United States
Environmental Protection
Agency

Office of Research and
Development
Washington, DC 20460

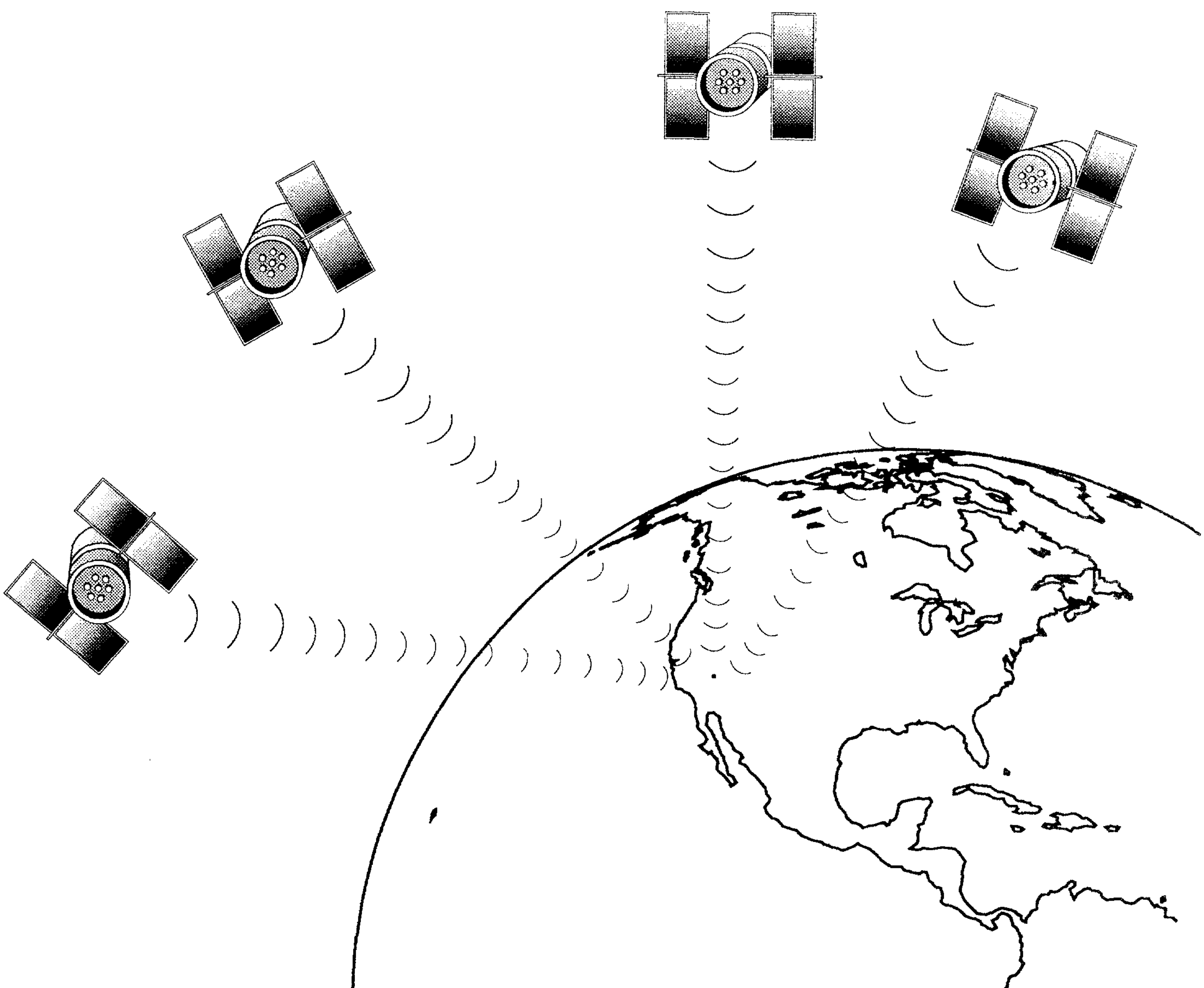
EPA/600/R-92/036
February 1992

EPA

GIS

Technical Memorandum 3:

Global Positioning Systems Technology and its Application in Environmental Programs



EPA/600/R-92/036
February 1992

GIS Technical Memorandum 3: Global Positioning Systems Technology and its Application in Environmental Programs

by

Robert Puterski[1]
Jerome A. Carter[1]
Mason J. Hewitt, III[2]
Heather F. Stone[2]
Lawrence T. Fisher, Ph. D.[1]
E. Terrence Slonecker[3]

[1]Center for Spatial Analysis, Environmental Programs Office
Lockheed Engineering & Sciences Company
1050 E. Flamingo Road, Suite 126, Las Vegas, Nevada 89119

[2]Remote and Air Monitoring Branch Advanced Monitoring Systems Division
Environmental Monitoring Systems Laboratory
U.S. Environmental Protection Agency
P.O. Box 93478, Las Vegas, Nevada 89193-3478

[3]Environmental Photographic Interpretation Center
Environmental Monitoring Systems Laboratory
U.S. Environmental Protection Agency
P.O. Box 1575 V.H.F.S., Warrenton, Virginia 22186

Project Officer
Mason J. Hewitt, III

ENVIRONMENTAL MONITORING SYSTEMS LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NV 89193-3478

NOTICE

The information in this document has been funded (wholly or in part) by the United States Environmental Protection Agency under contract 68-C0-0050 to Lockheed Engineering and Sciences Company, Inc. It has been subjected to Agency review. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Foreword

The U.S. Environmental Protection Agency (EPA) has long employed data of spatial orientation in pursuit of its mission to understand and protect the environment. For years, these data were applied in standard cartographic presentation techniques, either via hand-drawn or digital transposition from a source map. In either case, the map developer or analyst had the ability during this transposition to apply decision rules of logical consistency to make the map “right,” shift and offset map elements so that their relationships to each other did not violate inherent rules of consistency (e.g., streets do not cross buildings, city boundaries follow the delimiting streets). These adjustments and the inaccuracies introduced in the transposition process itself may or may not be considered viable, depending upon whether these adjustments and errors exceeded traditional map accuracy standards.

Regardless of the acceptability of these errors, they are virtually undetectable to the decision maker or technical analyst, who is presented with a map product. The nature of these errors in hard copy maps is attributable to the medium itself, which is not amenable to overlay and comparison analysis. More often than not, mapped data is presented in its own singular context, with few other types of spatially-correlated data simultaneously presented. However, with the advent of Geographic Information Systems (GIS), digital spatial data sets are generated and stored independently and then combined in analysis, making differences in resolution and accuracy of spatial data visually detectable. Although each separate data set may not violate its own accuracy standard, the use of these differing maps may produce a composite map that is perceived as being flawed. Recognizable inconsistencies may or may not detract from the accuracy of the spatial analysis of interest, depending upon the nature of the analysis. At a minimum, they possibly detract from the credibility of the analysis product.

Global Positioning Systems (GPS), originating from the U.S. military programs, have great potential for ameliorating these types of problems as well making errors easier to detect. With the ability to locate features with an accuracy of a few meters, this technology essentially lowers the detection limit for positional accuracy at low cost. Indeed, the U.S. National Geodetic Survey acknowledges that the accuracy of GPS positioning may exceed the accuracy of some benchmarks in the National Geodetic Reference System (NGRS) (National Geodetic Survey, 1990). Previously, cadastral surveys, which are relatively expensive, were considered to be the only highly accurate positioning system.

GPS technology is now enjoying many civilian sector applications. With this increasing demand, not only is the cost of units going down, but a tremendous amount of development effort is being applied toward increasing their portability, accuracy, and ease of data integration with popular mapping system applications. Proposals have been made within EPA to establish networks of survey base stations that would offer complete coverage of a Regional jurisdiction for roving GPS units. Such proposals shed light on the potential future for the use of GPS in EPA. By integrating GPS into the Agency’s regulatory data collection efforts, benefits in improved spatial analysis resolution could result in ‘lighter” solutions in protection, causation, and resortation decision making. Eliminating the range of uncertainty in positional data may offer opportunities for cost savings.

In comparison to highly accurate GPS data, the relative acceptability of EPA’s existing spatial data, in terms of resolution and accuracy, diminishes. Locational methods previously employed may no longer be suitable for applications and analysis that require the most rigorous spatial data quality available. The EPA has been aware of the locational errors in Agency-sponsored data collection efforts. And as the Agency seeks to integrate geographic analysis as part of its operations, these locational errors become apparent and many times embarrassing. In order to address this error source the EPA has adopted a Locational Data Policy (LDP). The purpose of the LDP is to "ensure the collection of accurate, consistently formatted, fully documented locational coordinates in all relevant data collection activities pursuant to EPA's mission (LDPGD, 1991)." In order to support the 25 m accuracy target specified within the LDP, the policy endorses GPS as the technology of choice. Collecting highly accurate GPS data requires careful planning. Once collected, consideration and thoughtful treatment of the data must be given vis-a-vis its use with data of substantially lower accuracy. This report seeks to provide EPA personnel information and guidance on this technology and its potential use in Agency applications. It reflects the best available information at the time of publication. GPS is a rapidly changing technology that will require constant attention if we are to achieve maximum benefit.

The GIS Technical Memorandum series is produced by the Geographic Information Systems Research and Development Program at EPA's Environmental Monitoring Systems Laboratory in Las Vegas, NV. The purpose of this series is to disseminate information on procedures, applications and the results of applied research in GIS and allied technologies. For more information contact:

GIS R&D Program Manager
U.S. EPA
EMSL-LV
P.O. Box 93478
Las Vegas, NV 89193-3478

Abstract

Global Positioning Systems (GPS) area location determination technology that offers significant opportunities for obtaining highly accurate locational data at low cost. In order for the technology to perform up to its capabilities in Agency applications, Environmental Protection Agency (EPA) staff will need to develop a greater understanding of the technology itself, coordinate systems, surveying, and basic geodesy. EPA has been collecting expertise in the use of this technology over the last 3 years via pilot use of GPS systems to enhance locational control in Agency projects. In order to operationalize the use of this technology within EPA, there also exists a need to develop concise standard operational procedures and methodologies for its use.

This document is a beginning toward fulfillment of these needs. It is intended to be an introductory reference that describes the technology and how it could be employed in EPA work. It provides an overview of survey methods from initial planning to data reduction and postprocessing. Ancillary but important issues such as reference datums and use with geographic information systems are covered in order to provide the reader additional context regarding the use of this spatial information in a project environment. Case studies performed by the Environmental Monitoring Systems Laboratory, Las Vegas, are also included in this document as auxiliary background that may provide helpful techniques.

Contents

Figures

Tables

Acknowledgements

The authors wish to acknowledge contributions and assistance, received in the research and development of this document, made by the following persons:

For assistance with pilot surveys in California and Connecticut, Dr. Arthur Lange of Trimble Navigation Systems and Mr. David Wolf of the U.S. Geological Survey.

For technical assistance, Mr. Donald Bundy and Mr. William H. Aymard of the U.S. EPA Environmental Monitoring Systems Laboratory at Las Vegas (EMSL-LV).

For editorial assistance, Mr. Douglas Elliot of the EMSL-LV and Ms. Donna Sutton of Lockheed Engineering & Sciences Company.

For external peer review and recommendations, Asta Miklius of the U.S. Park Service, Hawaii National Park, James R. Lucas of the National Geodetic Survey, and Dr. Arthur Lange of Trimble Navigation Systems.

For field form development, Mr. Greg Charles of EPA Region I and Mr. Terrence Slonecker of EMSL-LV.

Section 1
Introduction

A. Overview

Geographic Information Systems (GIS) technology has evolved rapidly in recent years to become a valuable tool in the analysis of environmental problems. As with any new technology, the need persists to continue research and develop methods to optimize the use of GIS by environmental scientists and managers. Toward this end, the Spatial Analysis Team (SAT), a component of the U.S. Environmental Protection Agency (EPA) Environmental Monitoring Systems Laboratory in Las Vegas, Nevada (EMSL-LV), has been conducting research since early 1989 into the use of Global Positioning Systems (GPS) technology as a source of locational data and as a quality control mechanism for GIS applications under the Superfund program.

This document is intended for use by personnel in all EPA Regional and Program Offices who need to improve locational information in environmental data bases. It provides fundamental information about the use of GPS and how they can be employed to support Agency activities. It is intended to supply the reader with information about geopositioning technology and methodologies, particularly for users of GIS, to ensure efficient and effective implementation of the technology and optimization of geopositional accuracy, and to understand how GPS can aid in establishing increased spatial accuracy in environmental data bases. To facilitate survey mission planning, software has been identified by this document that will enable the user to project satellite configurations at any given future date.

It should be recognized that GPS represents a rapidly growing and expanding technology, undergoing a seemingly continuous series of changes and improvements. While this document depicts the state of the technology at this time, it is possible that the science of GPS will have advanced technologically soon after the publication of this document. Therefore, this document provides a basic level of understanding of geopositioning and GPS technology and will be augmented with additional documentation as the technology continues to grow.

This section provides historical background information on geopositioning, describing (1) the technology from which GPS has evolved, (2) conventional surveying techniques that have traditionally been used in geopositioning, and (3) emerging technologies which, along with GPS, are redefining geopositioning accuracy standards.

Section 2 (Conclusions and Recommendations) summarizes the issues that the authors consider most important in implementation of the technology within EPA.

Section 3 (Global Positioning Systems) provides a discussion of all aspects of GPS technology, beginning with descriptions of the fundamentals of geopositioning from space. Information regarding the nature of GPS receivers will help readers understand the varied features and options that are available as suitable hardware components for global positioning. Also reviewed in this section area number of topics related to GPS spatial accuracy, factors affecting GPS positional accuracy, and the effect of GPS receiver dissimilarities.

Section 4 (Use of GPS in Environmental Applications) describes how GPS will continue to provide a valuable geopositioning resource for EPA activities. Included are descriptions of applications as a data collection and quality assurance tool for GIS projects, quickly and accurately collecting and recording, or verifying, positional information in a common geographic reference system. Other Agency applications are discussed as well, including the use of GPS as a positioning system in field sampling and remote sensing efforts.

Section 5 (Performing a GPS Survey) provides an outline for the planning and management of a GPS survey. All phases of conducting a GPS survey are included, from planning and reconnaissance, through the actual GPS survey methodology, to the processing of satellite transmitted positional data and integration of the data into a digital data base.

Appendix A (Sources of Additional Information on GPS) is a summary of sources that can be sought out for further information about GPS technology and for specific information on the status of the NAVSTAR constellation.

Appendix B (Glossary of GPS Terms) defines some common terms used in the GPS technical community.

Appendix C (Locational Data Policy) is the current official EPA policy on locational data requirements.

Appendix D (EPA Case Studies) details surveys that have been conducted on Superfund sites on the east and west coasts by EMSL-LV to explore the utility of the technology to EPA programs and, generally, for positioning of regulated facilities and monitoring stations.

Appendix E (PLOTSSF and CLEANSSF Processing Software) summarizes the capabilities of specific GPS processing software available from EMSL-LV.

Appendix F (Field Charts and Forms) is a collection of sample forms useful in conducting and documenting a GPS survey.

B. Geopositioning

Conventional Surveying

Geopositioning techniques and technologies have undergone considerable evolution in recent years, as evidenced by the emergence of systems like GPS. Many of the older, traditional positioning survey methods are being replaced by advanced geopositioning systems. These older survey methods tend to require more field time, are highly labor intensive, and are costly per feature identified. Although conventional surveying is still appropriate for high accuracy requirements in localized, accessible study areas, as employed today, these older methods are best used in concert with other more advanced and cost-effective techniques. Topographic, cadastral, and geodetic surveys are perhaps the three types of conventional surveying most impacted by advanced technologies like GPS.

Topographic surveys determine the elevation heights and contours of land surfaces. These surveys also serve to locate buildings, roads, sewers, wells, and water and power lines. The U.S. Geological Survey (USGS) has historically conducted topographic surveys in order to produce thousands of topographic maps at a scale of 1:24,000. These maps provide an excellent base for much of the EPA environmental analyses. As these maps become available in digital form, they are providing an important source of locational and geographic data for the Agency. GPS is currently being used to obtain more accurate positional information for many of these land features.

Cadastral surveys are performed to establish legal and political bounties, typically for land ownership and taxation purposes. A boundary survey is a type of cadastral survey which is limited to one specific piece of property. The U.S. Bureau of Land Management (BLM) relies on cadastral surveying to determine the legal boundaries of public lands. Published cadastral surveys are of importance to EPA, as for instance, where Potentially Responsible Parties (PRPs) and impacted parties on Superfund enforcement cases are concerned. GPS already can provide a highly accurate means of conducting boundary surveys of these types of facilities.

Geodetic surveys (i.e. control surveys) are global surveys made to establish control networks (comprised of reference or control points) as a basis for accurate land mapping. Geodetic surveys provide quantitative data on the absolute and relative accuracy of reference positions or physical monuments on the earth's surface. The U.S. National Geodetic Survey (NGS) is responsible for establishing a national geodetic control network for the entire country referenced to a national horizontal Datum. NGS also establishes the vertical Datum, the location of mean sea level from which most elevation data are determined or referenced. Highly accurate EPA geopositioning requirements should be attained with reference to a well defined geodetic survey or network. In many parts of the country, the NGS is employing GPS to establish or correct geodetic survey networks.

In the event that EPA will require or avail itself of conventional surveying to meet its geopositioning needs, it is important to understand these techniques, their strengths, and their limitations. EPA does and will continue to use products derived from conventional surveying methods. The geopositional accuracy of the products generated by EPA, USGS, NGS, and BLM can usually be obtained from these Agencies at the time of product acquisition.

Methods of Point Surveying

Global positioning systems technology is but one of a number of positioning techniques that have been developed since the late 1950's and are being used for establishing positions of points on or near the Earth's surface. Besides GPS, some of the advanced technology systems being utilized for geopositioning and navigation today include OMEGA, Loran-C, Transit, Inertial Survey Systems (ISS), VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME), Tactical Air Navigation (TACAN), Instrument Landing System (ILS), and Radiobeacons. The US Department of Transportation (DOT), primarily through the US Coast Guard (USCG) and the Federal Aviation Administration (FAA), is responsible for the application of these technologies for civil navigation, whereas the US Defense Department (DOD) oversees the use of these systems for military users.

OMEGA and Loran-C are two navigation systems that can be used for surveying and geopositioning. OMEGA uses ultra-low frequency transmissions from eight transmission stations. It is sensitive to changes in season and time of day due to the propagation characteristics of the low frequency signal. It is used primarily in marine and submarine navigation across most of the earth's surface. Its accuracy is considered to be 2 to 3 nautical miles (Ackroyd and Lorimer, 1990).

Loran-C is a navigation system that is generally unaffected by diurnal disturbances and is used for navigating in either sea or air. It employs radio signals centered at 100 kHz, and is pulsed to allow for time-difference measurement. In general, these two technologies are used mainly for navigational purposes, although Loran has been tested, with variable success, within the EPA for use as a geopositioning tool. Its effectiveness has depended upon a number of variables, including type of Loran receiver used, proximity to Loran transmitting stations, and proximity to high elevation or other obstructive landforms. Although military use of Loran-C and OMEGA will be phased out early in the 1990's, operation of these systems for use by civilians is guaranteed until at least the year 2000 (Wells et al., 1988). Of the two, Loran-C is considered the preferred option for EPA applications and only for coastal areas and along the mid-continent.

