

The Evolution of Global Positioning System (GPS) Technology

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Early in the race to space in the 1950s, the U.S. Department of Defense found that tracking the position of satellites could be used to track fixed bodies on the surface of the Earth. No one realized that the NAVSTAR GPS satellite constellation program, that began its research and development in 1973 and launching its first four satellites in 1978, would change the very nature of our world in the next two decades. The system later to be known simply as the Global Positioning System (GPS) would not only provide complex navigation and timing capability to the military but, might very well, be the backbone to energize the faltering economy in 2001. A myriad of evolving GPS applications and complementary technologies may spawn new, much needed economic growth. Advances in integrated circuit technology and high-volume applications have helped to bring the price of GPS receivers down to \$100–\$500. The size of GPS receivers has now been considerably reduced. Prices and device sizes will continue to fall in the next decade while the applications for this technology will continue to blossom. It should be no surprise when this technology affects each of us, and, is used in every home and business in some form during this decade.

KEYWORDS: global positioning system; GPS applications; satellite communications; global information infrastructure.

THE HISTORY OF GLOBAL POSITIONING SYSTEM (GPS) TECHNOLOGY

The launch of the low-Earth orbit satellite, Sputnik 1, by the USSR (Soviet Union) on October 4, 1957 may possibly mark the beginning of Global Positioning System (GPS) technology. Scientists studying the low-Earth orbit of this early satellite realized they could track the satellite by the relative strength of its radio signal. It was also recognized during the Sputnik satellite program, if scientists had the ability to track a satellite's position, this in turn would mean that a person on Earth could obtain his position on the globe if they could read the signal from the satellite in conjunction with knowing the exact orbit of the satellite.

Today, there are many types of satellite orbits that are being used, two of which can be described as either "low-Earth" or "geostationary" orbit. A geostationary orbit is also sometimes called stationary or synchronous orbit. A geostationary orbit is an orbit of an Earth's satellite whose period of rotation is exactly equal to the period of rotation of Earth about its polar axis (which is 23 h, 56 min, and 4.1 s) and whose trajectory is aligned with the Earth's equator. A satellite in this orbit will appear as if it is always in the same place in the sky when observed from a given point on the Earth. This orbit is at a distance of approximately 22,438 miles from the surface of the Earth. Communication satellites are usually placed into this orbit, with several satellites in the same orbit, distributed around the Earth to provide worldwide coverage for relaying the telecommunication signals (see Fig. 1).

Low-Earth orbits (LEOs) are generally either elliptical or circular orbits at rough altitude of less than 500 miles above the surface of the Earth. The orbital period at these altitudes varies roughly between

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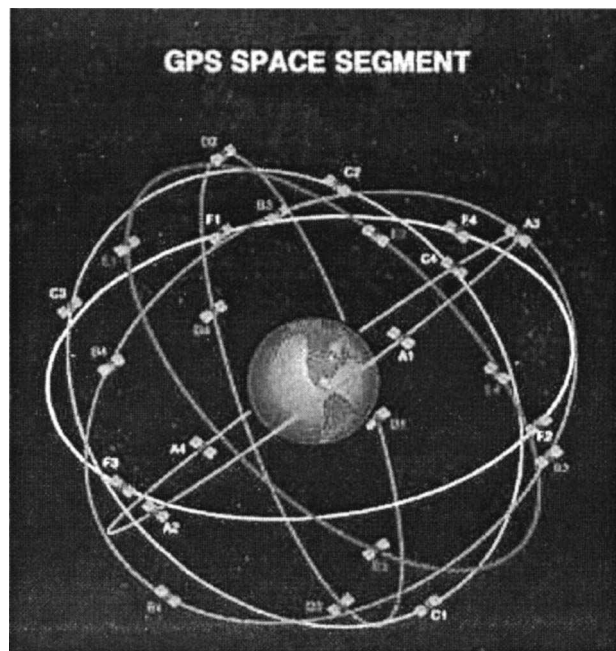


Fig. 1. GPS satellite constellation.

90 min and 2 h. The communication coverage radius of the satellite in LEO varies from 1900 to 2500 miles. However, there are several other issues that come into play when scientists calculate signal strength of a given location. The maximum time that a satellite in LEO is above the local horizon for an observer on the Earth is approximately 20 min. A complete global coverage system requires a large number of satellites in LEO, in multiple orbital planes, in varied inclined orbits. For instance, the current Iridium (Motorola) system, utilizes 66 satellites (plus six in-orbit spares) in six orbital planes inclined at 86.4° at an orbital height of 488 miles with an orbital period of 100 min, 28 s. Global coverage with this single system is approximately 5.9 million square (statute) miles per satellite.

Prior to the launch of Sputnik 1, the United States, in 1948, Army Signal Corps had transmitted radar signals to the moon and bounced them back to Earth proving that relatively low-power microwave signals could be transmitted into space, reflected, and detected again on Earth. In 1954, the U.S. Navy transmitted voice messages (on microwave carriers) to the moon and then detected their reflection back on Earth. On January 31, 1958, the United States launched their first satellite, Explorer 1. It provided preliminary information on the environment and conditions in space outside Earth's atmosphere. This resulted in the discovery of the Van Allen radia-

tion belts. Explorer 1 orbited the Earth more than 58,000 times before re-entering the Earth's atmosphere over the south pacific on March 31, 1970. The same year, the United States established NASA to facilitate development of space-based technology and launched a satellite named SCORE into LEO orbit. It received messages, taped them, and then retransmitted them back to Earth. The first voice broadcast from space to Earth was a Christmas greeting from U.S. President Eisenhower on December 19, 1958. Another very important, and practical development, in the history of satellite communications, was the NASA launch of Tiros I, the world's first weather satellite, launched in 1960 (see Fig. 2).

The images sent to Earth by Tiros I proved that the race to space would have major implications on the daily lives of the average citizen beyond that of national pride in developing the space program. It carried low-resolution television and infrared cameras and was in a circular polar orbit of about 375 miles. Today, providing communications via satellite is important for business but, using satellites for monitoring is important for life and, thus, this dual role in satellite applications has been maintained to date.

In 1964, U.S. submarines began using satellite communications as a method for positioning which

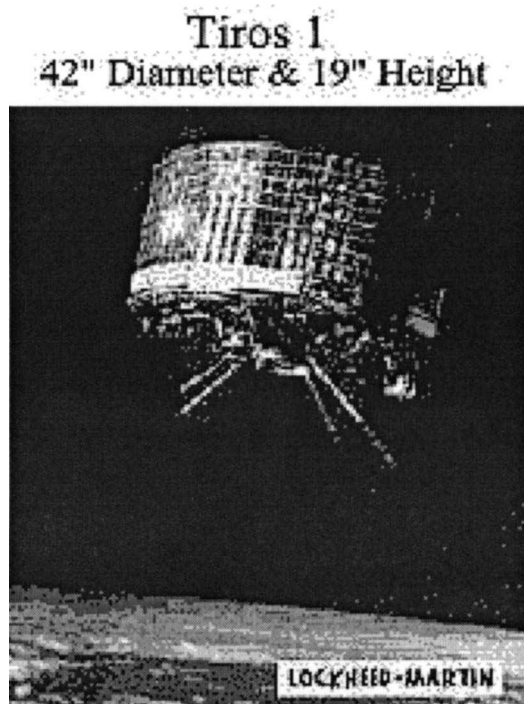


Fig. 2. U.S. weather satellite Tiros 1, launched in 1960.

is known as the TRANSIT system of GPS. It required only one satellite but, for that reason, a reading could only be taken roughly every 35–45 min. The submarine also had to be stationary. On May 31, 1967 the U.S. Navy launched the TIMATION I satellite which improved the TRANSIT system by placing an atomic clock inside the satellite. The atomic clock made it possible to determine the length of time it took a signal to leave the satellite and reach the receiver. Most importantly, the navigating vehicle could be in motion. Although the TRANSIT system was a significant leap forward in GPS technology, however, it suffered from poor accuracy. In the early 1970s, the U.S. military began a program now known as the NAVSTAR GPS program. R&D for NAVSTAR began in 1973. The proposed system offered several satellites for navigation as opposed to just one. Signal availability would be increased and mobile vehicles would not have to wait for long periods of time to get a reading. Originally named the Navigation Technology Program, the first four satellites of the NAVSTAR class constellation were launched in 1978. Today, the NAVSTAR system contains 24 satellites that each circles the globe once every 12 h. Five to eight satellites are visible from any point on Earth at any time, however, visibility should not be confused with availability. Satellites often sit too low to the horizon to be used effectively due to interfering obstacles and atmospheric signal scattering.

Telstar 1, a satellite built by AT&T, was the first satellite designed to detect microwave signals and amplify them for retransmission back to Earth. This transponder technology is still in use today. Although it was a LEO satellite, it linked Europe and North America, via television, on July 10, 1962, with a broadcast of Elvis Presley. Telstar 1 was the first satellite capable of broadcasting TV signals. The first experimental geosynchronous communications satellites were launched in 1963, Telstar 2 and Syncom 2 (Hughes Aircraft Corp.). Syncom 3 linked the 1964 Tokyo Olympics to the United States. In 1965, the Soviets launched the first of their Molnya satellites, which were placed in a high elliptical orbit. This unusual orbit enabled communication to northern latitudes not reachable by geostationary satellite coverage. In 1965, the first international geosatellite, Intelsat 1 was launched and provided the first truly global commercial satellite service. In 1969, Intelsat completed the first global geostationary satellite network. It was completed and operational only days before the first lunar landing, Apollo 11, July 20, 1969. Although today we take for granted the offering of

satellite services by private companies, in the beginning, all satellite communications were coordinated between countries through government authorized entities and agencies and were international by design. This changed in 1972, when Telesat, a Canadian company, began operation of the world's first domestic communications satellite, Anik 1, which was launched by NASA. It was the first satellite to provide services to the U.S. domestic market.

