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Environmental Applications of GPS

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ABSTRACT

The use of the Global Positioning System (GPS) has revolutionized air travel, ocean navigation, land navigation, and the collection of environmental data. Although a basic civilian GPS receiver can be purchased for as little as \$100, the receiver is only the tip of a 12 billion dollar iceberg! This paper will discuss the history and basic operation of the Global Positioning System, a satellite-based precision positioning and timing service developed and operated by the Department of Defense. It will also describe the accuracy limitations of the civil GPS service and how accuracy can be enhanced by the use of differential GPS (DGPS), using either the free National Differential GPS system, or commercial differential monitor stations. Finally, the paper will discuss the future accuracy upgrades of civil GPS as a result of recent federal policy decisions.

INTRODUCTION

In the 1970's, the NAVSTAR Global Positioning System (GPS), was conceived and developed primarily as a military tool for navigation and timing. Since GPS was intended primarily as a military system, capabilities were built in to deny potential adversaries the use of the most accurate GPS service. This intentional degradation of the accuracy of the civil GPS service is called Selective Availability (or SA). The early GPS developers, however, underestimated the ingenuity of the civilian users, who quickly developed enhanced GPS techniques, which not only eliminated the effects of SA but also eliminate other system errors, increasing optimum GPS position-fixing accuracy for civil users to less than a meter. This can be done either through near real-time techniques or by post-processing the GPS data.

In 1978, the first GPS development satellite was launched. In 1983, President Reagan offered GPS offered to all civil users free of direct charge indefinitely in response to the shoot down of the off-course Korean Air Flight 007 by a Soviet anti-aircraft missile. As GPS became operational, the number of civil users grew rapidly and quickly outgrew the number of military users. Since then, GPS has proved its worth in military operations with Operation Desert Storm and in numerous civil applications. In 1996, with the Presidential Decision Directive (1), management of the system was transferred from the Department of Defense (DoD) to the Interagency GPS Executive Board (IGEB), which is co-chaired by the Secretary of Defense and the Secretary of the Department of Transportation (DOT), with several

other federal departments participating. The DOT was established as the lead agency for civil GPS matters. This directive brought civil representation to management of the system.

Today, the DoD GPS Joint Program Office (JPO), the agency which develops and supports the GPS satellite constellation, is improving the system to keep up with worldwide demand. This effort, called GPS Modernization, is striving to upgrade the system capabilities by providing more system robustness, accuracy, and integrity.

NAVSTAR GLOBAL POSITIONING SYSTEM

The NAVSTAR Global Positioning System (GPS) consists of a 24 satellite constellation, circling the globe and spaced so that users on or near the earth's surface can receive radio signals from at least four satellites at the same time. GPS receivers use the satellite time and position information contained in these radio signals to compute precise, multi-dimensional position fixes. Since GPS data includes accurate timing from on-board atomic clocks, GPS receivers can also calculate the speed of their host platform (automobiles, ships, or aircraft).

The GPS is actually composed of three subsystems or Segments, the Space Segment, the Control Segment, and the User Segment. Each of the Segments is described below:

Space Segment

The Space Segment consists of the satellite constellation of the 24 NAVSTAR satellites. The satellites are arranged in 6 orbital planes inclined at 55 degrees relative to the equator, with 4 satellites per plane. With an orbital period of approximately 12 hours, virtually every location on earth is potentially in view of at least 5 to 8 satellites.

The current generation of satellites, called GPS Block IIF, are 5.3 meters across. Each solar powered satellite contains 2 rubidium and 2 cesium clocks, two L-band navigation radio transmitters at 1575.42 MHz (L1) and 1227.60 MHz (L2).

Control Segment

The NAVSTAR satellites are controlled by a Master Control Station located at Falcon Air Force base in Colorado Springs, Colorado. There are also five Monitor Stations (Hawaii, Kwajalein Island, Ascension Island, Diego Garcia Island, and Colorado Springs). The Monitor Stations passively track all satellites in view and send data to the Master Control Station where satellite data processing and control is accomplished. Control signals are then uplinked to the satellites from Diego Garcia, Kajalein, and Ascension Island.

