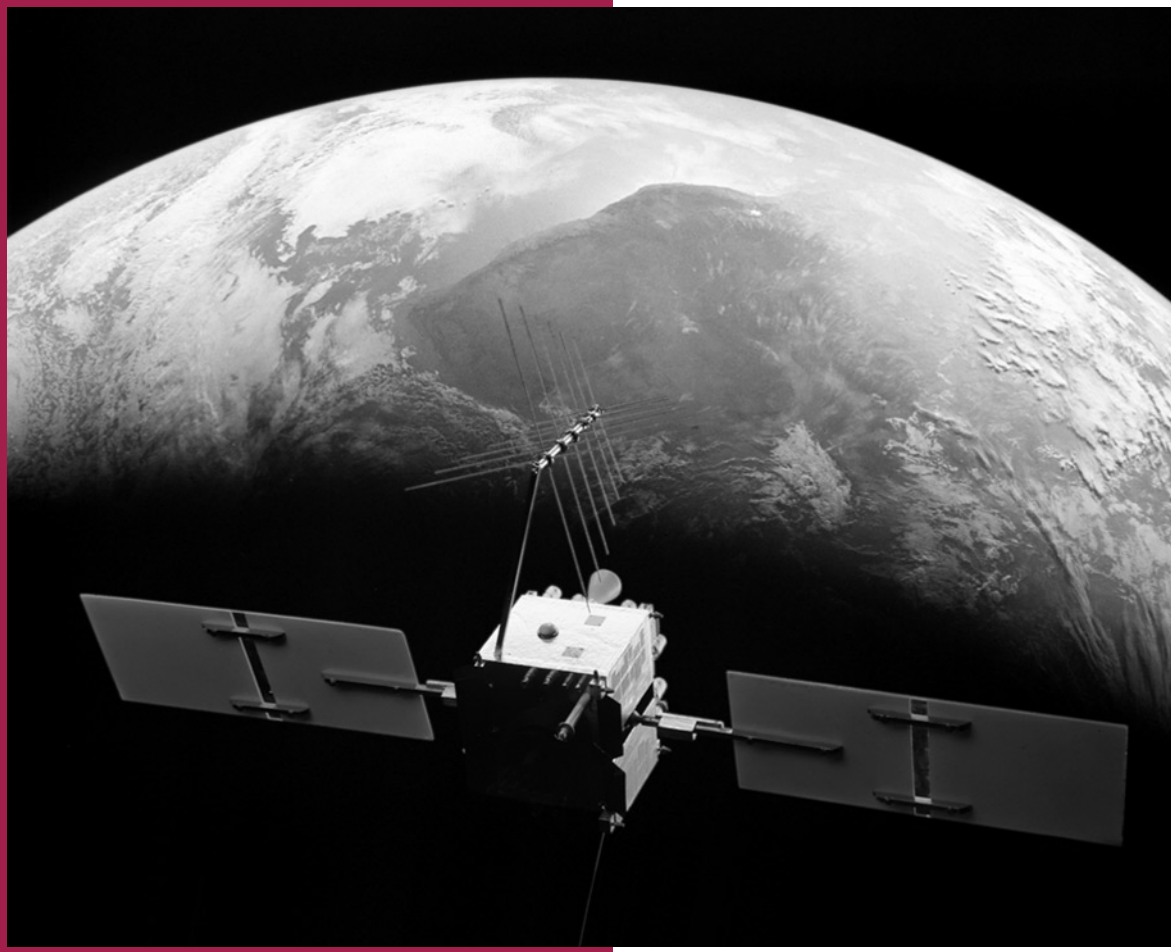
The Global Positioning System

The Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009-2957
http://www.aero.org/



THE AEROSPACE CORPORATION

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E. C. "Pete" Aldridge, Jr.
President and
Chief Executive Officer
The Aerospace Corporation

The men and women who created the Global Positioning System (GPS) were once young people like yourself. Each had a special interest in the marvelous order of mathematics and the physical laws affecting all our lives. They pursued a career in science or engineering and developed a navigation system that can tell you exactly where you are on Earth, any time of day or night, in any type of weather. The Aerospace Corporation is pleased to provide this booklet as an aid to your understanding of GPS.

