The Global Positioning System as a Complementary Tool for Remote Sensing and other Applications

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EARLY IN AUGUST 1990, U.S. troops pouring into Saudi Arabia as part of the Desert Shield build-up faced a critical challenge: how to deploy men and equipment quickly and safely across the treacherous sands of a trackless desert. In the days following the Iraqi invasion of Kuwait, maps of the area were more than a quarter-century old and of questionable accuracy. If advance elements of the 82nd Airborne Division were to successfully confront the military threat and come to the aid of Iraqi-occupied Kuwait, they would need accurate maps immediately.

Traditional cartographic techniques require considerable time to produce usable maps – too much time for this life-or-death situation. So, the U.S. Department of Defense and contractors providing cartographic services turned to two satellite-based technologies to create the needed maps quickly: Landsat multispectral imagery and the Global Positioning System (GPS).

First, technicians selected identifiable ground points visible in the satellite images, such features as crossroads, buildings, and geographical landmarks. Next they used portable GPS receivers to "position" each ground point, that is, to determine its exact location. These positions were then entered into a computer in which the digitized satellite image had already been stored. Using a special program, computer operators reshaped the satellite image to fit the GPS coordinates and produced a georeferenced, "photographic" map that military planners could were able to use in their operations.

This bit of recent military history provides a particularly dramatic example of techniques being used by increasing numbers of professionals in a wide variety of application areas who combine the accurate, instantaneous positioning capability of GPS with other technologies, including remote sensing, navigation, and vehicle tracking. GPS provides real-time three-dimensional positioning data with a horizontal accuracy of 25 metres or better – and, when all the satellites are in place, these data will be continuously available 24-hours-a-day from any point on or above the planet. "Differential" techniques, which use a receiver at a precisely known point to calculate corrections and transmit these to other receivers operating nearby, promise real-time accuracy of a few metres or even centimetres. "Postprocessed" data from differential GPS (DGPS) positioning have been used by geodesists and surveyors for years to provide accuracies of a centimetre or less over baselines hundreds of kilometres long.

Although the system was developed for, and is operated by, the U.S. Department of Defense, the GPS satellite signals are accessible free of charge to commercial and civilian users as well (although an on-board system for detecting nuclear detonations can, however, only be accessed by DoD users). Despite the enormous role of GPS in Desert Shield/Desert Storm – for navigation, missile guidance, artillery placement, and so forth – civil groups have outstripped military users in practical application of the new technology. As a passive system (one-way transmissions from satellites acquired by receive-only user sets), a limited amount of radio spectrum can support an unlimited number of users. Recent market studies have projected a worldwide market for military and commercial GPS equipment reaching between $4 and $6 billion a year by the mid-1990s.

Navigation, vehicle tracking, and geodetic surveying make up the largest categories of civil GPS applications today, although more esoteric uses are rapidly emerging, such as animal-habitat research, detecting structural deformation in dams and oil platforms, resource management, and monitoring environmental pollution and natural hazards such as volcanoes and earthquakes. In remote sensing, GPS has been used for several years to quickly survey ground control points for photogrammetry and to navigate the flight lines for photogrammetric aircraft. Now, sophisticated GPS techniques are eliminating the need for any ground control at all. GPS offers a flexible tool for ground-truthing data derived from airborne or satellite sensors, for aiding archaeological or mineral exploration, mapping vegetation and other resources, land-use planning, utility and highway construction, and so forth. Together with geographic information systems (GIS) and computer-aided design (CAD), it can help georeference base maps and other spatial data layers, and position- and time-tag assets entered into a GIS.