The first U.S. domestic communications satellite, and the world's first offered by a private company, was Western Union's WESTAR 1 which was launched in 1974 and was followed by WESTAR 2. In 1975, an east coast (USA) cable company, Home Box Office, began delivering TV programming down-linked from satellites to its cable subscribers. On September 30, 1975, it offered the Muhammad Ali/Joe Frazier boxing match (Thriller in Manila) to its cable viewers—one of the precursors to “pay for view.” In 1976, Ted Turner up-linked his WTBS Atlanta TV station to satellite to create the first “superstation.” Throughout the late 1970s, satellite applications continued to grow, from the involvement of National Oceanic and Atmospheric Administration (NOAA) in weather satellites and Earth observation to the 1979 sponsorship by the United Nations International Maritime Organization which provided a method of international telephone service and traffic-monitoring services on ships at sea. As the decade of the 1980s began, satellite technology had become a technology acceptable to business and science.

Second generation geostationary communication satellites were under development in the early 1980s that used higher frequencies for signal transmission that allowed the use of smaller diameter satellite antennas for video reception and opened the market for satellite delivered private data networks called VSATs (very small aperture terminals) and extended the application of SNG (satellite news gathering) services. Thus, it became more affordable and practical to deliver all news via SNG vehicles. Hybrid satellites were followed by dedicated high power, high frequency satellites designed exclusively for the DTH (direct to home) television market with the first applications in the European and Asian TV markets where high density urban populations and lack of TV cable networks made the marketing of small dish TV programming, commonly called DBS (direct broadcast services), a practical business endeavor. High power DBS satellites now transmit consumer programming to small dishes to homes in all corners of the globe. The newest satellite technology in commercial

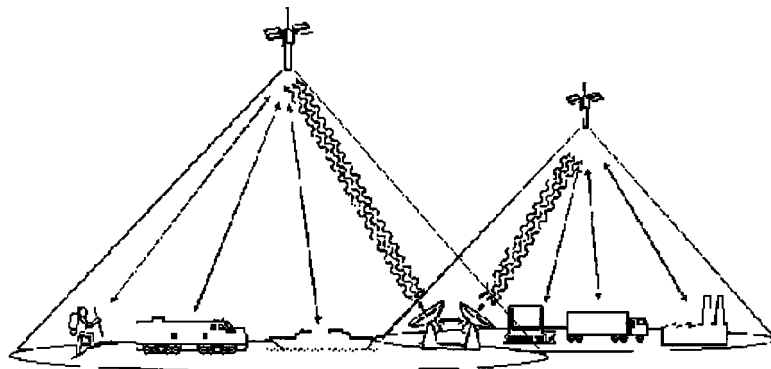


Fig. 3. GPS ground-based applications.

application operate at even higher frequencies allowing for even smaller satellite antennas. Yet, technology has not stood still as research continues on global communications network applications with smaller receivers including handheld units intersatellite communications.

The GPS is a dual-use (military–civil) satellite-based radio navigation system initially developed and currently maintained and operated by the U.S. Department of Defense (DoD). Current U.S. policy, embodied in a Presidential Decision Directive and confirmed in law by Congressional action, is that an Interagency GPS Executive Board (IGEB), cochaired by senior officials of the Departments of Transportation and Defense, provides management oversight to assure that GPS meets civil and military user requirements. GPS permits land, sea, and airborne users to determine their three-dimensional position, velocity, and time 24 h a day, in all weather, anywhere in the world with a precision and accuracy far better than other radio navigation systems available today or in the foreseeable future.

HOW GPS TECHNOLOGY WORKS

The GPS consists of three segments: space, control, and user. The space segment, consists of 24 operational satellites in six circular orbits 20,200 km (10,900 nm) above the Earth at an inclination angle of 55° with a 12-h period. The satellites are spaced in orbit so that at any time, a minimum of four satellites will be available to users anywhere in the world. The satellites continuously broadcast data to users throughout the world. There are currently 27 satellites in orbit, or three spares, which assure the availability

of 24 operational satellites (Dana, 2001; Huang, 2000) (see Fig. 3).

The control segment consists of a master control station in Colorado Springs, Colorado, with five monitor stations and three control up-link stations located throughout the world. Monitor stations track all GPS satellites in view and collect ranging information from the satellite broadcasts. The monitor stations send information they collect from each of the satellites back to the master control station, which computes extremely precise satellite orbits and orbit correction information. The information is then formatted into updated navigation messages for each satellite. The updated information is transmitted to each satellite via the control up-link stations, which also transmit and receive satellite control and monitoring signals.

The user segment consists of the receivers, processors, and antennas that allow land, sea, or airborne users to receive the GPS satellite broadcast signals and to use this information to compute their precise position, velocity, and time. The GPS concept is based upon satellite ranging or trilateration. It is a basic geometric principle that allows a GPS receiver to calculate its precise location and time-base as a function of the knowledge of its distance from other locations (satellite positions in this case). This concept requires four satellites to accurately position a receiver in three-dimensional space thereby, allowing the receiver to not only calculate its two-dimensional surface position on the Earth but, also its altitude. The satellites act as precise reference points transmitting, as part of their signal, a pseudorandom code. Using this code, the receiver measures the time delay for the signal to reach the receiver, which is the direct measurement of the apparent range (called a “pseudorange”) to the satellite. The measurements collected

in real-time from four satellites are processed to solve for the three dimensions of position (latitude, longitude, and altitude) and time.

Electromagnet signals travel near the speed of light (approximately 186,000 miles/s) in our atmosphere, requiring nano-second level measurement accuracy to resolve the GPS signals transit time. Thus, measuring the time delay from the instant that a satellite launches the signal into space until it is received could require the receiving device to have an atomic clock on board. The satellites do use an atomic clock for their time-base, however, it is highly impractical for receivers to carry such a device (Taubes, 2001). Instead, receivers use a simple, inexpensive quartz crystal time-base. The receivers calculate the precise time and positional data using the data received from the four satellites. The receivers' precise location is calculated by finding the geometric intersections of four spheres. The satellite's signal data combined with algorithmic corrections made by the receiver, attempt to compensate for atmospheric affects as well as Doppler and relativistic artifacts of motion (see Fig. 4).

Furthermore, the GPS ranging codes from each satellite and the time-base of the receiver must be adjusted so that they are synchronized with each other. If a system is out of synchronization by just 1 ms (1/1000th of a second) then our range (distance) measurement will be off by 186 miles (300 km). This much error is intolerable and, thus, the reason that the satellites in the GPS constellation have atomic clocks on board. These clocks are extremely precise and very expensive. They can cost a hundred thousand U.S. dollars each, and each satellite has several of them just to make sure that at least one will be working. Without

the ability to geometrically algorithmically calculate the precise time in a receiver, the cost-effective application of GPS technology could never be realized.

Time and Space

In three-dimensional space there are three unknown coordinates to be determined; that is, x , y , and z . An algebraic methodology can be used to solve position in two-dimensional space with the three unknown using three independent equations. We can use three range measurements from three satellites to set up the three equations that are needed. The fourth unknown comes from the need to resolve the third dimension of space, the z coordinate or altitude. Therefore, a range measurement from a fourth satellite and a fourth equation is necessary. Solving these equations is an easy job for a small microprocessor or microcomputer. This is how the position (x , y , and z) and the time are precisely calculated. Getting the exact time from this system is a bonus, and there are many applications in telecommunications and other fields where this precise time is needed in the control of data communication networks, frequency hopping spread-spectrum communication, and TDMA (Time Division Multiple Access) systems, where precise time permits all users to synchronize with each other (Heflin, 2001).

Fortunately, the satellite's orbit of the Earth is very predictable. The theoretical problem for predicting their location and motion was actually solved a long time ago by the great German astronomer and mathematician Johannes Kepler (1571–1639). He developed the laws and equations needed to describe the movements of heavenly bodies such as the moon around the Earth or the planets around the Sun. No surprisingly, man-made satellites also obey Kepler's laws. The monumental achievements of Sir Isaac Newton (1642–1727) and Albert Einstein (1879–1955) have also contributed to the success of GPS.

The orbits of the GPS satellites are known. The satellites broadcast a rough set of orbital information known as the almanac, which tells you where to look for each satellite in the sky at any given moment. A GPS receiver reads this almanac and writes the information into its nonvolatile memory (NVM), so that it won't forget when you turn the device off. Therefore, the GPS satellites not only transmit the ranging pseudorandom codes, but also send "data messages" about their orbital locations as well as other information.



Fig. 4. Portable GPS receiver by Garmin.

One might consider why wouldn't it be simpler to use geostationary satellites for GPS. There are several reasons why this isn't done. First of all, geostationary orbits have to be right over the equator, and users near the poles have very poor visibility of satellites in those orbits. Satellites in geostationary orbit travel approximately 23,000 miles above the equator and complete one circuit every 24 h, making them synchronous with the Earth's rotation so that they stay above the same spot on Earth all the time. Many communications satellites use this orbit, but it is not suitable for GPS satellites because they have to be spread out all around the world and not just above the equator. As mentioned previously, the GPS constellation consists of 24 satellites (three of which are spares). They travel roughly 11,000 miles above the Earth's surface in six different orbital planes with an orbital period of approximately 12 h. This makes it possible for the constellation to cover the globe evenly. The satellite constellation needs to be monitored and communicated with by a number of ground control stations operated by the U.S. Department of Defense (DoD). For the ground stations, being able to "see" the satellites twice a day is a convenience that enables them to check the satellites' positions and "health," and to upload data messages and position correction information for broadcasting to users.

