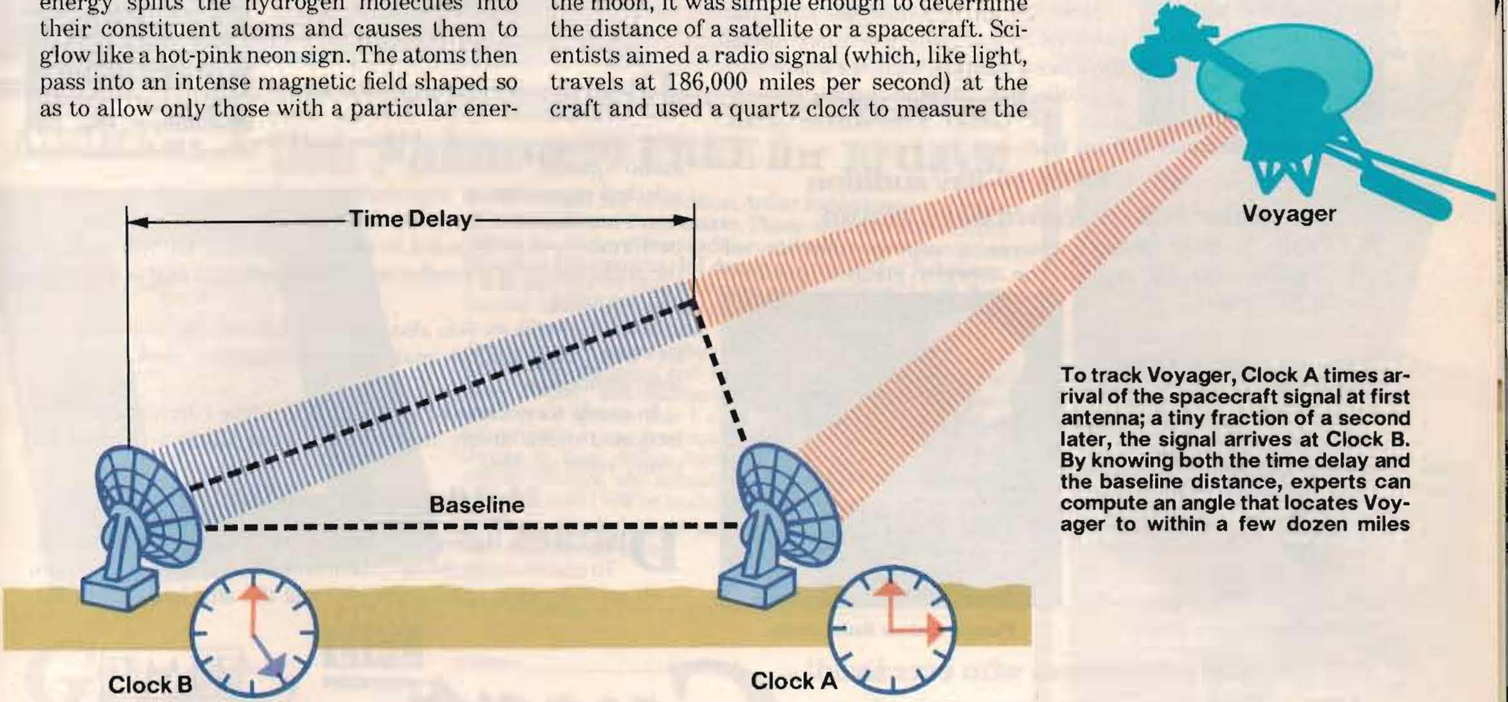
This atomic timepiece has no moving parts—except for the hydrogen gas that courses silently through its metal and glass veins. The gas flows into a small glass chamber called a dissociator, where radio-frequency energy splits the hydrogen molecules into their constituent atoms and causes them to glow like a hot-pink neon sign. The atoms then pass into an intense magnetic field shaped so as to allow only those with a particular energy to race, at two miles per second, into a quartz bulb coated inside with Teflon; other atoms are deflected. Says Vessot, "It's as if the atoms came in different varieties, and we could pick out the ones with higher energy."

At a rate of about 10 trillion per second, these atoms enter the bulb, ricochet off its walls some 25,000 times each, and then escape. But before leaving they transfer their energy in concert with one another to the microwave cavity in which the bulb is placed (see diagram on opposite page). This process generates a magnetic field within the cavity that oscillates exactly 1,420,405,751.68 times a second. "The stability of the cavity is crucial," says Vessot. "The rate of the clock will change noticeably if the cavity dimensions shift even the width of an atom." The oscillating magnetic field, in turn, produces a tiny electrical current in a loop antenna, which transmits a microwave radio signal with the same frequency. With a device to count the oscillations of that signal, the hydrogen maser becomes a clock. Under ideal conditions, a quart-sized tank of hydrogen could keep the clock running for ten years.