User Segment

The User Segment consists of the users GPS receivers. There are two types of receivers, civil receivers which receive and process the data on the GPS L1 frequency, and military receivers which can receive and process data on both the L1 and L2 GPS frequencies.

LIMITATIONS ON GPS ACCURACY

Civil GPS receivers use the Standard Positioning Service (SPS) signals on the L1 frequency to perform a triangulation computation on the position of the GPS satellites. The L1 signal contains both a Coarse Acquisition Code and navigation data. Because of irregularities in the ionosphere (which affect the time of arrival of the GPS signals) and other system errors, civilian GPS receivers have a horizontal accuracy of about +/- 15 meters (95 percent probability). However the Department of Defense currently distorts the SPS signals with Selective Availability (SA), a randomly generated error, which reduces horizontal

SPS accuracy to about +/- 100 meters (95 percent probability). Vertical positioning error with SA is +/- 156 meters (95% probability). Differential GPS, as discussed in the next section, can compensate for much of this error by using a reference signal from a second GPS receiver at a known location to eliminate system errors.

Military GPS receivers use the Precision Positioning Service (PPS) which utilizes both the L1 and L2 GPS frequencies. This allows the ionospheric errors to be compensated for. Additionally the signals are not altered by Selective Availability. This allows for a horizontal positioning error of 22 meters and a vertical accuracy of 27.7 meters (95% probability). The PPS is not available to civilian users at this time; however, GPS Modernization efforts will bring SPS accuracy to near the capability of the military signal.

In addition to SA, there are other unintentional sources of error which can affect the accuracy of GPS. These include clock and ephemeris errors, errors due to atmospheric delays, multipath errors, receiver noise, and errors due to poor satellite geometry. Accuracy is just one characteristic of GPS which can affect its adequacy for use in critical applications. Other operational characteristics to consider include integrity (that the signal is providing correct GPS data), continuity of service, availability (especially in challenging environments as in steep valleys), and resistance to radio frequency interference from other sources (2).

USING DIFFERENTIAL GPS AND HIGH ACCURACY SURVEYING SYSTEMS

Differential GPS (DGPS) can compensate for many of the errors in the Standard Positioning Service and produce a position fix within +/- 1 to 10 meters. Real-time Differential GPS uses a fixed reference station with a known geographic position, which transmits corrections to GPS users with compatible equipment. Corrections can also be recorded for post-processing. Differential correction signals can be received from the free National DGPS (NDGPS) system of ground beacons, or from commercial services using satellite or private radio beacons to broadcast differential corrections

National Differential GPS (NDGPS)

The U.S. Coast Guard transmits differential GPS signals from 54 sites throughout the U.S. The service is designed to provide accurate navigation for commercial and pleasure boats, but is usable in many inland areas. The signals are transmitted in the 200 to 500 kHz long wave radio band. A differential beacon receiver and a DGPS compatible GPS receiver are required to use the system (3). The National Railway Administration is converting obsolete U.S. Air Force Groundwave Emergency Network (GWEN) sites to DGPS monitor stations. This will add 33 inland DGPS sites. The combined system will provide free DGPS service to most of the U.S.

Commercial DGPS

There are several commercial subscription DGPS systems available. They require a monthly or yearly subscription fee and a special differential beacon receiver. OmniSTAR is a typical system. It consists of a nationwide network of reference stations which transmit differential corrections to a satellite system which retransmits the signals to subscribing DGPS users. OmniSTAR claims complete coverage of the U.S. and much of Canada (4). Other commercial systems use short range transmitters to cover specific geographic regions or transmit a sub-audible signal on the FM broadcast band.

Precision Surveying

It is possible to obtain accuracy on the order of millimeters to centimeters by using carrier phase tracking. The most precise systems use a reference station up to 30 km away from the remote station. Corrections are then post-processed on a microcomputer. These systems are complex and expensive,

and require skilled surveying technicians for operation and setup.