The ground stations need to measure and predict the satellites' position and speed precisely, because of variations in the ideal "Keplerian" orbits caused by solar winds and the gravitational pull of the moon and sun, for instance. A set of complete and unambiguous descriptions of a satellite's orbit and clock parameters is called an ephemeris. The satellites broadcast this ephemeris data to each GPS receiver, which processes them and uses them to make precise position corrections.

If the control segment finds that a satellite has deviated from its predicted orbit, it corrects the deviation by uploading new ephemeris message data to the satellite for broadcasting. The correction is not usually made by maneuvering the satellites back to their precise predicted orbit, because the variations are very small and it would be too difficult for the control stations to do that kind of thing all the time, especially because the fuel available for maneuvering on each satellite is very limited. The satellites are physically maneuvered only occasionally, when the control sector finds it difficult to predict ephemeris parameters for them.

Because the GPS satellites are not in geostationary orbit, there are relative speeds between the

receiver and the satellites. This causes the Doppler effect. Radio and light-wave frequencies shift if the source (transmitter) and observer (receiver) are in relative motion. The microwave signals that GPS satellites send out also shift in frequency because of the relative motion between your receiver and the satellites. This change in frequency, or Doppler shift, can be detected very easily by a GPS receiver, and is very useful in determining your speed and the direction you are moving.

Because the primary functions of a GPS receiver are to determine your position, time, and velocity, GPS users may assume that speed is determined simply by differentiating the position by dividing the position change by the time interval. This, however, is not the way a good GPS receiver performs the calculation. Position measurements are noisy, uncertain, or random in nature, and differentiation of such a noisy signal is not a good practice. Instead, velocity or speed should be determined by using the Doppler shift of the GPS satellite signals. It should be noted that if a satellite is directly above the receiver, the satellite's movement is perpendicular to the line of sight (from satellite to receiver) and there is no Doppler shift between the two at that particular moment. Additionally, to measure velocity to centimeter-per-second accuracy, centimeter-wavelength signals are needed. The wavelength of a microwave is in the centimeter range, and microwave signals are what GPS uses.

GPS ranging is a one-way communication and ranging technology with satellites broadcasting the data messages and sending the ranging code in only one direction. This is an extremely low-powered system. In fact, that the signal is really buried in the natural background radio noise. The receiver recovers this weak signal from the satellites by using spread-spectrum communication technology, a very tricky concept in communication theory that works by means of pseudorandom codes. Spread-spectrum communication is also used by spacecraft that are sent to explore other planets in the solar system, where distances are so great that the signal coming from the craft in deep space is so attenuated that it too is buried in the background noise by the time it reaches the Earth. Mathematically, the power or strength of a signal is inversely proportional to the square of the distance it has traveled. Spread-spectrum communication with pseudorandom code technology performs a sort of amplification on the signal so that it can be recovered by the receiver. A lot of time is needed to sort out the extremely weak GPS signals from all the background noise that GPS receivers pick up. This

means that the transmission of data messages from GPS satellites can be very slow. It takes 12.5 min for a GPS satellite to send out its full set of data messages at this speed. In other words, GPS uses spread-spectrum pseudorandom code communication technology in such a way that data transmission speed is sacrificed in exchange for low-power performance and an omnidirectional antenna characteristics (Dana, 2001).

Today's GPS receivers are cheaper, better, and more accessible to users than ever before. They perform more reliably than early receivers, and they do more things. Even better, their cost is continuing to fall year-over-year making it affordable for thousands of applications. Thanks to the advances in semiconductor technology and microelectronics design automation that have taken place over the past two or three decades, the complicated electronic circuits used in GPS receivers can now be integrated into a small silicon chip with a silicon die size of about 0.3 in.² resulting in smaller receiver sizes can fit into many more end-applications.

GPS Position Error Mitigation

As noted previously, the GPS uses satellites as reference points for trilateration of a position on the Earth, in the air above the Earth, or even in space. Because we know precisely where all of the satellites are in their orbits, we can use their positions to triangulate another unknown position. Trilateration and the Cartesian coordinate systems used by GPS for the computing of positions are based on the Pythagorean theorem, which describes the relationship between the lengths of the three sides of right triangles. This relationship is $a^2 + b^2 = c^2$. Because the GPS is designed to have the potential of achieving a precision of location to less than an inch, the message data from the satellites and the receivers must be able to correct all sources of errors, no matter how small such as the Earth's imperfect rotation, the influence of atmospheric effects, and GPS time. Precession (which means the motion of the axis of rotation) and other small irregular variations in the Earth's rotation affect the orbital positions of the GPS satellites, and the corrections for those variations are broadcast in the satellite data messages. The software program inside your receiver uses this data to fine-tune its distance computations.

Other sources of error are caused by ionospheric and tropospheric disturbances as well as signal refraction. A way to measure a radio signal's delay in

the atmosphere is by comparing two signals of different frequencies. This is just like the color dispersion one can observe in a prism where the lower frequency of red light is refracted less than the higher frequency of violet light because the lower frequency gets delayed (or slowed down) more than the higher frequency. There is a formula to describe this phenomenon: a signal slows down at a rate inversely proportional to the square of its frequency. This is the method of determining ionospheric error that is usually used in military equipment and in high-end, expensive, dual-frequency GPS receivers. GPS satellites broadcast on two frequencies: L1, or 1575.42 MHz, and L2, or 1227.6 MHz. Dual-frequency receivers can receive both of these frequencies and carry out the ionospheric correction by making measurements simultaneously on these two well-spaced frequencies. Most civilian receivers, however, can receive only the L1 frequency, because the cost of dual-frequency receiver technology is relatively high.

A GPS receiver also has another way to utilize math models. It uses an ellipsoidal model of the Earth's shape to estimate the latitude, longitude, and altitude of the receiver. The equatorial radius of the Earth is 6378.137 km and its polar radius is 6356.762 km; the difference is due to a slight flattening of the Earth caused by its spinning. Because, it does not coincide precisely with the Earth's surface, this model causes discrepancies in the altitude calculation of the GPS receiver. Precision satellite clocks and time measurements are the key to the accuracy of GPS positioning. Since GPS time is based on atomic standard time, and is continuous, therefore, there are no leap seconds like there are in universal coordinated time because the GPS cannot tolerate any such discontinuity in the time count. The GPS navigational messages that the satellites broadcast provide correction parameters for GPS time.

The Relativity of GPS

GPS is one of the first man-made, operational systems, other than the particle accelerators, that has significant relativistic effects which must be considered. One reason is that the GPS satellites may have a large speed relative to the receiver on Earth. Even though GPS satellites' speed around the Earth is not comparable to the speed of light, it does cause a minor synchronization problem which needs to be adjusted by the system operation and the user equipment (GPS receivers). The clocks on the satellites would run a

little slower than the identical clocks down on Earth, if it is not de-tuned somehow to account for the relativistic effects. These effects by themselves may not be significant because they are so minor. Nevertheless, considering that this system carries a precision atomic frequency standard and that measurements can be made to accuracy in the nanosecond range, the relativistic effects need to be taken into account if a receiver is to be able to resolve position to less than 1 in. A GPS receiver needs to first figure out the relative speed between a satellite and itself from the almanac, orbital data of the satellites, or Doppler measurements and, then, combine the relativistic correction with other clock correction factors broadcast by the satellite message data to get the TRUE GPS time needed to solve for position.

If a GPS system design is not designed to consider the relativistic effects, it may introduce an error in its position and time output. The GPS correlation also needs to account for is the rotation of the Earth during the time of transit of the GPS signal from satellite to receiver because the speed of light is a finite number. The satellite's position is computed at the time of transmission of the signal, however, the user's receiver is computing position at a slightly later time. During this transit time the Earth has rotated a little and this rotation must be considered. In addition, the time of transit for different satellites is not equal because the ranges or distances from each of them are not equal.

Differential GPS

The trick to differential GPS (DGPS) is to use a reference receiver station located at a precisely known position. The reference receiver, just like any other GPS receiver, knows where the satellites are supposed to be from the orbital data. Because the reference receiver also knows its own precise location, it can compute the distance to each satellite and divide that distance by the constant speed of light to get the delay time (the amount of time it takes the signal to travel from the satellite to the receiver). The receiver compares this computed delay time with the measured delay time, and the difference between the two becomes the error estimate of the signal from the satellite (Kaplan, 1996; Trimble Navigation Limited, 2001). The reference station broadcasts this error estimate to GPS receivers in the vicinity, which use it to adjust their position calculations. Most of the error sources, we mentioned previously which affect both the reference station and the receivers, can

be eliminated by this process. As a result, precision within 1 m can be attained; for surveying receivers, the accuracy can even reach the centimeter level.

WAAS and LAAS

For many civilian applications, such as use as a primary navigation aid, the use of GPS must meet certain stringent safety requirements such as improved availability and integrity. For instance, GPS doesn't currently provide users with timely notification of a satellite failure or excessive error. Also, if GPS is to be used together, compatibility issues like time standards and reference coordinate systems must be resolved. However, a geostationary augmentation service can make up for these shortcomings.

The Wide Area Augmentation System (WAAS) program, being implemented by the U.S. Federal Aviation Administration, is designed to provide this service. Under this system, GPS integrity and differential correction data, are calculated by a network of ground reference stations. A corresponding network in space is made up of geostationary satellites like INMARSAT. The service provided by WAAS is for use primarily in the United States.