Transit is a satellite positioning technology, similar to GPS, which generally provides a high degree of accuracy at a reasonable unit cost. It generates positions based on measurements of the Doppler effect produced as the satellites move in their orbits. Although less accurate than GPS, Transit is still considered a useful technology because of its speed and accuracy of operation as compared to conventional surveying, and its affordable cost. Military use of Transit is scheduled to be replaced by GPS by 1994. At that time, U.S. government operation of the Transit system will cease (Wells et al., 1988).

Inertial Survey Systems are self-contained and highly mobile systems which detect relative compass direction by using gyroscopes. The most effective application of ISS is to measure unknown points that are located between known control points. ISS may serve some EPA needs where EPA and/or contractual personnel are in the field with vehicles which could potentially be equipped with ISS. When ISS is combined with GIS, they are mutually supportive.

VOR/DME and TACAN provide the basic guidance for enroute air navigation in the U.S. Military and civil aviation use of both systems will be phased out by 1997. Long-term continued operation of VOR/DME for civilian use remains uncertain, though the system will continue to be available until at least 2000.

ILS is a passive system used commercially for precision aircraft radar approach navigation. The Federal Aviation Administration is currently investigating the continued use of this geopositioning technology and may recommend transitioning to a system based on GPS. A similar active system is PAR, or precision radar, used mostly by the military. Both systems have a very short range.

Radiobeacons for military applications will be discontinued by 1997. A decision on continued operation of these widely used facilities by the civilian community will not be made for some time (Wells et al., 1988).

Of all the advanced geopositioning technologies, GPS holds the greatest promise for EPA due to its relative flexibility, accuracy, ease of use, cost benefits, and longevity.

Section 2
Conclusions and Recommendations

With proper planning GPS can provide accurate coordinates sufficient to meet the requirements of the Locational Data Policy. While receiver technology and software is still rapidly evolving, the technology itself is stable and proven. The U.S. Government will continue to invest in GPS architecture and infrastructure for some time to come. As discussed in the findings of the Locational Accuracy Task Force (LDPIG, 1991), there are a number of issues associated with the GPS-based accuracy standard that need to be addressed in order to undertake an Agency-wide implementation. This section will discuss these issues and offer some recommendations based on the topics examined in this report.

Issues/Concerns

Cost of implementation

The costs of an Agency implementation are unknown at this time and will only become clear after a robust requirements analysis. There are many unknowns related to the numbers and types of GPS units required at the Regional level. It is safe to say that with complete implementation of the Locational Data Policy, the need for receivers could be quite high. A national procurement vehicle could be an option for cost containment.

Another factor that will influence costs is community-based networks. A community network will assist with the correction of GPS data after field collection by providing a correction data stream from a fixed station receiver. The use of a C/A code receiver for the fixed station is expensive and it is unknown how many community networks are needed to service the needs of the EPA. Costs could be controlled by sharing equipment with other agencies or investing in correction data broadcasts offered by some satellite communication companies.

Selective availability

The intentional degradation of satellite signals by the Defense Department to inhibit real-time use is the principal criticism levied against proponents of GPS for use in navigational applications. Selective availability is an intentional error that can be corrected using postsurvey processes in the office. The section "Fundamentals of Satellite Positioning," explains the technical aspects of selective availability. For most field collection projects this is not a problem. If selective availability is implemented, real-time use may not be possible.

Interoperability of vendor equipment

With the variety of equipment available, each manufacturer has developed different methods of capturing and relaying data such as phase measurements, time, and station information. The vendor community has not offered any data exchange standards that would allow the interoperability of P-code receivers. As a potentially large user of GPS data from many sources, the Agency should become active in the development of GPS exchange standards.

Recommendations

In order to integrate GPS into the operations of the EPA it is recommended that implementation be supported by a program which provides for training, methods development and applications research along with an aggressive program to influence the vendor community.

A robust methods and applications development program is necessary because the technology has not been explored fully. New and more efficient applications could be developed with dedicated effort. Pushing the technology toward greater user utility will require concerted effort to pioneer new products and product add-ens in conjunction with the vendor community. This dedicated effort will require a well designed training effort to provide educational outreach so that consistent methods and procedures are employed.

This implementation will have to be accompatied by funds designated to support these functions.

Section 3
Global Positioning Systems

The Navigation Satellite Time and Ranging Global Positioning System (NAVSTAR GPS) has been under development by the DOD since 1973 as a result of the merger of the U.S. Navy's TIMATION Program and the U.S. Air Force's 621B Project. Both of these programs were initiated in the mid-1960s to develop a passive navigation system using measured distances to orbiting satellites. Although the original goal of GPS was to provide ground, sea, and air units of the United States military and its NATO allies with unified, high-precision, all-weather, instantaneous positioning capabilities, in its present phase GPS is freely available for anyone to use. The technology will continue to be available to civilians, perhaps with certain restrictions, once the system is fully operational, affording 24-hour, three-dimensional positioning, by mid-1993 (Wells et al., 1988).

A. Components of a GPS

There are three major elements to the operational GPS complex: the control segment, the space segment, and the user segment (Figure 1). All three of these segments are required to perform positional determination.

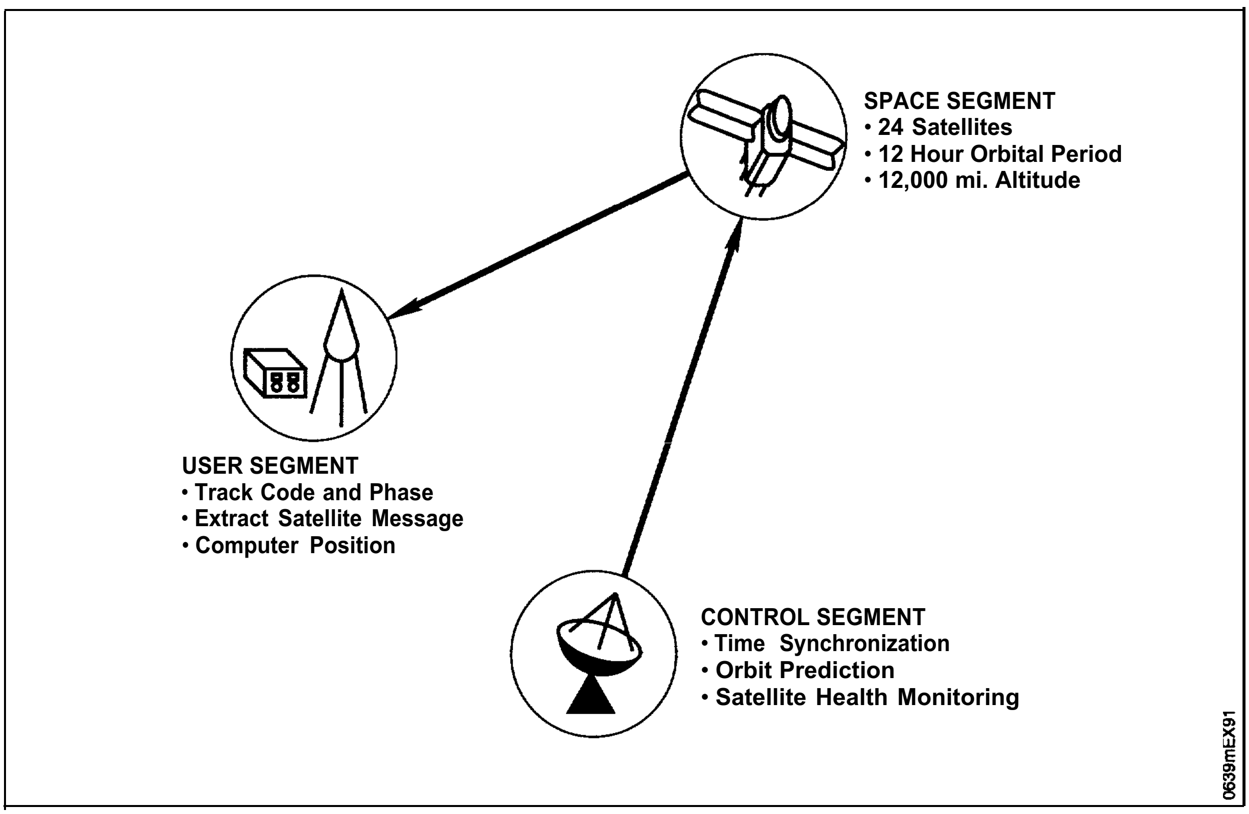


Figure 1. Three major components of the operational GPS complex.

Control Segment

The Control Segment consists of five monitoring stations (Colorado Springs, Ascension Island, Diego Garcia, Hawaii, and Kwajalein Island). Three of the stations (Ascension, Diego Garcia, and Kwajalein) serve as uplink installations, capable of transmitting data to the satellites, including new ephemerides (satellite position as a function of time), clock corrections, and other broadcast message data, while Colorado Springs serves as the master control station. The Control Segment is the sole responsibility of the DOD who undertakes construction, launching, maintenance and virtually constant performance monitoring of all GPS satellites.

The DOD monitoring stations track all GPS signals for use in controlling the satellites and predicting their orbits. Meteorological data also are collected at the monitoring stations, permitting the most accurate evaluation of tropospheric delays of GPS signals. Satellite tracking data from the monitoring stations are transmitted to the master control station for processing. This processing involves the computation of satellite ephemerides and satellite clock corrections. The master station controls orbital corrections when any satellite strays too far from its assigned position, and necessary repositioning to compensate for unhealthy (not fully functioning) satellites.

Space Segment

The Space Segment consists of the constellation of NAVSTAR earth orbiting satellites. In November of 1991, there were 16 satellites in orbit, 5 of the original prototype (Block I) design, and 11 the operational (Block II) design. The current Defense Department plan calls for a full constellation of 24 Block II satellites (21 operational and 3 in-orbit spares) to be deployed by 1993. The satellites are arrayed in 6 orbital planes inclined 55 degrees to the equator. They orbit at altitudes of about 12,000 miles each, with orbital periods of 12 sidereal hours (i.e., determined by or from the stars), or approximately one half of the Earth's period of rotation. The current GPS constellation provides approximately 12 hours of 3-D position fixes per day in North America. As more satellites are launched on the planned 60- to 90-day interval, the GPS window will expand until a full constellation will provide users with the ability to obtain three-dimensional positional information for any point on the face of the Earth, 24 hours a day. Block III GPS satellites are presently in the design phase. Current plans call for these to replace the Block II generation, beginning in the late 1990's.

A slightly confusing situation exists in that there are two satellite reference numbering systems. The NAVSTAR or space vehicle numbers (SVN) is the older of the two and is based on launch sequence. The second numbering system, known as the pseudo-random number (PRN) or space vehicle identity (SV ID), is more commonly used and is based upon orbital arrangement.

User Segment

The User Segment consists of all Earth-based GPS receivers. Receivers vary greatly in size and complexity, though the basic design is rather simple. The typical receiver is composed of an antenna and preamplifier, radio signal microprocessor, control and display device, data recording unit, and power supply (Wells et al., 1988) (Figure 2). The GPS receiver decodes the timing signals from the "visible" satellites (four or more) and, having calculated their distances (refer to discussion below), computes its own latitude, longitude, elevation, and time. This is a continuous process and generally the position is updated on a second-by-second basis, output to the receiver display device, and, if the receiver provides data capture capabilities, stored by the receiver logging unit.

B. Fundamentals Of Satellite Positioning

Satellite positioning operates by measuring the time delay of precisely transmitted radio signals from satellites whose position can be very accurately determined. Furthermore, with the help of a few

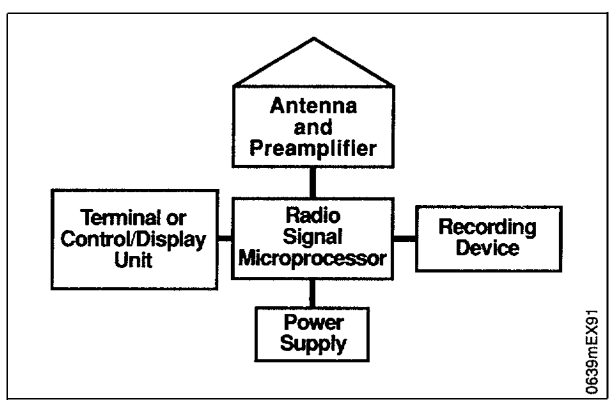


Figure 2. GPS receiver configuration.

fundamental laws of physics, the positions of these satellites as a function of time (their ephemerides) can be rather easily predicted. By measuring the distances (or range vectors) between a survey point of unknown location on the surface of the earth and the predicted positions of a number of orbiting satellites, it is possible to derive the position of the unknown survey point.

GPS Signal Structure

There are two radio frequency bands available for transmission of satellite positioning signals; they are centered on frequencies of 1575.42 and 1227.6 MHz. The two frequencies, or "carriers", are called Link 1 and Link 2 (L1 and L2), respectively, and carry a number of modulated signals. These signals require a wide band width of 2 MHz because there are so many signals being simultaneously transmitted. The high frequency of the carrier bands is essential to avoiding significant ionospheric effects.

The modulating signals appear random but in fact are carefully chosen sequences of binary values (zeros and ones), using a mathematical algorithm which generates the sequences that repeat during a fixed time interval. Both the satellites and GPS receivers generate the same code sequences at precisely the same intervals. The three types of code (described below) have varied periods, and repeat as frequently as every millisecond or as infrequently as every 267 days. The codes are referred to as pseudo-random noise (PRN) codes. The satellites transmit three different types of PRN codes.

Since the pattern of electronic pulses in the PRN code is known, the matching or aligning of receiver-generated and satellite-generated PRN codes provides the means by which satellite distance can be derived. If the comparison of PRN codes is conducted over a period of time, the number of signal "matches" increases, thereby providing a means of clearly recognizing even very faint signals.

C/A-code and P-Code

One PRN code, known as the Coarse/Acquisition code (C/A-code), consists of a sequence of 1,023 binary values or "chips", generated at a rate of 1.023 million chips per second. This results in a sequence repetition every millisecond. The C/A-code is considered the standard GPS code and is sometimes referred to as the "civilian code." Compared with the P-code described below, the C/A code is considered to be less precise, ±100 meters vs. ± 16 meters without correction.

A second PRN code, known as the Precise or Protected code (P-code), consists of another sequence of binary values, and repeats itself only after 267 days. Each 1-week segment of this code is unique to one GPS satellite and is reset each week. The P-code is carried at 10 times the frequency of the C/A-Code, and can be encrypted to enable exclusive military use. In actuality, with newest receiver designs, there is practically no difference in the accuracy of measurements made with either C/A or P-code (Hum, 1989). However, the P-code is not entirely secure; the equation that generates the P-code (and, thus, the structure of the code itself) is now well known (Ackroyd and Lorimer, 1990).

Y-Code

Another PRN code, the Y-code, is now being transmitted on Block II satellites. It is also for military use and its encryption is more secure than the P-code. Y-code works by adding a mask to the P-code that is then removed by the receiver. Decryption requires use of a special code key which is printed on a microprocessor.

While PRN code may seem an overly sophisticated approach to transmitting a radio signal, it in fact enables GPS to be the practical and relatively inexpensive utility that it is. Without PRN, each GPS receiver would require its own large parabolic satellite dish, much like those needed for satellite television reception. By matching and "amplifying" the PRN codes generated by receiver and satellite, GPS satellites do not need to be highly powerful and expensive, and receivers with very small antennas are sufficient to pick up the signals.

It is through access to the Y-code and the means to compensate for manipulation of orbit data and clock frequency that permits selective availability. Currently, the standard positioning service (SPS), available to everybody, provides access to the C/A code, both L-codes, P-code, and the navigation message. The precise positioning service (PPS) provides access to these codes plus the Y-code used to operationalize selective availability.

Navigation Message Contents

The carrier frequencies and codes are modulated to carry numerous messages that are necessary to perform positioning calculations. The code is broken into 1500-bit frames, transmitted over 30 seconds. Each frame contains five subframes. Each subframe is made up often, 30-bit words. Some of the subframe information does not vary from frame to frame (subframes 1,2, 3). Subframes 4 and 5 will "page" data from frame to frame, with up to 25 pages in a master frame which will take 12.5 minutes to transmit (Wells et at., 1986). Table 1 summarizes subframe message content.

Measuring Range Vectors

A variety of techniques can be used to measure earth-to-satellite range vectors. GPS utilizes what is referred to as one-way radio ranging to determine satellite distances. With radio ranging, every GPS satellite and all earth-based GPS receivers simultaneously generate an identical PRN signal. The timing of the satellite radio signal transmissions, traveling at the speed of light, is calibrated by atomic clocks aboard each satellite. Each satellite transmits the coded signal towards earth, where it can be captured by the user's receiver.

When a satellite signal arrives at the earth-bound receiver, its signal is simply matched to that generated by the receiver. The receiver measures the time difference between identical segments of satellite-generated and receiver-generated signal in order to determine the length of time needed for the signal to travel from satellite to receiver.

A GPS receiver is capable of making only two types of measurements: pseudo-range and carrier beat phase (Wells et al., 1988).

Table 1. GPS Data Message Content

Subframe	Content (*)
1	Flags (L2 code&data, week, satellite accuracy& health) Age of data Coefficients for clock corrections
2	Satellite ephemeris
3	Satellite ephemeris
4	25 pages with: Satellite almanac Ionospheric model coefficients Clock data Antispoof flag Satellite configuration Satellite health Other special messages and reserved space
5	25 pages with: Satellite almanac Satellite health

**(all frames include handshaking telemetry)*

Pseudo-range

Pseudo-range is conceptually quite simple and is the measurement made by most GPS receivers. Pseudo-range is the time shift required to line up matching segments (called code epochs) of satellite-generated and receiver-generated and receiver-generated code (Figure 3), multiplied by the speed of light. Ideally, the time shift is the difference between the time of signal transmission and the time of signal reception. In fact, the relative motion of the satellite with respect to the receiver (the Doppler effect) causes the two time frames to differ, which introduces a bias into the measurement. Lack of precise synchronization between the satellite and receiver clocks also can create clock bias, affecting all measurements equally while using a specific receiver. These biased, time-delayed measurements are thus referred to as pseudo-ranges.

A rule of thumb for estimating the precision of pseudo-range measurements is 1 percent of the period between successive code epochs. For the P-code, successive epochs are 0.1 microsecond apart, implying a measurement precision of 1 nanosecond. When multiplied by the speed of light, this implies a range measurement precision of 30 centimeters. For the C/A-code, the numbers are 10 times less precise, or a range measurement precision of 3 meters.

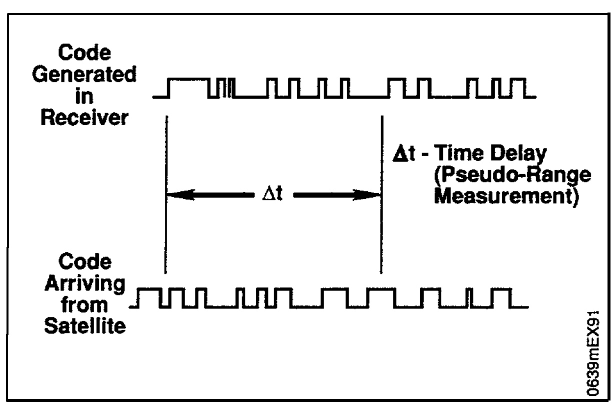


Figure 3. Pseudo-range time shift.

