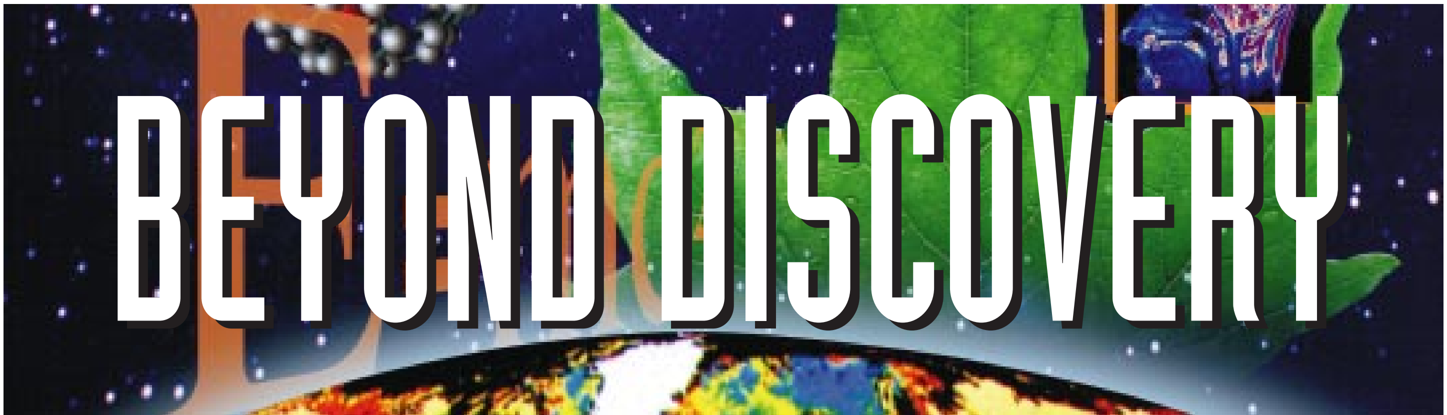

THE PATH FROM RESEARCH TO HUMAN BENEFIT™

THE GLOBAL POSITIONING SYSTEM
The Role of Atomic Clocks

Where am I? The question seems simple; the answer, historically, has proved not to be. For centuries, navigators and explorers have searched the heavens for a system that would enable them to locate their position on the globe with the accuracy necessary to avoid tragedy and to reach their intended destinations. On June 26, 1993, however, the answer became as simple as the question. On that date, the U.S. Air Force launched the 24th Navstar satellite into orbit, completing a network of 24 satellites known as the Global Positioning System, or GPS. With a GPS receiver that costs less than a few hundred dollars you can instantly learn your location on the planet—your latitude, longitude, and even altitude—to within a few hundred feet.

This incredible new technology was made possible by a combination of scientific and engineering advances, particularly development of the world's most accurate timepieces: atomic clocks that are precise to within a billionth of a second. The clocks were created by physicists seeking answers to questions about the nature of the universe, with no conception that their technology would some day lead to a global system of navigation. Today, GPS is saving lives, helping society in countless other ways, and generating 100,000 jobs in a multi-billion-dollar industry. The following article, adapted in part from an account by physicist Daniel Kleppner, describes how basic research into the nature of time and ways to measure time accurately contributed to development of the GPS. It provides a dramatic example of how science works and how basic research leads to technologies that were virtually unimaginable at the time the research was done.

Where Is He?

It was 2:08 in the morning of June 6, 1995, when a U.S. Air Force pilot flying an F-16 fighter over Serbian-held positions in Bosnia-Herzegovina first heard "Basher 52" coming over his radio. "Basher 52" was the call signal of American pilot Captain Scott O'Grady, whose own F-16 had been shot down by Serbian forces in that area 4 days earlier. The pilot would say later that hearing O'Grady's call signal was like hearing a voice from beyond the grave. O'Grady's F-16 had been hit by a Serbian ground-to-air missile and had exploded immediately. Although the 29-year-old pilot had managed to eject

American F-16 pilot Captain Scott F. O'Grady arrives on the deck of the USS Kearsarge in the Adriatic Sea after his June 1995 rescue from Serb-controlled territory in Bosnia-Herzegovina. A GPS receiver concealed in his life vest enabled Marines to pinpoint the downed pilot's location, leading to a successful rescue operation. (AP/Wide World Photos) safely, his wingman had seen no parachute come out of the flaming debris.