Europe has a similar augmentation system called the European Geo-stationary Navigation Overlay Service, or EGNOS. To cover the Asia-Pacific region, Japan has its MTSAS program. The Local Area Augmentation System (LAAS) is a ground-based system that provides additional navigational pseudosatellite signals in a local area, usually near an airport, to enable aircraft to approach and land safely in almost zero-visibility conditions. Global interoperability of these systems is imperative. The space-based augmented GPS navigation systems will gradually replace the present ground-based aircraft navigation and air traffic control systems, which have remained basically unchanged since the end of World War II.

Present air routes have to pass over navigation facilities near populated areas, where electric power is available to run the equipment. Trans-oceanic flights must pass over islands that serve as waypoints on which ground navigation facilities are located. The resulting air routes are often indirect, crowded, and inefficient. This is just like ocean shipping in prechronometer times, when shipping lanes were terribly constricted. A restructuring of air routes based on GPS navigation can take advantage of the great circle distance, which is the shortest distance between any two points on the globe. The FAA and other civil aviation authorities around the world are

pushing forward with new air traffic control and navigation systems based on GPS and communications applications.

GPS and GIS

Most stand-alone GPS receivers can tell you your position by showing the latitude, longitude, and altitude of the receiver. A display of coordinates like 24° North, 121° East, and 100 m altitude might not be very helpful to you in locating your position. It would be more useful to know where you are on a map. The Geographic Information System (GIS) is a database of maps that are stored in computers. The GIS can be much more sophisticated than a paper map. It can be three-dimensional, displaying the Earth's surface terrain, and it can include everything you need to know such as the location of a gas station or a picture of a tourist site. Car navigation systems that combine GPS and GIS systems are expected to be the largest market sector for GPS applications for the first 10 years in the 21st century.

GPS altitude, or elevation, is not actual height above the ground nor is it the elevation above sea level. GPS receivers without GIS have no knowledge of the real world. It is the software in your GPS receiver that computes your position, altitude, and speed. The software uses an ellipsoid model to approximate the surface of the Earth. The calculated GPS height is the vertical distance above the imaginary, mathematical surface of this sphere. This is a smooth ellipsoid surface that carries no terrain information such as is provided by GIS. This fact combines with other GPS errors to make things even worse. For example, there have been instances of pilots failing to use their GPS receivers improperly, ignoring their baro-altimeters during low-latitude maneuvering, and losing their aircraft into the sea.

How Is GPS Used and Who Can Use It?

GPS receivers collect signals from satellites that are about the immediate horizon. They display the user's position, velocity, and time, as needed for maritime or aeronautical applications. Some display additional data, such as distance and bearing to selected waypoints. In this way, the U.S. Military uses this technology, for instance, to guide missiles to a known target anywhere on the surface of the Earth. They also use the technology for troop location, vehicle navigation, mapping, and surveying.

GPS is used to support land, sea, and airborne navigation, surveying, geophysical exploration, mapping and geodesy, vehicle location systems, farming, transportation systems, and a wide variety of other additional applications. Telecommunication infrastructure applications include network timing and enhanced 911 for cellular users. Global delivery of precise and common time to fixed and mobile users is one of the most important, but least appreciated functions of GPS.

WHAT'S THE STATUS OF GPS?

The GPS reached full operational capability July 17, 1995. Per U.S. Policy and Law, the GPS Standard Positioning Service is available to civil users worldwide for their peaceful transportation, scientific, and other uses free of direct user charges. At that time, GPS provided two levels of service: A Standard Positioning Service (SPS) for general civil use and an encoded Precise Positioning Service (PPS) primarily intended for use by the Department of Defense and U.S. allies. The SPS is the standard specified level of positioning and timing accuracy that is available, without restrictions, to any user on a continuous worldwide basis. The SPS accuracy specifications, given below, include the effects of Selective Availability (SA). SA is the terminology the DoD uses to say that they are randomly dithering, or forcing inaccuracy in the GPS signal. SPS provides accuracy (for position, the accuracy with respect to geographic, or geodetic coordinates of the Earth) within: 100 m horizontal, 156 m vertical, 340 ns time. SPS coverage is continuous and worldwide (Dana, 2001).

Per a White House, Office of Science and Technology Policy, National Security Council, Fact Sheet entitled "U.S. Global Positioning System Policy" dated March 29, 1996: "It is intention of the United States to discontinue the use of GPS Selective Availability (SA) within a decade in a manner that allows adequate time and resources for our military forces to prepare fully for operations without SA. To support such a decision, affected departments and agencies will submit recommendations in accordance with the reporting requirements outlined in this policy." Additionally, beginning in 2000, the President will review the continuing need for maintaining the SA capability. Reports to the President for the annual determination will be made jointly by civil agencies working with the DoD. In fact, as of May 1, 2000, President Clinton, ordered GPS SA to be immediately terminated

thereby making all commercial receivers roughly 10 times more precise.

GPS is owned and operated by the U.S. Government as a national resource. The DoD is the “steward” of GPS technology, and as such, is responsible for operating the system in accordance with the signal specification. The March 1996 Presidential Decision Directive, passed into law by Congress in 1998, essentially transferred “ownership” of GPS from the DoD to the Inter-Agency GPS Executive Board (IGEB). The IGEB is cochaired by members of the Department’s of Transportation (DOT) and Defense, and is comprised of members of the Departments of State, Agriculture, Commerce, Interior, and Justice as well as members from NASA and the Joint Chiefs of Staff. It allows for both civil and military interests to be included on all decisions related to the management of GPS.

The DoD is required by law to “maintain a Standard Positioning Service (SPS) as defined in the Federal Radio-navigation Plan and the Standard Positioning Service Signal Specification that will be available on a continuous, worldwide basis,” and, “develop measures to prevent hostile use of GPS and its augmentations without unduly disrupting or degrading civilian uses.” These strict requirements and current augmentation systems should actually make DoD use of the system transparent to the civil user.

As per DoD plans, they will continue localized testing of the system by military and development teams but the testing will fall under strict notification guidelines of safety-of-life users such as Coast Guard and FAA. U.S. transportation, public safety, economic, scientific, timing, and other users rely on GPS extensively. In aviation and maritime transportation, GPS is used for “safety of life” navigation and it is a critical system for these applications.

GPS AS A NAVIGATIONAL STANDARD

GPS has the potential to support en-route, terminal, and precision approach operations for all 12,000 airports in the United States to include heliports in the United States and offshore areas. In addition, GPS will likely serve a vital navigation function for aircraft on the ground at airports. Because of the increased accuracy of GPS, aircraft can be routed to their destinations more efficiently. Estimates are that GPS could save the airlines up to 1% in fuel costs and 2% in flight time per year. This may not sound like much, but it

translates into annual savings of millions of dollars in operating costs. Another cost saving is that associated to the decommissioning of traditional ground-based navigation aids, which are expensive to operate and maintain.

The cost to equip an aircraft with a GPS receiver varies depending on the type of the receiver, the degree of difficulty of the installation, the sophistication of the aircraft and existing avionics, and the level of services desired. Also, the cost of equipping will vary depending on whether GPS is to be used as a stand-alone system or as part of a Flight Management System (FMS). Most vendors provide a package price that includes the receiver equipment, installation, and an airworthiness inspection. These packages can range anywhere from approximately \$3500 for a general aviation Instrument Flight Rules (IFR) package to \$10,000+ for more sophisticated packages on commercial aircraft.

The Federal Aviation Administration (FAA) certified GPS for use over the ocean yet interference has been experienced precluding the use of GPS. GPS avionics that are used as a primary means of oceanic navigation have built in Receiver Autonomous Integrity Monitoring (RAIM) functions to provide integrity of navigation. Integrity is the notification of Hazardously Misleading Information (HMI). In the rare circumstance of a loss of the integrity function, flight crews can use backup procedures to insure safe navigation until the RAIM function is restored. The RAIM function is limited by the size of the GPS constellation that is available at any moment in time.

Completion of GPS based aircraft approach paths could happen as soon as 2005, however, many skeptics believe that the FAA will not complete the necessary changes until 2012. The total cost based on more than 12,000 affected aircraft approach paths (usually more than one per airport) is at least \$240 million. This isn’t very much money considering the cost savings that could be realized. U.S. based airlines spend more than \$21 billion per year on fuel alone. A 1% savings per year would amount to approximately \$210 million, which would allow for a return on investment period of less than 14 months.

Most industry experts believe that GPS technology will need to be upgraded at airport sites to increase safety. The upgrade is called LAAS, and it provides additional aircraft positioning data through ground-based stations. This technology is likely to cost up to \$500 thousand per airport.

EVOLVING THE GPS TECHNOLOGY INDUSTRY

Although GPS was originally designed for use primarily by United States and allied military forces and is now an integral part of our military operations, it is also becoming an increasingly important component of the Global Information Infrastructure (GII). The precise positioning information provided by GPS has a wide range of applications such as mapping and surveying, air traffic management, personal transportation systems, location-specific communication, and global atmospheric research.

There are increasing demands for GPS from military, civil, commercial, and scientific users, and the commercial GPS equipment and services industry is expected to grow from \$7 billion to \$11 billion by the year 2002. GPS applications have also been adapted to the personal computer. These applications have been used for purposes such as automatic position reporting, tracking people, tracking vehicles, and even tracking weather balloons and model rockets.