If you are interested in pursuing an exciting career in navigation or a related field, I encourage you to study mathematics and science in junior high and high school. By becoming proficient in these areas, you will lay the groundwork for an understanding of physics and astronomy—the building blocks of the science of navigation.

This booklet provides basic information on the subject. It is intended to stimulate your interest. Your school librarian can help you locate additional details on the many fascinating fields supporting the use and exploration of space.

Has anyone ever asked you what career you wanted to pursue?

Imagine being an archaeologist on an expedition to the Yucatan Peninsula in Mexico. After preparing for your trip for months, you are certain that somewhere close by are the ruins of villages once populated by Mayan Indians. The forest is dense, the sun is hot, and the air is moist and humid. The only way you can record where you have been, or find your way back to civilization, is by using the almost magic power of your GPS receiver.

Or let's suppose you are an oceanographer for the International Ice Patrol. You may be responsible for finding icebergs that form in the cold waters of the north Atlantic Ocean. Some of these icebergs are 50 miles long. They are a major threat to the ships that travel those waters, and more than 300 of them form every winter.

Using a GPS receiver, you are able to help ships avoid disaster by zeroing in on the position of the icebergs and notifying ship captains of their locations, perhaps averting disaster.

There will probably be a time soon when every car on the road can be equipped with a GPS receiver, including a video screen installed in the dashboard. The in-dash monitor will be a full-color display showing your location and a map of the roads around you. It will probably monitor your car's performance and your car phone as well. Systems as amazing as this one are already being tested on highways in the United States.

Cover: Photo illustration by The Aerospace Corporation/NASA

What is GPS?

GPS, which stands for Global Positioning System, is the only system today able to show you your exact position on the Earth anytime, in any weather, anywhere. GPS satellites, 24 in all, orbit 11,000 nautical miles above the Earth. They are continuously monitored by ground stations located worldwide. The satellites transmit signals that can be detected by anyone with a GPS receiver. Using the receiver, you can determine your location with great precision.

GPS is one of history's most exciting and revolutionary developments, and new uses for it are constantly being discovered. But before we learn more about GPS, it's important to understand a bit more about navigation.

What is Navigation?

Since prehistoric times, people have been trying to figure out a reliable way to tell where they are and to help guide them to where they are going. Cavemen probably used stones and twigs to mark a trail when they set out hunting for food. The earliest mariners followed the coast closely to keep from getting lost. When navigators first sailed into the open ocean, they discovered they could chart their course by following the stars. The ancient Phoenicians used the North Star to journey from Egypt and Crete. According to Homer, the goddess Athena told Odysseus to "keep the Great Bear on his left" during his travels from Calypso's Island. Unfortunately, the stars are only visible at night—and only on clear nights.

The next major developments in the quest for the perfect method of navigation were the magnetic compass and the sextant. The needle of a compass always points north, so it is always possible to know in what direction you are going.

The sextant uses adjustable mirrors to measure the exact angle of the stars, moon, and sun above the horizon. However, in the early days of its use, it was only possible to determine latitude (the location on the Earth measured north or south from the equator) from the sextant observations. Sailors were still unable to determine their longitude (the location on the Earth measured east or west). This was such a serious problem that in the 17th century, the British formed a special Board of Longitude consisting of well-known scientists. This group offered £20,000, equal to about a million of today's dollars, to anybody who could find a way to determine a ship's longitude within 30 nautical miles.

The generous offer paid off. In 1761, a cabinetmaker named John Harrison developed a shipboard timepiece called a chronometer, which lost or gained only about one second a day—incredibly accurate for the time. For the next two centuries, sextants and chronometers were used in combination to provide latitude and longitude information.

In the early 20th century several radio-based navigation systems were developed, which were used widely during World War II. Both allied and enemy ships and airplanes used ground-based radio-navigation systems as the technology advanced.