Now O'Grady had been on the ground behind enemy lines for 4 days, surviving on grass and insects, sleeping by day under camouflage netting, and moving by night. He had finally risked radio contact with fliers, who verified his position and called in the Marines—in particular, the 24th Marine Expeditionary Unit and its expert team for Tactical Recovery of Aircraft Personnel, or TRAP. Within 4 hours, the search and rescue team had lifted off from the USS *Kearsarge* in the Adriatic Sea and headed toward Bosnia. By 6:50 a.m., they had picked up O'Grady in a dramatic textbook rescue, had weathered Serbian small-arms fire, and were heading back home. Later that day in Alexandria, Virginia, William O'Grady, the young flier's father, was informed that his son was alive and safe.

The press would hail O'Grady as a hero, and O'Grady himself would give credit and thanks to the Marines who "risked their lives to get me out." But another factor allowed the Marines to perform their crucial role in the rescue operation with surgical precision. When O'Grady had gone down, his life vest contained a portable radio receiver tuned in to a network of 24 satellites known as the Global Positioning System (GPS). O'Grady was able to determine his position behind enemy lines—longitude, latitude, and altitude—to within a few hundred feet, and he was then able to signal that position to the Air Force fliers overhead and to the Marines who were sent in to rescue him. One cannot help wondering whether O'Grady and his rescuers knew that some of the technology that made this remarkable rescue possible had grown out of basic research on the fundamental properties of atoms and nuclei some 60 years earlier.

Originally conceived as a navigational tool for the military, the Global Positioning System has spawned many commercial applications in an industry that some predict will reach $30 billion in annual revenues in the next decade: here, a built-in locator device for automobiles. (Trimble Navigation Ltd.)

Time and Location, Precisely

GPS makes it possible to answer the simple question "Where am I?" almost instantaneously and with breathtaking precision. The new technology utilizes atomic clocks that keep time to within a billionth of a second. They were created by scientists who had no idea that the clocks would someday contribute to a global system of navigation. The system made its public debut to rave reviews in the 1991 Gulf War. U.S. troops used it for navigation on land, sea, and in the air, for targeting of bombs, and for on-board missile guidance. GPS allowed U.S. ground troops to move swiftly and accurately through the vast, featureless desert of the Arabian Peninsula.

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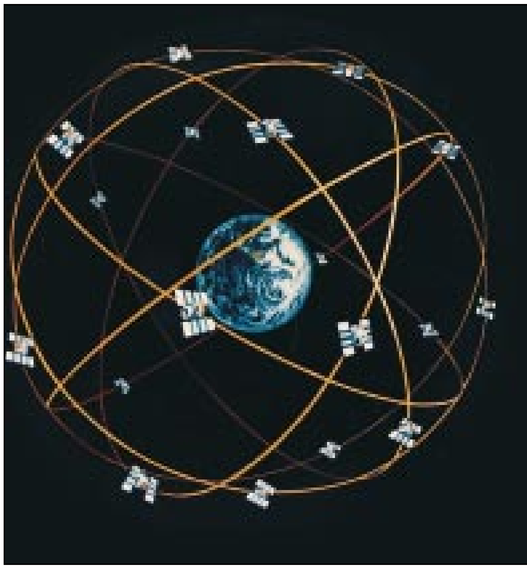
Since then, GPS technology has moved into the civilian sector. Today, GPS is saving lives, helping society in many other ways, and generating jobs in a new multi-billion-dollar industry. Advances in integrated-circuit technology—the technology used to make computer chips—soon will lead to GPS receivers and transmitters the size of credit cards, so small and so inexpensive that virtually any vehicle can have one installed and any person can carry one.