Civil Applications Overview

The success of GPS in large-scale civil use is attributable almost entirely to the revolution in integrated circuits, which has made the receivers compact, light, and an order of magnitude less expensive than thought possible 20 years ago. The first geodetic-quality receivers, introduced in the mid-1980s, provided code and carrier phase measurements from four to six satellites and were priced at over \$100,000. Receivers with much greater capabilities are now available for less than \$10,000. As late as 1980, it had been hoped that the receiver manufacturers would be able to produce a basic GPS receiver for the mass market for about \$2000. Price barriers, however, fell quickly. An industry milestone was reached in 1992 with the introduction of the first handheld receiver priced below \$1000. In 1997, the industry breached the \$100 barrier with a pocket-size receiver running on two AA batteries. There are now hundreds of GPS receiver models on the market and pricing is going the way of the calculator in the 1970s and 1980s.

Knowledge of one's precise three-dimensional position by itself is only of academic interest for most users. However, the position information can be invaluable if given in relation to the intended path, showing points of interest and potential hazards: a

hiker's position in relation to a trail; a car on a moving street map; or a boat in relation to islands and obstacles. Combined with communication technology, such as a cellular phone, the knowledge of position can be life saving, reducing search and rescue to simply rescue. The full power of GPS would be realized in civil applications in combination with other technologies, especially communication systems and geographic databases. The civil applications of GPS may be divided roughly into: (1) high-precision (millimeter-to-centimeter level) positioning; (2) specialized applications such as aviation and space; (3) land transportation and maritime uses; and (4) consumer products. While the positioning capability of GPS receives most attention among the civil users, GPS is also a global source of precise time. The use of GPS as a timing service is growing rapidly in the electric power and telecommunication industries (see Fig. 5).

One of the most surprising and unintended beneficiaries of GPS is the geodesists and geophysicists. They have developed techniques to achieve millimeter-level accuracy in relative positioning with GPS carrier phase measurements. These techniques are now being used to study tectonic plate motion and crust deformation, Earthquakes, volcanic processes, ice sheet processes and postglacial rebound, and variations in Earth's rotation. In these studies, the answers generally are not needed in real time, and

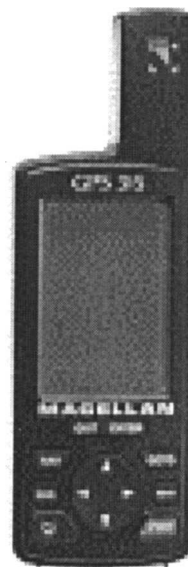


Fig. 5. Handheld GPS receiver by Magellan.

data collected over hours and days at different locations are post processed to obtain estimates of relative position vectors which are accurate to millimeters distances. The value of GPS in studies of the dynamics of Earth has been enhanced greatly by the establishment of the International GPS Service for Geodynamics (IGS), which coordinates collection and analysis of GPS measurements recorded continuously at sites around the world.

The high-precision positioning capability of GPS is also being used to monitor deformations of large engineering structures in real time under actual loads such as bridges and towers under actual traffic and wind-loading conditions. Such measurements are typically accurate to centimeter distances. GPS-based precise estimates of position and altitude of an aircraft are proving invaluable in airborne surveys. Atmospheric scientists are using GPS measurements for precise, real-time characterization of electron densities in the ionosphere and water vapor content of the troposphere. Actually, the market for high-precision GPS receivers for scientific studies is rather small. The techniques developed in these studies, however, have become indispensable tools of the surveyors and map-makers, creating a large market for high-end GPS receivers and services. The field of surveying has been revolutionized by GPS with vast improvements in accuracy, speed, and economy.

The convergence of GPS and personal computer technologies has made it possible to collect vast amounts of positional data and to organize them into geographic databases. A number of positioning and attribute collection systems are currently on the market. At its simplest, such a system typically consists of a backpack containing a battery-powered personal computer with a GPS card and radio modem to receive differential corrections for real-time DGPS, and, a handheld keyboard and display unit. An equipped user can walk around gathering information and entering it through the keyboard to create or update a spatial database showing the location and status of every utility pole or manhole in a town or a map showing concentrations of toxic or radioactive wastes. Such geographic databases are becoming invaluable tools for monitoring and management of forests and coastlines. Until a few years ago, civil aviation relied entirely on ground-based radio navigation aids. Such aids are expensive to operate and maintain, and large parts of the world lack even the basic radio navigation infrastructure. GPS is widely seen as the most important advance in civil aviation since the advent of radio

navigation, with a potential to greatly enhance both the economy and safety of air operations.

Civil aviation is a demanding application with stringent requirements on accuracy, integrity, and continuity of navigation service. To ensure that these requirements would be met by a navigation system, the regulatory authorities have created avionics standards and certification criteria. GPS has been certified for use in the U.S. airspace as a supplemental system for en-route, terminal, and nonprecision approach phases of flight, and as a primary system for oceanic and remote area operations. A GPS augmentation system to support instrument approach and landing under poor visibility conditions is also prescribed by the FAA. GPS receivers aboard satellites in low Earth orbits would become the primary source for position, velocity, altitude, altitude rate, and time, replacing an array of sensors and reducing the cost and complexity of spacecraft. A number of successful experiments and demonstrations have been carried out in various space missions in the last 10 years, and a few spacecraft have actually integrated GPS measurements into their operational control systems. The International Space Station is designed to use GPS for navigation, attitude determination, tracking of vehicles approaching the station, and as a source of time for scheduling vehicle operations. GPS measurements have been used extensively for orbit determination, both in real time and postprocessing mode, and GPS has been shown to perform much better than any ground-based tracking system in use today. Orbital altitude determination based on GPS has been demonstrated but not used routinely yet. This would change with the introduction of a new generation of GPS receivers designed with hardware and software capabilities for orbital applications.

The largest current application of GPS is in land transportation, especially vehicle navigation and tracking. GPS-based systems and services for motorists, commercial fleets, public transit, and emergency response agencies are in great demand, and a vast majority of the GPS receivers manufactured in 1998 were intended for this market. Rental-car companies now routinely offer GPS-based navigation and route-guidance systems. High-end cars have incorporated GPS-based roadside assistance systems and automatic vehicle location systems as standard features. Railroad companies are considering GPS for positive train monitoring and control. In time, GPS-based services would offer the motorists the best route to their office, given the traffic and road conditions of that day.

At least four satellites are required to be in view for three-dimensional navigation with GPS, as noted previously. Terrain, foliage, and buildings, however, can obstruct parts of the sky, and maintaining four or more satellites in track continuously is often impractical for land vehicles. A land-vehicle navigation system must, therefore, supplement GPS with dead-reckoning sensors such as gyroscopes, compasses, odometer, inclinometer, and accelerometers. These sensors cannot provide the absolute position, but they can measure change in position accurately over a short period. DGPS can provide absolute position, but only intermittently.

There are millions of pleasure boats, fishing boats, ferries, cruise lines, cargo lines, and oil tankers in the world. All would benefit from GPS. Because the oil spill caused by the grounding of Exxon Valdez, the harbors are exploring active monitoring of the oil tankers. A promising approach is to transmit DGPS-derived tanker positions via radio link to a control station monitored by the harbor authorities. Such automatic dependent surveillance (ADS) would make the harbor operations safer and more efficient. A similar concept has been proposed for the surveillance of air traffic. The consumer market for GPS products is believed to be vast and is expected to see an explosive growth in the next 5–10 years. At present, this market consists basically of inexpensive handheld receivers for hikers, backpackers, and fishermen. The convergence of wireless communications, Internet, and GPS technologies is seen as the key to the consumer market. Two-way messaging devices incorporating GPS technology are on the market now with which a user can navigate and communicate his or her position, course, or any other information, to anyone on Earth who has an e-mail address. When combined with access to databases for services, this would lead to development and growth of “location-aware” services directing a user in an unfamiliar place to a gas station, an Italian restaurant, or a tourist attraction. The consumer market will continue to be fueled by single-chip GPS receivers costing \$10 or less. These integrated circuits (chips) are available today. Such receivers will be integrated into an array of consumer products: personal digital assistants, personal communicators, and security devices for personal possessions ranging from cars to computers.

GPS is a worldwide resource of unprecedented accuracy and precision for time and frequency. The national and international laboratories, which serve as standards for time and frequency rely on GPS as

a source of time and for time transfer. An inexpensive GPS receiver can provide estimates of time with an accuracy previously offered only by atomic standards, and GPS-derived time, therefore, is a logical choice for recording times of events for scientific purposes and correlating events recorded at different geographic locations. GPS has also become an essential element of the commercial and industrial infrastructure as a source of precise time. The electric utilities are using GPS to analyze the state of a power grid via precisely synchronized measurements of the voltage phasor at different substations. In the future, GPS-synchronized measurements are expected to become an essential element of power system control. GPS is also being used increasingly to synchronize the elements of telecommunications networks. In fact, GPS is now used to set the clocks at the major Internet nodes, and the time is passed down to the local-area networks.

Geo-Location, Mapping, and Surveying

On March 29, 1996, the United States approved a comprehensive national policy on the future management and use of the U.S. GPS technology. The policy states that the United States “will continue to provide the GPS Standard Positioning Service for peaceful civil, commercial, and scientific use on a continuous, worldwide basis, free of direct user fees. We will cooperate with other governments and international organizations to ensure an appropriate balance between the requirements of international civil, commercial, and scientific users and international security interests.” This policy points not only to the changing nature of national security, but also to the growing utility of and expectations for this advanced technology (Red Sword Corporation, 2001).

The NOAA’s National Geodetic Survey maintains the National Geodetic Reference System. This is a framework of approximately 1.5 million precisely located monuments that serve as a common base of reference for surveying, mapping, and construction. The United States is now developing a highly accurate, national coordinate system known as the National Spatial Reference System (NSRS). As part of this effort, the United States is establishing a network of GPS Continuously Operating Reference Stations (CORS). GPS-based information will help us construct Geographic Information Systems (GISs) to support scientific research and environmental and natural resource

decision-making in the coastal zone and other areas (NASA, 2001).

