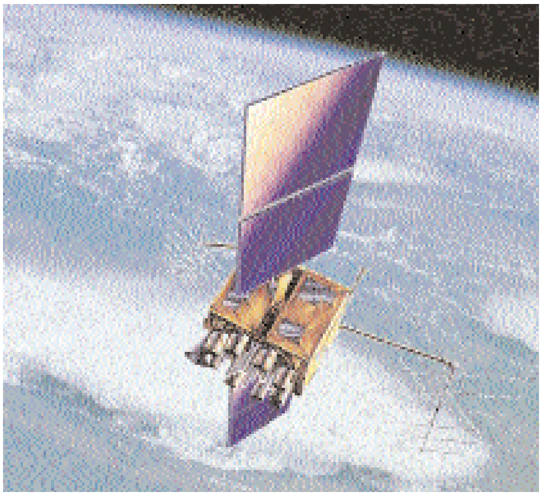
**FORUM**

by Neil Ashby

# Global Positioning System: A High-Tech Success



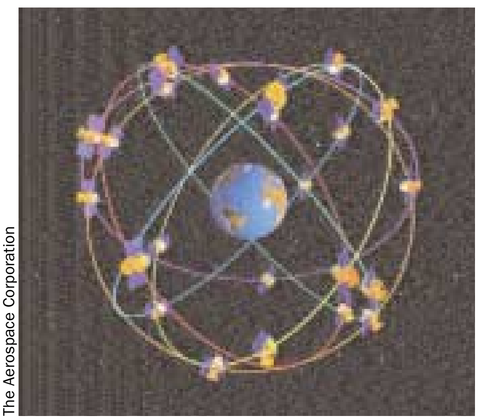
Lockheed Martin

**Image of a Global Positioning System satellite of the current generation (termed Block IIR) superposed on a monsoon image from an early Challenger mission.**

Since the beginning of history, wayfarers and mariners have wanted to know their position and time. Improvements in the art of navigation have historically developed hand-in-hand with industry and technology. As civilization advanced, the compass, sextant, chronometer, and gyroscope each provided increasingly accurate navigation tools. Now, inexpensive receivers using synchronized signals from Earth-orbiting satellites are available to provide accurate position, velocity, and time measurements anywhere on or near Earth. Few if any large engineering systems rely so broadly on fundamental physics and technology applications as do modern navigation satellite systems, such as the U.S. Global Positioning System (GPS).

Accurate position and time, combined with advanced technology, can lead to some amazing applications. Guided by a synthesized voice, a blind person can walk down a street and into a particular door in a building. And vehicle operators use this mode of navigation with increasing frequency. Animal and vehicle tracking using the GPS allows more careful management of these assets. Disposable GPS receivers dropped through tropical storms transmit higher-resolution measurements of temperature, humidity, pressure, and wind speed than any other method—a use that has improved our understanding of how tropical storms intensify.

Slight movements of bridges or buildings, in response to various loads, can be monitored in real time. Relative movements of Earth's crust can be accurately measured in a short time, contributing to a better understanding of the tectonic processes within the planet and, possibly, to future predictions of earthquakes. With the press of a button, a lost hiker can send a distress signal that includes his or her location. These and many other creative applications of precise positioning are leading to a rapid economic expansion of GPS products and services.



The Aerospace Corporation

**Figure 1. The GPS includes 24 satellites distributed unevenly in six orbital planes, each plane with an inclination 55° from Earth's equatorial plane, and each orbit almost circular with a period of 11 h 58 min.**