Carrier Beat Phase

The received frequency of a GPS satellite signal is different than the frequency transmitted by the satellite, and is continually changing due to the Doppler effect. Carrier beat phase is the phase of the signal which remains when the satellite carrier frequency (L1 or L2) is different or "beat" with the constant frequency generated in the receiver (Figure 4). To make this measurement, the receiver must be able to determine the difference in carrier wavelengths (or cycles) between the satellite and receiver signals. Because the wavelength of the carrier is much shorter than the wavelength of the PRN codes, the precision of carrier beat phase measurements is much higher than the precision of code pseudoranges. For the GPS L1 carrier signal, the wavelength is about 20 centimeters. Using the rule of thumb that phase measurements can be made to about one percent of the wave-length, this implies a precision of 2 millimeters, permitting very high precision positioning for certain applications.

Obtaining the initial number of integer cycles of the carrier between satellite and receiver is very difficult, if not impossible. Realistically, an assumption must usually be made about the initial (unknown) cycle ambiguity. Once this assumption is made, it is critical that an integer cycle count be maintained as the satellite-to-receiver range changes with time. When an interruption occurs, for any of a variety of reasons, in reception of the satellite carrier frequency ("loss of lock"), the receiver effectively "loses count" of the number of cycles between satellite and receiver signals. This is known as cycle slip.

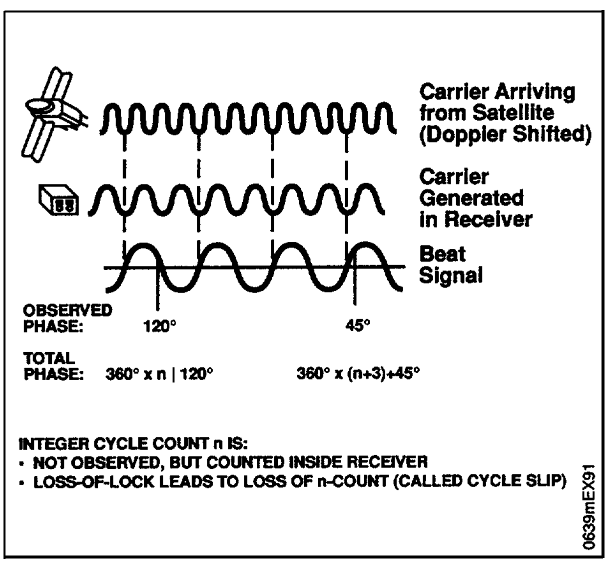


Figure 4. Carrier beat phase.

Overcoming initial cycle ambiguity and minimizing cycle slip problems typically requires a higher quality GPS receiver, meticulous antenna placement, as well as lengthy and uninterrupted ranging sessions. These requirements restrict the use of carrier beat measurements for real-time applications.

The position of a point on or above the Earth's surface can best be described in terms of one or two general reference frames. In the first case, the position is defined with respect to a well-defined coordinate system, commonly a geocentric system (i.e., a system whose point of origin coincides with the center of mass of the Earth). This is known as point positioning and is illustrated in Figure 5. Alternatively, the point can be described using relative positioning, in which another surface point of known location, such as a benchmark or control monument, serves as the origin of a local coordinate system (Figure 6), such as a State Plane system.

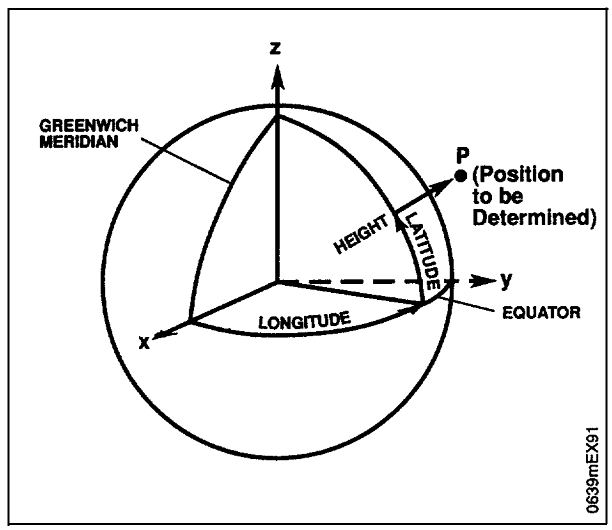


Figure 5. Point positioning.

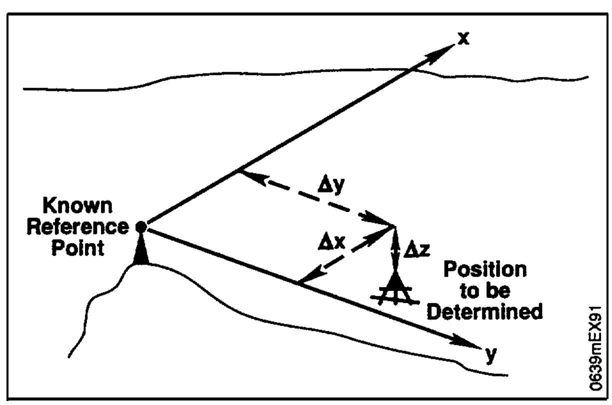


Figure 6. Relative positioning.

Positioning from satellite ranges is based on the same principle used in traditional terrestrial surveying methods. Simply stated, by measuring the distances to three noncoincident points of known positions, a triangulated solution can be attained. GPS extends this general concept to a space-based system, measuring the distances to three or more nonplanar satellites and triangulating the position of a survey point accordingly. Analogous to the point and relative position modes described above, there are two modes of satellite positioning: absolute and differential. The distinctions between these two operational modes of GPS are very significant in terms of methodology and accuracy (Figure 7).

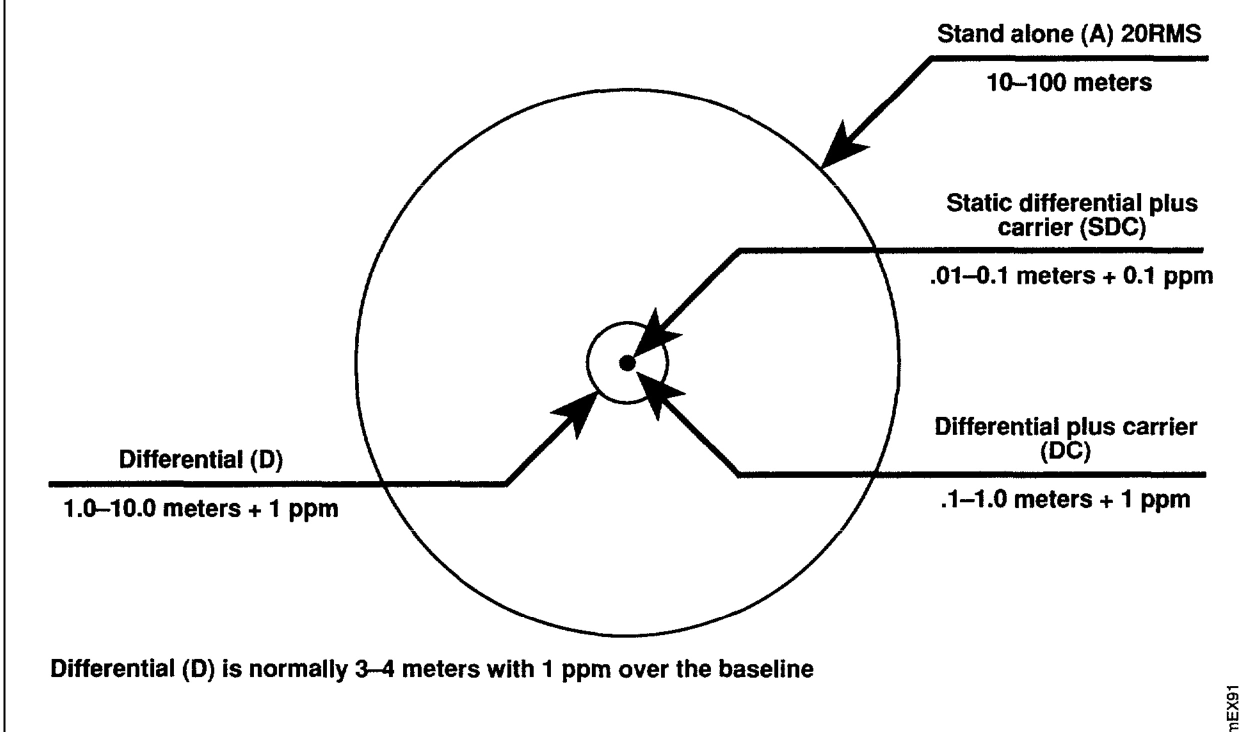
Absolute positioning

This mode of positioning relies upon a single receiver station. It is also referred to as "stand-alone" GPS, because, unlike differential positioning, ranging is done strictly between the satellite and the receiver station and not using a ground-based reference station to assist with the computation of error corrections. As a result, the positions derived in absolute mode are subject to unmitigated errors inherent in satellite positioning (see section below, Factors Affecting GPS Accuracy). Overall accuracy of absolute positioning is considered to be no greater than 50 meters at best by Ackroyd and Lorimer, and ±100-meter accuracy by the U.S. Army Corps of Engineers.

Differential positioning

Relative or Differential GPS carries the triangulation principle one step further, with a second receiver at a known reference point (Figure 8). To further facilitate determination of a point's position, relative to a known earth surface point, this configuration demands collection of an error correcting message from the reference receiver.

Differential-mode positioning relies upon an established control point. The reference station is placed on the control point; a triangulated position from the satellites is derived, and then compared it to the control point coordinate. This allows for a correction factor to be calculated and applied to other roving GPS units used in the same area and at the same time. Inaccuracies in the control point's coordinate are directly additive to errors inherent in the satellite positioning process. Error corrections



Source: Dr. James W. Sennott, Bradley University, 1991

Figure 7. GPS operating modes and accuracy potential.

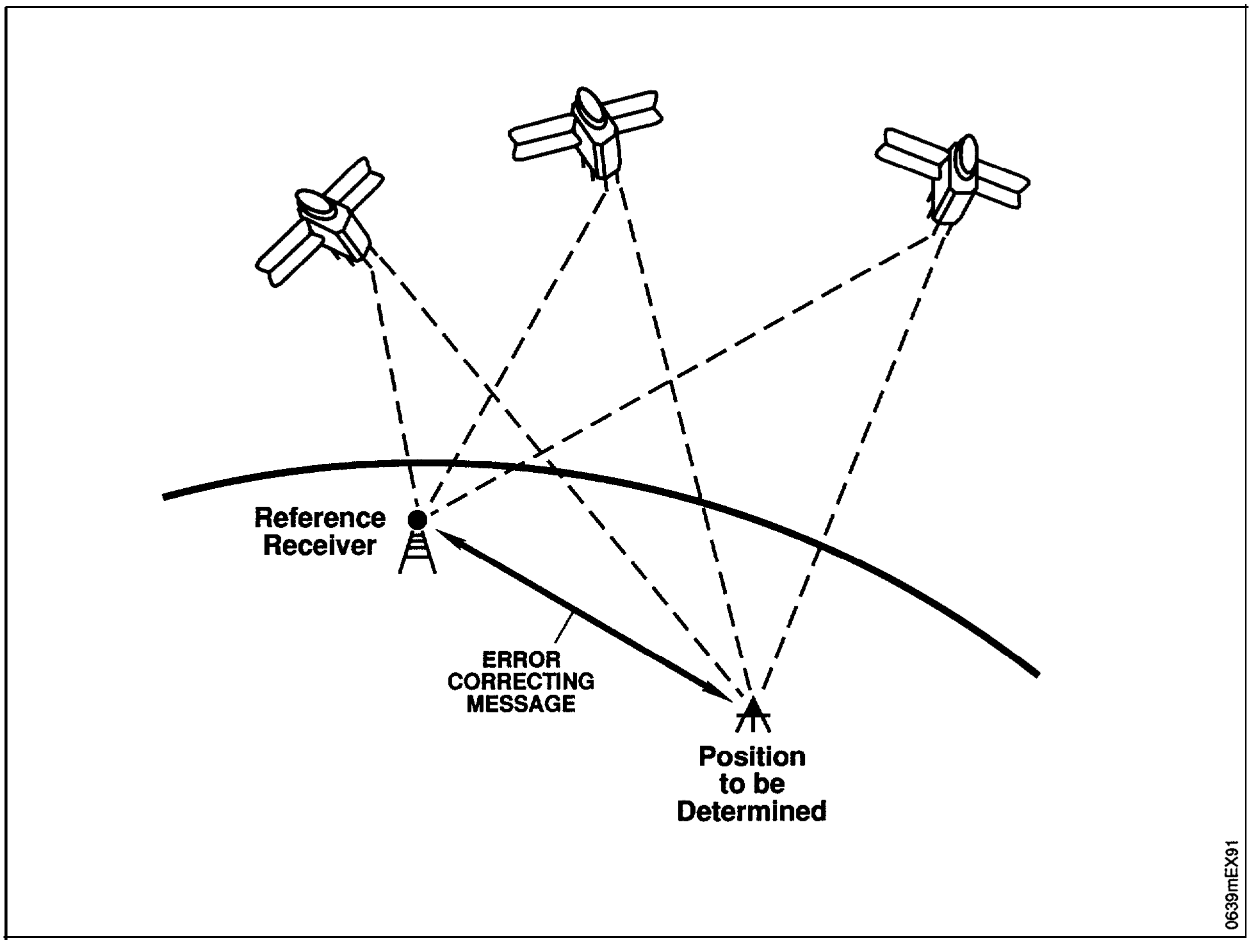


Figure 8. Differential GPS.

derived by the reference station vary rapidly as the factors propagating position errors are not static over time. This error correction allows for a considerable amount of error to be negated, potentially as much as 90 percent. A summary of the impact differential positioning has on the overall error budget is presented in Table 2.

The assumption made when operating in differential mode is that bias and random error factors affecting the reference station are equally affecting roving units operating off the station. For this fundamental assumption of common errors to be true, the units must be tracking the same satellites and must be within a range of approximately 2,000 kilometers of the reference receiver (Denaro, 1990). Other sources indicate that the effective range for separation of reference and roving stations may be less, on the order of 500 km (Ackroyd and Lorimer, 1990).

The range restriction is imposed due to the two factors which contribute to the "spatial decorrelation" of the errors. The frost range-reducing factor is that, for widely separated stations, the direction cosines from satellite to receiver may differ, causing a differing observation of satellite ephemeris error. Second, the error produced by atmospheric disturbances to the C/A code transmission is dependent upon the path the transmission takes through the atmosphere. The variability of this error at geographically separated units may be significant because atmospheric propagation errors account for as much as 60 percent of total positioning error. Given the current conditions of selective availability (SA), the intentional degradation C/A code accuracy by DOD, the reference receiver station data should be recorded and transmitted at least every 20 seconds to update the error correction (Kruczynski, 1990) (Ackroyd and Lorimer, 1990).

For static or stationary mode of positioning, data from the roving station should be collected for a period of 3 to 5 minutes: additional time spent at a location beyond this period will not enhance positional accuracy significantly. According to testing done by the U.S. Air Force at the Yuma Proving

Table 2. Error Budget for Conventional GPS vs. Differential

Error source	Conventional C/A Code Accuracy 1 sigma error (meters) Bias	Random	Total	Differential C/A Code Accuracy 1 sigma error (meters) Bias	Random	Total
Ephemeris data	3.5	0.0	3.5	0.0	0.0	0.0
Satellite clock	1.5	0.7	1.7	0.0	0.7	0.7
Ionosphere	4.0	0.0	4.0	0.0	0.0	0.0
Troposphere	0.0	0.5	0.5	0.0	0.5	0.5
Multipath	0.0	1.0	1.0	0.0	1.0	1.0
Receiver	0.0	0.05-3.5	0.05-3.5	0.0	0.05-3.5	0.05-3.5
Calibration site residual	0.0	0.0	0.0	0.0	1.9	1.9
UERE (RMS)	5.5	3.7	6.7	0.0	4.2	4.2
Filtered UERE (RMS)	5.5	0.9	5.6	0.0	1.1	1.1
1 sigma vertical axis error	VDOP = 2.5		14.0			2.6
Maximum vertical error (SFO)	VDOP = 15.6		87.4			16.4

Source: Dr. Bradford Parkinson, Stanford University, 1991.

Grounds, differential positioning yielded horizontal accuracies of 2 to 5 meters (Kruczynski et at., 1986) (Kruczynski, 1990). Vertical errors in differential mode will be larger than horizontal error.

Techniques of Correction

Pseudo-Range vs. Positional Corrections

There are two types of positional connections: corrections to the computed latitude, longitude, and elevation, and corrections to the pseudo-ranges between the satellites and the roving station. The latter method is more complicated in that a range correction factor for each satellite must be computed (four or more ranges to be corrected), and the correction must compensate for clock bias which will differ between each receiver station.

There are significant differences between the two correctional methodologies that have implications on the utility of all data collected. Receiver units, while operating in either static or dynamic mode, are constantly scanning available satellites and locking onto the best configuration for accuracy. Reference stations are operating in the same manner. However, they may not necessarily always lock onto the same set of satellites at any given moment. The method for pseudo-range correction is more flexible because it does not require that both receivers be locked onto the same satellites; the reference station will provide corrections for all satellites in view. The positional correction methodology requires that positioning be based on the same set of satellites at both the reference and roving stations. Receivers record information on the constellation in use along with the positional coordinates derived; this allows for a comparison of constellations used during post-processing. With positional corrections, if the constellations used do not match, that coordinate must be thrown out and not used in final coordinate computation. Given that as many as 200 coordinate fixes may be collected for a point position over a 3- to 5-minute recording session, some loss of individual data points may not affect the feasibility of deriving a coordinate solution for a point.

Real time vs. postsurvey correction processing

Differential positions can be derived either in real time, or via postsurvey processing. Real time differential positioning requires a dedicated communications link, such as VHF-FM radio across which the correction signal can be transferred, and a radio-wave receiver hardware option on the roving unit. The differential correction data is transmitted at a low data rate in a standard data format termed RTCM SC-104, defined by the Radio Technical Commission for Maritime Services.

An alternative real-time correction scheme transmits data from the reference station in the same frequencies and formats as the satellites themselves;

this is called a “pseudo satellite” approach. Real-time positioning has advantages for applications that involve use of GPS for guidance to a given coordinate, such as in tightly designed environmental data collection (derivation of positions postsurvey is not applicable). However, postprocessing-derived positions tend to be more accurate because the correction process can be supervised and enhanced via sophisticated processing techniques that require greater computer processing capabilities than are available in the roving units. Supervised processing might include editing of outliers (possibly due to swings in SA error and multipath) and adding missing data (particularly applicable for mobile positioning which might involve positioning in areas where the satellites may have been intermittently masked). In fact, postprocessing affords such greater relative accuracy that real-time positioning should only be considered for applications that need to be determined while in the field (Wells et al., 1988). However, some environmental monitoring that requires sampling at a predetermined position will demand real time capabilities. So far, EPA has not performed any GPS surveying that involved real-time positioning. The accuracy of this mode of operation has not yet been explored by this Agency.