Maritime Navigation

The need for maritime navigation tools has been evident long before the use of the quadrant or the sextant. The use of GPS could dramatically change the nature of maritime navigation. About 9% of all U.S. trade by weight and 48% by value is carried by maritime transportation. NOAA is responsible for producing nautical charts for the United States, and its efforts are coordinated with those of other maritime nations. These charts help ensure safe navigation for a wide range of enterprises such as commercial transport, naval operations, and commercial and recreational fisheries, maritime recovery, and provide essential information for effective coastal zone management and planning. The creation of nautical charts is undergoing a revolution with the availability of GPS, digital storage and display systems, and technologies such as multibeam fathometers, side-scan sonars, and airborne lasers. GPS has the potential to dramatically improve the safety and efficiency of maritime transportation systems (NASA, 2001).

Global Observation Systems

New types of infrastructure are very important in observing and monitoring global environmental conditions and processes. It would be very valuable for the international community to work together to expand the World Weather Watch into a full global observing system for the atmosphere, land, and ocean. Global observation systems are a key to monitoring and understanding global environmental systems and to improving our prediction capabilities. Internationally, there are plans for implementing a Global Climate Observation System (GCOS), Global Terrestrial Observing System (GTOS), and a Global Ocean Observing System (GOOS). These systems will use GPS technology as a means to map climatic, terrestrial, and oceanic information.

In the United States, NOAA has a leadership role in implementing GOOS. They are now seeking to ensure the long-term operational support of the Tropical Atmosphere Ocean (TAO) array under GOOS and GCOS. The TAO array is comprised of 68 GPS equipped, moored buoys and provides real-time monitoring of sea surface temperatures, surface winds, and upper ocean thermal structure across the Pacific Ocean. This data is essential to improving climate

forecasts. TAO has been supported by the United States and other countries in the region. Global observation systems hold great promise for the future. But, given funding constraints, the United States will need to be creative in designing and implementing these systems (NASA, 2001).

Precision Agriculture

Precision Agriculture (PA) is an emerging high-technology agricultural management system. Congressional interest centers on federal support for research in Precision Agricultural and is enabling the development of the technologies. Growing competitive pressures stemming from globalization of agricultural markets, improved yields, and new environmental concerns contribute to the reliance of farmers on technological innovation. Increased acceptance and reliance on emerging information technologies are becoming part of U.S. agricultural production. PA refers to the technologies that use sensing and georeferencing GPS-based innovations to apply more precise inputs based on a field's biophysical variability.

Producers first determine the variability within their fields by relating crop production and/or soil attribute data to geographic coordinates using a GPS receiver. These data become the basis for digital soil fertility and variability mapping. The objective of PA is to quantify and manage spatial and temporal variability that exists in virtually every field. Rather than applying fertilizer, seed, pesticide, or water at a uniform rate across an entire field, growers use computer technologies to continually adjust their input applications as they operate their equipment based on the biophysical variability of their land. Estimates suggest that less than 4% of U.S. farmers are using PA technologies. The goals of PA are increased yields and reduced costs. PA is a management system that may do for agriculture essentially what just-in-time production has done for manufacturing (Red Sword Corporation, 2001).

Farmers face significant, but not prohibitive, start-up costs before they achieve potential long-term efficiencies. These costs include yield monitoring, crop scouting, and soil testing over multiple growing seasons and learning how to use remote sensing, the Global Information System (GIS), and Variable Rate Application Technologies (VRT). Individuals may either buy this technology directly or contract for various services providers. Yield monitoring for corn, wheat, or soybean could cost \$4000–\$7000; soil sampling has been estimated at \$3–\$7 per acre or more.

A truck-mounted computer system and GIS software could add an additional \$3000. Soil grid sampling could become an annual expense but, spread over sufficient acreage, this cost has been acceptable to adopters. Other sensor-based applications, sometimes referred to as “on-the-go” sensing, are also evolving.

Individual farm returns on PA investment will vary by the management skills of operators, by the biophysical properties of each field, and by the interactive effects of altering various inputs. The limited data on economic returns to date show mixed results, which is not unexpected given the difficulty of maintaining any consistency of the system between comparative sites. As the technology matures, however, more growers may be likely to consider at least some of the PA technologies either through direct purchase or through contracting for PA services. Information on the adoption of PA is fragmented and rates also are difficult to determine because PA is a group of techniques that can be adopted in different combinations and at different times rather than a single farming system. Published USDA data indicates that about 64,000 farms (about 3.2% of total farms) used computer-aided chemical application or GPS technologies in 1995.

Using GPS signals for guidance, this new tractor could help ease the monotony of endless plowing. Those of us who think corn comes from the grocery store may not appreciate the difficulties farmers face. Driving a tractor isn't like driving a car. There are no yellow lines. The farmer must use his hood ornament, a gun sight, to line up the tractor with a distant landmark, like a notch in the mountains. By aiming for that notch, he can keep the tractor's path straight within about a foot. He's also pulling a plow, typically 30 feet wide. The driver must not only stay focused on the distant mountain, but constantly turn and look to make sure the item in tow is still in line. Poor visibility also makes driving tough. A farmer also needs a windless day to spray fertilizer or pesticide. In the near future, an automated tractor could solve these problems. By calculating its current position and the path it needs to follow, a robotic tractor can drive a precise path, perfectly matching rows to one another in the worst of weather conditions (NASA, 2001).

GPS in Sports

GPS receivers are being carried in hot air balloons during trans-Atlantic racing. The GPS receivers

are used as navigational aids and to verify world records. In addition, velocity and direction information from the GPS allow the users to identify wind currents. Furthermore, position information supplied by the GPS allows rescuers and recovery crews to pick up a downed crew's location. GPS receivers are being used during the America's Cup races for navigation as well as for recovery of crews that have been washed overboard or have abandoned ship. GPS is used in conjunction with radio modems to track the position of each boat. Competition glider pilots are using GPS navigation to map air currents and three-dimensional position such that pilots can recurrently enter updrafts with a high degree of precision, maximizing the effect of the updraft (NASA, 2001).

Archeology and Educational Research

Researchers at Heidelberg College in Ohio conducted a search for archaeological remains of the Battle of Fallen Timbers, where U.S. soldiers fought and defeated a confederation of Native American tribes. Archaeologists used the GPS to assess and map the exact location of battle-related artifacts, which will help define and preserve the battlefield. Marine archaeologists used the GPS to guide their research vessel while hunting for old shipwrecks off. Position repeatability is key to returning to a shipwreck site for continuous recovery (NASA, 2001).

Aviation

Other than the obvious GPS application for aviation, the High Altitude Long Endurance (HALE) autonomous Unmanned Aerial Vehicle (UAV) implements GPS. Global Hawk flies above 60,000 feet for over 30 h completely autonomously. The UAV is able to perform global navigation and complete autonomous landings using precision GPS navigation and differentially aided DGPS navigation (Barth and Farrell, 1999; NASA, 2001).

Environment

Researchers at the University of West Florida use DGPS to study coastline erosion caused by hurricanes. The position of the beach and dunes were measured with GPS before and after the passage of a hurricane and the effect of the storm was measured and visualized in a GIS.

Handheld GPS units are used by agency staff to field locate environmental sources such as monitoring points, regulated ground water supply wells, permitted discharges and regulated storage tank locations. This location information is used to prepare geographic information system files for maps and for computer simulations and analysis (NASA, 2001).

Forestry and Agriculture

Using a well-surveyed site (such as a pasture), DGPS-capable receivers, a DGPS base station, and fixed receivers, herds of cattle have been instrumented for tracking. The study ascertained animal behavior patterns over longer timeframes and in otherwise inaccessible areas with less manpower, and without disrupting the animals' normal behavior patterns (NASA, 2001).

Geographic Information Systems

Mapping and survey grade GPS products and services are used to construct and maintain golf courses. GPS units are used to locate structures for a local emergency services "911" program. GPS receivers are used to locate infrastructure such as fire hydrants, water meters and valves, gas meters, utility poles, etc. for use in a detailed geographic information system. Roadway alignments and intersections are also being collected via GPS units (NASA, 2001).

Ground Transportation

Companies that maintain large fleets of vehicles need to track their vehicles' current locations. GPS receivers that act as vehicle-locating devices are becoming a standard part of fleet tracking systems. Public services of states and municipalities are starting to use GPS in vehicle guidance systems for low-visibility snow plowing. Furthermore, these guidance systems are being used to provide "vision" for emergency vehicles during inclement weather (NASA, 2001).

GPS is being used for companies that have drivers in the field. Typical users include HVAC, electrical, plumbing, telecommunications, couriers, etc. Receivers collect vehicle data, such as maximum speed, vehicle location, length of time at specific location, and activation of specific events associated with vehicle. Information is then used to measure vehicle and driver productivity. Management reports provide

data in a variety of formats, including number of stops, average stop length, and the percentage of total time spent on service calls (NASA, 2001).

Natural Disasters

The California Governor's Office of Emergency Services used GPS after the Northridge earthquake to assess damages and to measure ground deformation. Because earthquakes destroy recognizable landmarks, precise location information is critical to accurate damage assessment and subsequent remediation (NASA, 2001).

Public Health and Safety

A variety of GPS survey systems measure the shifting of buildings to ensure their safety after earthquakes, bombings, and other disasters. The Oklahoma City Survey Division and its contractors used several GPS survey systems to measure the shifting of buildings surrounding the Alfred P. Murrah Federal Building after its bombing in 1995 (Red Sword Corporation, 2001).