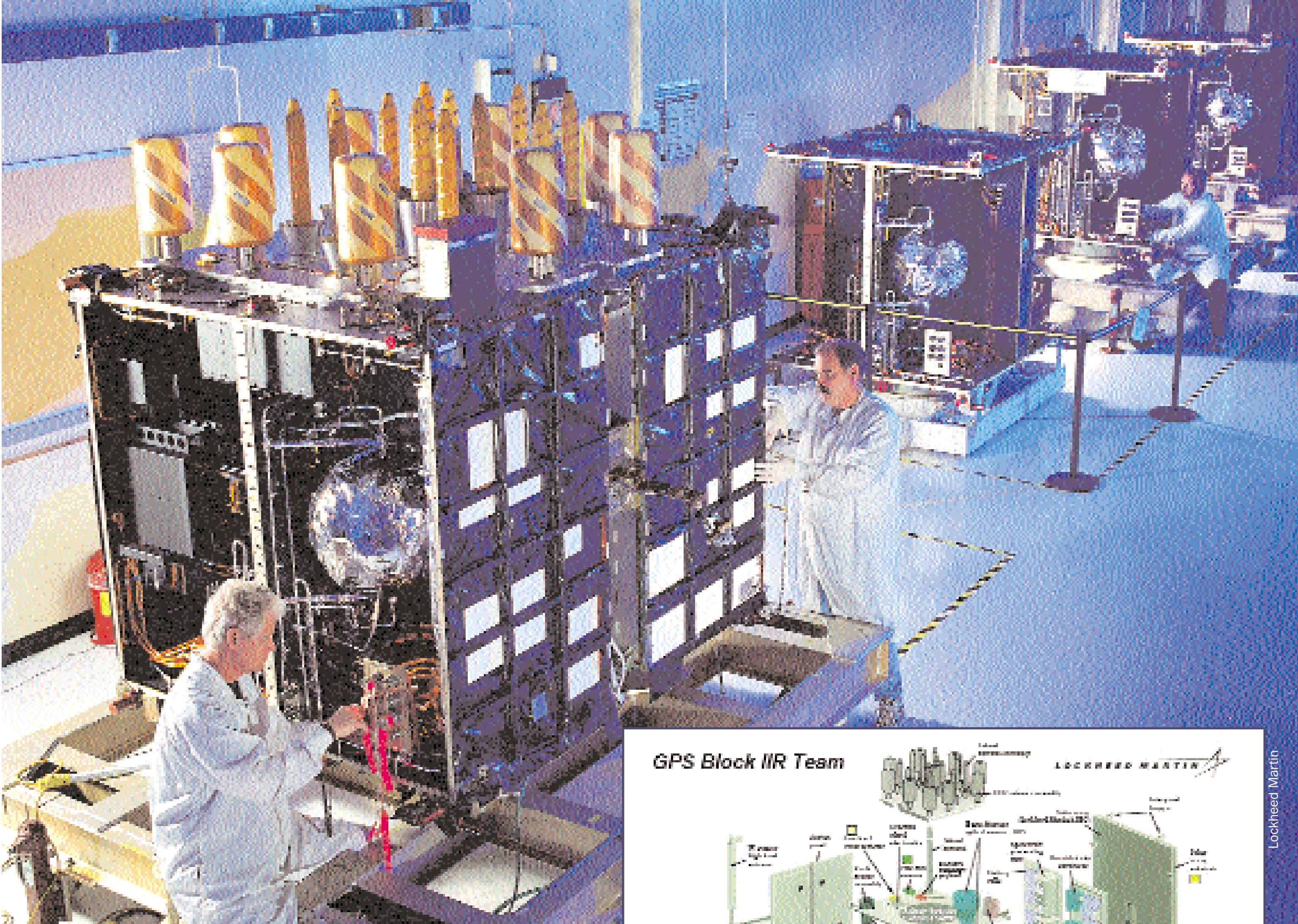
As a military system, the GPS has provided remarkable benefits to civilian users free of direct cost, and drawn some competition. The Russian GLONASS system is similar in many respects to the GPS, but now only 8 of the intended 24 satellites are operating in Earth orbit. The European GALILEO system, currently in the design phase, will use hydrogen masers as orbiting time references, and it will be funded by direct charges to users.

The orbiting segment of the GPS consists of 24 satellites (and, typically, two or three orbiting spares): four satellites in each of six different planes inclined 55° from Earth's equatorial plane (Figure 1). The satellites are positioned within their planes so that, from almost any place on Earth, at least four are above the horizon at any time. The nominal satellite altitudes—about 20,000 km—are chosen so that an observer fixed on the ground will "see" a given satellite at almost exactly the same place on the celestial sphere twice each day.