Postprocessing involves the use of data filtering and smoothing routines. The Kalman filter and smoothing routines are applied recursively to the data forward and backward, reducing the variability of positions at a given collection point. The filtering and smoothing routines are used on both the roving and receiver station data streams. The filtering reduces the affect of signal noise and multipath. Using differential positioning in this way, the standard deviation of the error for a point location can be reduced to 1.5 meters, from typical stated accuracy on the order of 3 to 5 meters (Lange and Kruczynski, 1989).

Static and Kinematic Positioning

GPS can be used to position both stationary and moving objects. If the receiver is stationary (static positioning), multiple range vectors to each of several satellites are calculated. Such redundant observations provide a higher level of accuracy for the determined position. When using static positioning, the GPS operator typically has a choice of real time or postprocessed results. With real-time processing, each successive observation at the same location is processed so as to provide an improvement over the previously determined position, whereas in postprocessing mode the data is simply stored for later refinement and generation of data of potentially higher quality.

When the receiver is moving (kinematic positioning), instantaneous positions or “fixes” are made, ideally from four range vectors observed simultaneously. There is generally no redundancy in the data and normally a real-time solution is sought, consisting of one fix at a time. The resulting string of fixes can usually also be postprocessed using one of a number of existing smoothing operations, as a means of improving the quality of the positional fix (Wells et al., 1988).

Static and kinematic positioning techniques can be used in either absolute or differential mode. Of the various conjurations possible, “relative semi-kinematic positioning” has proven to be a very efficient and accurate means of obtaining positional information. The concept calls for one stationary receiver serving as a base station, preferably but not necessarily upon a known survey marker, and a second roving receiver.

C. GPS Hardware Features and Options

While GPS is becoming a basic utility that can be used in a wide range of applications, it is important to recognize the rapidly expanding nature of the technology and the broad spectrum of GPS hardware available. Proper selection of the appropriate equipment requires a careful analysis of the intended application of the device. The main factor in this selection is accuracy requirements, although other factors of importance are cost, ease of operation, and the amount of data to be collected.

There are two broad groups of receivers: those that track satellites sequentially, and those that can track four or more satellites simultaneously. Sequencing receivers must sequence through four different satellites before they can calculate a position. Continuous receivers have multiple channels and can devote one channel to each of four satellites simultaneously, permitting continuous, real-time position measurements.

Sequencing Receivers

Sequencing receivers, which share one channel with several satellites, usually have less circuitry, and are less expensive, requiring less power to operate. Unfortunately, the sequencing can interrupt positioning and can limit overall accuracy. Subspecies of sequencing receivers include starved power single channel receivers, single-channel receivers, fast-multiplexing single-channel receivers, and two-channel receivers. Multi-channel receivers have distinct advantages with respect to canopy cover, buildings, and other obstructions.

Starved Power Single-Channel Receivers

These receivers are designed for portability and are usually powered by small batteries. In order to limit power consumption, they may only take a position reading once or twice per minute and turn themselves off between readings. Low cost means they are well suited as a personal locational device for hikers or weekend sailors. Their accuracy is typically better than most LORAN systems and, unlike LORAN, they work anywhere in the world. The main disadvantages of this type of receiver are degraded accuracy, limited user interfacing, and, unlike more sophisticated devices, their inability to measure vehicle or vessel velocity with any precision.

Single-Channel Receivers

Standard single-channel receivers remain on continuously. Consequently, these devices use more electric power but are slightly more accurate and can measure velocity as long as there are no significant accelerations or course alterations.

Fast-Multiplexing Single-Channel Receivers

More complex circuitry enables this type of device to sequence between satellites much more quickly. As a result, the device can make ranging measurements while it is also monitoring a satellite data message. It can function continuously, but the enhanced circuitry results in the device costing as much as a two-channel sequencing receiver, which is much more flexible and more accurate.

Two-Channel Sequencing Receivers

The addition of a second channel to a GPS receiver increases its capabilities significantly. A second channel immediately doubles the system signal-to-noise ratio, meaning it can lock onto signals under more adverse conditions and can track satellites closer to the horizon. A two-channel receiver never has to interrupt its navigation functions because, while one channel is continuously monitoring positioning data, the other is acquiring the next satellite. In addition, velocity measurements are typically much more precise.

The disadvantages of a two-channel design are that it has been historically more costly to construct and requires more power to operate. Since the advent of large-scale integrated circuits, however, the cost of adding a second channel has been substantially reduced. Two-channel receivers do remain typically more expensive than their single-channel counterparts, largely because most users who seek the higher accuracy and continuous functions of a two-channel device usually also want a more sophisticated package of user controls and displays.

Continuous Multichannel Receivers

Continuous multichannel receivers are presently the receiver of choice for most applications requiring high accuracy. These are capable of simultaneously monitoring four or more satellites and can give instantaneous position and velocity. They are designed in 4, 5, 6, 8, and even 10 and 12 channel configurations, and are often used in surveying and scientific applications. With four channels, a receiver can double the signal-to-background noise ratio of a two-channel receiver and quadruple that of a single-channel system.

With current technology, receivers with a minimum of six channels mark a significant threshold with respect to functionality and performance. Five of the channels can be used to continuously track 4+ satellites and the sixth channel can be devoted to collecting data messages. Receiver manufacturers can use data messages to track such things as carrier signal, ephemeris reports and other differential correction information.

Besides the obvious advantage of being able to continuously measure a position, multichannel receivers can also reduce the Geometric Dilution of Precision (GDOP) problem (see section below, Factors Affecting GPS Accuracy). Instead of relying on a calculation of the four best positioned satellites, some of these systems are capable of tracking all satellites in view, in order to get the absolute minimum GDOP. Multichannel receivers are specified to have an accuracy of 1 centimeter ±1 millimeter for each kilometer of baseline. For example, two survey grade receivers separated by 10 km will compute a separation of 10 km ±21 cm (Lange and Kruczynski, 1989).

D. Factors Affecting GPS Accuracy

The concept of accuracy is central to any method of spatial measurement and is essential to understanding GPS technology. The level of positional accuracy possible in a given positioning exercise is highly variable and is a function of the chosen means of communicating the concept of spatial accuracy, as well as the different survey and positioning techniques employed.

Expressing Positional Accuracy

Positional accuracy is usually expressed in one of two ways. The proportional error method is expressed as the position error divided by the distance to the origin of the coordinate systems used (Figure 9) and is usually expressed in parts per million (ppm). Proportional accuracy can be defined for point positioning as well as for differential positioning. In point positioning (referenced to the geocentric center of the earth), a 10-meter en-or in the position of a point represents an error of 10 m divided by the radius of the earth (6.371×10^6m) and is equal to 1.6 parts per million (1.6 ppm). In a differential positioning scenario using two earth surface points 100 km apart, a proportional accuracy of 1.6 ppm would require that the relative position of the points be known to within 16 centimeters (0.16 m position error/100,000 m baseline length = 1.6 ppm).

A second method of expressing positional accuracy which is more commonly used is confidence regions, either ellipses (two-dimensional cases) or ellipsoids (three-dimensional cases). Confidence regions are areas or volumes, physical confidence regions, that will contain the true location at a preselected level of probability, as shown in Figure 10 (Wells et al., 1988).

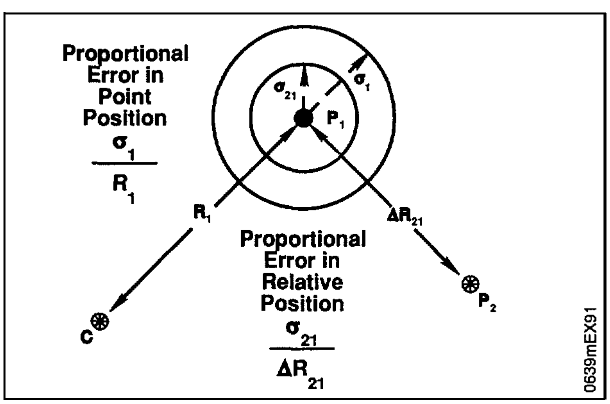


Figure 9. Proportional error.

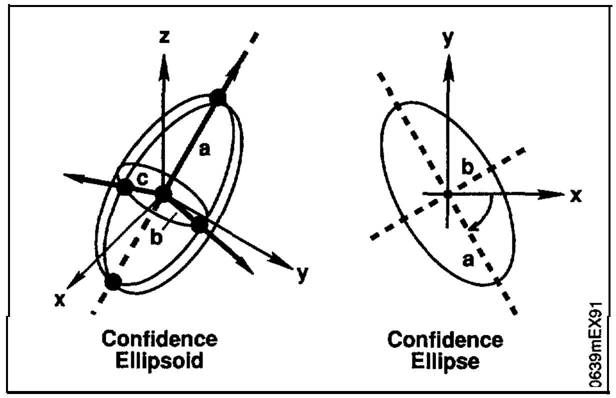


Figure 10. Confidence regions.

Classes of Surveys

Classes of surveys are prepared by the Federal Geodetic Control Council and provide a measure of the accuracy required and used within the U.S. The advent of GPS technology has resulted in a reassessment of the applicability of these classes. In many cases, GPS exceeds the standards established by these survey classes.

A first order survey yields position or closing to 1 part in 100,000 (10 ppm) and is used for applications such as national geodetic network control and the study of small earth crustal movements. A second order survey has two classes, the first class producing results between first order accuracy and accuracy of 1 part in 50,000 (20 ppm), the second class accurate to 1 part in 20,000 (50 ppm). Second order surveys are used for coastline, inland waterway, and interstate highway surveys. A third order survey also has two classes with class one being accurate to 1 part in 10,000 (100 ppm), used for local surveys, while third order class two is the lowest class, accurate to one part in 5,000 (200 ppm). Third order surveys are used for establishing control for local developments, topographic and hydrographic surveys, and other similar projects.

GPS provides a tool for surveying to 1 part in 100,000 in 45 minutes of satellite tracking and 1 part in 500,000 for 2 hours tracking. Even greater accuracy exceeding 1 part in 1,000,000 is possible using more advanced continuous, or “survey-grade,” receivers which are described earlier in this document.

Factors Affecting Positioning Accuracy

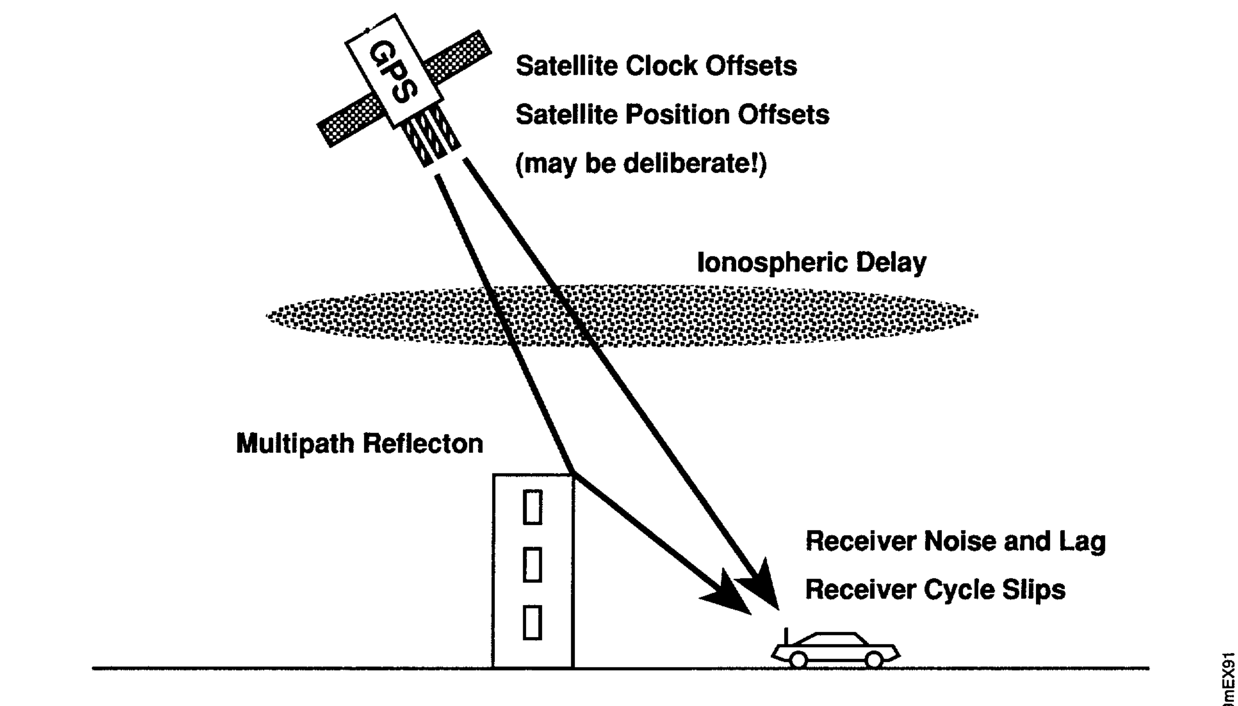
The accuracy of GPS positioning depends upon the satellite geometry constellation, biases or errors in the range measurements. Geometric "strength" varies with satellite visibility and positions and, therefore, it is a consideration in survey planning. Biases influencing GPS measurements are primarily related to either inherent imperfections in the receiver or satellite, or represent observation dependent distortions, such as variations in signal propagation. Biases are typically removed or at least suppressed in differential-mode operation or in data averaging. The sources of bias and error include satellite clock errors, satellite ephemeris errors, unmodelled atmospheric delays, multi-path signals, receiver internal noise, and selective availability y (Figure 11).

Satellite Geometric Strength

The effect of satellite geometry is expressed as the geometric dilution of precision (GDOP). There are several components of GDOP, though of primary concern here is the positional dilution of precision (PDOP). Simply stated, the PDOP is a measure of the geometrical strength of the GPS satellite configuration. The level of accuracy associated with positional measurements will vary depending upon the relative angles between the range vectors of two or more satellites. Generally, the higher the value of the PDOP the greater the uncertainty in the position of the receiver. Conversely, the lower the GDOP and PDOP, the more accurate the instantaneous point position may be. The best dilution of precision occurs with one satellite directly overhead and three others equally spaced around the horizon, as low in the sky as possible without risking obstruction by terrain or other obstacles.

The GDOP can be considered a scalar factor that represents the contribution of the constellation geometry to potential positioning accuracy. This factor could be multiplied by the composite pseudo-range measurement error to get an overall error estimate. If the pseudo-range measurement error is 10 meters and the GDOP is 3, an overall accuracy of 30 meters is potentially achievable (Ackroyd and Lorimer, 1990).

The PDOP value changes with time, as the satellites travel along their orbital paths, and with survey point location, since the satellite configuration is dependent upon the position from which it is



Source: Dr. James W. Sennott, Bradley University, 1991

Figure 11. Error sources.

observed. PDOP is also affected by topographic relief, because the satellite and receiver require direct line-of-sight for the satellite signals to be received, and otherwise desirable satellites may be blocked from view. Receivers are usually set to reject satellites closer to the horizon than a specified angle called the mask angle.

Related dilution of precision concepts include horizontal dilution of precision (HDOP), and vertical dilution of precision (VDOP). The HDOP relates simply to the two dimensional fix (which requires one fewer satellite), and the VDOP reflects the potential to measure elevation accurately.

Range Measurement Accuracy

Range measurement accuracy is affected by a combination of considerations. Table 3 shows some of the range measurement biases: small variations in the accuracies of the satellite atomic clocks; slight uncertainties regarding the actual satellite ephemeris; errors due to the electronics within the receiver; and ionospheric and atmospheric delays in the propagation of the GPS signal. One of the more important of these considerations is cycle slip, instances where satellite signal reception was interrupted.

Together, these sources of error give each GPS measurement a variable level of uncertainty. Fortunately, the assorted sources of uncertainty combined do not typically add up to a very significant measurement error and, for the most part, can be predicted and removed mathematically, by the receiver or during postprocessing via data averaging or removal of outlier data.

Clock error

Post-modeling timing difference between receiver clocks and the more reliable satellite clocks is an error intrinsic to the passive nature of the receiver units. If the receiver units were to transmit clock information to the satellite, clocks could be synchronized and clock errors overcome. However, as GPS was developed as a military application, transmission of a signal from a receiver unit possibly would betray the location of the user. Precise calibration of these clocks is critical to the accurate determination of a satellite's range vector. Clock error or time offset is multiplied by the speed of light to derive the user equivalent range error. Thus, an error in calibration of 1 microsecond creates an error in range of approximately 300 meters (Wells et al., 1988). Since prohibitive cost precludes outfitting every GPS receiver with its own atomic clock, slight variations in clock calibrations become an inherent part of determining range vectors. In order to offset this timing problem, it is necessary to determine the coincident range vector to a fourth satellite. Ranging to a fourth satellite permits correction of any errors related to residual clock bias within the receiver.

Table 3. Typical Range Vector Measurement Errors

Error Source	Error
Satellite Clock Error	2 feet
Ephemeris Error	2 feet
Receiver Errors	4 feet
Atmospheric Propagation	12 feet

Ephemeris error

Errors in the satellite orbit data or ephemeris as transmitted in the C/A code lead to positioning errors that can be as much as 20 meters off. Enhanced ground tracking capabilities are to be developed that will reduce this source of error to around 5 meters in the future (Wells et al., 1988). However, again by operating in differential mode, much of this source of error can be removed. Selective availability (see discussion below) contributes significantly to inaccuracies in the orbital data broadcast.

Ephemeris error may also result from orbital adjustments made to the constellation. It is a slow process to move the satellites because maneuvers are performed in such a way as to minimize the expenditure of on-board propellant. During the period of movement, which may extend over a few months, the satellite is still sending navigation messages, but its utility in positioning is degraded. It is possible to obtain the precise ephemeris for the day of a survey after the fact from the NGS. Currently, you must wait up to 2 months before this information is available and it is provided at a fee. However, for highest accuracy positioning during periods of repositioning, it may be necessary to recalculate positional solutions with the precise rather than the orbital information contained in the navigation broadcast message at the time of the survey.

Atmospheric delays

The ionosphere is that area of the atmosphere where free electrons exist, generated by the ultra violet radiation from the sun. In this region, approximately 50 to 1,000 kilometers above the Earth's surface, the electromagnetic GPS signal is dispersed to some degree by the ionized gas molecules. Tropospheric interferences vary according to meteorological conditions (temperature, water vapor content, and atmospheric pressure). These factors cause delays in signal reception that correlate to positional inaccuracy. For absolute mode operation, atmospheric delays are a significant source of error. It is possible to model atmospheric delay simulating its contribution to the error budget. However, when operating in differential mode, it is not considered to be a necessary error suppression mechanism (Kruczynski, Abby, and Porter, 1985).

Cycle slips

One other type of range measurement error occurs when continuous satellite signal reception is interrupted. For an instant, the receiver experiences ambiguity as to which cycle of the C/A code it is receiving. This will lead to what is known as cycle slip. The best way to deal with significant slip problems is to examine and edit data, removing positions obtained immediately after signal breaks.