So far, the Harvard-Smithsonian maser group has built 15 clocks for satellite-tracking stations, radio telescopes, and research labs in the United States and Europe. Vessot calls them "my children" and, like a proud father, rattles off their accomplishments. Their latest triumphs: tracking the Voyager spacecraft to Jupiter, Saturn, and beyond.

As long as man strayed no farther than the moon, it was simple enough to determine the distance of a satellite or a spacecraft. Scientists aimed a radio signal (which, like light, travels at 186,000 miles per second) at the craft and used a quartz clock to measure the time it took the signal to reach the target and return to earth. "But as spacecraft ventured farther and farther out," says Richard Sydnor, a time and frequency expert at the Jet Propulsion Laboratory in California, "we needed much greater precision in determining distance and location." They got it with something called very long baseline interferometry (VLBI). In this technique, two or more widely separated radio telescopes, synchronized with maser clocks, look simultaneously at the same object. Even now, as Voyager 2 speeds toward Saturn (see illustration above), large parabolic dishes at tracking stations in California, Spain, and Australia are transmitting radio signals to the spacecraft and receiving them back. The distances between stations are known, and by using the difference between the precise arrival times of the Voyager signals at each station, experts can compute an angle that locates the spacecraft to within a few dozen miles. That is a remark-

*continued on page 82*



**To track Voyager, Clock A times arrival of the spacecraft signal at first antenna; a tiny fraction of a second later, the signal arrives at Clock B. By knowing both the time delay and the baseline distance, experts can compute an angle that locates Voyager to within a few dozen miles**

able feat; Voyager is now hundreds of millions of miles from the earth. James Moran, a radio astronomer at Harvard, puts it this way: "It's like being in Boston and measuring the width of Lincoln's nose on a penny held over San Francisco. One antenna would only tell us that the penny is somewhere in California." For deep-space tracking, VLBI is totally dependent on maser clocks; timing errors as small as a billionth of a second could lead to trajectory changes that would put a spacecraft many miles off course—enough to endanger a mission.

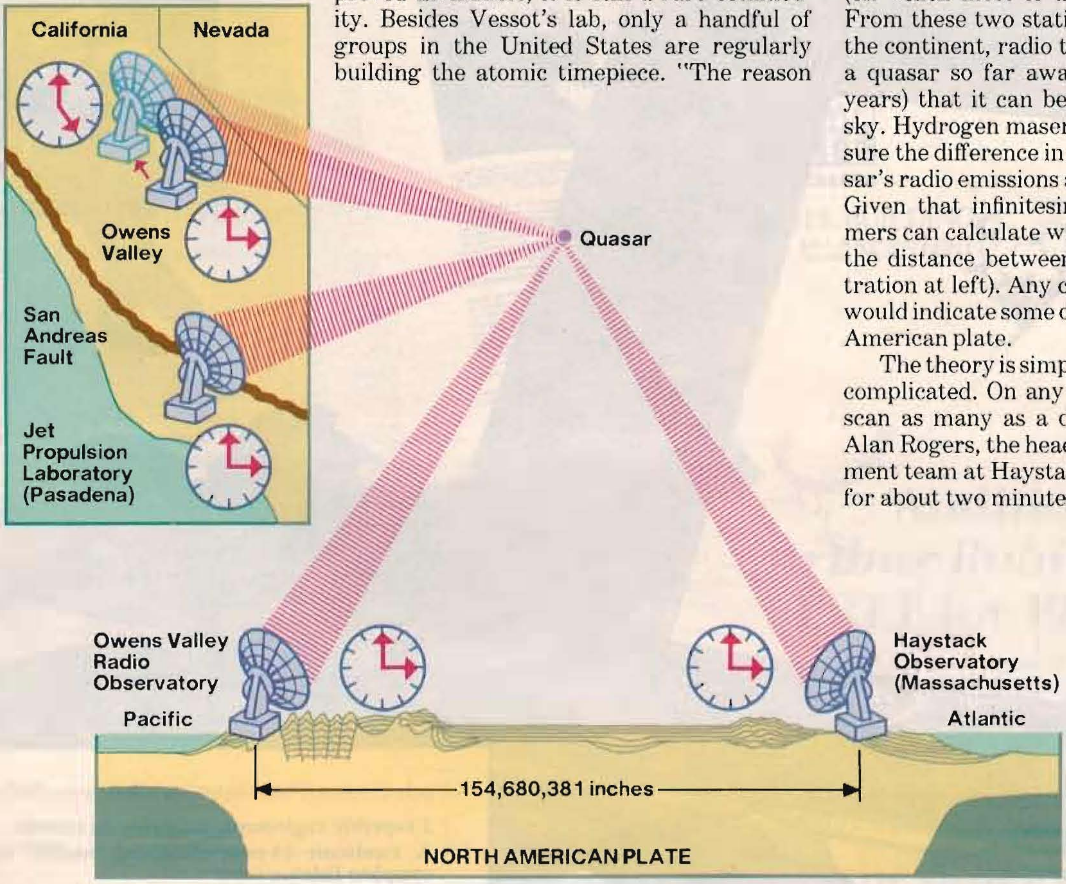
VLBI has opened new windows for astronomy. Says Anthony Readhead, a radio astronomer at Caltech, "With these very accurate atomic clocks, it is possible to record the signals from several telescopes separately on tape. The tapes are then sent to a central processor, where they are synchronized and the signals combined." This kind of telescope network has resolving power as great as that of a single radio telescope with a diameter the width of a continent. This enables astronomers to detect details in distant radio sources, like galaxies and quasars, that in the terrestrial sky have angular widths as small as 300 billionths of a degree (by comparison, the sun and moon each span about half a degree).