TYPICAL ENVIRONMENTAL APPLICATIONS

GPS has been used for a wide variety of environmental applications, both stand-alone and differential GPS receivers have been used, depending on the accuracy requirements. For general environmental surveys, a standard civil GPS receiver (non-DGPS) can be used if the application can tolerate the +/- 100 m accuracy. Most environmental applications require some form of DGPS with its +/- 10 m accuracy. DGPS data is suitable for most mapping and geographic information system (GIS) applications. Several typical environmental applications are described below.

Lake Water Quality Study

Bechtel Environmental, Inc. of Oak Ridge, Tennessee performed an early GPS assisted water quality study in 1991 (5). Both stand-alone and differential GPS receivers were used to map sampling positions for PCB contamination on Hartwell Lake, located on the Georgia - South Carolina border. At that time, 1991, the GPS constellation of 24 NAVSTAR satellites was not fully in place, so a limited number of hours were available each day for GPS operations. During part of the study, Selective Availability was turned off by the DoD due to the Gulf War. Later in the study differential GPS, with a portable reference station was used (the U.S. Coast Guard DGPS system was not yet operational).

Oil Spill Tracking

The National Oceanic and Atmospheric Administration (NOAA) developed a GPS based oil spill tracking system (6). An airborne tracking system consisting of a stand-alone GPS receiver and a custom datalogger was used to track oil slicks from the air. The datalogger was configured with custom keys to annotate the data record with flags on slick quality, appearance, and other characteristics. The system was first deployed on the Exxon Valdez oil spill. Data was post-processed and used to validate NOAA oil slick models. A GPS equipped drifter buoy was also developed by NOAA and the U.S. Minerals Management Service (MMS). Dropped into an oil slick by helicopter, the buoys drift along with the slick, and telemeter GPS coordinates via the TIROS satellite system.

Radioactive Waste Contamination Survey

The Hanford Site in Washington State, was until the mid-eighties, the primary source of plutonium for the U.S. nuclear arsenal. After plutonium production at the site was stopped in 1989, a radiological survey of hundreds of square miles of potentially contaminated land was required. Westinghouse Hanford Company developed a unique monitoring vehicle called the Mobile Surface Contamination Monitor (MSCM – II). Based on a heavy duty four wheel drive farm tractor, the MSCM – II has sensitive scintillation counters mounted on a front-end loader arm. Data from the counters is processed by an on-board computer system and combined with latitude and longitude coordinates from a differential GPS system, and operator entered attributes (7). Data is later downloaded and integrated with Geographic Information System applications.

Landfill Gas Monitoring

Municipal solid waste landfills emit landfill gas, a mixture of carbon monoxide and methane. Landfill gas emissions are being controlled by gas extraction systems consisting of well, piping, and flares, engines, and gas turbines. Periodic surveys of surface emissions from landfills are required to measure the efficiency of the control system and to comply with federal and state air emission regulations. Most landfills use an expensive and tedious survey technique in which a technician walks the landfill (some cover hundreds of acres) and records data from a portable flame ionization methane detector. There is considerable ambiguity as to the location of sample points unless a survey team is used to accurately record the location of "hot spots". An improved method has been developed which uses an all terrain

vehicle equipped with on board monitoring equipment, differential GPS, and computer data logger (8). This DGPS based system is both more economic and more accurate.

PRACTICAL CONSIDERATIONS

Terrain

GPS receivers require acquisition of at least four satellites to generate a three dimensional position fix, three satellites for the position, and the fourth for timing information to synchronize the GPS receiver clock to the atomic clocks on board the NAVSTAR satellites. Some terrain features such as canyons or nearby hillsides may not permit acquisition of the required four satellites because they may be blocked from view. It may be possible to get a fix at a different time of day when the satellites are in a different position relative to the user.

Record Keeping

Always keep a notebook to provide a backup to the on board memory in the GPS receiver. At a minimum record landmark names, approximate location, and time and date.

Coordinate Systems

The choice of coordinate system will depend on the ultimate use of the data. For many projects, latitude and longitude coordinates are preferred. However it is much easier to use Universal Transverse Mercator (UTM) coordinates in the field as they can be easily plotted on standard 7-1/2 minute series topographic maps. GPS receivers can be set to transform coordinates from one system to another.