A BRIEF HISTORY

The Global Positioning System began as a secret military program, growing out of Navy and Air Force research in the late 1960s. The first satellite was launched 22 February 1978, one in a series of prototype or Block I spacecraft engineered and manufactured by Rockwell International. The U.S. Air Force Space Systems Division at Los Angeles Air Force Base, through its NAVSTAR GPS Joint Program Office (JPO), manages the system as the executive agency for the Department of Defense (DoD). The Operational Control Segment (OCS), directed from the Master Control Station at Falcon Air Force Base in Colorado Springs, maintains the satellites' orbital position and timing accuracies. The OCS also includes four monitoring stations, located on Ascension Island in the South Atlantic, Diego Garcia in the Indian Ocean, Kwajalein in the Pacific Ocean's Marshall Islands, and on Oahu in Hawaii. Originally intended for orbital insertion from space shuttles, the Block IIs have been launched from special McDonnell Douglas Delta II rockets in the wake of the tragic Challenger incident. Through an office at the Omega Navigation System Center in Alexandria, Virginia, the U.S. Coast Guard exercises responsibility for providing civilians with information on the status of the system, including satellite "health," planned orbital maneuvers, and launches.

By early 1992, a total of 17 Block I and Block II satellites were on orbit and operating. That effectively provided a worldwide two-dimensional positioning capability (latitude and longitude only) 24 hours a day and an average of 19 hours of three-dimensional positioning capability (latitude, longitude, and height). A full 21-satellite constellation is still expected to be in place by late 1993.

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GPS TECHNOLOGY

GPS receivers calculate a position by simultaneous ranging (or measurement of distance) to three or more satellites that are transmitting continuous L-band radio signals. When the full operational constellation is completed in 1993, 21 Navstar GPS satellites (plus three active, on-orbit spares) will be circling the Earth twice a day in six orbital planes about 20,180 kilometres out. The orbital planes are spaced equally 60 degrees apart and inclined at 63-degree angles to the equator. With appropriate equipment, GPS users will be able to determine their positions nearly instantaneously anywhere in the world, 24 hours a day, with a precision better than any other navigation system available today or in the foreseeable future.

The GPS satellite microwave radio signals – centered on 1575.42 MHz for the so-called L1 carrier and 1227.60 MHz for L2 – contain three key ingredients: the satellite identification, precise time provided by atomic clocks on the satellites, and the orbital location of the satellite. Each satellite transmits its navigation message with a unique pseudorandom noise (PRN) code that identifies and distinguishes its signal from the other GPS space vehicles. The signal actually provides two levels of coded operation, a Precise Positioning Service (PPS) that uses the P (precise) code carried on both L1 and L2 frequencies, and the Standard Positioning Service (SPS) available from the C/A (coarse acquisition) code broadcast only on the L1 carrier.

A GPS receiver computes distances to the satellites using the basic formula of the speed of light (and radio signals) multiplied by the elapsed time since the signal's transmission. Satellite time-keeping is accomplished with either rubidium (early Block I) or cesium (late Block I and subsequent generations) frequency standards. Ranging to three satellites will provide a two-dimensional horizontal (latitude/longitude) position fix, and use of four or more satellites' signals generates a three-dimensional solution. An extra satellite is needed to determine – through a mathematical computation known as double-differencing – the time offsets between the atomic clocks on the satellites and the less-accurate clocks in the receivers.

PPS horizontal accuracies are in the 10- to 20-metre range, although some users have claimed stand-alone positioning capability close to five meters. System designers originally anticipated that the C/A code would produce horizontal accuracies of about 100 metres, but actual experience has demonstrated a precision close to that of PPS – somewhere in the 15- to 30-metre range, depending on the available satellite constellation and the type of equipment used. With the signals, receivers can also calculate a user's velocity and the precise time.

POLITICAL LIMITATIONS

Its origin and continued operation as primarily a military system, however, has saddled the Global Positioning System with certain technical and operational limitations that affect its utility for civilian users. Chief among these are policies regarding selective availability (SA) and antispoofing (AS). SA is a method of denying unauthorized GPS users access to the full accuracy of the system by introducing slight errors into the time and orbital-position data broadcast in the satellites' navigation message. National security and military officials pressed for introduction of such a technique so as to assure U.S. and allied military forces an advantage over potential enemies in the navigational resource available to them. Consequently, Block II satellites were outfitted with the SA capability. Block I spacecraft are not subject to signal degradation.