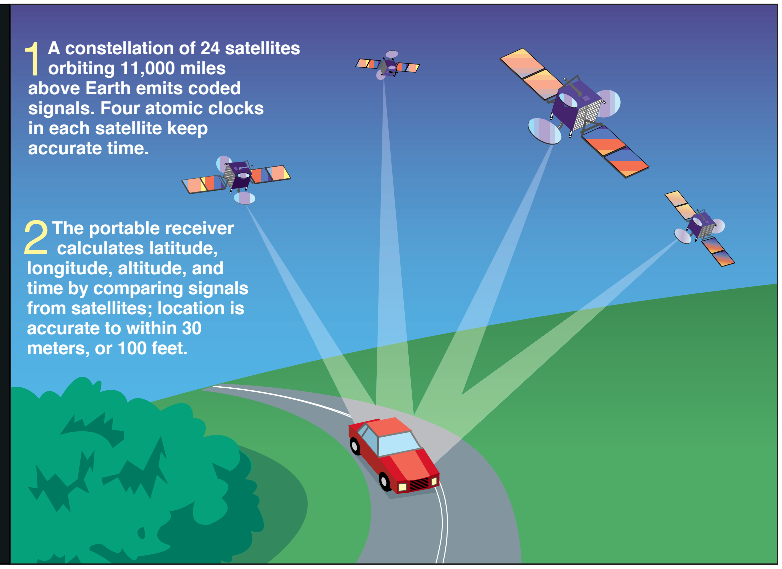
In just a few short years, applications for GPS already have become almost limitless:

- Emergency vehicles use GPS to pinpoint destinations and map their routes.
- GPS is used to locate vessels lost at sea.
- Trucking and transportation services use GPS to keep track of their fleets and to speed deliveries.
- Shipping companies equip their tankers and freighters with GPS for navigation and to record and control the movement of their vessels.

THE GLOBAL POSITIONING SYSTEM: HOW IT WORKS



Rockwell International



Adapted from *The Washington Post*

• Pleasure boaters and owners of small commercial vehicles rely on GPS for navigation.

• Civilian pilots use GPS for navigation, crop-dusting, aerial photography, and surveying.

• Airlines have saved millions of dollars by using GPS to hone their flight plans; GPS can be used for instrument landing at small, as well as large, airports and is making new air-avoidance systems possible.

• GPS is used regularly for mapping, measuring the earth, and surveying. GPS has been used to map roads, to track forest fires, and to guide the blades of bulldozers in construction processes, making grading accurate to within a few inches.

• Earth scientists use GPS to monitor earthquakes and the shifting of the earth's tectonic plates.

• Telecommunications companies increasingly rely on GPS to synchronize their land-based digital networks, comparing their reference clocks directly with GPS time.

• Satellite builders use GPS receivers to track the positions of their satellites.

• GPS is being installed in automobiles so that drivers not only can find out where they are but also can be given directions. In Japan, 500,000 automobiles have already been equipped with a GPS-based navigation system.

That's just the beginning. The current worldwide market for GPS receivers and technology is estimated at over $2 billion and is expected to grow to over $30 billion in the next 10 years.

It Started with Basic Research . . .

The history of GPS is an account of how basic research first made possible a vital defense technology and then a variety of important commercial applications. Many other technological advances also contributed to the development of GPS, among them satellite launching and control technologies, solid state devices, microchips, correlation circuitry, time-difference-of-arrival technology, microwave communication, and radionavigation. This account focuses on how the quest for understanding the nature of the atomic world, in particular the creation of atomic clocks to study relativity and Einstein's physics, led to the creation of highly accurate clocks and how those were later put to use, in combination with satellite tracking technology, to satisfy the basic human desire to know where we are and where we are going.

For centuries, the only way to navigate was to look at the position of the sun and stars and use dead reckoning. Even after modern clocks were developed, making it possible to find one's longitude, the most accurate instruments could yield a position that was accurate only to within a few miles. However, when the Soviet Union launched *Sputnik* on October 4, 1957, it was immediately recognized that this "artificial star" could be used as a navigational tool. The very next evening, researchers at the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT) were able to determine the satellite's orbit precisely by observing how the apparent frequency of its radio signal increased as it approached and decreased as it departed—an effect known as the Doppler shift. The proof that a satellite's orbit could be precisely determined from the ground was the first step in establishing that positions on the ground could be determined by homing in on the signals broadcast by satellites.