Multipath

Another factor affecting positioning accuracy is the phenomenon of multipath, wherein a satellite signal arrives at a receiver via two or more different paths. This is usually observed when operating near large reflecting obstacles, which act in effect as extensions of the receiver's antenna. These problems can be minimized or avoided through careful survey preparation and receiver/antenna positioning; in particular, avoidance of proximity to metal buildings and bodies of water is recommended. It should be noted that interference might be encountered from reflective objects within buildings that are not visible to the field crew performing the survey.

Selective Availability

Since March 25, 1990, the accuracy of position frees obtainable by civilians has been intentionally degraded by the DOD. Where employed, this degradation will utilize an operational mode called selective availability (S/A). S/A will affect the accuracy of the C/A code by artificially creating a significant clock and ephemeris error in the satellites. When S/A is operating, positional data via absolute mode positioning may be so inaccurate as to be completely inappropriate. Since S/A has been in effect, absolute positional error has increased an additional 50 to 200 meters. Ironically, the need to deploy large numbers of commercial grade GPS units in the Persian Gulf War prompted DOD to turnoff selective availability during the hostilities. It appears likely that it will be reintroduced soon.

To get a good position fix in the presence of S/A, differential GPS can be used. As described earlier, differential GPS utilizes a stationary reference GPS receiver, set up on a known location, to determine exactly the degree of error contained in the satellite data. The reference receiver is set to record a reference file, within which any deviations from "truth" will be logged. Consistently anomalous departures from the actual known position of the reference receiver betray the presence of S/A. The reference file generates a time-tagged position correction that can be applied to a remote GPS data file collected using another receiver, at an unknown location, within a few hundred kilometers from the reference location.

Because some of this error can be effectively overcome by operating in differential mode, the rate at which signal degradation varies is of concern. The clock "dither" is more rapid and changing than ephemeris degradation. Because the change of rate direction can be at approximately 3-minute intervals, differential position correction codes must be recorded at the reference station with greater frequency (Ackroyd and Lorimer, 1990).

The continued access to useful and reliable GPS signals and related information by the civilian community rests in the hands of the DOD. The existing arrangement originated in 1983 and has spawned the development of an expansive civilian GPS industry. The arrangement, allowing civilian access to the capabilities of the GPS Standard Positioning Service (SPS) has been confirmed in every edition of the Federal Radionavigation Plan (FRP). The FRP is a Congressionally mandated, joint DOD and DOT effort to reduce the proliferation and overlap of federally funded radionavigation systems. The FRP is designed to delineate policies and plans for U.S. government-provided radionavigation services, and is issued biennially, or more frequently if necessary. Nonetheless, although civilian access to GPS signals is clearly established in the FRP, signal availability and accuracy remains subject to change without advance warning, at the discretion of DOD (U.S. DOT/DOD, 1984).

The true impact of S/A on the day-to-day operational effectiveness of civilian GPS activities remains rather unclear. A complete review of S/A effects has not been performed by the authors, nor has such a review been published as yet.

E. Future Of GPS Technology

Barring significant new complications due to S/A from DOD, GPS as an industry will likely continue to develop in the civilian community. There are currently more than 50 manufacturers of GPS receivers, with the trend continuing to be toward smaller, less expensive, and more easily operated devices. While highly accurate, portable (hand-held) receivers are already available, current speculation envisions inexpensive and equally accurate "wristwatch locators," and navigational guidance systems for automobiles. However, there is one future trend that will be very relevant to EPA's use of this technology. Community base stations and regional receiver networks are GPS management and technological innovations that will make GPS surveying easier and more accurate.

Community Base Stations

Regional Networks of Receiver Stations

The development of networks of geographically separated GPS receiver stations for differential positioning across large areas is a concept that is currently under consideration by some of the EPA Regional Offices. These receivers will be strategically based to provide for optimal differential positioning across their entire jurisdictional area. This would make GPS surveying one step easier in that a second receiver station would not need to be positioned at a fried location for each survey event. A survey team would simply need to identify the receiver station best used for differential positioning in that area, and either record in real time the reference station error correcting data or acquire the logged base station data for use in post processing.

The development of a national network of community base stations is still a research topic at this time. Concerns include how far from a base station a receiver may be before degradation in accuracy occurs. This will ultimately determine the required density of base stations. consequently, additional research is required before large investments can take place.

Real-Time Differential Correction

Real-time differential correction is required for certain applications such as precise navigation and may be a practical long term solution for all GPS data collection. Differential correction requires an "anchor" point of known coordinates. By using existing or other communications satellites data can be collected at these sites, processed, immediately unlinked, and then broadcast via another channel into a receiver. Several commercial firms are currently exploring the marketing of such data via leased mobile satellite services (MSS) with user subscriptions.

The satellite industry is moving to set aside part of the L-band radio frequency to accommodate GPS differential correction data streams. If accepted by the FCC, this would enable differential correction data to be a standard broadcast just like the GPS locational data. A simple upgrade to existing GPS receivers would enable real-time correction and provide true coordinates on the receiver display. This technological development would certainly impact the need for widespread networks of community base stations.

Similarly, low cost field units are now appearing that provide digital, voice and video links to Earth-orbiting satellites with user-transparent relay links to anywhere in the world. Satellite access costs are also falling below the $10/minute threshold. One could envision that these units could be deployed to emergency response sites or set up as nodes in areas where intensive data collection will occur.

Section 4
Use Of GPS For Environmental Applications

A. GIS *Applications*

GPS has been assessed as both a data collection and quality assurance tool for GIS applications. Positional data can be collected quickly and accurately and recorded within a common geographic reference system. Point locational information can be obtained in a fraction of the time required for conventional surveys, permitting a field crew, for example, to quickly and accurately gather positional data for a large number of wellheads or sample collection points. Line or polygonal features, such as a street network or boundary of an industrial facility, can be digitally mapped equally as easily. The GPS receiver is simply transported to a convenient starting point, placed in logging mode, and the street network is followed or the facility boundary circumnavigated until the feature or features of interest are digitized. The data could then be extracted from the receiver's data logger, loaded to the appropriate GIS platform, and the positional data converted to the desired GIS data import format.

With the data logging capabilities of most GPS receivers, the coordinates, time, and other attribute information may be collected and then exported to a GIS data base with no manual digitizing operation. Since GPS provides a common reference system, data from GPS sources and from sources rectified with GPS register with each other and with the multisource data within the GIS data base. Moreover, the spatial quality of GIS data can be established by comparing the representative positional attributes of the data with their "true" GPS-derived locations.

The following represent a few of the enhancements which GPS lends to EPA GIS applications:

1. Provides a bridge to collection of state plane coordinates for GIS projects and to establishment of legal boundaries and absolute site locations for waste sites;
2. Gathering of precise locational data for specific site features such as well heads, underground tanks or drums;
3. Obtain accurate positional information without the need for line of site between points necessary to do a traditional survey, thereby rendering insignificant buildings and other obstructions in and around large urban areas. This capability also eliminates the need to obtain access to hostile properties and sensitive areas such as wildlife reserves and wilderness areas; and
4. Provide a high quality locational accuracy assessment tool for implementation and enforcement of the EPA's Locational Data Policy. Accuracy assessments can be conducted within a very short period of time compared to conventional survey techniques. GPS-derived data sets can be used for comparison to data collected through other methods and representing the same features.

B. Field Sampling

1. Provide a means to navigate to any point (e.g. sample location) in the air, on the sea, or on the land. A single C/A receiver will deliver navigational accuracy of approximately 20 meters. Post-processing can reduce this error to about 3 meters or less;
2. Ensure positional accuracy for data gathered during times when relative controls are not possible due to heightened levels of urgency (e.g. oil spill events). In these situations, positional data can later be referenced to a state coordinate system with the knowledge that accuracy will not be lost; and
3. Allow for the collection of samples at known, well-defined locations within a site in a much shorter time than locating collection points by

conventional survey methods. The reduced time, which can be as short as a few seconds to record a GPS position, greatly reduces the exposure time of personnel doing the sample collecting.

C. Remote Sensing

1. Provide photogrammetric control by establishing photo-control points of horizontal and vertical positions. An accurate position can be obtained without the expense and time required for conventional surveys. Since GPS utilize a worldwide standard reference system, limits of a common grid reference system due to independent benchmarks are avoided; and
2. Provide sensor navigation and positioning for remote sensing instruments such as cameras, line scanners, and other active and passive measurement devices. These instruments can be accurately positioned during data collect and the position data base can be stored for post processing and greater accuracy. This technique applies to aircraft-based systems as well as space satellites.

D. Real-time Attribute Coding Software

An innovative software product recently made available is GeoLink software, from GeoResearch of Billings, Montana. GeoLink allows automatic real-time input of GPS satellite data into an ARC/INFO GIS format, using a mobile or base station PC. ARC/INFO is the GIS software currently in use by the EPA. With this capability digital map products can be created in the field. Preceded geographic feature attributes can be simultaneously attached to the collected GPS data or added as a feature location is acquired. Attributes and positions then can be displayed graphically on the PC as they are acquired; this capability allows easy updating of old data and visual verification of newly acquired data. It has advantages over photo interpretation with the GPS user being able to see under trees and through identification of very small objects. The use of GPS for windshield surveys is the simplest and most cost efficient method of spatial attribute updating (Puterski, 1990).

Section 5
Performing a GPS Survey

A GPS survey of the type used in the Old Southington, Connecticut and San Gabriel, California studies (see Appendix D) can be divided into five major segments (Slonecker and Carter, 1990);

A. Planning

B. Reconnaissance

C. Survey Execution

D. Data Reduction and Processing

E. Integration of GPS into a Data Base

Each of these segments is described below. Particular attention is drawn to problems experienced in the field. Appendix F, Field Charts, contains a number of checklists and forms which complement the discussion. These prototypes were developed for experimental projects using the hardware and software available. While obviously oriented toward a particular receiver and software, these forms are useful models in performing a survey with any equipment. The other appendices provide descriptions on additional sources of information and ancillary data vital to the success of a GPS survey.

A. Survey Planning

Define Objectives of Survey

It is clearly important to initially establish the ultimate objectives of a GPS survey. Recognition of these objectives early in the project planning process will help to focus the rest of the planning phase. The accuracy requirements for the positional data needs to be defined, paying particular attention to the EPA Locational Data Policy (Appendix C). From the discussion above, some distinct survey objectives might include:

- registration of remotely sensed photography or imagery;
- evaluation of locational data quality of existing data; and
- sample data collection following precise coordinates in a monitoring plan.

Define Project Area

This step is designed for establishing the overall project area and defining the limits of the survey. Maps and/or aerial photos should be utilized extensively to familiarize the crew with the area prior to the actual field work. For identifying the study area and surrounding environment, 7.5 minute topographic maps are ideal. For locating particular sites by address a local street map will be required. A complete understanding of the project area transportation network will also enable the field crew to maximize the effectiveness of their field time.

Determine Observation Window and Schedule Operations

This involves determining the precise window of satellite availability and scheduling accordingly. The incomplete status of the satellite constellation dictates that surveys are currently restricted to several hours per day. Optimization of the schedule is dependent upon the size of the crew, the level of accuracy desired, the logistics of setup, and the travel between control points.

A current satellite visibility almanac is invaluable in planning a survey mission. Provided by several vendors, these almanacs provide information on the availability of satellite coverage. Since satellite orbits are periodically adjusted, these almanacs require updating every several months. Most vendors provide updates using either electronic bulletin boards or regular mail. For final verification of availability, contact the U.S. Coast Guard GPS Users Service for information on the entire system or any individual satellites that may be deactivated during your scheduled field work. Information is also broadcast by WWV/WWV# at 15 minutes past each hour.

The Agency has arranged for EPA users to acquire one such almanac, the Satellite Visibility and Geometry Analysis Software (SATVIZ) from Trimble Navigation. SATVIZ is an easy-to-use PC based software program which provides information critical to the various components of planning a GPS survey: satellite availability, elevations, azimuths, and GDOP calculations. Appendix A provides information on how to contact Trimble Navigation.

Several rules of thumb exist regarding available windows and angles above the horizon. Most almanac software will yield good results for windows within one half degree of the survey station (approximately 30 miles). If your survey mission will span greater distances, then you may wish to iterate calculations for several planned survey locations. For angles above the horizon, optimal results are achieved with satellites 25 degrees above the horizon. However, as little as 10 degrees works fine in areas of minimal obstruction.

Accuracy is heavily dependent upon the amount of observation time and number of observations taken at each point. It is generally agreed that observation time can be reduced by increasing the quality of observation time, i.e. observing a maximum number of satellites during 3-D viewing periods.

Establish Control Configuration

In this step, known control points and/or benchmarks are located for both horizontal and vertical control. This is usually accomplished by researching the records of various Federal, State and local agencies such as the National Geodetic Surveyor the state geodetic survey. It is advisable to have, where possible, at least two control points each for both vertical and horizontal positions so that there is a double check for all control locations. The reference for NGS benchmark information is provided in Appendix A.

It is of paramount importance that the reference datum within which the monument is located be defined. The discussion provided later in this section explains the reasons in detail. For horizontal coordinates, the North American Datum of 1927 (NAD 27) or the newer Datum of 1983 (NAD 83) will be specified. For vertical control coordinates, the National Geodetic Vertical Datum of 1929 (NGVD 29) or the new North American Vertical Datum of 1988 (NAVD 88) will be referenced. If the NGS has redefined the benchmark coordinates to correspond to the newer datums, coordinates will be available for both datums.

If the monument is located in a controlled-access setting, the appropriate individuals should be contacted to obtain admittance. The station recovery section of monumentation data sheets provided by NGS describe in detail how to locate a particular point and whom to contact for access.

Sensitivity to factors contributing to multipath are particularly important for positioning a receiver station and antenna. In particular, control points/areas should not be near power lines, substations or large metal objects which can cause multipath interference and corrupted data. Since observation of these proximate features may not be possible until the survey reconnaissance is performed, having backup sites ready will save time.

Choosing control points for use as base stations may require a physical inspection of the site. Ideal locations will have a near 100 percent clear view of the sky and be easily accessible. They should also be located in area of low vehicular and pedestrian traffic.

Select Survey Locations

Obtain a list of the facilities or routes targeted for data collection. A good suggestion is to organize the site lists alphabetically by city and alphabetically by street name within each city. This will facilitate initial route planning to visit each and serve as a master list. If possible, plot the general location on afield map and highlight a local street map to serve as a general navigation aid. Similarly, plot potential base stations to serve as control points on a 7.5 minute topographic map and local street map.

The survey points/areas must be accessible during the satellite window of availability, which currently may occur during unusual hours (e.g. 1 am to 5 am). If the survey point to be obtained is located on private property, care should be taken to pursue appropriate notification and access protocol. This includes preparation of a letter of introduction and formal contact with the property owner/manager. A sample letter is included in Appendix F, Field Chain. Access to points “on-site” within private property such as business facilities are typically not appropriate for night time surveys.

The points/areas should have continuous and direct line-of-site to the path of the satellites in the sky. Based on the view provided by satellite window planning software such as SATVIS, and the survey team's knowledge of the natural and man-made topographic features, it may be possible to predict masking.

As with control points, obstructions and other factors can cause interference and corrupted data during the survey. It is advisable to note any adverse conditions on a form when collecting data. This will be helpful in the postprocessing phase.

If point data being collected is to be used as control for photogrammetric operations, then the point locations must be photoidentifiable on the imagery to be used for photo registration. If the registration is to be used with historic imagery, the locations should be landmarks present and identifiable for the entire period of history to be reviewed. Such landmarks might be corners of the street network that have remained constant, street/railroad intersections, hydrants or other public works.

Equipment Logistics

Survey planning action items in this area include: determination of equipment availability (laptop PC, GPS units, transport vehicle, monumentation equipment), and checking equipment for necessary repair and maintenance (batteries charged in PC and GPS unit, PC disk loaded with necessary software and has available disk space).

This is the time to collect and pack field survey equipment. In addition to the above items, experienced crews carry everything from a compass and tape measure to manuals and almanac printouts. A suggested checklist is provide in Appendix F.

B. Reconnaissance

The Reconnaissance phase is an important part of a successful GPS operation and is usually performed by an individual or crew at some point prior to the arrival of the full field team. The purpose of this phase is to:

Locate and Verify Control Point Locations

This is critical to the success of the overall survey. Often, monuments have been damaged, stolen, buried or vandalized. If a control point cannot be recovered, a replacement must be located. This can drastically change the schedule and logistics of the field survey. Also, it may be found that a monument's location has shifted somewhat. There are currently state and federal initiatives to improve coordinate networks as part of the effort to upgrade to NAD 83 (see discussion of datums below).

Plan to visit each of the control points at least twice during the survey. Collecting redundant data is useful in determining the quality and accuracy of the overall survey. The duration of each fix should be approximately 3-5 minutes.

Preview Instrument Locations

Obtain permissions and verify accessibility. It will often be necessary to coordinate activities with property owners, local law enforcement, and/or land management officials in order to ensure safe and authorized access to the instrument locations. Field verify that there are not any visible multipath-contributing or masking features. Identify any natural or man-made obstacles to direct access to survey point.

Physically Establish Point Locations

This is accomplished by using a standard surveying marker such as an iron pipe, a hub and tack, or a brass nail. All points should be documented with detailed descriptions in a log book (refer to Appendix F for a sample form). If nearby multipath or masking features are unavoidable, note their presence. It may be necessary to physically offset the GPS control point from an obstructed benchmark. This can effectively be accomplished using a compass and tape measure.

C. Survey Execution

The actual GPS survey consists of:

Establishing a Schedule of Operations

This involves determining the window of satellite configuration availability and scheduling the GPS sessions. This is dependent on the size of the crew, the level of accuracy desired, and the logistics of setup and travel between control points. Maximum data quality and collection efficiency can be obtained by arranging travel time to coincide with periods of 2-D or no satellite coverage and actual data collection periods to coincide with periods of 3-D satellite visibility.

Presurvey: The Day Before

Plan on arriving the day before. Charge all batteries. Many GPS collection systems utilize a battery system which requires either 8-hour or overnight charging. For example, the Polycorder used with the Trimble Pathfinder system utilizes a Ni-Cad battery that should not be charged over 8 hours. Review the travel routes to survey sites and base stations, if required, and coordinate with local personnel. Review use of unfamiliar equipment and understanding of procedures.

Predata Collection: Establishing a Base Station

The type of survey will dictate if a base control station in the field is required. If required and the location is not secure or if the data collection period is particularly long, some of the survey crew may be required to remain at this site. Logistical considerations will need to be scheduled, i.e. shut down periods for downloading files, changing battery packs, and when to terminate collection. Once setup at a base station begins, the GPS units will need to be initialized. Depending upon the location and familiarity with equipment, this activity can take anywhere from a few minutes to a couple of hours.

Data Collection: Performing the GPS Survey

The crew must warm-up, check and program the receiver for proper operation. Most vendors currently recommend collecting fixes for discrete point data for a period of 3-5 minutes, at a one or two second interval. Many software packages require approximately 35-40 readings per point to perform statistical analyses such as t-tests.

Depending on the unit being utilized, sufficient battery power must be available and the receiving antenna must be leveled on a tripod and centered exactly over the control point location. Log sheets containing critical information on position, weather, timing, height of instrument, and local coordinates must be maintained. Once the session is completed, the receiving equipment must be disassembled, stored, and log and tape files documented.