Under an agreement between the Department of Defense and Department of Transportation, the amount of SA-induced inaccuracy can not exceed 100-metres horizontally and 150 metres vertically 95 percent of the time. The degradation of horizontal accuracy should not exceed 300 metres for 99.9 percent of the remaining time. DoD policy calls for the SA function to be implemented more or less full time even during the developmental stage of the satellite constellation. It was turned on in the months before Iraq's invasion of Kuwait, then turned off to accommodate the large number of C/A-code receivers used during the military confrontation and associated postwar operations. Early in November 1991, DoD once again reactivated SA.

Antispoofing, which is accomplished by encrypting the precise code, was designed to prevent military enemies from broadcasting imitation P-code signals. It requires units equipped with a special decryption key to obtain correct data transmitted in a satellite's navigation message. In 1990, the Defense Department announced its intention to implement AS and encrypt the P-code once the fully operational constellation was in place. Implementation of SA and AS during peacetime remains a controversial issue, with many commercial and civilian users advocating their activation only in times of political unrest or war.

GPS IN REMOTE SENSING

Most frequent uses of GPS are to precisely determine the location of the sensor itself, to georeference the area presented in the images, or to position particular items or assets within the image area. This may involve such rough and ready measures as overflying an area and logging aircraft positions and assets or features on the ground. Alaskan environmentalists, for instance, have used that technique in tracking migration patterns of caribou in a North Slope area where an oil pipeline might be laid. As the plane passes over a herd, a technician enters the numbers and types of animals into a datalogger, which simultaneously receives position inputs from a GPS receiver. In Yellowstone Park, the sensing equipment is an infrared camera detecting hotspots in the pavement of the highways in the geothermally active area. Monitored data is used to predict roadbed deterioration and help design maintenance plans. The on-board GPS unit logs the location of the aircraft camera at the time the infrared imagery was captured and allows an accurate map of the road system to be created later.

In the early days of establishing the GPS satellite constellation, survey companies began using GPS to determine the location of ground markers used by photogrammetrists. GPS proved of particular value in areas of rough terrain, where traditional line-of-sight surveying techniques are laborious and costly. GPS operators were able to go directly to predetermined sites and record positions, rather than establish transverse loops with a number of extraneous intermediate observation points that were used only to bring control along to the next marker. The cost and labor advantages were great enough to justify scheduling project work around the limited hours of availability of sufficient satellite radio signals to obtain accurate positions.

Recently, state and federal agencies with survey responsibilities have begun applying techniques that eliminate the need for ground control. This is accomplished by using GPS for precise navigation along predetermined flightlines and for establishing the position of the metric camera's focal point and inclination at the moment of film exposure. Rear Admiral Austin Yeager, director of NOAA's Coast and Geodetic Survey, recently reported increased field productivity of more than 30 percent using GPS in agency surveys. The GPS-enhanced photogrammetry techniques have been a particular aid in mapping low-lying coastal areas that make ground access difficult. Staffers at the Agricultural Research Service's Remote Sensing Research Laboratory in Beltsville, Maryland, have demonstrated the ability to georeference an airphoto mosaic using GPS control points with an accuracy comparable to or better than points digitized from USGS 1:24,000-scale maps. Researchers at the University of Texas Applied Research Laboratories in Austin have also made substantial progress in developing photogrammetric techniques, in part an outgrowth of field experience gained from road-design surveys conducted for the state's Department of Highways and Transportation. Australia's Department of Lands has also supported work in this area. And, perhaps the ultimate confirmation of the prospects for such techniques comes from Germany's Carl Zeiss company, which has developed a commercial GPS-based photoflight management system to support its RMK TOP aerial survey camera products.