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In the years that followed, the U.S. Navy experimented with a series of satellite navigation systems, beginning with the Transit system in 1965, which was developed to meet the navigational needs of submarines carrying Polaris nuclear missiles. These submarines needed to remain hidden and submerged for months at a time, but gyroscope-based navigation, known as inertial navigation, could not sustain its accuracy over such long periods. The Transit system comprised a half-dozen satellites that would circle the earth continuously in polar orbits. By analyzing the radio signals transmitted by the satellites—in essence, measuring the Doppler shifts of the signals—a submarine could accurately determine its location in 10 or 15 minutes. In 1973, the Department of Defense was looking for a foolproof method of satellite navigation. A brainstorming session at the Pentagon over the Labor Day weekend produced the concept of GPS on the basis of the department's experience with all its satellite predecessors. The essential components of GPS are the 24 Navstar satellites built by Rockwell International, each the size of a large automobile and weighing some 1,900 pounds. Each satellite orbits the earth every 12 hours in a formation that ensures that every point on the planet will always be in radio contact with at least four satellites. The first operational GPS satellite was launched in 1978, and the system reached full 24-satellite capability in 1993.

Considering how extraordinarily sophisticated the technology is, the operating principle of GPS is remarkably simple. Each satellite continuously broadcasts a digital radio signal that includes both its own position and the time, exact to a billionth of a second. A GPS receiver takes this information—from four satellites—and uses it to calculate its position on the planet to within a few hundred feet. The receiver compares its own time with the time sent by a satellite and uses the difference between the two times to calculate its distance from the satellite. (Light travels at

A Chronology of Selected Events in the Development of GPS.

This timeline of selected events emphasizes early research in physics, notably atomic clocks, that contributed to the development of the Global Positioning System and illustrates the value of such long-term basic research in the ultimate achievement of important benefits to society. It does not provide a complete portrait of the development of GPS.

1938-1940
I.I. Rabi invents molecular-beam magnetic resonance at Columbia University in 1938. He and his colleagues apply magnetic resonance to fundamental studies of atoms and molecules. Possibility of atomic clock to measure gravitational red shift is discussed. Rabi is awarded the Nobel Prize for this work in 1944.

1949
Norman Ramsey invents separated-oscillatory-field resonance method at Harvard University, for which he was awarded the Nobel Prize in 1989. Jerrold Zacharias proposes using Ramsey's method to create cesium-beam "fountain" clock that would be accurate enough to measure gravitational red shift.

1949
National Bureau of Standards operates atomic clock based on microwave absorption in ammonia gas. Work starts on cesium-beam atomic clock.

1954
Charles Townes at Columbia University demonstrates operation of the first maser based on emission of radiation from ammonia molecules. Townes shared the 1964 Nobel Prize in physics.

1954-1956
Zacharias and National Company develop the first self-contained portable atomic clock, the Atomichron.

1957
***Sputnik* is launched in October by the Soviet Union. Satellite Doppler tracking is inaugurated at MIT Lincoln Laboratory and Johns Hopkins Applied Physics Laboratory (APL). Navy Transit program is started at APL in December.**

1959
Albert Kastler and Jean Brossel, working in Paris and at MIT, develop methods of optical pumping. Kastler is awarded the Nobel Prize for this work.

This article was published in 1997 and has not been updated or revised.

186,000 miles per second: if the satellite time happened to be, for example, one-thousandth of a second behind the GPS receiver's time, then the receiver would calculate that it was 186 miles from that satellite.) By checking its time against the time of three satellites whose positions are known, a receiver could pinpoint its longitude, latitude, and altitude.

The method just described would require that both the satellites and the receiver carry clocks of remarkable accuracy. However, having a receiver pick up a signal from a fourth satellite allows the receiver to get by with a relatively simple quartz clock—like that used in most watches. Once the receiver has made contact with four satellites, the system takes over and computes its position almost instantaneously.

For the system to work, the receiver has to know exactly where the satellites are and the satellites have to be able to keep reliable and extraordinarily accurate time. Accuracy is ensured by having each satellite carry four atomic clocks, the most accurate timing devices ever made. Reliability is ensured by the satellites' 11,000-mile-high orbits, which put them far above the atmosphere and keep them moving in very predictable trajectories. The Department of Defense monitors the satellites as they pass overhead twice a day and measures their speed, position, and altitude precisely. That information is sent back to the satellites, which broadcast it along with their timing signals.