While the hydrogen maser clock has proved invaluable, it is still a rare commodity. Besides Vessot's lab, only a handful of groups in the United States are regularly building the atomic timepiece. "The reason is simple," says Victor Reinhardt, head of the maser program at NASA's Goddard Space Flight Center in Maryland. "We're like craftsmen. It takes four people a whole year to make just one maser. Merely coating the storage bulb with Teflon is a black art."

To construct its second generation of maser clocks, Goddard is working with the Applied Physics Laboratory of Johns Hopkins University. Says Reinhardt, "Our aim has been to build clocks that can go out to remote radio-antenna sites where there aren't controlled laboratory conditions." One way that this was done was to equip each of the new Goddard-APL masers with a microcomputer that monitors the clock's frequency and sends corrective signals if it detects any variations in the oscillations.

These maser clocks will be used in NASA's Crustal Dynamics Project, which will monitor movements of the tectonic plates that comprise the earth's crust, using both fixed and mobile tracking stations all over the globe. Some tests have already been done. Astronomers at the Owens Valley Radio Observatory in California and the Haystack Observatory in Massachusetts have been doing a bit of cosmic surveying, using VLBI to measure changes in the North American plate (on which most of the United States rests). From these two stations on opposite sides of the continent, radio telescopes are trained on a quasar so far away (several billion light-years) that it can be considered fixed in the sky. Hydrogen maser clocks are used to measure the difference in arrival times of the quasar's radio emissions at the two observatories. Given that infinitesimal difference, astronomers can calculate with astonishing accuracy the distance between the stations (see illustration at left). Any change in that difference would indicate some deformation of the North American plate.

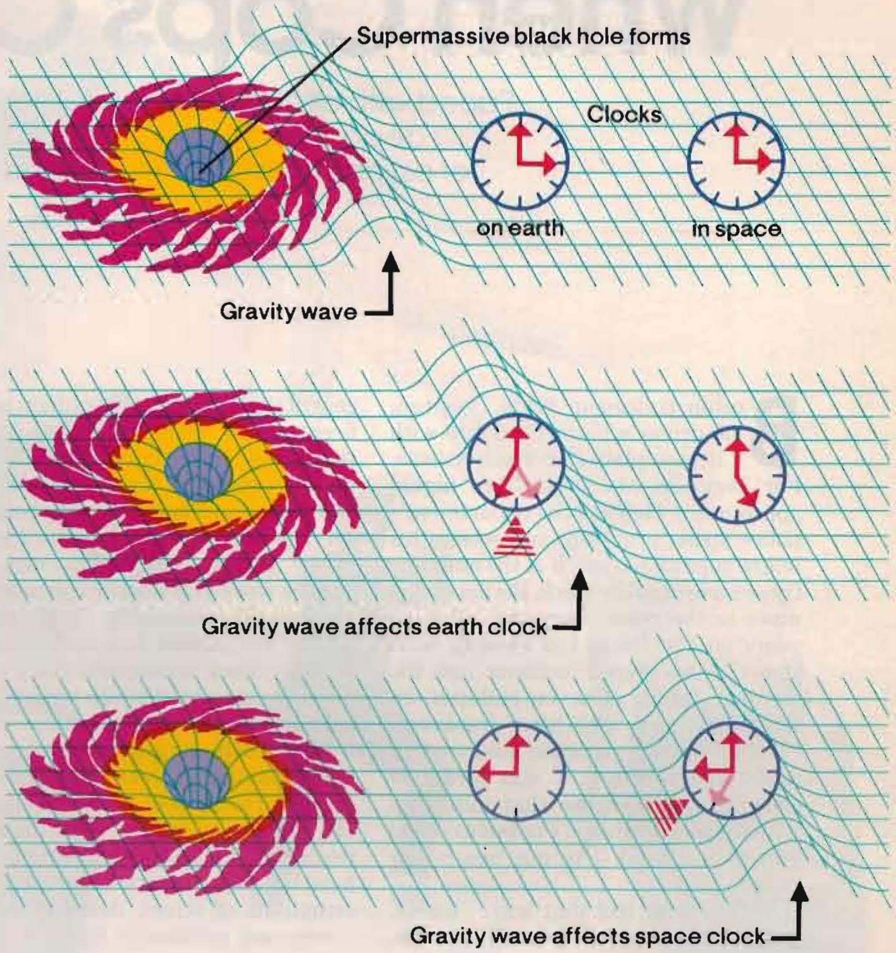
The theory is simple; the technique is more complicated. On any one test, the telescopes scan as many as a dozen quasars. Explains Alan Rogers, the head of the crustal-measurement team at Haystack, "We time one source for about two minutes, then quickly move the