Atomic clocks in the satellites transmit synchronous timing signals toward Earth. Position determination is based on Einstein's principle of the constancy of the speed of light, which is valid in a local nonrotating reference frame fixed to Earth's center. The signals also carry navigation information—data from which the receiver computes the satellites' positions and transmission times. Receivers on or near Earth observe the arrival times of signals from the satellites using as reference an oscillator such as a quartz crystal. If the arrival times of signals from four or more satellites are measured at the same time, then the position and time of the receiver can be calculated accurately with the aid of the transmitted navigation data.

The need for atomic clocks in the GPS is easily understood. To reduce the effect of a clock error to less than 1 m, the time error on the clock must be less than that needed for light to travel 1 m—about 3 billionths of a second (3 ns). The clock error should be less than 3 ns for at least one orbital period (nearly half a day), so the fractional error must be less than 1 part in $10^{13}$. Only atomic clocks can achieve such performance.

Louis Essen and John V. L. Parry built the first atomic clock in 1955 at the National Physical Laboratory in Teddington, England. Today's orbiting GPS clocks have errors in the range of only 1 to 10 ns per day (Figure 3). Furthermore, microcircuit-fabrication techniques have led to dramatic reductions in the mass, size, and cost of atomic clocks. One such clock, containing 1 g of rubidium,



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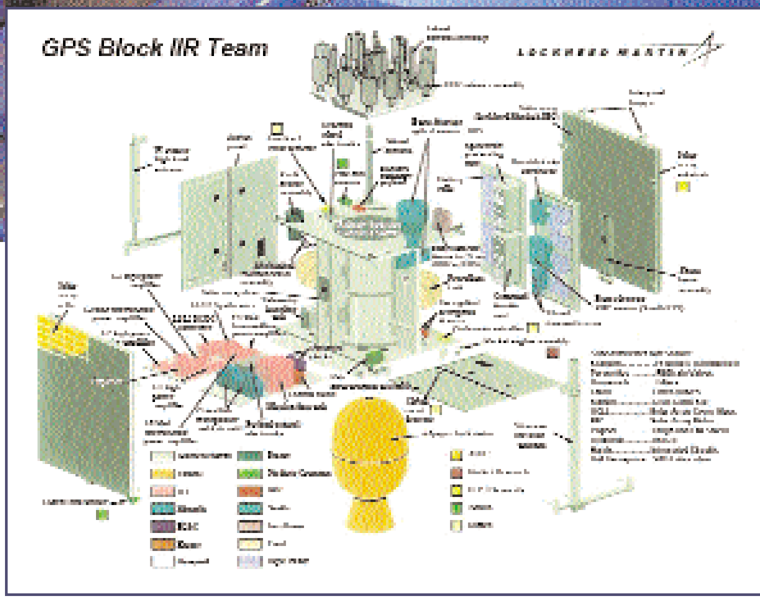



**Figure 2. Spiral structures on top of this Block IIR satellite on the assembly line are antennas that beam circularly polarized electromagnetic radiation toward Earth. Exploded view of Block IIR satellite at right shows about 30 subcontractors that developed various components of the satellite assembly.**

is expected to have a design life of 20 years.

GPS orbiting atomic clocks are based on the hyperfine interaction between the magnetic moment of an unpaired valence electron in an alkali atom, such as cesium or rubidium, and the nucleus's magnetic moment. Precise measurements of the oscillations of two specific hyperfine energy levels in these atoms provide the clocks' measure of time. Currently, the International Standard (SI) second is defined as 9,192,631,770 periods of the oscillation, corresponding to the two hyperfine levels of the ground state of cesium-133.

Data transmitted by GPS satellites are continuously monitored by receiving stations and forwarded to a master control station, where satellite orbits are computed and clock performance is checked for accuracy and stability. The updated orbital and clock data are then sent to the satellites for retransmission to users. Until recently, five remotely operated monitoring stations were located around the world. Stations operated by the National Imaging and Mapping Agency, a part of the U.S. Department of Defense (DOD), have joined these stations. Several independent organizations—including the International GPS Service and Caltech's Jet Propulsion Laboratory—also operate receiving stations and provide precise information about GPS satellite orbits to the public

## Origins

The GPS arose from the U.S. military's need for more accurate navigation. In the early 1960s, the Air Force and Navy intently studied precise ways to determine the distance and relative velocity of satellites as a means of navigation. The first such satellite system was the Navy's TRANSIT, which used measured Doppler shifts of signals transmitted from satellites for navigation. TRANSIT