The U.S. Federal Prison System is exploring the use of GPS for monitoring the whereabouts of released prisoners in the first 6 months after they are released. State penitentiaries are using GPS to track the activities of inmates that are on temporary leave or work release (NASA, 2001).

Another company has developed a GPS-based navigational system that can guide the blind to the locations of business and other entities within a city. The technology uses GPS mapping services which are translated into audio messages describing the user's location and proximity to businesses and public services.

Space Applications

In an experiment that could change the way satellites are flown in Earth's orbit, the U.S./French TOPEX/Poseidon satellite has successfully completed the first-ever NASA autonomous navigational maneuver. The experiment, which was designed to help validate technology that allows Earth-orbiting satellites to autonomously adjust their orbits, was conducted in early December from the TOPEX/Poseidon mission control room at the Jet Propulsion Laboratory.

The importance of this maneuver lies in the fact that it provides confidence that autonomous satellite actions can be affordably developed and executed at an acceptable level of risk. It is the first step in demonstrating a complete autonomous navigation system for Earth-orbiting satellites.

In the experiment, flight controllers up-linked software to TOPEX/Poseidon that autonomously planned the satellite's actions and generated a series of commands to steer it. The software required minimal input from ground controllers, consisting only of changes in velocity and the time to execute the maneuver. The software then computed the changes in satellite orientation and the amount and timing of satellite thruster burns with no further input from ground controllers.

TOPEX/Poseidon was selected for this experiment because it is an operational satellite that needs to precisely maintain its ground track. It also has an on-board computer that could be used for the experiment without interrupting or jeopardizing satellite normal operations. This computer is part of the experimental GPS receiver that is normally used for precision orbit determination.

NASA's first mission planned to test completely autonomous navigation is the New Millennium Program's Earth Orbiter 1 launched in early 2000. Trans-orbital is investigating the possibility of using GPS signals for range determination beyond Earth's orbit. A preliminary experiment is scheduled for the 2001 TrailBlazer lunar probe to be launched late in 2001.

NASA's Human Space Flight systems will make extensive use of GPS onboard the Space Shuttle, International Space Station, and the Emergency Crew Return Vehicle. In addition, NASA's Earth resource monitoring satellites use GPS to determine their exact location while their instruments are taking scientific measurements (NASA, 2001).

Surveying and Mapping

A pilot based in Rochester, Minnesota charges farmers roughly \$200 an hour to fly a small aircraft at low elevations and take infrared photographs of farmland. The plane flies only 40 mps (meters per second) which allows the digital infrared camera to take images with a resolution of about six square inches per pixel. A GPS unit on top of the camera automatically links every shot that is taken to a geographic spot. An image could illustrate a need for irrigation in a specific area. Soon a software program will help farmers

record the data and compare images from 1 year to the next.

The Minnesota Department of Natural Resources uses various types of GPS equipment and software to map features in the field. A few examples include state park trails and campsites, public water accesses, snowmobile trails, state forest roads, wells, fishnets, and others. GPS is also used by members of the Minnesota Interagency Fire Center (MIFC) to battle forest fires (NASA, 2001).

Telecommunications

GPS is used to determine radio paths and topography at remote locations. An international bank is now using GPS to verify trade information between London and New York. The GPS technology adds an accurate time stamp to the information for verification of the trade's price (NASA, 2001).

Weather Forecasting

The U.S. National Weather Service sends up radiosonde balloons twice daily from more than 100 sites. The term "radiosonde" is a contraction for radiosounding device. The instrument measures the ambient pressure, temperature, and moisture. The balloons are now being equipped with GPS technology to provide a more accurate representation of the time and location at which temperature, humidity, pressure, and wind readings are taken. Precise readings of atmospheric conditions can be relayed to a central database and can be used for short or long-term atmospheric condition tracking. Furthermore, forecasters can use GPS for short-term storm prediction when it is coupled with weather recording instrumentation and a radio modem (NASA, 2001).

Wildlife Biology

GPS can be used to track and locate hunting dogs, wildlife, etc. There are radio-tracking devices on the market today that can do this, but they are often limited to a range of about 5–10 miles.

GPS receivers are being used in conjunction with VHF radio transmitters to study winter movements and conifer use of white-tailed deer in Minnesota. One major issue is the observation bias that results from a deer that may bed under thick conifer canopy cover (NASA, 2001).

Vehicle Driver and Passenger Safety

In the event of a threatening situation or medical emergency, the driver hits a panic button, which immediately reports the alarm and the vehicle's location to the base station. Or in a marine emergency, a distress message is sent reporting the ship's position and heading. In the event of theft, Automated Vehicle Location (AVL) helps you quickly locate and recover your vehicle and cargo. The real-time map display capabilities of AVL allow your dispatchers to help guide drivers through unfamiliar areas, thereby getting vehicles to their destinations faster (Trimble Navigation Limited, 2001). By integrating your AVL system with mobile data terminals or computerized devices, you can benefit from the advantages of digital messaging. For example, with voice communications the driver must be in the vehicle to respond, and then he or she must remember or write down the information. With digital messaging, however, the driver does not have to be present and the information remains on the display terminal. Also, digital messaging can be sent to a specific vehicle, rather than broadcast to the entire fleet. Altogether these benefits can improve the speed and efficiency of communications.

The data logging capabilities of AVL make it easier to document response time, schedule adherence, driver performance, and any other obligations you may have as a contracted service provider. Given all the information AVL provides, you can make much more efficient decisions whenever you need to add a pickup stop for a vehicle that is already en route. By analyzing the performance data of a fleet recorded by AVL, companies are better able to optimize routes and schedules. For example, drivers could use mobile data terminals and customized software to submit field reports electronically after each job, rather than filing paperwork at the end of the day. This reduces paperwork and makes information available immediately. Customers can be given better estimates for time to arrival. AVL can also be used as a convenient service for customers. For example, auto clubs may install AVL equipment so that their members can call for guided navigation in the case that they get lost. Or the auto club could remotely unlock the car doors in case the motorist gets locked out, or dispatch a tow truck to the vehicle's exact location if needed. In some cases AVL may be used to comply with regulations, such as the International Marine Organization's requirement for a Global Maritime Distress and Safety System, or local requirements for taxi fleets to install a driver safety system. In some businesses, AVL can be

used to help ensure that their drivers and field service technicians are at an appropriate location.

Currently AVL and GPS systems are used by ambulance services, mountain rescue services, fire departments, police, public buses, postal services, waste disposal companies, long-haul trucking, delivery couriers, armored cars, taxis, limousines, airport shuttles, rental vehicles, utility companies, cable companies, private security companies, tow trucks, snow plows, auto clubs, roadside service, merchant shipping, fishing fleets, high-value cargo trailers, railway cars, and construction equipment (NASA, 2001). This is not a comprehensive list but it gives an example of how vast the list of applications for GPS has become.

U.S. DGPS Radio Beacon

The Nationwide Differential GPS project will add DGPS radio beacon sites throughout the United States. This system adds ground-based GPS radio beacons to the GPS satellite constellation. It enables the transmission of the highly accurate position data of the beacon, which is used to provide precise altitude, latitude and longitude information for correlation with the information provided by the satellite constellation. The beacon service is valuable in cases where one or more of the satellites of the four available at any time goes out of service for any reason. The plan is to cover every spot with signals from at least two transmitters. The U.S. Coast Guard started the DGPS radio beacon project in 1992 and began reporting status for the DGPS radio beacon system in the fall of 1996. Starlink Corporation built its first receiver back in 1993. There were three transmitters at that time.

Sometime later, the U.S. Army Corps of Engineers decided to give the radio beacons a try. The success of the DGPS radio beacon users did not go unnoticed. The Federal Railroads Administration was looking for a system to improve safety for trains. They did studies and decided to make a major push for nationwide DGPS coverage using the radio beacons. The radio beacon could provide accurate location and trajectory information of every train in the nation for the purpose of collision avoidance and transportation scheduling.

GPS and Wireless Advertising

As the Federal Government stopped scrambling the GPS signal allowing the more precise position data

to be used by all users, it opened up a plethora of new commercial and consumer applications. First among them is the auto industry, which plans to sell GPS mapping and driver services as a bonus to their customers. Outdoor sporting companies are also interested. They will market GPS to campers and sailors as a safety and navigation tool. However, there's a less obvious industry eager to capitalize on the technology. The advertising industry is looking to use GPS to target consumers with a precision never before seen. The idea is that someone who uses a wireless data network is going to respond to an ad that gives him a coupon to buy a Coke from a machine as he walks by it. Wireless content delivery is in its infancy in this country. There is no question that it is poised to become the next big Internet platform. Wireless devices such as mobile phones, personal digital assistant gadgets, and super-pagers are taking off. This means that advertising will quickly adapt, geared to the different dynamics of a wireless world. All told, companies are expected to spend as much as \$2.9 billion on wireless advertising in the United States by 2004, according to Ovum, a technology consulting firm.

Although wireless advertising is barely off the ground in the United States, it has taken off in Asia and Europe, where countries are years ahead of the United States in wireless phone and Internet device use. In Japan, for instance, I-mode, a wireless Internet service from phone giant NTT, has more than 6 million subscribers, with 25,000 more joining each day. I-mode has drawn advertisers such as Tokyo department store Kei-Qyu, which advertises special discounts to elite customers via their cell phones. In Europe, likewise, a more highly developed wireless market is proving to be a testing ground for advertising, with U.S. agencies leading the way. New York-based 24/7 has run 15 limited wireless campaigns—trials intended to reach 10,000 or so consumers for European clients, including KPN, a Dutch telecom; Football365, a London-based sports portal; and DressMart, a Swedish online clothing store. Agency.com is working with London-based Carphone Warehouse, the largest European wholesaler of mobile phones, to create a customizable wireless portal that delivers weather forecasts, local news and e-commerce services to wireless subscribers. Examples of wireless advertising in the United States, though, are harder to find. Intraware and Orinda, a California-based company, is an early innovator. It uses AvantGo, a content distributor to wireless devices, to solicit 500,000 technology professionals on their PDAs. When the target audience members

fired up their Palm devices, they were greeted with a simple text-and-graphics message, which described Intraware's online software sales and services and asked them to submit their e-mail address for more information.