If another session is scheduled, this process must be conducted quickly and efficiently so that the crew can beat the next location and be set up in time for the scheduled window of satellite availability.

If the survey to be performed will span over numerous days, it is likely that the data will be transferred from the GPS to a lap top PC with some regularity. Data from the base station as well as the roving unit will need to be collected with equal frequency.

Leveling

If a correlation to a known vertical datum is required, a leveling survey must be performed from a known benchmark to at least one of the GPS control points and closed back. It is desireable to level to more than one of the GPS points and to close on a second vertical control point.

Locating Facilities

A recommended strategy for locating facilities involves conflation of the street address and facility name. Often an address is located but confirmation of the name is not possible. Reasons may vary from vacancy to a change in ownership. Data should still be collected and any discrepancies well documented. Many problems can resolved at a later time. Other problems, such as poor signage in rural areas, can be overcome by asking for information from local postal workers and delivery persons.

Returning From The Field

This is the time to perform other postsurvey tasks. Before leaving the site, document any unique problems. After returning from the field, complete other housekeeping chores such as recharging the system and cleaning the equipment. Use checklists to make sure equipment is in working order and any consumable supplies are reordered.

D. Data Reduction and Processing

Data reduction and processing consist of:

Data Transfer

There are currently two common methods for collecting data in the field, using an intermediate device such as a Polycorder or directly into a laptop/notebook personal computer. With the latter method some users subsequently perform all processing directly on the same device. More commonly, data is transferred to another machine. This consists of reading the raw data from the GPS cassette tapes or other media into a structured database for processing. As with any computer data backup copies should be made immediately.

Initial Processing

The electronic GPS data stream may not be immediately useable. It normally consists of satellite navigation messages, phase measurements, user input field data and other information that must be transferred to various files for processing before computations can be accomplished. Depending upon the hardware and software vendor, many of these operations are transparent to the user. There are five components to the initial processing phase performed by GPS "firmware," software that comes with the GPS units:

1. Orbit Determination: using satellite navigation messages, one unambiguous orbit for each satellite is computed;
2. Single-Point Positioning: clock corrections and parameters for each receiver are computed;
3. Baseline Definition: general locations of receiving stations are established, computing the best pairs of sites for baseline definition;
4. Single Difference File Creation: the differences between simultaneous phase measurements to the same satellite from two sites. This is the basic data from which network and coordinate data will be derived; and
5. Data Screening and Editing: automatic and manual screening of the single difference files and editing of data obviously affected by breaks, cycle slips, or multipath.

In some instances, depending on the type of maintenance and upgrades that are going on to the NAVSTAR constellation at the time of the survey, utilization of the actual ephemeris rather than the ephemeris projected prior to the survey date may improve solution accuracy. Actual ephemerides are available 2 weeks after a given survey date.

In the data screening and editing step above, there are at least three considerations that might be taken in editing. Outlier position data can be removed from a data file. This editing should be guided by establishing an absolute deviation threshold, using the mean coordinate as a reference. The threshold criteria might be varied to determine the sensitivity of the solutions to this editing. Data points collected immediately after a break in the data stream, such as in the event of masking, should be edited out because these positions will be less reliable. Finally with S/A operational, removal of two-dimensional positions (e.g., positions obtained when the satellite configuration was not strong enough for obtaining three-dimensional positions) may be advisable because S/A seems to have such a large effect on the altitude; although altitude is not specifically solved in a 2-D fix, the altitude of the position impacts the solution.

Computation

This component uses the pre-processed data to compute the network of sites and give a full solution showing geographical coordinates (latitude, longitude and ellipsoidal height), distances of the vectors between each pair of sites in the network, and several assessments of accuracy of the various transformations and residuals of critical computations. If the standard deviation for a differential mode position is greater than 5 meters, removal of outlier coordinates and recalculation of a position mean is advised (Lange, 1990).

A number of software programs exist to assist with this phase of processing. In particular, the EPA Environmental Monitoring Systems Laboratory, Las Vegas, Nevada (EMSL-LV), is currently developing a suite of programs that will be available in the future to all regional offices. These programs will include PLOTSSF and CLEANSSF. Designed to work with the Trimble SSF file, these modules can be used to display statistics about each point and editing of outliers. Further information is provided in Appendix E.

E. Integration of GPS Data into a GIS Data Base

Rectification of Datum

In recent years, NGS has redefined the shape of the earth, called a reference datum. Analogous to adding a leap second to the official clock, the new datums differentially correct the shape and therefore positions on the earth's surface. Unlike the clock, the adjustment is not uniform over the earth's surface. Consequently, it will require many years to convert old maps and digital data bases.

If the GPS data are to be introduced into an existing map data base, it may be necessary to convert either the existing data or the GPS data in order to match the reference datums. The North American Datum of 1927 (NAD 27) has been replaced in recent years as the official horizontal datum by the North American Datum of 1983 (NAD 83). Although NAD 83 is much more consistent and accurate than its predecessor, many surveying and mapping coordinates in the United States are still referenced to NAD 27. Consequently, datum inconsistencies confront the land surveying and mapping communities.

The principle differences between NAD 27 and NAD 83 are functions of the reference ellipsoids or spheroids (i.e., simple geometric approximations for the shape of the earth) chosen for each datum. NAD 27 depends upon an early approximation, known as the Clarke Spheroid of 1866, while NAD 83 relies on the more precise Geodetic Reference System of 1980 (GRS 80). The Clarke Spheroid of 1866 was designed to fit only the shape of the conterminous United States, utilizing a specific Earth surface coordinate pair as its center of reference. On the other hand, GRS 80, and the essentially equivalent WorldGeodetic System of 1984 (WGS 84), is a geocentric ellipsoid, utilizing the Earth's center of mass as its center of reference. This fact facilitates computing correct geometric relationships on a global and continental scale.

As NAD 27 has been in use for over 50 years, there is certainly a potential for datum inconsistency in the development of a digital cartographic or geographic data base. The impact of the datum change must be viewed in light of 1) the mapping scales of interest within the cartographic or geographic product or data base, and 2) the magnitude of the shifts between datums. The differences between NAD 27 and NAD 83 vary with respect to location, from as little as zero to in excess of 100 meters.

If the average datum shift within a region of geographic interest is less than the stated accuracy standard necessary to properly represent the area of interest, then a "correction" or transformation to NAD 83 is not necessary. A transformation between datums will likely be necessary only when the difference between datums exceeds the reqisite accuracy of the geographic product (Dewhurst, 1990). As of 1986, the National Geodetic Survey had completed adjustment of 270,000 geodetic control stations to NAD 83 with 1 part in 100,000 accuracy. Many states desire higher accuracy in their networks now that it is obtainable using high-grade GPS equipment. Many are in the process of or are considering upgrading Order A and B networks to 1 ppm accuracy. Those committed to this upgrade as of June, 1990, include: Washington, Oregon, New Mexico, Wisconsin, Tennessee, and Florida. NGS has issued an implementation strategy for such upgrades. The coordinate recordation will include a reference in the following format, "NAD 83 (Adjustment of 199X)" (Bodnar, 1990).

Several different methods of transforming coordinate data are well accepted in the geodetic and surveying communities. A rapid and accurate transformation methodology, known as NADCON, has been developed by the National Geodetic Survey (NGS). NADCON software has been adopted by the Federal Geodetic Control Committee (FGCC) as the standard for coordinate conversions between NAD 27 and NAD 83, Results indicate that NADCON is accurate to approximately 15 centimeters for the conterminous United States, where good geodetic control exists. Remote areas where geodetic control is sparse or nonexistent may experience somewhat less accurate results, but seldom in excess of 1.0 meter (Dewhurst, 1990). This conversion is recommended for map data that is smaller than 1:200 scale.

Copies of NADCON are available from the National Geodetic Survey. For further information contact:

The National Geodetic Survey
National Geodetic Information Branch
N/CG 174
NOAA
Rockville, MD 20852
Phone: (301) 443-8631

For Agency users of Environmental System Research Institute's ARC/INFO GIS software, NADCON is being released with Revision 6.0. For users who will not be installing that version in the immediate future, a program called CDATUM is currently available from EMSL-LV. This program, written in FORTRAN 77 for the VAX, will convert datums for any coverage.

Copies of CDATUM are available from EMSL-LV. For further information contact:

Mason J. Hewitt
GIS Program Manager
EMSL-LV
P.O. Box 93478
Las Vegas, NV 89108
Phone: (702) 798-2377 FTS 545-2377

Users of vertical measurements from GPS receivers should also understand the heights provided by GPS are not elevations above sea level. In conventional surveying horizontal measurements are referenced to a theoretical ellipsoid, a mathematically defined regular surface, and vertical measurements are referenced to a geoid, an irregular surface along which the gravity potential is equal at every location. The geoid is equivalent to the surface to which oceans would conform over the entire earth if free to adjust based on mass and rotational forces. Because the earth's mass is unevenly distributed the geoidal surface is irregular. Three-dimensional coordinates of GPS data refer to heights above the ellipsoid, not the geoid.

Simple software techniques are typically provided by vendors to assure discrepancies in the undulations between the geoid and ellipsoid with magnitudes no greater than 30 meters. Where precise measurements referenced to mean sea level are required, most more elaborate computer programs are available from NGS to obtain accuracies of the order of 5 to 10 millimeters. Some of these require additional field work with respect to sampling data at numerous known benchmarks. The professional surveying community and GPS vendors are currently working closely to provide more efficient solutions to the derivation of vertical measurements.

NGS is currently readjusting vertical geodetic data to produce the North American Vertical Datum of 1988 (NAVD 88). The NAVD 83 readjustment will remove distortions from the continent-wide vertical geodetic (height) reference system. This project is planned for completion in 1991. The vertical adjustment combines a large-scale resurvey of the U.S. vertical control network, replacement of missing or destroyed benchmarks, and a readjustment of the entire vertical control network. The result will be a greatly improved, up-to-date height reference system for all of North America. The conversion of the vertical datum will result in up to a 2-meter shift. This may not be a concern for most spatial data as the amount of shift falls within the range of uncertainty of vertical accuracy for differential positioning (National Geodetic Survey, 1990).

References

Ackroyd, Neil, and Robert Lorimer. Global Navigation: A GPS User's Guide. Lloyd's of London Press, Ltd, 1990.

Bodnar, Captain A. Nicholas. National Geodetic Reference System Statewide Upgrade Policy. National Geodetic Survey, June 1990.

Corn, David. Surveying By Satellite. Catalyst, February 1990, pp. 43-44.

Denaro, R. P. and R. M. Kalafus. Advances and Test Results in Differential GPS Navigation. The Journal of Navigation, vol. 43:1, pp. 32-40, 1990.

Dewhurst, W. T. Shift-On-A-Disk. Converting Coordinate Data from NAD 27 to NAD 83. ACSM Bulletin, No. 126, 1990, pp. 29-33.

Hartl, P. H. Remote Sensing and Satellite Navigation: Complementary Tools of Space Technology. Photogrammetric Record, vol. 13:74, pp. 263-275, 1989.

Hum, J. GPS, A Guide to the Next Utility. Trimble Navigation Ltd. Sunnyvale, California, 1989, 76 pp.

Kruczynski, L. R. and A. F. Lange. Geographic Information Systems and the GPS Pathfinder System: Differential Accuracy of Point Location Data. Trimble Navigation, Limited study report, 1990.

Kruczynski, L. R. Differential GPS: A Review of the Concept and How To Make It Work. Trimble Navigation, Limited study report, 1990.

Kruczynski, L. R., W. W. Porter, D. G. Abby, and E. T. Weston. Global Positioning System Differential Navigation Test at the Yuma Proving Ground. The Institute of Navigation, 1986.

Lange, A. F. and L. R. Kruczynski. Global Positioning System Applications to Geographic Information Systems. Proceedings from the Ninth Annual ESRI ARC/INFO User Conference, Palm Springs, Calfornia, 1989. 4 pp.

Langely, R. B. Innovation Column: Why is the GPS Signal So Complex? GPS World, Vol. 1:3, pp. 56-59, 1990.

Locational Data Policy Implementation Guidance (LDPIG). U.S. EPA Office of Information Management Resources, Washington, D. C., 1991.

McDonald, K. D. GPS Progress and Issues. GPS World, Vol. 1:1, p. 16, 1990.

McDonald, K. D., E. Burkholder, B. Parkinson, J. Sennott. GPS for the Environmental Protection Agency, Course 355. Navtech Seminars, Inc., November 1991.

National Geodetic Survey. National Geodetic Reference System Statewide Upgrade Policy. 1990.

Puterski, R. GPS Applications in Urban Areas. Proceedings from the Tenth Annual ESRI ARC/INFO User Conference, Palm Springs, California, vol. 1, 1990, 12 pp.

Slonecker, E. T. and J. A. Carter. GIS Applications of Global Positioning System Technology. GPS World, Vol. 1:3, pp. 50-55, 1990.

U.S. Department of Defense/Department of Transportation, 1984. Federal Radionavigation Plan. Final Report: March 1982-December 1984. U.S. Department of Defense Document #DOD-4650.4 and U.S. Department of Transportation document #DOT-TSC-RSPA-84-8.

Wells, D., N. Beck, D. Delikaraoglou, A. Kleusberg, E. J. Krakiwsky, G. Lachapelle, R. B. Langley, M. Nakiboglu, K-P Schwarz, J. M. Tranquilly, and P. Vanicek. Guide to GPS Positioning. Canadian GPS Associates. Fredericton, New Brunswick, Canada. 1988.

Appendix A
Sources Of Additional Information On GPS

Information Sources Within the EPA

The Environmental Monitoring Systems Laboratory - Las Vegas (EMSL-LV) is EPA's Center for Excellence in remote sensing, GIS and geoprocessing. EMSL-LV has extensive experience with various geopositioning techniques including GPS technology. It is strongly recommended that EMSL-LV be contacted prior to action involving geoprocessing for advice on appropriate geopositioning methods or for technical assistance. For more infonnation please contact:

Mason Hewitt
(702) 798-2377
(FTS) 545-2377, or
E. Terrence Slonecker

Information Sources Outside the EPA

GPS Satellite Clock Behavior and Related GPS Information

The U.S. Naval Observatory provides dial-up, on-line access to GPS information computer fries. Access requires full duplex, seven data bits, even parity, upper case.

U.S. Naval Observatory
Washington, D.C. 20392-5100
300 or 1200 baud (202) 653-1079
2400 baud (202) 653-1783

Precise GPS Orbit Information

Government: Precise orbital positions and velocities based on post computations of tracking data collected from stations of the Cooperative International GPS Tracking Network (CIGNET) are available from the National Geodetic Survey (NGS). Satellite orbital data are scheduled to be available 2 weeks after the tracking data are collected. For a description of formats, fee schedule, or to order data, contact:

National Geodetic information Center,
N/CG17
National Geodetic Survey
National Ocean Service, NOAA
Rockville, MD 20852
(303) 443-8775

Commercial: Precise orbital data is available from the Aero Service Division, Western Atlas International, using data obtained from its tracking network stations. For a description of format, fee schedule, or to order data, contact:

Mr. Jim Cain
Manager, GPS Service Division
Western Atlas International
3600 Briarpark Drive
P.O. Box 1939
Houston, TX 77251-1939
(713) 784-5800

GPS Satellite Status and Health

NAVSTAR/GPS Operational Control System
Falcon Air Force Base
Colorado Springs, CO 80914-5000

Recorded daily operations report
(719) 550-2115

Live Mission Operations Controller
(719) 550-2363

Performance of GPS Satellite Survey Systems

GPS Test Coordinator
Instrument Subcommittee
Federal Geodetic Control Committee
c/o National Geodetic Survey, NOAA
N/CG14, Rockwall 306
Rockville, MD 20352
(301) 443-8171

The Civil GPS Service (CGS)

The CGS is evolving under the guidance of a steering committee representing the civil user community and the Department of Transportation. CGS will serve as a source of information and point of contact for civil users, and GPS status and information will be disseminated by the Civil GPS Information Center. For information, contact:

Chairman, CGS Steering Committee
U.S. Department of Transportation
Research and Special Programs Administration
400 7th Street NW, Room 8405
Washington, DC 20590
(202) 366-4355

The U.S. Coast Guard GPS Information Center (GPSIC)

The U.S. Coast Guard GPS Information Center (GPSIC) is now (June 1990) providing GPS operational advisory broadcasts (OAB) on a "test and evaluation" basis. Users have access to the service 24 hours a day, although live operation of the center initially will be limited to 8:00 a.m. to 4 p.m. eastern time, Monday through Friday, except federal holidays. Information available through the center consists of current constellation status, future scheduled outages, and an almanac suitable for making GPS coverage and satellite visibility predictions.

A voice recording that presents a brief summary of the constellation status can be reached at (703) 866-3826. More detailed information is available through a computer bulletin board system:

300, 1200, or 2400 bps (703) 866-3890
4800 or 9600 bps (703) 366-3894

For additional information on the center or the bulletin board write to:

Commanding Officer
U.S. Coast Guard
Omega Navigation System Center
7323 Telegraph Road
Alexandria, VA 22310-3998
(703) 866-3806

A brief GPS update is also provided hourly by GPSIC and radio stations W and WWVH, operated by the National Institute of Standards and Technology on frequencies of 2.5, 5, 10, and 20 MHz. WWV, at Fort Collins, CO. broadcasts this message at 15 minutes past the hour. WWVH, in Hawaii, repeats the same message at 15 minutes before the hour.

GPS Bulletin

The GPS Bulletin is prepared and disseminated bimonthly by the National Geodetic Survey (NGS), Charting & Geodetic Services, National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA) under the auspices of the Global Positioning System Subcommission, Commission VIII, of the International Coordination of Space Techniques for Geodesy and Geophysics (IUGG). Although the Bulletin is intended to serve as a means to disseminate GPS information primarily to those involved in the practice of high-precision geodesy and geodynamics, there is information of general interest for the GPS community.

For more information, contact:

Miranda Chin
N/CGl14, Rockwall 419
National Geodetic Survey, NOAA
Rockville, MD 20852
(301) 443-2520

Available GPS Training

American Congress of Surveying and Mapping (ACSM)

ACSM offers a comprehensive GPS training program that involves a series of l-to 3-day courses at locations nationwide. Courses available include: Basic GPS for Surveyors, Planning and Executing GPS Surveys, Processing GPS Data, and Data Adjustment and Transformation. For more information, contact:

American Congress of Surveying and Mapping
210 Little Falls Street
Falls Church, VA 22046-4392
(703) 241-2446

Canadian GPS Associates

Offers courses taught by experts that are tailored to specialized audiences at locations worldwide. Courses cover all aspects of GPS satellite navigation and surveying technology. For additional Information, contact:

Dr. David Wells
Canadian GPS Associates
P.O. Box 3184
Postal Station B
Fredericton, New Brunswick, E3A 5G9

Canada
(506) 453-5147

Navigation Technology Seminars, Inc. (NAVTECH)

NAVTECH offers a curriculum of courses that cover about 12 different aspects of GPS satellite navigation and positioning technology. The curriculum includes a course on Basics of the GPS and one on Basics of Surveying with GPS. For additional information, contact:

Carolyn P. McDonald, President
Navigation Technology Seminars, Inc.
1900 N. Beauregard Street
Suite 106
Alexandria, VA 22311
(703) 931-0500

P.O.B. Publishing Co.