A Tool to Study Nature

GPS itself was born as a military tool, but the atomic clocks that made GPS possible originated in basic research shortly before the Second World War. It was then that scientists found that high-precision techniques developed to study fundamental atomic structure could be used to make an atomic clock. Their inspiration had to do not with ultraprecise navigation, but rather with the dream of making a clock good enough to study the nature of time itself—in particular, the effect of gravity on time predicted by Einstein's theory of gravity and known as the gravitational red shift.

Until the late 1920s, the most accurate timepieces depended on the regular swing of a pendulum. They were superseded by more accurate clocks based on the regular vibrations of a quartz crystal, which could keep time to within less than one-thousandth of a second per day. Even that kind of precision, however, would not suffice for scientists who wanted to study Einstein's theory of gravity. According to Einstein, a gravitational field would distort both space and time. Thus, a clock on top of Mount Everest, for instance, was predicted to run 30 millionths of a second per day faster than an identical clock at sea level. The

1960
Ramsey and students Kleppner and Goldenberg operate hydrogen maser at Harvard University.

1960-1965
Rubidium optically pumped clock is introduced. Cesium frequency standards are installed in most international time-standard laboratories.

1961
Development of GPS begins at Aerospace Corporation as a system designed to meet military needs.

1964-1965
First position fix from a Transit satellite is computed aboard Polaris submarine.

1967
Transit system is made available to civilian community.

1968
Standards of a Defense Navigation Satellite System are defined.

1973
Development of Navstar GPS is approved by the Department of Defense.

1974
First GPS test satellite, from Timation program, is launched to test rubidium clocks and time-dissemination techniques.

1977
Test satellite incorporating principal features of later GPS satellites, including first cesium clocks in space, is launched.

1978-1985
Ten prototype GPS satellites are launched, built by Rockwell International.

1989-1993
Series of 24 satellites are launched at about 6 per year. Final satellite is launched on June 26, 1993.

1996
White House announces that a higher level of GPS accuracy will be available to everyone.

only way to make measurements this accurate was to control a clock by the infinitesimal oscillations of the atom itself.

Barton Silverman, *New York Times*

Harvard University

Two pioneering scientists whose work contributed to the Global Positioning System: left, I.I. Rabi's research on the fundamental properties of atoms and nuclei led to his invention of a technique called magnetic resonance on which the first atomic clock was based; right, Rabi's former student, Norman Ramsey, laid the groundwork for the development of the cesium-beam "fountain" clock and invented the hydrogen maser, devices that redefined timekeeping.

Rabi's Clock

According to the laws of quantum physics, atoms absorb or emit electromagnetic energy in discrete amounts that correspond to the differences in energy between the different electronic configurations of the atoms, i.e., different configurations of the electrons surrounding their nuclei. When an atom undergoes a transition from one such "energy state" to a lower one—it emits an electromagnetic wave of a discrete characteristic frequency, known as the resonant frequency. These resonant frequencies are identical for every atom of a given type—cesium 133 atoms, for example, all have a resonant frequency of exactly 9,192,631,770 cycles per second. For this reason, the cesium atom can be used as a metronome with which to keep extraordinarily precise time.

The first substantial progress toward developing clocks based on such an atomic timekeeper was achieved in the 1930s at a Columbia University laboratory in which I.I. Rabi and his students studied the fundamental properties of atoms and nuclei. In the course of his research, Rabi invented the technique known as magnetic resonance, by which he could measure the natural resonant frequencies of atoms. Rabi won the 1944 Nobel Prize for his work. It was in that year that he first suggested—"tossed off the idea," as his students put it—that the precision of these resonances are so great that they could be used to make a clock of extraordinary accuracy. In particular, he proposed using the frequencies of what are known as "hyperfine transitions" of the atoms—transitions between two states of slightly different energy corresponding to different magnetic interactions between the nucleus of an atom and its electrons.