Map courtesy of Dr. Seymour Schwartz

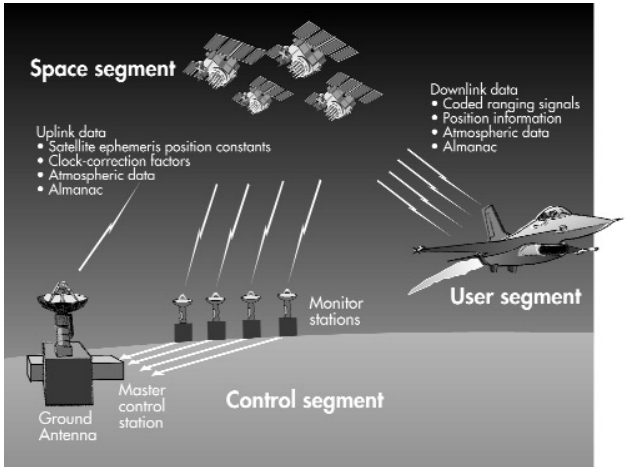
A few ground-based radio-navigation systems are still in use today. One drawback of using radio waves generated on the ground is that you must choose between a system that is very accurate but doesn't cover a wide area, or one that covers a wide area but is not very accurate. High-frequency radio waves (like UHF TV) can provide accurate position location but can only be picked up in a small, localized area. Lower frequency radio waves (like AM radio) can cover a larger area, but are not a good yardstick to tell you exactly where you are.

Scientists, therefore, decided that the only way to provide coverage for the entire world was to place high-frequency radio transmitters in space. A transmitter high above the Earth sending a high-frequency radio wave with a special coded signal can cover a large area and still overcome much of the "noise" encountered on the way to the ground. This is one of the main principles behind the GPS system.

GPS Elements

GPS has 3 parts: the *space segment,* the *user segment,* and the *control segment.* The space segment consists of 24 satellites, each in its own orbit 11,000 nautical miles above the Earth. The user segment consists of receivers, which you can hold in your hand or mount in your car. The control segment consists of ground stations (five of them, located around the world) that make sure the satellites are working properly.

One trip around the Earth in space equals one orbit. The GPS satellites each take 12 hours to orbit the Earth. Each satellite is equipped with an accurate clock to let it broadcast signals coupled with a precise time message. The ground unit receives the satellite signal, which travels at the speed of light. Even at this speed, the signal takes a measurable amount of time to reach the receiver. The difference between the time the signal is sent and the time it is received, multiplied by the speed of light, enables the receiver to calculate the distance to the satellite. To measure precise latitude, longitude, and altitude, the receiver measures the time it took for the signals from four separate satellites to get to the receiver.



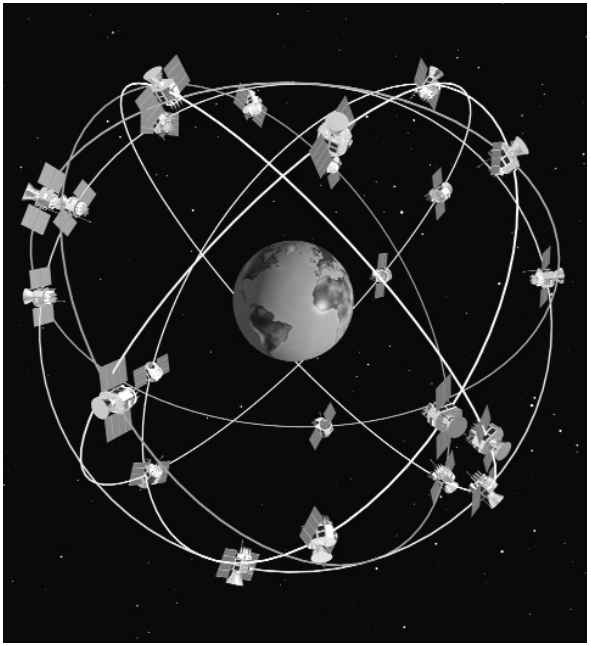
GPS consists of three major segments: the space segment, the user segment, and the control segment.