**Radio telescopes are trained on a quasar to measure crustal movements on earth. They show that the North American plate has remained rigid for the past five years but that California is more active. Over one period of eleven weeks, Pasadena, on the Pacific plate, and Owens Valley moved eight inches farther apart**

antenna to the next source, all in coordination with the telescope at Owens Valley. This continues for twenty-four hours until we've assembled enough information to solve the distance." Enough means filling up 20 computer tapes, each capable of storing 50,000 novels. When data on the Owens Valley and Haystack tapes are matched, scientists extract about a hundred bits of useful information for every 100 million bits gathered. "We crunch more data in one night than the IRS handles in a year," says a Haystack computer expert.

Even while astronomers are perfecting their techniques, they have produced some interesting results. The distance between the Massachusetts and California stations—on opposite edges of the North American plate—has remained a steady 154,680,381 inches, give or take an inch, for the past five years. This means that there has been no large-scale deformation of the plate between the stations. But elsewhere there has been action. In California, VLBI measurements between Owens Valley, on the North American plate, and the Jet Propulsion Laboratory in Pasadena, across the San Andreas fault on the Pacific plate, show periods of stability followed by rapid movement. During one 11-week period, the 209-mile distance between the two sites grew by about eight inches and an earthquake shook the Imperial Valley near the Mexican border. Was there a connection? Scientists are not sure; more measurements may provide the answer.



**A gravity wave is emitted as a supermassive black hole forms. By seeing how the wave varies the frequency of a clock on earth, then one deep in space, scientists think they could detect this ripple in space-time**

The next stop for maser clocks may be deep space. Vessot has already rocketed a 90-pound maser clock 6,200 miles above the earth, where gravity is weaker than at the surface. This test provided additional verification of Einstein's prediction that time speeds up in a weaker gravity field. Within the next decade, Vessot and Larry Smarr, an astrophysicist with the University of Illinois, hope to send a 40-pound clock much farther out, perhaps near Jupiter, to hunt down another relativistic consequence of Einstein's theories: gravity waves.

Einstein said that when matter accelerates or vibrates in a certain way, it sends off ripples, or gravity waves, in the fabric of space-time. But scientists figure that these waves are so weak that only those produced by extremely massive bodies can be detected. For example, when a black hole millions of times as massive as the sun forms in the heart of a galaxy, it may produce waves strong enough to be detected. Such gravitational bursts could be reaching the earth from outer space anywhere from once a week to once a year. As the wave passed the earth, the deformation in space-time would cause the frequency of an earth-based clock to change by an infinitesimal amount. Traveling on at the speed of light, the pulse would later affect Vessot and Smarr's space clock hundreds of millions of miles farther away (see illustration above). By comparing the variations in the frequencies of the two clocks, scientists would be able to recognize a unique "gravity wave signature."

"When we do this, it will be as exciting as when Galileo first turned an optical telescope on the sky," says Vessot. Eventually, a "gravity telescope" based on arrangements of atomic clocks may bring into "view" exotic astrophysical objects more bizarre than pulsars and quasars. Adds Vessot, "It will enable us to go back to the dawn of creation."

But for the time being, Vessot is concentrating on improving the clock. The Harvard-Smithsonian group is experimenting with cooling the maser with liquid helium to temperatures near absolute zero (−459.67 degrees Fahrenheit) in order to improve its performance even more. Does Vessot's obsession with accurate timekeeping extend outside of the laboratory? Not really. "I have an eighteenth century grandfather clock at home that is nowhere near as accurate as the maser, but I wouldn't give it up for the world." ▣