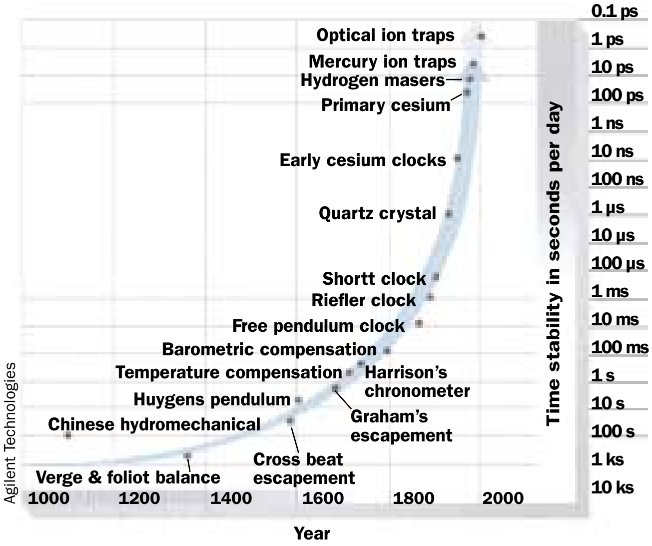



**Figure 3. Improvements in the performance of clocks over the past thousand years include atomic clocks in the GPS that can be as accurate as 1 billionth of a second (1 ns) per day.**

satellites operated between 1962 and 1996. As a result of information gained with this system, researchers better understood the small effects of solar radiation pressure, atmospheric drag, and higher multipoles of Earth's gravity field, which provided important information for satellite orbit prediction.

Another program, the Naval Research Laboratory's TIMATION project, provided both accurate position and precise time to passive terrestrial observers. (A passive user need not emit a signal that might reveal his or her location.) A master clock on the ground regularly updated the satellites' clocks. The spaceborne clocks were linked to the user's receiving equipment by ranging signals broadcast by satellites. Improved clock stability allowed more precise determinations of a satellite's location and also lengthened the time between required satellite-position updates. Two TIMATION satellites, each bearing a quartz clock accurate to about 1 part per billion, were orbited: one in 1967 and the other in 1969.

In the late 1960s and early 1970s, the Air Force's Space and Missile Systems Organization developed its 621B program, in which satellites transmitted a signal using pseudorandom noise to resist jamming. The 621B program provided users their altitude as well as latitude and longitude. This system was tested using aircraft between 1968 and 1971. But in 1973, the TRANSIT, TIMATION, and 621B projects were combined into the joint services GPS/NAVSTAR program. The first NAVSTAR satellite, NTS-2, was launched in 1977, and it carried a cesium atomic clock as its time reference. The GPS was first deployed for extensive military use in 1990 during the Gulf War, and it became fully operational with a full complement of 24 satellites in 1995.

The GPS has benefited greatly from the long-term attention and funding provided through the DOD for development, testing, and procurement. The initial contract for 12 GPS Block I satellites went to Rockwell International (1978–1988). Rockwell also received a follow-on contract for 9 Block II and 19 Block IIA satellites, which were launched between 1989 and 1995. Martin Marietta, now Lockheed Martin, won a production contract for 21 Block IIR satellites (Figure 2), originally intended for deployment between 1996 and 2001. However, production of 12 of these satellites has been delayed for modernization, which will improve navigation capability for all users. A third generation of GPS satellites, designated Block IIF, is on the drawing boards. Total DOD funding for the GPS for fiscal 2002 was $318 million for research, development, testing, and evaluation and $178 million for procurement.