The GPS system can tell you your location anywhere on or above the Earth to within about 300 feet. Even greater accuracy, usually within less than three feet, can be obtained with corrections calculated by a GPS receiver at a known fixed location.

To help you understand the GPS system, let's take the three parts of the system—the satellites, the receivers, and the ground control—and discuss them in more detail. Then we'll look more closely at how GPS works.

Satellites in Space

As we've said, the complete GPS space system includes 24 satellites, 11,000 nautical miles above the Earth, which take 12 hours to go around the Earth once (one orbit). They are positioned so that we can receive signals from six of them nearly 100 percent of the time at any point on Earth. You need that many signals to get the best position information.



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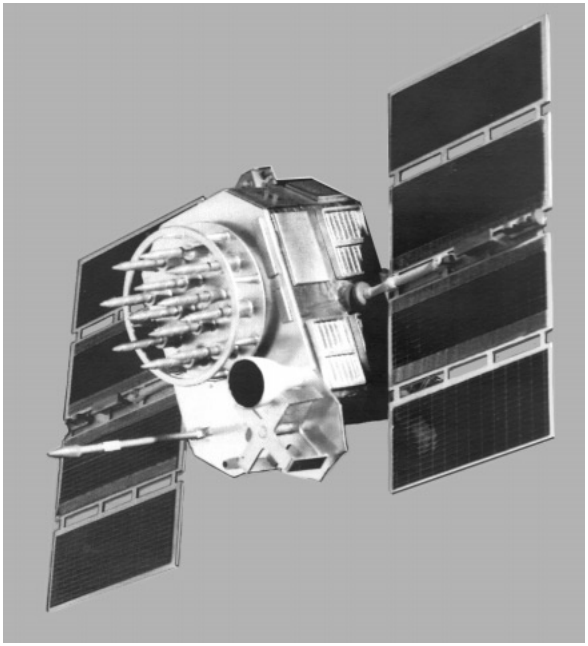
The 24-satellite constellation orbits 11,000 nautical miles above Earth. Each satellite completes its orbit every 12 hours. This diagram gives you an idea of satellite positions and is not to scale.

Satellites are equipped with very precise clocks that keep accurate time to within three nanoseconds—that's 0.000000003, or three billionths, of a second. This precision timing is important because the receiver must know exactly how long it takes for its signal to get to each satellite and return. By knowing the exact amount of time the signal has taken to get back from each satellite, it can calculate its position.

The first GPS satellite was launched in 1978. The first 10 satellites were developmental satellites, called Block I. From 1989 to 1993, 23 production satellites, called Block II, were launched. The launch of the 24th satellite in 1994 completed the system.



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GPS Block II is a production satellite first launched in 1989. Block II consists of 24 satellites, the last one launched in 1994.

Ground Control Stations

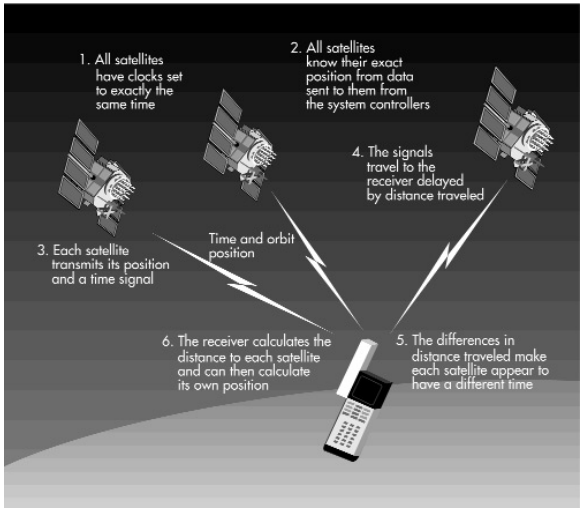
The GPS control, or ground, segment consists of unmanned monitor stations located around the world (Hawaii and Kwajalein in the Pacific Ocean; Diego Garcia in the Indian Ocean; Ascension Island in the Atlantic Ocean; and Colorado Springs, Colorado); a master ground station at Falcon Air Force Base in Colorado Springs, Colorado; and four large ground antenna stations that broadcast signals to the satellites. The stations also track and monitor the GPS satellites.