P.O.B. offers a series of seminars entitled "Practical Surveying with GPS." For more information, contact:

P.O.B. Publishing Company
5820 Lilley Road, Suite 5
Canton, MI 48187
(313) 981-4600

University of Montana

The University of Montana School of Forestry and Center for Continuing Education, in cooperation with the USDA Forest Service Missoula Technology &Development Center, offers a course on Introduction to Satellite Navigation in Resource Management. For more information, contact:

Center for Continuing Education
University of Montana
Missoula, MT 59812
(406) 243-4623 or 243-2900

California State University

Seminars, workshops, and short courses on GPS satellite surveying are offered through the Department of Civil and Surveying Engineering, School of Engineering, California State University, Continuing Engineering Program. One- to 3-day courses are offered either at the Fresno campus or off campus at a hosted facility. For additional information, contact:

Department of Civil and Surveying Engineering
School of Engineering
California State University, Fresno
Fresno, CA 93740-0091
(209) 294-2889

Appendix B
Glossary of GPS Terms

Absolute positioning - positioning mode in which a position is identified with respect to a well-defined coordinate system, commonly a geocentric system (i.e., a system whose point of origin coincides with the center of mass of the earth).

Anywhere fix - The ability of a receiver to start position calculations without being given an approximate location and time.

Baseline - A baseline consists of a pair of stations for which simultaneous GPS data has been collected.

C/A code - The standard (Clear/Acquisition) GPS code; also known as the "civilian code" or "S-code".

Cadastral survey - survey performed to establish legal and political boundaries, typically for land ownership and taxation purposes.

Carrier - A radio wave having at least one characteristic (e.g. frequency, amplitude, phase) that can be varied from a known reference value by modulation.

Carrier beat phase - the phase of the signal which remains when the incoming Doppler-shifted satellite carrier signal is beat (the difference frequency signal is generated) with the nominally-constant reference frequency generated by the receiver.

Carrier frequency - the frequency of the unmodulated fundamental output of a radio transmitter.

Channel-A channel of a GPS receiver consists of the radio frequency, circuitry, and software necessary to tune the signal from a signal GPS satellite.

Chip - In the GPS world, a chip is the transition time for individual bits in the pseudo-random sequence.

Clock bias - the difference the clock's indicated time and true universal time.

Control segment - a world-wide network of GPS monitoring and control stations that ensure the accuracy of satellite positions and their clocks.

Cycle slip - a discontinuity of an integer number of cycles in the measured carrier beat phase resulting from a temporary loss-of-lock in the carrier tracking loop of a GPS receiver.

Data message - a 1500 bit message included in the GPS signal which reports the satellite's location, clock corrections, and health.

Differential positioning - precise measurement of the relative positions of two receivers tracking the same GPS signals.

Dilution of Precision - the multiplicative factor that modifies range error. It is caused solely by the geometry between the user and his or her set of satellites; known as DOP or GDOP.

Doppler-aiding - a signal processing strategy that uses a measured doppler shift to help the receiver smoothly track the GPS signal. This allows more precise velocity and position measurement.

Doppler shift - the apparent change in the frequency of a signal caused by the relative motion of the transmitter and receiver.

Dynamic positioning - See Kinematic positioning.

Ephemeris - the predictions of current satellite position that are transmitted to the user in the data message.

Fast-switching channel - a single channel which rapidly samples a number of satellite ranges. "Fast" implies that the switching time is sufficiently short (2 to 5 milliseconds) to recover the data message.

Federal Radionavigation Plan (FRP) - Congressionally mandated, joint DoD and Department of Transportation (DOT) effort to reduce the proliferation and overlap of federally funded radionavigation systems. The FRP is designed to delineate policies and plans for U.S. government-provided radionavigation services.

Frequency band - a particular range of frequencies.

Frequency spectrum - the distribution of signal amplitudes as a function of frequency.

Geodetic surveys - global surveys done to establish control networks (comprised of reference or control points) as a basis for accurate land mapping.

Geometric Dilution of Precision (GDOP) - see Dilution of Precision.

Handover word - the word in the GPS message that contains synchronization information for the transfer of tracking from the C/A to P-code.

Ionosphere - the band of charged particles 80 to 120 miles above the earth's surface.

Ionospheric refraction - the change in the propagation speed of a signal as it passes through the ionosphere.

Kinematic positioning - Kinematic positioning refers to applications in which the position of a non-stationary object (automobile, ship, bicycle) is determined.

L-band - the group of radio frequencies extending from 390 MHz to 1550 MHz. The GPS carrier frequencies (1227.6 MHz and 1575.42 MHz) are in the L-band.

Mask Angle - the minimum acceptable satellite elevation above the horizon to avoid blockage of line-of-sight.

Multipath error-errors caused by the interference of a signal that has reached the receiver antenna by two or more different paths. This is usually caused by one path being bounced or reflected.

Multi-channel receiver - a GPS receiver that can simultaneously track more than one satellite signal.

Multiplexing channel - a channel of a GPS receiver that can be sequenced through a number of satellite signals.

North American Datum of 1927 (NAD 27) - older and obsolete horizontal datum of North America. NAD 27 depends upon an early approximation of the shape of the earth, known as the Clarke Spheroid of 1866, designed to fit only the shape of the conterminous United States, and utilizing a specific Earth surface coordinate pair as its center of reference.

North American Datum of 1983 (NAD 83) - official horizontal datum of North America. NAD 83 relies on the more precise Geodetic Reference System of 1980 (GRS 80), employs a geocentric ellipsoid model, utilizing the Earth's center of mass as its center of reference.

North American Vertical Datum of 1988 (NAVD 88) - effort underway by NGS to readjust the North American Vertical datum. The NAVD 88 readjustment will remove distortions from the continent-wide vertical geodetic (height) reference system.

P-code - the Precise or Protected code. A very long sequence of pseudo-random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz, which repeats about every 267 days. Each l-week segment of this code is unique to one GPS satellite and is reset each week.

Point positioning - See Absolute positioning.

Positional Dilution of Precision (PDOP) - measure of the geometrical strength of the GPS satellite configuration.

Precise Positioning Service (PPS) - the most accurate dynamic positioning possible with GPS, based on the dual frequency P-code.

Proportional error - one means of expressing positional accuracy, expressed as the position error divided by the distance to the origin of the coordinate system used, stated in parts per million (ppm).

Pseudo-lite - a ground-based differential GPS receiver which transmits a signal like that of an actual GPS satellite, and can be used for ranging.

Pseudo-random noise (PRN) code - a signal with random noise-like properties. It is a very complicated but repeated pattern of 1's and 0's.

Pseudo-range - a distance measurement based on the correlation of a satellite transmitted code and the local receiver's reference code, that has not been corrected for errors in synchronization between the transmitter's clock and the receiver's clock.

Relative positioning - The determination of relative positions between two or more receivers which are simultaneously tracking the same GPS signals.

S-code - See C/A-code

Satellite configuration - The state of the satellite constellation at a specific time, relative to a specific user or set of users.

Satellite constellation - the arrangement in space of a set of satellites.

Selective availability (S/A) - intentional degradation of the performance capabilities of the NAVSTAR satellite system for civilian users by the U.S. military, accomplished by artificially creating a significant clock error in the satellites.

Slow switching channel - a sequencing GPS receiver channel that switches too slowly to allow the continuous recovery of the data message.

Space segment - the space-based component of the GPS system (i.e. the satellites).

Standard positioning service (SPS) - the normal civilian positioning accuracy obtained by using the single frequency C/A code.

Static positioning - location determination when the receiver's antenna is presumed to be stationary in the earth. This allows the use of various averaging techniques that improve accuracy by factors of over 1000.

User segment - the component of the GPS system that includes the receivers.

Y-code - classified PRN code, similar to the P-code, though restricted to use by the military.

Appendix C
EPA Locational Data Policy

Locational Data Policy Implementation Guidance (LDPIG). 1991. U.S. EPA Office of Information Management Resources, Washington, D.C.

1. Purpose. This policy establishes the principles for collecting and documenting latitude/longitude coordinates for facilities, sites and monitoring and observation points regulated or tracked under Federal environmental programs within the jurisdiction of the Environmental Protection Agency (EPA). The intent of this policy is to extend environmental analyses and allow data to be integrated based upon location, thereby promoting the enhanced use of EPA's extensive data resources for cross-media environmental analyses and management decisions. This policy underscores EPA's commitment to establishing the data infrastructure necessary to enable data sharing and secondary data use.

2. Scope and Applicability. This policy applies to all EPA organizations and personnel of agents (including contractors and grantees) of EPA who design, develop, compile, operate or maintain EPA information collections developed for environmental program support. Certain requirements of this policy apply to existing as well as new data collections.

3. Background.

   a. Fulfillment of EPA's mission to protect and improve the environment depends upon improvements in crossprogrammatic, multi-media data analyses. A need for available and reliable location identification information is a commonality which all regulatory tracking programs share.

   b. Standard location identification data will provide a return yet unrealized on EPA's sizable investment in environmental data collection by improving the utility of these data for a variety of value-added secondary applications often unanticipated by the original data collectors.

   c. EPA is committed to implementing its locational policy in accordance with the requirements specified by the Federal Interagency Coordinating Committee for Digital Cartography (FICCDC). The FICCDC has identified the collection of latitude/longitude as the most preferred coordinate system for identifying location. Latitude and longitude are coordinate representations that show locations on the surface of the earth using the earth's equator and the prime meridian (Greenwich, England) as the respective latitude and longitude origins.

   d. The State/EPA Data Management Program is a successful multi-year initiative linking State environmental regulatory agencies and EPA in cooperative action. The Program's goals include improvements in data quality and data integration based on location identification.

   e. Readily available, reliable, and consistent location identification data are critical to support the Agencywide development of environmental risk management strategies, methodologies, and assessments.

   f. OIRM is committed to working with EPA Programs, Regions and Laboratories to apply spatially related tools (e.g., geographic information systems (GIS), remote sensing, automated mapping) and to ensure these tools are supported by adequate and accurate location identification data. Effective use of spatial tools depends on the appropriate collection and use of location identifiers, and on the accompanying data and attributes to be analyzed.

g. OIRM's commitment to effective use of spatial data is also reflected in the Agency's comprehensive GIS Program and OIRM's coordination of the Agency's National Mapping Requirement Program (NMRP) to identify and provide for EPA's current and future spatial data requirements.

4. Authorities.

a. 15 CFR, Part 6 Subtitle A, Standardization of Data Elements and Representations.

b. Geological Survey Circular 878-B, A U.S. Geological Survey Data Standard, Specifications for Representation of Geographic Point Locations for Information Interchange.

c. Federal Interagency Coordinating Committee on Digital Cartography (FICCDC)/U.S. Office of Management and Budget, Digital Cartographic Data Standards: In Interim Proposed Standard.

d. EPA Regulations 40 CFR 30.503 and 40 CPR 3 1.45, Quality Assurance Practices under EPA's General Grant Regulations.

5. Policy.

a. It is EPA policy that latitude/longitude ("lat/long") coordinates be collected and documented with environmental and related data. This is in addition to, and not precluding, other critical location identification data that may be needed to satisfy individual program or project needs, such as depth, street address, elevation or altitude.

b. This policy serves as a framework for collecting and documenting location identification data. It includes a goal that a 25-meter level of accuracy be achieved; managers of individual data collection efforts determine the exact levels of precision and accuracy necessary to support their mission within the context of this goal. The use of global positioning systems (GPS) is recommended to obtain lat/longs of the highest possible accuracy.

c. To implement this policy, program data managers must collect and document the following information:

(1) Latitude/longitude coordinates in accordance with Federal Interagency Coordinating Committee for Digital Cartography (FICCDC) recommendations. The coordinates may be present singly or multiple times, to define a point, line, or area, according to the most appropriate data type for the entity being represented.

The format for representing this information is:

t/-DD MM SS.SSSS (latitude)
t/-DDD MM SS.SSSS (longitude)

where:

- Latitude is always presented before longitude
- DD represents degrees of latitude; a two-digit decimal number ranging from 00 through 90
- DDD represents degrees of longitude; a three-digit decimal number ranging from 000 through 180
- MM represents minutes of latitude or longitude; a two-digit decimal number ranging from 00 through 60
- SS.SSSS represents seconds of latitude or longitude, with a format allowing possible precision to the ten-thousandths of seconds
- + specifies *latitudes north* of the equator and *longitudes east* of the prime meridian
- \- specifies *latitudes south* of the equator and *longitudes west* of the prime meridian

(2) Specific method used to determine the lat/long coordinates (e.g., remote sensing techniques, map interpolation, cadastral survey)

(3) Textual description of the entity to which the latitude/longitude coordinates refer (e.g., north-east corner of site, entrance to facility, point of discharge, drainage ditch)

(4) Estimate of accuracy in terms of the most precise units of measurement used (e.g., if the coordinates are given to tenths-of-seconds precision, the accuracy estimate should be expressed in terms of the range of tenths-of seconds within which the true value should fall, such as "+/- 0.5 seconds")

d. Recommended labelling of the above information is as follows:

- "Latitude"
- "Longitude"
- "Method"
- "Description"
- "Accuracy."

e. This policy does not preclude or rescind more stringent regional or program-specific policy and guidance. Such guidance may require, for example, additional elevation measurements to fully characterize the location of environmental observations.

f. Formats, standards, coding conventions or other specifications for the method, description and accuracy information are forthcoming.

6. Responsibilities.

a. The Office of Information Resources Management (OIRM) shall:

(1) Be responsible for implementing and supporting this policy

(2) Provide guidance and technical assistance where feasible and appropriate in implementing and improving the requirements of this policy

b. Assistant Administrators, Associate Administrators, Regional Administrators, Laboratory Directors and the General Counsel shall establish procedures within their respective organizations to ensure that information collection and reporting systems under their direction are in compliance with this policy.

While the value of obtaining locational coordinates will vary according to individual program requirements, the method, description and accuracy of the coordinates must always be documented. Such documentation will permit other users to evaluate whether those coordinates can support secondary uses, thus addressing EPA data sharing and integration objectives.

7. Waivers. Requests for waivers from specified provisions of the policy may be submitted for review to the Director of the Office of Information Resources Management. Waiver requests must be based clearly on data quality objectives and must be signed by the relevant Senior IRM Official prior to submission to the Director, OIRM.

8. Procedures and Guidelines. The *Findings and Recommendations of the Locational Accuracy Task Force* supplement this policy. More detailed procedures and guidelines for implementing the policy are issued under separate cover as the *Locational Data Policy Implementation Guidelines.*

Appendix D
EPA Case Studies

I. Puget Sound Near-Shore Habitat Inventory

EMSL-LV, EPA Region 10, the Washington Department of Natural Resources, and the Puget Sound Authority have been participating in an interagency project the last few years to inventory near shore habitats of Puget Sound. Aircraft multispectral scanner (MSS) imagery and field verification data of representative habitat types were used to conduct the inventory. Both of phases of the project, data collection and verification were able to effectively use GPS to provide valuable information. During MSS data acquisition, GPS provided accurate positional information at all times, so that image data could be subsequently rectified to earth coordinates.

Collection of ground verification data is an ideal use of GPS technology. Near-shore habitats of Puget Sound do not have natural or cultural features which can be used as ground control to gee-reference MSS imagery. Field data assists the image analyst to identify surface features visible on the MSS imagery. Field experts in marine and estuarine near-shore habitats visit representative habitat types and characterize each site by substrate type, vegetation, and orientation to Puget Sound. This information is recorded on field sheets. GPS data is collected at each field site to ensure that image analysts can accurately correlate field data to image data.

The field data is used to assess the accuracy of thematic maps produced from analysis of MSS imagery. Therefore, exact location of data collected in the field is necessary. Use of GPS technology during field reconnaissance ensures gee-positional accuracy of reference data for image analysis and verification data for assessing absolute accuracy of the MSS classifications.

Logistics planning for field data collection, using GPS, in near-shore habitats is complicated by the limited GPS satellite visibility during periods of low tide. Logistics planning for field data collection involves coordinating low tide with GPS satellite visibility windows. All field activities not directly involved with data collection such as travel between sites and data reduction were arranged around low tide and satellite visibility.

Procedures to characterize sites within near-shore habitats of Puget Sound utilizing GPS were tested prior to the MSS data acquisition mission. A Trimble Pathfinder portable position recording systems instrument was operated in a remote mode. A Trimble 4000st instrument was operated in the reference or base station mode. Spatial data as well as site characterization data were collected at representative near-shore habitats in the Puget Sound area. Data forms, pre-survey and post-survey forms proved invaluable. The forms assist field crews to properly operate and maintain GPS equipment and data files.

The experience of this project indicates field work is best organized as a three step process:

- Mission planning
- Data collection
- Post Processing data

Mission Planning

The first step in mission planning is to define the job requirements, project area, and number of points of data collection. The second step in mission planning is to develop a work plan. The plan must fit job requirements and be scheduled efficiently. Since the satellite constellation is presently incomplete, the geometry of the constellation is also important. Most suitable geometry has a single satellite directly overhead and the remaining three equally distributed in the hemisphere 10 degrees above the horizon.

Mission planning involves scheduling travel between data collection points. Point locations are selected where GPS receivers have clear view of the satellites. Schedules for sites with obstructions (i.e. cliffs, buildings) must be arranged when satellite visibility clears obstructions. Logistical optimization is achieved if travel occurs during periods without satellite visibility.

Before travel is initiated, the location of horizontal and vertical control monuments and benchmarks must be determined. These will be used in the post-processing phase to provide differential correction. The last factor in mission planning requires the review of data collection points in light of permits and permission necessary to gain access to the site.

Data Collection

Lock on at least 4 satellites must be established and lock maintained on the 4 satellites between all measurement epochs. A recommended rule of thumb is to record data at each collection point for approximately 3 minutes with a recording rate of 1 fix per second.

Processing Data

Differential correction requires that a base station log data concurrent with logging at remote sites. The correction algorithms require accurate knowledge of the position of the base. Raw measurements are needed for "measurement space" differential corrections. The rule of thumb used recommends logging intervals of 5 seconds for fixes, and 10 seconds for raw measurements.

Low standard deviations should not be taken as a measure of accuracy, but rather of repeatability. S/A as well as other systematic errors and biases may well introduce significant errors which can only be removed by methods such as differential correction.

In many instances, standard deviations of corrected data sets are higher than those of the original data. This is explained by the result of random noise contributed independently by two receivers. However, the noise components can be expected to have zero mean, so simple averaging of the corrected data should effectively compensate.

Conclusions from this project include:

When 2-D fixes must be acquired, care must be taken to supply the receiver with as good an estimate of elevation as possible. Otherwise, very large positional errors will result. Wherever possible, 3-D fixes should be acquired, even if this requires re-visiting a site or waiting until satellite availability y is favorable.

Reviewing data as soon after acquisition as possible is highly desirable. All data should be critically examined to search for clearly erroneous or suspect points. The process of discarding outlier points appears to be a good strategy and is recommended.