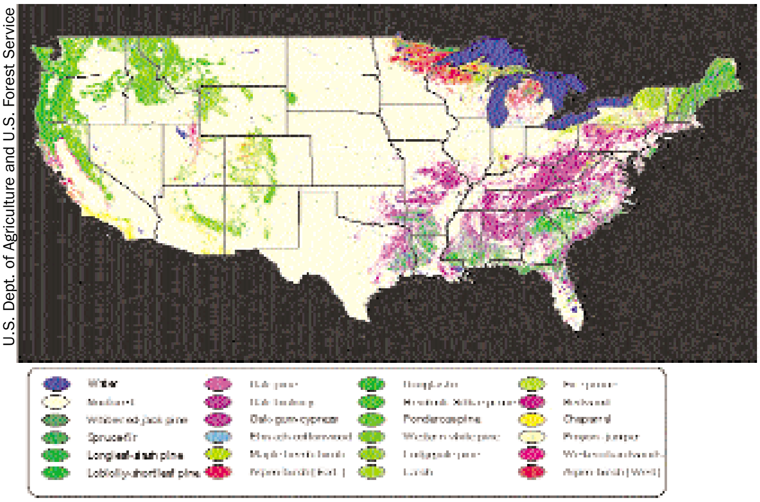
## Receivers

GPS receivers do not follow a standard design. The structures of GPS signals from space, as well as the encoding of navigation data, are specified in a publicly available document known as the "ICD-200 Interface Control Document." Receiver designers use this information to develop designs adapted for particular applications—from ship and aircraft navigation to uses by hikers and land surveyors. Thus, receiver designs vary widely in complexity and cost. A receiver intended to accurately compare primary time standards at two widely separated standards laboratories will be much more complex than a receiver intended for recreational use. Competition among manufacturers and advances in the mass production of integrated circuits have rapidly lowered receiver prices. A unit for an individual now costs about $100.

GPS signals are weak and easily obscured by buildings or forest cover, and they may suffer multiple reflections from buildings, vehicles, rocks, and other surfaces near a receiver, which results in an inaccurately computed position. Hence, the system has been judged insufficiently reliable for safety-critical applications such as blind-landing approaches by commercial aircraft, and GPS improvements are being developed and deployed worldwide. The Federal Aviation Administration, for example, is developing the Wide Area Augmentation System to provide precise guidance to pilots using airports and airstrips that have no precision-landing systems. Such projects will use signals similar to those from the GPS but transmitted from geostationary or other satellites, which help improve the integrity and accuracy of space-based positioning.

Precise position information can assist in the careful husbandry of natural resources—for example, the forest cover of the contiguous 48 states (Figure 4). The databases from which such maps emerge are periodically verified by field studies using GPS equipment. The resolution of such data is on the order of 1 mile. Similar maps of mineral resources can be of great value in the discovery and extraction of ore deposits. However, some data may not always be available to the general public because of a law enacted by Congress in 1991, known as the Privacy Amendment, that limits public access to some of the information that is contained in these databases.

Agriculture uses GPS receivers in real-time decisions about whether conditions are right to apply pesticides or fertilizers, which minimizes waste and helps prevent environmental damage. Sites of sunken vessels or underwater ruins with historically important artifacts can be precisely determined using the GPS so that archaeologists can easily return to them. Huge ore trucks or earth-moving machines can be fitted




U.S. Dept. of Agriculture and U.S. Forest Service

**Figure 4. Map of forest cover data obtained by advanced very high resolution radiometry and aided by field measurements using the GPS.**

with receivers and controlled remotely with minimal risk of collision or interference with other equipment. And many trucking companies track the locations of their fleets with the GPS.

Recent marketing studies predict that the GPS will have a significant economic impact in the near future. For example, the Federal Communications Commission recently mandated that wireless phones must automatically provide their location to 911 emergency-service providers; several companies are pursuing GPS-based solutions to this mandate. An economic study by Allied Business Intelligence (Oyster Bay, NY) estimated that sales of GPS equipment and services will grow to more than $34 billion by 2006. Revenue for the European GALILEO system is projected to be 10 billion euro (about $10 billion) per year.

Millions of receivers are manufactured and sold every year, and their prices are dropping as mass production increases. As receiver costs decrease, many opportunities will emerge for creative new uses of global-navigation satellite systems, particularly in the integration of miniature receivers with new applications such as robotic control, speech synthesis, proximity detection, and applications yet to be invented.

# Further reading

*GPS World Markets 2002*; Allied Business Intelligence: Oyster Bay, NY, 2002; 210 pp.

Parkinson, B., Spilker, J. J., Jr., Eds.; *The Global Positioning System: Theory and Applications*, Vols. I and II; American Institute of Aeronautics and Astronautics: Washington, DC, 1997; 793 pp. and 627 pp. Ω

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