Receivers

GPS receivers can be hand carried or installed on aircraft, ships, tanks, submarines, cars,

Photo courtesy of Magellan Systems

GPS is used by surveyors, utility companies, and oil and gas explorers for precise positioning.



Principles behind the Global Positioning System are simple. The system is based on the measurement of the distance between the receiver and the satellites.

and trucks. These receivers detect, decode, and process GPS satellite signals. More than 100 different receiver models are already in use. The typical hand-held receiver is about the size of a cellular telephone, and the newer models are even smaller. The hand-held units distributed to U.S. armed forces personnel during the Persian Gulf war weighed only 28 ounces.

How GPS Works

So you can more easily understand some of the scientific principles that make GPS work, let's discuss the basic features of the system. The principle behind GPS is the measurement of distance (or "range") between the receiver and the satellites. The satellites also tell us exactly where they are in their orbits. It works

something like this: If we know our exact distance from a satellite in space, we know we are somewhere on the surface of an imaginary sphere with radius equal to the distance to the satellite radius. If we know our exact distance from two satellites, we know that we are located somewhere on the line where the two spheres intersect. And, if we take a third measurement, there are only two possible points where we could be located. One of these is usually impossible, and the GPS receivers have mathematical methods of eliminating the impossible location.

An Amazing System

We now have a fairly clear picture of the GPS system. We know that it consists of satellites whose paths are monitored by ground sta-

tions. Each satellite generates radio signals that allow a receiver to estimate the satellite location and distance between the satellite and the receiver. The receiver uses the measurements to calculate where on or above the Earth the user is located.

Now that we have an idea about how the GPS functions, let's see how we can put it to work for us. As you might imagine, GPS has many uses in both military and civilian life.

Military Uses for GPS

Although the GPS system was completed only recently, it has already proved to be a most valuable aid to U.S. military forces. Picture the desert, with its wide, featureless expanses of sand. The terrain looks much the same for miles. Without a reliable navigation system, U.S. forces could not have performed the maneuvers of Operation Desert Storm. With GPS, the soldiers were able to go places and maneuver in sandstorms or at night when even the troops who lived there couldn't. Initially, more than 1,000 portable commercial receivers were purchased for their use. The demand was so great that, before the end of the conflict, more than 9,000 commercial receivers were in use in the Gulf region. They were carried by foot soldiers and attached to vehicles, helicopters, and aircraft instrument panels. GPS receivers were used in several aircraft, including F-16 fighters, KC-135 aerial refuelers and B-52 bombers; Navy ships used them for rendezvous, minesweeping, and aircraft operations.

GPS has become important for nearly all military operations and weapons systems. In addition, it is used on satellites to obtain highly accurate orbit data and to control spacecraft orientation.

Photo courtesy of Magellan Systems

More than 9,000 GPS receivers were used by U.S. and coalition forces during Operation Desert Storm.

GPS is based on a system of coordinates called the Worldwide Geodetic System 1984 (WGS-84), similar to the latitude and longitude lines you see on wall maps in school. The WGS-84 system provides a built-in frame of reference for all military activities, so units can synchronize their maneuvers.

GPS Uses in Everyday Life

The GPS system was developed to meet military needs of the Department of Defense, but new ways to use its capabilities are continually being found. As you have read, the system has been used in aircraft and ships, but there are many other ways to benefit from GPS. We'll mention just a few.

During contruction of the tunnel under the English Channel, British and French crews started digging from opposite ends: one from Dover, England, one from Calais, France. They relied on GPS receivers outside the tunnel to check their positions along the way and to make sure they met exactly in the middle. Otherwise, the tunnel might have been crooked.

Remember the example of the car with a video display in the dashboard? Vehicle tracking is one of the fastest-growing GPS applications. GPS-equipped fleet vehicles, public transportation systems, delivery trucks, and courier services use receivers to monitor their locations at all times.