Researchers at the U.S. Forest Service's Nationwide Forestry Applications Program in Salt Lake City, Utah, have moved beyond still photography to develop a method that couples real-time differential GPS with an airborne video system. Each frame can display coordinate information about the video or thematic image in a caption overlay, for use in a variety of forestry applications, including law enforcement, environmental mapping and monitoring, forest pest and fire management, and resource surveys. Features seen on the video tape can be accurately plotted using the displayed DGPS coordinates. Imagery can also be converted into a digital format using a computer with an image-capture board and image-processing system. Digitized images in raster format can be georeferenced, mosaicked, and used to update GIS databases.

The GPS/satellite-image mapping techniques described at the outset of this article have also been applied to more benign endeavors, including a U.S.-funded reforestation project in the Sudan. Staff from the U.S. Department of Agriculture and the U.S. Geological Survey used Landsat thematic mapper scenes to create a 1:100,000-scale base map of the project area, which supported subsequent overlays of vegetation and other resource information.

Satellite-derived multispectral imagery, combined with GPS ground control, is increasingly used for oil and mineral exploration. Potential ore-bearing soils reflect light with distinctive signatures, but require ground truthing to match images with geologic samples. Similar techniques have been applied by University of Utah researchers and others to map vegetation in forests. Researchers at Hunter College assisted a UNICEF campaign to eliminate Dracunuculiasis, or Guinea worm infection, by using GPS to identify the coordinates of uncharted West African villages (many of which were moved regularly) and build this into a GIS database. GPS helped UNICEF assess the impact of its educational, water, chemical treatment, and other interventions to check the reinfection rates of the disease.

NAVIGATION AND VEHICLE TRACKING

GPS is poised for burgeoning growth as a navigation aid, for air, land, sea, and space vehicles. Commercial and recreational marine vessels already provide an active market for GPS sensors and receivers, often used in tangent with electronic charts and graphic displays. In space, NASA plans to put GPS on board several new satellites scheduled for launch during this decade, and several hundred low-Earth-orbiting and geostationary satellites proposed for providing mobile satellite services in the next few years will incorporate GPS for tracking and navigation tasks. In Japan, tens of thousands of motorists have purchased luxury models of Toyotas, Mazdas, and other automobiles that feature GPS-based navigation and guidance systems. Coupled with dashboard-mounted color monitor screens that display a map of the local highway or street network, a blinking cursor shows the vehicle's location as determined by an on-board GPS unit. Introduction of similar products in the United States awaits completion of accurate digital maps for the American road system. GPS navigation sensors are currently being incorporated in new aircraft design, including Boeing's multibillion-dollar 777 now under development, and most air transport companies have plans to retrofit existing aircraft with GPS as soon as standards and certification processing have been completed. General aviation and business aircraft already have adopted navigation equipment that includes GPS capabilities.

When coupled with a suitable data communications capability and a central processing and monitoring facility, GPS can support a variety of vehicle tracking operations. Denver, Colorado, and Dallas, Texas, are implementing GPS-based systems for managing bus and other public transit vehicles. With the locations of vehicles available for display on monitor screens in real-time, operations managers can determine if buses have gotten off their prescribed routes and schedule or have experienced mechanical failures or other difficulties. Similar systems providing route guidance and traffic advisories to private vehicle operators are currently under way in Chicago, Illinois, and Orlando, Florida, and commercial trucking and delivery services are adopting the technology as well. Burlington Northern has developed a prototype advanced railroad electronics system that uses GPS and a variety of other on-board sensors to monitor and manage the flow of rail freight. Police, fire, and emergency service providers are assessing GPS-based systems for dispatch and incident management operations. Under the auspices of the International Civil Aviation Organization, the United States and other nations are moving toward adoption of a transoceanic air traffic surveillance and control system based on GPS and communication satellites. The improved accuracy and timeliness of position determination will increase the number of aircraft that can safely travel the most popular air routes.