In such a clock, a beam of atoms in one particular hyperfine state passes through an oscillating electromagnetic field. The closer the oscillation frequency of that field to the frequency of the hyperfine transition of the atom, the more atoms absorb energy from the field and thereby undergo a transition from the original hyperfine state to another one. A feedback loop adjusts the frequency of the oscillating field until virtually all the atoms make the transition. An atomic clock uses the frequency of the oscillating field—now perfectly in step with the precise resonant frequency of the atoms—as a metronome to generate time pulses.

Rabi himself never pursued the development of such a clock, but other researchers went on to improve on the idea and perfect the technology. In 1949, for instance, research by Rabi's student Norman Ramsey suggested that making the atoms pass twice through the oscillating electromagnetic field could result in a much more accurate clock. In 1989 Ramsey was awarded the Nobel Prize for his work.

Practical Applications

After the war, the U.S. National Bureau of Standards and the British National Physical Laboratory both set out to create atomic-time standards based on the atomic-resonance work of Rabi and his students. The first atomic clock was established at the National Physical Laboratory by Louis

Essen and John V.L. Parry, but this clock required a roomful of equipment. Another of Rabi's former associates, Jerrold Zacharias of MIT, managed to turn the atomic clocks into practical devices. Zacharias had plans for building what he called an atomic fountain, a visionary type of atomic clock that would be accurate enough to study the effect of gravity on time that had been predicted by Einstein. In the process, he developed an atomic clock small enough to be wheeled from one laboratory to another. In 1954, Zacharias joined with the National Company in Malden, Massachusetts, to build a commercial atomic clock based on his portable device. The company produced the Atomichron, the first commercial atomic clock, 2 years later and sold 50 within 4 years. The cesium atomic clocks used in GPS today are all descendants of the Atomichron.

By 1967, research in atomic clocks had proved so fruitful that the second was redefined in terms of the oscillations of a cesium atom. Today's atomic clocks are typically accurate to within 1 second in 100,000 years.

Physicists have continued to experiment with novel variations on the atomic-resonance ideas of Rabi and his students and to put them to work in atomic clocks. Rather than using magnets, one technique makes use of a phenomenon known as optical pumping to select out the energy levels of the atoms that will do the timekeeping and employs a beam of light to force all the atoms in the beam into the desired state. This work led to a Nobel Prize for Alfred Kastler of the École Normal Supérieure in Paris. Today, many atomic clocks use optically pumped rubidium atoms instead of cesium. The rubidium clocks are considerably less expensive and smaller than cesium clocks, but they are not quite as accurate.

Another type of atomic clock is known as the hydrogen maser. Masers originated in research on the structure of molecules by Charles Townes and his colleagues at Columbia University in 1954, work for which Townes shared the 1964 Nobel Prize in physics. The maser, which is the precursor of the laser, is a microwave device that generates its signal by direct emission of radiation from atoms or molecules. While Townes's original maser used ammonia, Ramsey and his colleagues at Harvard developed a maser in 1960 that operates with hydrogen and serves as an atomic clock of extreme precision.

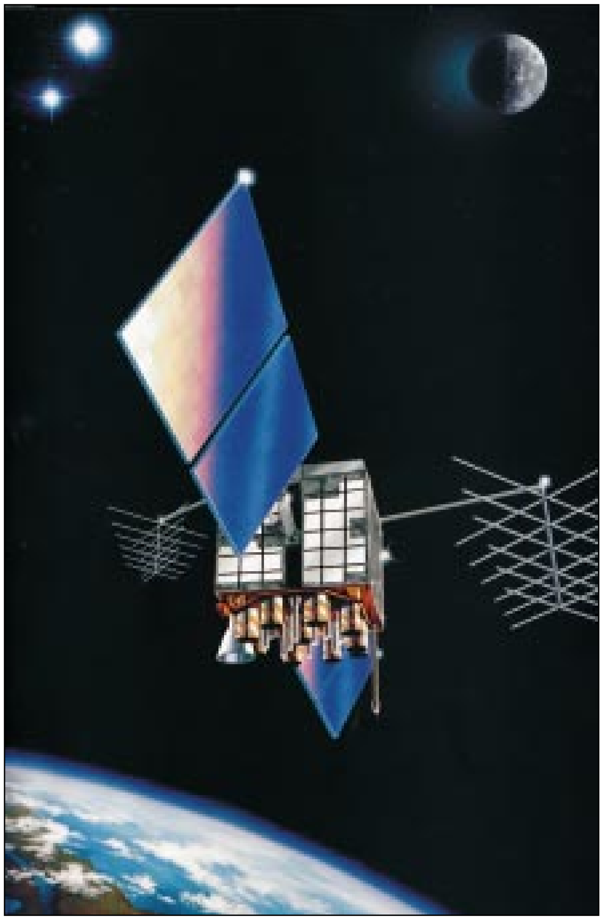
By 1967, research in atomic clocks had proved so fruitful that the second was redefined in terms of the oscillations of a cesium atom. Today's atomic clocks are typically accurate to within 1 second in 100,000 years. Our nation's primary time standard is the recently inaugurated atomic clock at the National Institute of Standards and Technology, called NIST-7. Its estimated accuracy is to within 1 second in 3 million years.