Vindigo, another pioneer, already has plans for GPS-based advertising. The company distributes city guide information to handheld devices, providing tips on where to eat and the best places to be seen. Currently, Vindigo users download information from the company's Web site while their handheld device is attached to a PC. When the software program is used to locate a nearby restaurant or store, a small ad appears at the bottom of the screen for another establishment. In the wireless future, the download will be taken out of the process, and positioning satellites can direct a hungry diner to nearest bistro as well as pitch them on another restaurant just around the corner. High-precision targeting is central to the promise of wireless advertising. This is also what makes this proposition a bit sleazy from a consumer's perspective. One end of the scenario is that as you're walking down the block, your phone goes off as you pass every store and tells you that there's a 50% off-sale. It is likely, at least for U.S. consumers, that this form of advertising will be short lived and will be replaced by more advanced user advertisement targeting technologies (NASA, 2001).

For years, the U.S. market has lacked a standard technology for translating Internet data to information that can be displayed over wireless devices which held back advertising. The industry has now adapted the Wireless Application Protocol (WAP) enabling companies to distribute Internet-ready information to wireless devices equipped to receive it. WAP-ready devices are now starting to debut in the United States, but the industry still lacks a standard way to distribute advertisements across all devices simultaneously. For advertising to flourish in a wireless environment, finding those standards that will enable firms to reach massive audiences is perhaps more important than making use of intensely accurate targeting.

NEW OPPORTUNITIES AHEAD IN THE "BUSINESS OF SPACE"

Tracking advancements in science and technology may lead to identification of new products and services for small businesses. Excerpted from remarks by Kenneth C. Brill, Acting Assistant Secretary for Oceans and International Environmental and

Scientific Affairs, U.S. Department of State to the First International Space Business Assembly, Reagan International Trade Center, Washington, DC, November 2, 1999, State Department's Role—"We at the State Department are not a so-called technical agency, but we have an intense interest in the latest developments in space exploration, space technology, and space commerce as a consumer, facilitator, and promoter. The Department of State is a big consumer of space products and services. We use satellites for instantaneous communication with our more than 200 embassies and consulates overseas. We use remote sensing imagery and the GPS to mediate border disputes, monitor refugee flows and human rights abuses, and respond to natural disasters. Many of the global issues facing us today can only be dealt with if we understand their scientific underpinnings. Information from space-based instruments is central to the good science we try to bring to bear on global issues. Ozone monitoring, deforestation, fish conservation, coral reef degradation, climate monitoring, these are but a few of the areas where we rely heavily on scientific analysis of data from space to inform our decision making and build international consensus." The State Department has a significant role to play in facilitating space cooperation. Cooperative ventures that would have been unthinkable 20 years ago have become commonplace. Moreover, space activities are no longer monopolized by a handful of governments. Commercial spending on space now exceeds government spending, and at least 50 countries have space programs of some sort. The State Department has the task of consulting with other countries and international organizations to promote GPS as a worldwide standard for global navigation. United States achieved a breakthrough last year with Japan, the world's largest user of GPS consumer products, when former President Clinton and Prime Minister Obuchi issued a Joint Statement on GPS cooperation.

TECHNICAL ISSUES TO OVERCOME

The FAA is working to ensure that a single event, like signal jamming, does not cripple the ability to continue to provide navigation services for aviation. The FAA has conducted numerous interference and risk mitigation studies in conjunction with the DoD and other government agencies. All current navigation systems in the United States can be interfered with and jammed. This is a primary concern of the

FAA, as it is deeply involved in ensuring the best possible protection to the GPS signal, including being able to respond to individual acts of intentional or unintentional interference and jamming. Also, the United States is currently planning improvements to the GPS constellation (second and third civil frequencies, increased signal power, additional satellites) that will make the entire system less susceptible to interference and jamming (Hoffman-Wellenhof *et al.*, 1997).

The FAA is also working to ensure that a single event, such as nuclear detonation in space or jamming, does not cripple the ability to continue to provide navigation services for aviation. Since the inception of the FAA's GPS program, there have been a number of interference and risk mitigation studies underway with other government agencies. While these studies are planned to continue, there is virtually no way for the FAA to guarantee or preclude a catastrophic event from occurring. Jamming can be done on all current FAA systems and is a primary concern of the FAA's Spectrum Policy and Management Office. They are involved in the process of ensuring the protection of the GPS signal including being able to respond to individual acts of intentional or unintentional jamming.

A nuclear detonation in a war would have significant consequences on all communication systems. A nuclear Electromagnetic Pulse (EMP) would disrupt or destroy all avionics and electronics that are not EMP hardened, in a bunker, or otherwise protected. GPS satellites are designed and built to provide the highest level of protection against hostile acts as they are a critical component of our national defense. To destroy a GPS satellite in orbit would require a high level of sophistication of engineering and manufacturing capability. Any attempt to destroy a GPS satellite would more than likely be viewed as an act of war.

The FAA's cost benefit analysis for WAAS does not consider the need for a backup system. WAAS is being designed to be a replacement system for the existing ground-based navigation infrastructure that provides capability for en route precision aircraft approach. As with all navigation aids, radio frequency interference, unintentional or intentional, is always a concern. A number of methods for minimizing unintentional interference have been identified and tested and others are being investigated. The FAA is also working with the DoD and other agencies to make sure augmentation systems, such as WAAS, detect and mitigate these effects.

THE FUTURE OF THE GPS

The future of the \$20 billion GPS, as envisioned by the Joint Program Office GPS Modernization effort, includes enhancements to make GPS more robust and useful. Increasing signal power in combat theaters, for example, would make signals easier to acquire and harder to jam. Changing the coding structure would make signals harder to alter and easier to lock onto during combat.

When future GPS satellites migrate to the new Evolved Expendable Launch Vehicle, the Joint Program Office would also be able to offer almost 800 W of power on the satellite, a vast increase from the original specification. No final decisions have yet been made on what to do with the extra power and payload capacity. It is also important to increase the constellation size. Besides increasing signal power, users would like up to 30 satellites in the GPS constellation in order to reduce vulnerability to jamming. What GPS may look like in the future depends on how well we can protect the GPS operating frequencies in the short run. Government sources have stated that now is the time to make a commitment to go from a “weak” to a “strong” system. These sources have also stated that it will likely take an additional \$750 million over and above current spending levels to get a strong modernization program underway.

Other programs include: the Defense Advanced GPS Receiver, which is expected to be awarded in the next 2 years, and a new-generation Miniaturized Airborne GPS Receiver. The latter will take an open-systems approach to reduce the cost of integrating and upgrading GPS gear. The Defense Advanced Research Projects Agency is also developing advanced navigation technologies and miniaturizing GPS user equipment. The agency’s GPS Guidance Package program, for example, which integrates fiber-optic inertial guidance with GPS in a seven-pound package. The DoD is also working on smaller, more accurate clocks for GPS receivers, allowing faster startup and signal acquisition and reacquisition in a jamming environment. One contractor, Q-Tech, is expected to introduce clocks for handheld units next year that will provide up to three orders of magnitude greater accuracy than today’s receivers while requiring the same power levels.

Further into the future, the agency is looking at putting pseudolites—which are satellite surrogates on tactical unmanned aerial vehicles to broadcast GPS signals locally. Low-power (less than 1 W), low-

cost (less than \$1200 per unit), man-portable INS/GPS (fiber-optic inertial guidance and GPS-based system) units for infantry and weapons system operations are also in the works.

CONCLUSION

One thing that makes GPS so exciting is that the theorems and theories that guided the development of GPS stretch over hundreds of years and involved individuals with names such as Pythagoras, Kepler, Newton, and Einstein. It also covers the entire spectrum of physics and its practice including communications, computers, software engineering, semiconductors, microelectronic design, and automation and, in fact, every discipline of modern technology.

It is said that GPS will be the next utility, and that it will be available free of charge. It will, like other utilities such as the electricity, running water, and the telephone, become a part of everyone’s daily life. A GPS receiver will soon cost no more than a pocket radio or a watch, meaning that everybody will be able to afford one. The applications of this new breed of high-tech capability are limited only by your imagination. However, the satellite-based principles on which GPS receivers operate are considered so esoteric that most people don’t bother with them or else misunderstand them (see Fig. 6).

GPS based products will likely fuel the next economic expansion of the free world. This technology has the potential to add more than \$20 billion to our U.S. economy in the next 5–10 years. The key to



Fig. 6. Casio Pathfinder GPS watch.

making GPS technology as common as a wristwatch is cost, practical application availability, and the precision of the GPS signal that is continuously available to the consumer market. Current estimates and trends for GPS receivers would indicate that the cost of a given pocket GPS receiver should be less than \$20 by 2005. Also, key to the continued development of the industry is the continued government and commercial research and technology deployment necessary to improve the current GPS satellite constellation and ground-based systems.

United States government policy in this area over the last 10 years has been ambiguous and, at times, hostile toward the further development of space-based technology. Fortunately, commercial resources have been able to overcome the governmental policy abyss by investing in GPS technology. The future of GPS technology in our society is certain. Only politics, money, and application development stand in the way of the future.

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