II. Old Southington Landfill Superfund Site Southington, Connecticut

In 1988, EPA and the U.S. Geological Survey conducted a pilot project designed to demonstrate the use of GIS technology in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), often referred to as Superfund, Remedial Investigation (RI) process. The site chosen for this study was Old Southington Landfill, in Southington, Comecticut. The database developed for this project contained data layers derived from both large-and small-scale sources, though there were typically little or no large-scale, site-specific data available in digital form that could be directly input into an ARC/INFO GIS data base. Consequently, the existence of data of different source scales and resulting variable resolution presented obvious spatial relationship problems when the data layers were combined.

This problem was solved by way of analytical photogrammetry and digital cartography. These technologies permitted the rectification and integration of aerial photography and digital data. Current and historical aerial photography were obtained from various sources and used to make large-scale digital maps of roads, cultural features, hydrography, hypsography, historical site land-fill activity and other thematic overlays. This data was combined with property parcel maps, monitoring well locations and sampling data to create a number of application scenarios designed to show how GIS and remote sensing technologies could be utilized to meet the information needs of the CERCLA remedial investigation process.

During the development of this project, the issue of spatial accuracy came to the forefront when the large- and small-scale data layers were overlaid at a common scale and significant spatial variations were identified. In order to assess these variations, a map accuracy test had to be conducted. The first step in the accuracy testing scenario was to establish engineering quality control around the site area. This was done via a GPS survey in December, 1988. Using well-defined aerial photo points and three Magnavox WM101 GPS receivers, X, Y, and Z coordinates were established for nine ground control points over 2 days of static observation. Post-processing results indicated accuracy of 2 centimeters in closure. These control points were then used to photogrammetrically recompile the base maps and conduct accuracy tests on all digital and analog maps used in the project.

III. San Gabriel Basin Superfund Project, California

In 1986, EPA conducted its first GIS demonstration project, using the San Gabriel Basin in the eastern portion of Los Angeles, California. Basin ground water had been determined to be heavily contaminated with organic solvents, and the entire basin had been placed on the National Priorities List as a Superfund site. Furthermore, numerous Resource Conservation and Recovery Act (RCRA) sites were identified in the basin, further complicating an already complex issue of contaminant source identification. The overall objective of the San Gabriel Basin Demonstration GIS project was to illustrate some of the GIS capabilities useful in support of implementing legislation and regulations enforced by the EPA's Office of Emergency and Remedial Response, Office of Solid Waste, and Office of Groundwater Protection.

The San Gabriel Basin Demonstration GIS Project has since evolved into an operational GIS mode, in support of EPA Region 9's CERCLA remedial investigation process. An extensive network of monitoring and water supply wells, in conjunction with sophisticated ground water flow modelling, is being used to delineate the extent of contaminant plumes and project their migration. The ultimate goal of this effort will be to assess possible sources and identify parties responsible for the contamination of ground water, forming the basis for eventual litigation for cost recovery. The EPA is committed to quantifying the spatial accuracy of the GIS data base, particularly with respect to well locations and boundaries of potential source facilities.

The San Gabriel Basin GPS survey was conducted in late January and early February, 1989, using three portable Trimble Navigation Pathfinder GPS receiving units. The issues being addressed in the San Gabriel survey were similar to those in the Old Southington project, specifically the maintenance of spatial accuracy and quality control when source data of varying scales and resolutions are combined for display and analysis in a GIS data base. Additionally, a third major objective was defined: the test and evaluation of a Trimble Navigation Pathfinder GPS receiver, its portability, and its ability to output spatial data directly into an ARC/INFO GIS format.

The first step in the spatial accuracy testing of the data base was to evaluate GPS as a means of assessing the quality of the digital transportation network coverage already existing in the GIS data base. Streets and street intersections frequently define facility boundaries, while proximity to them commonly was the original basis for plotting well locations. Assuming its spatial accuracy could be verified, the transportation data layer or coverage was generally regarded as a likely template or baseline coverage for spatial quality assessment of the GIS data base.

The GPS survey of the street network was accomplished by simply driving the streets of the San Gabriel Basin, in relative semikinematic mode, with one Pathfinder receiver and data logger inside and the antenna mounted atop the survey vehicle. Data was collected at 1-second intervals, effectively digitizing the route followed. A second Pathfinder (reference receiver) was placed atop an established benchmark in a secure location, programmed to collect data at 3-second intervals. The data collected was downloaded in the field from the data recorder of the roving unit to a portable personal computer, converted to a binary format, and differentially corrected using the data file from the reference receiver.

In order to test and evaluate the convertibility of GPS data to an ARC/INFO format, normal postprocessing of the GPS data stream was modified slightly. The downloaded binary file was converted by means of a relatively simple program to a user-defined text file format containing X, Y, Z coordinate values for each point of data collection. The format of the text file allowed direct input of the coordinate values, in units of decimal degrees, to

ARC/INFO in an ARC: GENERATE format. The data files were then GENERATED into an ARC/INFO coverage where they could be digitally compared to the transportation coverage in the San Gabriel data base.

Although specific methodology has yet to be developed for quantitative comparison of digital line features, the results of the survey have provided a means of visual qualitative verification of the accuracy of the ARC/INFO transportation network coverage. Once these methodologies are established and rendered operational, the transportation layer can then be utilized as a baseline coverage in further spatial QA/QC efforts.

The other primary objective of the San Gabriel GPS survey involved selection of a sampling of wellheads, based on their importance to the ground water modeling effort. These wellheads were GPS surveyed and the results used to rectify the well locations as represented in the GIS data base. Collecting data in static differential mode, field surveyors collected and recorded data continuously for 5 minutes at each sample wellhead. Additionally, the GPS receiver provided the surveyors with the ability to record descriptive information related to the wells and the data collection effort. Although time constraints limited the survey sample size, the technique was proven effective in both positional data entry and accuracy assessment. Spatial accuracy an expanded GPS survey would permit rectification of the entire well locations coverage, and a significantly increase the level of confidence with which the EPA and its contractors could conduct ground water modelling efforts.

Conversion of the downloaded well location data files to ARC/INFO followed the same process described for the conversion of the GPS-generated transportation network, with a couple of slight variations. The only difference of consequence is that records in the data files contain the mean position of each wellhead, as averaged over 5 minutes of data collection.

Appendix E
PLOTSSF and CLEANSFF Processing Software

Two software utility programs have been developed by EMSL-LV for visualizing and cleaning GPS data files. These utilities are specific to Trimble Navigation's SSF format. The two utilities, called PLOTSSF and CLEANSFF, operate in the PC DOS environment and require a 286 CPU with coprocessor and VGA graphics as a minimum.

CLEANSSF is an outlier rejector that iteratively calculates means and standard deviations of positions and rejects any that lie beyond a fixed number of standard deviations. The user is presented with a display that boxes the data and allows the viewing of outliers. Based on the needs of the user, several iterations of the process may be used to eliminate all outliers. This program has proven useful on data sets after differential correction and to get the tightest fit possible for GPS point data.

PLOTSSF is a visualization tool that displays two concurrent plots, one X-Y and one elevation. The two plots evolve, second by second, as the file is processed. The user has the option to capture portions of the GPS data stream into separate files to view tabular displays of position, elevation, and time. In addition, ARC/INFO UNGENERATE files may be used as background during the session to provide a spatial reference for the GPS data. The PLOTSSF utility is especially useful for reviewing a GPS field session, analyzing distinct segments of a transect, performing terrain analysis, or analyzing travel routing.

The utility software is available to all Agency GPS users. It includes some demonstration files that allow the user to get a feel of how the two utilities work. For further information, contact:

Mason Hewitt
GIS Program Manager
EMSL-LV
P.O. Box 93478
Las Vegas, NV 89193
Phone: (702) 798-2377 FTS 545-2377

Appendix F
Field Charts and Forms

The following are a series of sample checklists and other forms used in various GPS prototype applications. These include the following:

- GPS Survey Steps
- Presurvey Checklist
- Field Equipment
- Last Minute Checks
- In the Field Checks
- Postsurvey Checklist
- Sample Letter of Introduction
- GPS Station Recovery Form
- Trimble Pathfinder Pre-survey Checklist
- Field Notes - GPS Data Acquisition
- Planning and Data Sheet
- Trimble Pathfinder Instrument Initialization
- Field Notes - GPS Data Acquisition
- GPS Field Sheet
- GPS Data Reduction Lab Sheet

GPS Survey Steps

______ Define Objectives

______ Establish Study Area

______ Determine Observation Window

______ Schedule Operations

______ Establish Control

______ Select Survey Locations

______ Arrange Equipment Logistics

______ Perform Reconnaissance

______ Establish Base Stations

______ Conduct Survey

______ Transfer Data

______ Process Data

Presurvey Checklist

______ Obtain List of Facilities

______ Obtain Current Almanac

______ Call Coast Guard to Verify Satellite Availability

______ Obtain Control Points from NGS or Local Source

______ Obtain 7.5 min Topographic Maps

______ Obtain Local Street Maps

______ Prepare Letter of Introduction

______ Collect and Pack Field Equipment

Field Equipment

_______ GPS Equipment

_______ Laptop or Other Field Computer

_______ 7.5 minute maps

_______ aerial photo if available

_______ Camera

_______ Film

_______ Compass

_______ Tape Measure

_______ Binoculars

_______ Field Forms

_______ Clip Board

_______ Calculator

_______ GPS Hardware/Software Manuals

_______ Mini Tape Recorder

_______ Hard Copy of Almanac

_______ Rain Gear

_______ Two-way radio communication (i.e., CB, cellular phone, etc.)

Last Minute Checks

______ Charge Batteries

______ Verify Almanac

______ Target Travel Route

In The Field Checks

______ Find Base Stations

______ Initialize Equipment

______ Begin Collecting Data

Postsurvey Checklist

Name: ______________________________

Date: ______________________________

Unit ID& Number: ____________________

1 System Battery Recharged?

2 All Data Files Downloaded?

3 All Data Files Erased?

4 Polycorder Battery Recharged?

Sample Letter of Introduction

Note: All letters requesting access to property should be on official stationary, include both a day and evening phone number, and any other appropriate information. The example below has been used by an Agency contractor.

July 4, 1991

To Whom it May Concern,

The below named individuals are employees of the Bionetics Corporation and under contract to the U.S. Environmental Protection Agency (contract Number 68-03-3532). These individuals will be collecting field data in the area of Chattanooga, Tennessee, during the month of November, 1990.

Mary Brown
Bill Johnson
John Smith

Their efforts are in support of official U.S. Environmental Protection Agency research. Please extend to them all possible courtesy and consideration.

Additional information may be obtained by calling 703-349-8970.

Sincerely,

E. Terrence Slonecker
Environmental Scientist
U.S. Environmental Protection Agency

GPS Station Recovery Form

Station Name ______________________ ID ______________________

Project ______________________ Date ______________________

Observer ______________________

Location ______________________

To find the station ______________________

Special requirements for GPS use (offsets, obstructions) ______________________

Access needs (owner, where to get keys to locked gates, etc.) ______________________

Trimble Pathfinder Pre-survey Checklist

Name: ______________________
Date: ______________________

Unit ID& Number: ______________
Use of Unit: Base or Remote

Location of GPS Use: ______________ State
Site Name: ______________________

Directions: Check the blank to indicate the item was checked or fill the blank with the setting used for the respective option.

Menu Option — Enter a check or the setting used

5. Data Logging

1. Set Intervals . . . . .Position: ____________
Raw: ____________

2. Memory Check . . . . .Bytes: ____________
Files: ____________

Should be approx. 390,000 bytes and 49 files for a cleared memory

6. GPS Status . . . . .Good Stats

2. Receiver Stats . . . . .Sys Batt: ____________ >10.0
CDU/DR Batt: ____________ OK
Ant volts: ____________ <5.0

Connect antenna, polycorder, and system battery to receiver to obtain accurate stats.

8. System Options

0. Init. Altitude . . . . ____________

2. Pos. Fix Mode . . . . ____________

3. Altitude Ref. . . . . ____________

4. Units of Measure . . . . ____________

7. CLK/Time Zone

1. Set Time Zone . . . . ____________

8. GPS Parameters — Recommended Settings

Dynamics Code:	____________	
El Angle Mask	____________	10
Sig Lvl Mask:	____________	6
PDOP Mask:	____________	12
PDOP Switch:	____________	10

**Note: GPS Parameters should be set the same for both the BASE and REMOTE units.*

Field Notes - GPS Data Acquisition

Date: Tree/Begin: Time/End:

Site Name:

Measurement Location

Sketch Location

GPS Survey Crew Members:

GPS Operator: Field Data Recorder:

File Information:

Remote File Name:
Base File Name:

Position Fix Mode: 2D / 3D

File Downloaded to PC

Differential Corrections:

	Total # Fix/Corr. #Fix
Measurement Space File Name:	/
Solution Space File Name:	/

Planning and Data Sheet

ID:

Observer Name(s):

Date:

Julian Date:

Station Name:

Base Station:

Observ. Session:

Project Name:

Project No.

Station Observing:

Location:

Latitude (dd mm ss.ssss) Longitude

Elevation | Geoid Undulation | Height

Elevation + Geoid Undulation = Height

Antenna Height

Corrected to Verticle? **YES** **NO**

Inches: Meters:

Time

Universal Time Code
Starting Time: ________ Ending Time: ________

Local
Starting Time: ________ Ending Time: ________

Disk:

Satellite Vehicles

Station (File Name)

Misc. (weather, etc.)

Sketch...

Remarks...

Obstruction Sketch completed? **YES** **NO**

Back up disk made? **YES** **NO**

Data sheet prepared by: ________________________________

Adapted from "Practical Surveying with GPS," Geotronics AB, 1989.

Trimble Pathfinder Instrument Initialization

The following is a guide to set up a Trimble Pathfinder

Menu Option

6 GPS Status

*0 - Satellite selection
lists satellites being used for the GPS solution
GPS tracking status (Doing Posn fixes; No GPS Time yet; Only 2 Usable SV)
Solution mode employed i.e. 3-D displayed
PDOP, VDOP, and HDOP values displayed

*1 - Signal Levels (Useful if > 5)

2 - Receiver Status

	Good Stats	
Sys Batt	>10.0	<10.0 = must recharge polycorder
CDU/DR Batt	OK	ext = connected polycorder to external system
Ant volts	<5.0 (check ant if not 3.5-4.2)	
	5.0 if not connected	

3 - Local and GMT time - polycorder time (not satellite time)

* 7 SV Status

PolyTANS uses satellite vehicle (SV) orbit almanac data stored in the TANS receiver to compute the current satellite visibility.

Scroll (up/down arrows) through satellite list to see current:

Satellite status
azimuth and elevation angles in degrees
User Range Accuracy (URA) in meters
Enabled field

Left/right arrows toggles between SV and enable fields. Once the Enable field is selected, the up/down arrows change Enabled to Disabled. Do not disable a satellite you intend to use. This “is useful to disable a satellite that has Selective Availability activated. An indication that SA has been activated is if the User Range Accuracy (URA) field is >64. (URA is expressed in meters and cannot be changed in menu option 8, submenu 4).
Disabled satellites are not listed.

8 System Options

The user sets several operational parameters for both the TANS receiver and the POLYCORDER

0	Init. Altitude	(very imp if taking 2D fixes)
1	Init. Position	(initial frees are calculated quicker if a significant distance between old fix and new fix occurs i.e. between Nevada and Washington)
2	Posn Fix Mode	use 0 Auto 2-D/3-D

3	Altitude Ref	use 0 WGS-84 / NAD -83
4	Units of Measure	use 0 KM: KPH: m
*5	North Reference	use 0 True North
*6	Magnetic Declination	use Manual:
*7	Clock/Time Zone See users manual This is a very Important Setting	Set GMT first w/ -1- PDT= -7
8	GPS Parameters	
	1 Dynamic Code	use 1 = land
	Then these parameters appear	
	El Angle Mask	use 10
	Sig Lvl Mask	use 6
	PDOP Mask	use 12
	PDOP Switch	use 10
9	Beeper on/off	

GPS parameters should be set the same for both base and remote units

** Optional parameters to check. Check these settings if problems arise.*

Field Notes - GPS Data Acquisition

Date: Time/Begin: Time/End:

Site Name:

Measurement Location

Sketch Location

Gps Survey Crew Members:

Gps Operator: Field Data Recorder:

File Information:
Remote File Name: Position Fix Mode: 2D 3D
base File Name:

File Downloaded to PC

Differential Corrections:

Total # Fix/Corr. #fix

Measurement Space File Name: /

Solution Space File Name: /

GPS Field Sheet

GPS Unit #:
Crew Members: GPS Operator Data Recorder:
Base Station ________________ (location)
Project Name ________________ Project No.____________________

Date	Site #	Site Name	PCorder File	Time Begin	Time End	PSN Fix Mode	PDOP	Approx Latitude	Approx Longitude	PC File
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	
/ /				:	:	2D 3D		N	W	

GPS Data Reduction Lab Sheet

Analyst:
Date: Disk:
Project No.: Project Name: Datum:

Remote (PC) File Name	Total # Fixes	Base File Name	Corr # fixes	File Edited?	Recalc Stats?	Final Latitude	Final Longitude	Std. Dev.
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	
				Y N		N	W	

TECHNICAL REPORT DATA
(Please read instructions on the reverse before completing)

1. REPORT NO. EPA 600/R-92/036	2.	3. RECIPIENT'S ACCESSION NO. PB92-169358
4. TITLE AND SUBTITLE GIS TECHNICAL MEMORANDUM 3: Global. Positioning Systems Technology and Its Application in Environmental Programs		5. REPORT DATE February 1992
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert Puterski		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lockheed Engineering & Sciences Company 1050 E. Flamingo Road, Suite 126 Las Vegas, NV 89119		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory-Las Vegas P.O. Box 93478 Las Vegas, NV 89193-3478		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA 600/07

15. SUPPLEMENTARY NOTES

16. ABSTRACT Global Positioning Systems (GPS) are a location determination technology that offers significant opportunties for obtaining highly accurate locational data at low cost . In order for the technology to perform up to its capabilities in Agency applications, Environmental Protection Agency (EPA) staff will need to develop a greater understanding of the technology itself, coordinate systems, surveying, and basic geodesy. EPA has been collecting expertise in the use of this technology over the last 3 years via pilot use of GPS systems to enhance locational control. in Agency projects. In order to operationalize the use of this technology within EPA, there also exists a need to develop concise standard operational procedures and methodologies for its use.

This document is a beginning toward fulfillment of these needs. It is intended to be an introductory reference that describes the technology and how it could be employed in EPA work. It provides an overview of survey methods from initial planning to data reduction and postprocessing. Ancillary but important issues such as reference datums and use with geographic information systems are covered in order to provide the reader additional. context regarding the use of this spatial information in a project environment. Case studies performed by the Environmental Monitoring Systems Laboratory, Las Vegas, are also included in this document as auxiliary background that may provide helpful techniques.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES 70
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

"U.S. Government Printing Office 1992 — 648-003/41836

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati, OH 45268

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35

Please make all necessary changes on the above label, detach or copy, and return to the address in the upper left-hand corner.

If you do not wish to receive these reports CHECK HERE ☐; detach, or copy this cover, and return to the address in the upper left-hand corner.

EPA/600/R-92/036