Over the years, all three clocks—the cesium-beam clock, the hydrogen-maser clock, and the rubidium clock—have seen service in space, either in satellites or in ground control systems. GPS satellites ultimately rely on cesium clocks that resemble those conceptualized by Rabi 60 years ago.

In 1993, 2 decades after it was conceived in the Pentagon, GPS became fully functional with the launching of its 24th satellite. The satellites are operated by the U.S. Air Force, which monitors them from five ground stations around the world. The data gathered are analyzed at the Air Force Consolidated Space Operations Center in Colorado, which transmits daily updates to each satellite, correcting their clocks and their orbital data.

GPS and the Future

It is often forgotten that GPS is still a military device built by the Department of Defense at a cost of $12 billion and intended primarily for military use. That fact has led to one of the few controversies surrounding the remarkably successful system. As with any new technology, progress brings risk, and GPS potentially could be used to aid smugglers, terrorists, or hostile forces. The Pentagon made the GPS system available for commercial use only after being pressured by the companies that built the equipment and saw the enormous potential market for it. As a compromise, however, the Pentagon initiated a policy known as selective availability, whereby the most accurate signals broadcast by GPS satellites would be reserved strictly for military and other authorized users. GPS satellites now broadcast two signals: a civilian signal that is accurate to within 100 feet and a second signal that only the military can decode that is accurate to within 60 feet. The Pentagon has also reserved the ability to introduce errors at any time



Twenty-four Navstar satellites—each the size of a large automobile and weighing some 1,900 pounds—circle the earth in 11,000-mile-high orbits. The satellite system, built by Rockwell International and operated by the U.S. Air Force, was completed in 1993, 20 years after it was first conceived in the Pentagon. (Lockheed Martin Astro Space)

into the civilian signal to reduce its accuracy to about 300 feet.

In March 1996, the White House announced that the higher level of GPS accuracy will be made available to everyone, and the practice of degrading civil GPS signals will be phased out within a decade. The White House also reaffirmed the federal government's commitment to providing GPS services for peaceful civil, commercial, and scientific use on a worldwide basis and free of charge.

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The future of GPS appears to be virtually unlimited; technological fantasies abound. The system provides a novel, unique, and instantly available address for every square yard on the surface of the planet—a new international standard for locations and distances. To the computers of the world, at least, our locations may be defined not by a street address, a city, and a state, but by a longitude and a latitude. With the GPS location of services stored with phone numbers in computerized "yellow pages," the search for a local restaurant or the nearest gas station in any city, town, or suburb will be completed in an instant. With GPS, the world has been given a technology of unbounded promise, born in the laboratories of scientists who were motivated by their own curiosity to probe the nature of the universe and our world, and built on the fruits of publically supported basic research.

This article, which was published in 1997 and has not been updated or revised, was adapted by Gary Taubes from an article written by MIT scientist Daniel Kleppner for ***Beyond Discovery: The Path from Research to Human Benefit***™*, a project of the National Academy of Sciences. The Academy, located in Washington, D.C., is a society of distinguished scholars engaged in scientific and engineering research and dedicated to the use of science and technology for the public welfare. For more than a century, it has provided independent, objective scientific advice to the nation.*

April 1997