Map Datums

All maps are referenced to a map datum. The GPS receiver must be setup to match the datum used on the map being used to plot the coordinates. Most topographic maps use the NAD 27 datum. If an incorrect datum is used, plotted points could be as much as 100 m off.

Equipment Selection

GPS receivers are available from a number of vendors. There are two basic categories of receivers, consumer grade and commercial grade. Consumer grade GPS receivers are lightweight, handheld, and have the capacity to store several hundred fixes (or waypoints). Some have provisions for connecting external antennas, a computer port, and a DGPS receiver connection. Prices in the \$100 to \$300 range are typical. Consumer grade GPS receivers, particularly with an added DGPS receiver, are adequate for many smaller environmental monitoring jobs.

Commercial grade GPS receivers are more rugged and heavier. They are typically equipped with either built-in DGPS receivers or have DGPS ports. The main difference is that they have the capacity to store thousands of points. They also have available software to interface with GIS and computer aided design systems. Prices for commercial grade GPS receivers are in the thousands of dollars.

FUTURE UPGRADES TO STANDARD GPS ACCURACY

Most civil GPS applications require much better accuracy than that offered by the SPS. Recent GPS Policy is striving to address the service accuracy and robustness needed for civil GPS applications. Many of these applications concern "safety of life services," such as commercial aviation, emergency vehicle location and dispatching, and harbor navigation.

For civil GPS users, the most beneficial GPS Policy direction came about with the Presidential Decision

Directive of March 1996 (1). This directive defined policy on the future management and use of GPS, including: 1) continuing to provide the GPS Standard Positioning Service for peaceful civil, commercial, and scientific use on a continuous, worldwide basis, free of direct user fees, 2) discontinuing the use of GPS Selective Availability within a decade, and 3) establishing a permanent Interagency GPS Executive Board, jointly chaired by the Department of Defense and Transportation, to manage GPS and U.S. Government GPS augmentations.

In March 1998, Vice President Gore announced that two new civil GPS signals would be provided by the US in order to improve accuracy and robustness of the civil Standard Positioning System (9). These two new frequencies will improve accuracy by eliminating timing and ranging errors due to distortions in the ionosphere. One of the signals will be transmitted on the existing GPS L2 frequency which is currently used by military users. The second new civil frequency will be assigned in a protected frequency band suitable for "safety of life" services, as civil aviation.

The addition of a third civil frequency, however, will probably mean a minor increase in the price for a GPS receiver initially. Existing civil receivers will not be able to receive the new frequencies. However, as in most consumer electronics, the price of a GPS receiver will continue to decline while the consumer gets more capability, as microelectronics and manufacturing technology advance. These new civil signals will be added to the next generation of NAVSTAR GPS satellites, the Block IIF satellites, scheduled for first launch in 2003, as part of a \$400 million GPS Modernization Program which is scheduled for completion by 2005.

Selective Availability

GPS accuracy with SA turned off will not replace the accuracy of GPS with DGPS corrections. However, "low-end" (inexpensive) receivers would provide for greater accuracy with better capability to make ionospheric corrections. The availability of more accurate, lower cost receivers means that GPS can become a more widespread tool. This means even more integration of GPS into everyday applications. Beginning in 2000, the President will make an annual determination on the continued use of GPS Selective Availability, with the goal of discontinuing its use by 2006.

CONCLUSIONS

GPS technology can be used to improve the accuracy of environmental monitoring by providing accurate spatial coordinates that can be correlated with environmental measurements. This correlated data can be used to calibrate environmental models, and prepare GIS maps. Low cost differential GPS equipment will provide spatial accuracy in the +/- 10 meter range.

Civil GPS users can expect increased accuracy to be available in the near future with the addition of the second and third civil GPS frequencies. Further accuracy improvement will result when Selective Availability is discontinued by 2006. However the use of Differential GPS techniques is still recommended for most environmental applications.

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