GPS is also helping to save lives. Many police, fire, and emergency medical service units are using GPS receivers to determine the police car, fire truck, or ambulance nearest to an emergency, enabling the quickest possible response in life-or-death situations.

Automobile manufacturers are offering moving-map displays guided by GPS receivers as an option on new vehicles. The displays can be removed and taken into a home to plan a trip. Several Florida rental car companies are demonstrating GPS-equipped vehicles that give directions to drivers on display screens and through synthesized voice instructions. No more getting lost on the way to Disney World!

Mapping and surveying companies use GPS extensively. In the field of wildlife management, endangered species such as Montana elk and Mojave Desert tortoises are being fitted with GPS receivers and tiny transmitters to

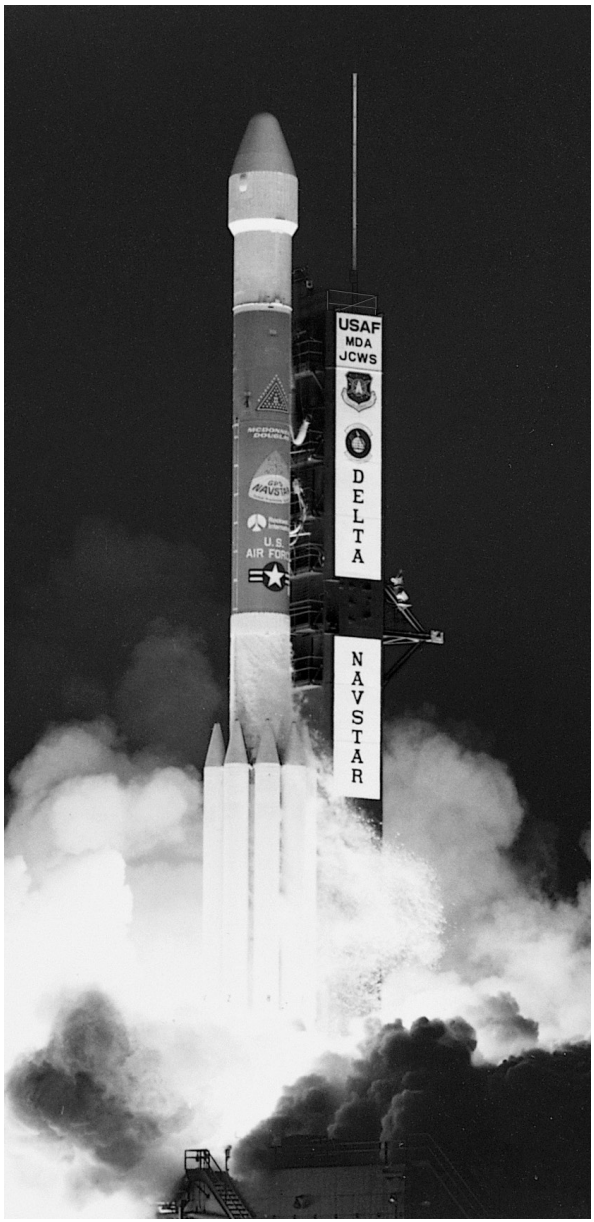
Photo courtesy of Magellan Systems

A biologist in Brazil uses a hand-held GPS receiver in wildlife research projects.

help determine population distribution patterns and possible sources of disease.

GPS-equipped balloons are monitoring holes in the ozone layer over the polar regions, and air quality is being monitored using GPS receivers. Buoys tracking major oil spills transmit data using GPS. Archaeologists and explorers are using the system. Anyone equipped with a GPS receiver can use it as a reference point to locate or find another location. With a basic knowledge of math and science, plus a hand-held GPS receiver, you could be an instant hero if you and friends got temporarily lost on a camping trip.

The future of GPS is as unlimited as your imagination. New applications will continue to be created as technology evolves. The GPS satellites, like handmade stars in the sky, will be guiding you well into the 21st century.



Photograph courtesy of McDonnell Douglas

An Air Force-launched Delta II carried the 18th GPS satellite into orbit in February 1993. By March 1994, all 24 GPS satellites were orbiting the Earth.

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The Aerospace Corporation was one of the GPS team members honored with the 1992 Robert J. Collier Trophy, awarded by the National Aeronautic Association for the "greatest achievement in aeronautics in America."

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2350 East El Segundo Blvd.
El Segundo, CA 90245-4691
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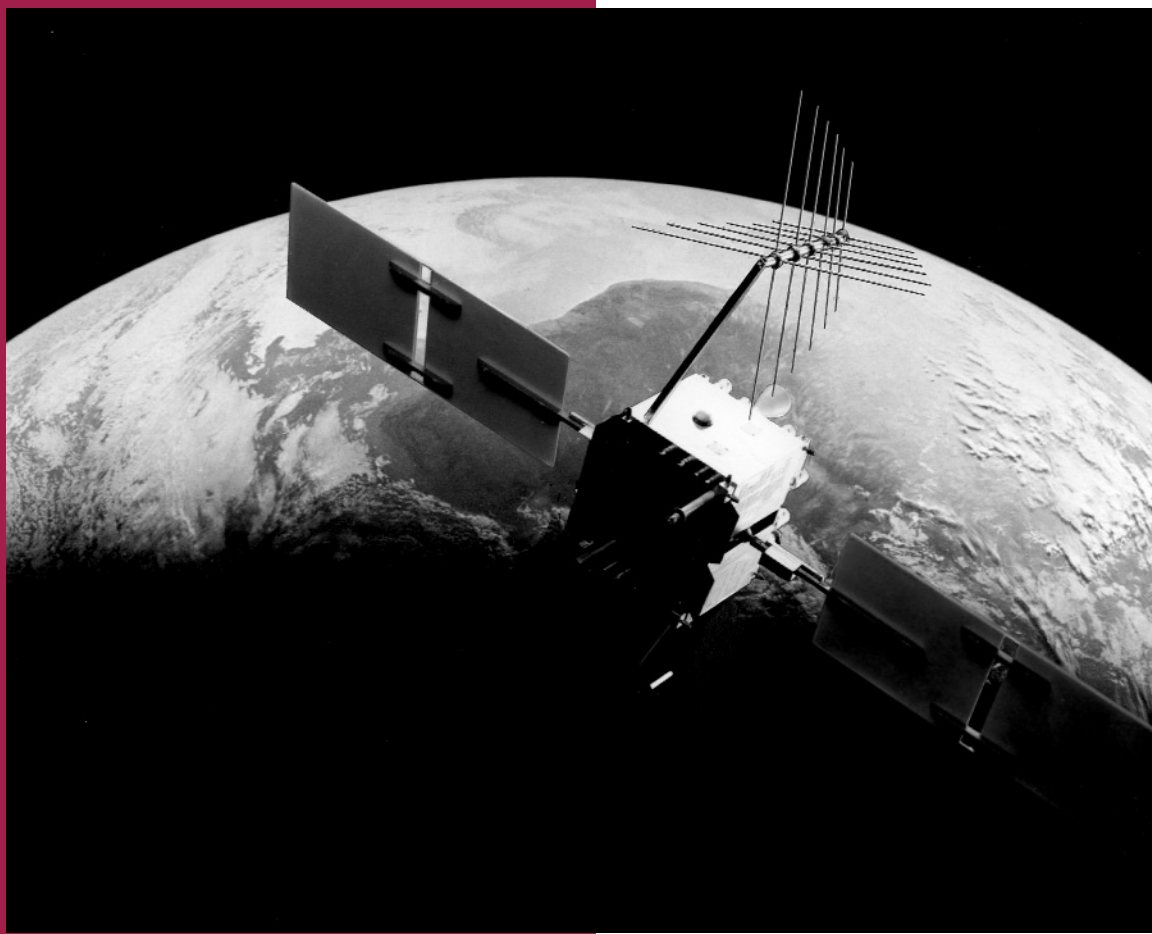
Los Angeles, CA 90009-2957



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