A NATIONAL SPATIAL DATA SYSTEM FRAMEWORK: CONTINUOUSLY OPERATING GPS REFERENCE STATIONS

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Introduction

The key to a successful Geographic Information System (GIS) is the ability to interrelate, combine, and compare spatially referenced data sets. This requires that all data sets be positioned relative to a common coordinate system. Positional accuracies required can vary widely from data set to data set, but for a GIS to be successful the required accuracies for all data sets must be achieved relative to a common coordinate system. While it is possible for each GIS to chose its own coordinate system, such a course would ultimately be disastrous nationally. Data sets could not be effectively exchanged between groups and products from different groups' GIS could not be made to match. If the goals of a National Spatial Data Infrastructure (NSDI) are to be achieved successfully, a common coordinate system must be used nationwide.

It should be understood that we are speaking of the coordinate system used internal to a GIS. This is where a common coordination system is essential. One would expect products to be made available relative to many different coordinate systems to satisfy the individual needs of different applications. This is easily achieved through the use of standard coordinate transformation algorithms.

A framework is being developed to define and provide access to a common national coordinate system that will be used to meet GIS and other positioning needs and will be used as a basis for navigation, thereby, assuring compatibility between location of vehicles (land, sea, and air) being navigated and relevant earth-surface parameters. This framework is based on Global Positioning System (GPS) technology. It will take the form of continuously operating reference stations (CORS) located throughout the Nation.

Choosing a Coordinate System

The coordinate system appropriate for most GIS applications in the United States is the North American Datum of 1983 (NAD 83) coordinate system. This is the coordinate system relative to which the National Geodetic Survey (NGS) currently publishes positions of the monumented reference points of a national spatial reference system (NSRS). It is the coordinate system relative to which all new Federal mapping products are referred and is the coordinate system legally adopted by many states. Finally, it is the coordinate system being adopted by the U.S. Coast Guard (USCG), the Federal Aviation Administration (FAA), and the U.S. Army Corps of Engineers (COE) for the positioning of their GPS reference stations which provide the real time GPS correctors used for navigation. The NAD 83 coordinate system is directly relatable to other commonly used coordinate systems. Another coordinate system often used for production of maps and charts is the World Geodetic System of 1984 (WGS 84). At the time of their implementation, care was taken to see that the NAD 83 and WGS 84 coordinate systems were compatible. Currently, NAD 83 and WGS 84 coordinates will agree at the 1- to 2-meter level, which is the level of accuracy to be expected of points referred to the WGS 84 coordinate system. Thus, for most mapping and charting purposes, the NAD 83 and WGS 84 coordinate systems can be considered equivalent.

An additional commonly used type of coordinate system is the International Terrestrial Reference Frame (ITRF). This type of coordinate system is produced by an international scientific organization, the Internation Earth Rotation Service (IERS) using data from other space systems in addition to GPS. This coordinate system is a worldwide system which takes into account the fact that the earth's surface is divided into segments, known as tectonic plates, which are in constant motion relative to one another at rates of 2 to 20 cm/yr. Because of plate motion, positions of points relative to a worldwide coordinate system such as an ITRF system must change with time. An ITRF coordinate system is essential for certain applications, such as the computation of GPS satellite orbits using data from a worldwide station network.

The NAD 83 and ITRF coordinate systems are defined at the 2- to 3-centimeter level and it is possible to transform coordinates between the two at this accuracy level. The position of a point relative to an ITRF coordinate system is a function of time and is defined by giving a position at some initial time, for example, the beginning of 1988 (1988.0) and its change in position with time (usually a linear function of time). The NAD 83 coordinate system is a coordinate system that is fixed with respect to a particular tectonic plate, the North American Plate. Of the 50 states, all but Hawaii, California west of the San Andreas Fault Zone, and a small part of southern Alaska lie on the North American Plate. To a high degree of approximation, the North American plate moves as a rigid body without deforming. This allows NAD 83 coordinates for most points in the United States to be unchanging. Conversions are available to go from NAD 83 coordinates to ITRF (1988.0) coordinates using a six parameter transformation (three rotations and three translations). ITRF coordinates at other times can be determined by using velocity information.

Defining the Coordinate System

A coordinate system such as the NAD 83 coordinate system is nominally a geocentric coordinate system. Thus, the origin of the coordinate system is inaccessible. In this situation the coordinate system is defined or realized by coordinates assigned to a set of points on the earth's surface. The NAD 83 coordinate system is currently realized by the coordinates assigned to measurement points associated with about a dozen large, dish antennas of radio telescopes located in the United States. These radio telescopes, in conjunction with similar equipment around the world, use a technique known as Very Long Baseline Interferometry (VLBI). With this VLBI technique, signals from very distant radio sources are used to differentially position the VLBI stations worldwide with an accuracy of 1 to 2 cm. The VLBI stations are initially positioned in an ITRF coordinate system with their position defined by giving, for each station, an initial epoch position and a set of velocities. The NAD 83 coordinates are then derived by applying a six parameter transformation to the initial epoch coordinates to make them agree, on the average, with coordinates obtained for these points in the original NAD 83 determination.

Providing Access to the Coordinate System

For a coordinate system to be useful to anyone constructing a GIS it must be possible to position relative to it without undue effort and at reasonable cost. This would clearly not be the case if all that were available to users were the positions of the measurement points of a small number of VLBI stations. Increased access to the national coordinate system can be achieved in several ways. The most common method of providing increased access up until now has been to extend the points of known position to include a large number of monumented stations. These monumented stations usually have the form of brass disks affixed to concrete monuments or solid rock or identifiable points located on the top of deep-driven steel rods. Positioning of these points relative to the NAD 83 coordinate system is currently a sequential process. GPS receivers are collocated at the VLBI sites used in defining the NAD 83 coordinate system and the GPS antenna phase centers of these receivers related to the VLBI measurement points. Then differential GPS, using the carrier phase observable, is employed to locate a small number of monumented stations relative to the collocated GPS receivers. There are normally three to five such stations located in each state. These are referred to as A-order stations. GPS surveys are then performed to establish a denser network of monumented stations, several tens to several hundred stations per state, the number depending upon the size of the state and existing requirements. These stations are referred to as B-order stations. The A- and B-order stations are commonly referred to as the High Accuracy Reference Network (HARN) in a state. Once the HARN is in place, NGS performs a readjustment of all classical geodetic surveys and local GPS surveys to obtain positions for other existing monumented points in the state relative to the HARN stations.

This hierarchial approach produces a large number of monumented points (hundreds of thousands) with positions relative to the NAD

83 coordinate system. The positions of these stations relative to the coordinate system vary in accuracy from a few centimeters to a few tens of centimeters with the accuracy decreasing as one moves down the hierarchial chain.

With current GPS capabilities, another method of providing access to the NAD 83 coordinate system exists and will become increasingly important. This is the use of GPS CORS. With the highly accurate orbits for the GPS satellites now available, it is possible with 50 to 100 CORS operating nationwide for any user with the proper GPS equipment to position a point relative to the NAD 83 coordinate system to whatever accuracy level is required without undue effort by differentially positioning directly relative to a CORS. Because of the vast amount of data produced by a CORS, these stations can be positioned relative to one another and to the NAD 83 coordinate system with an accuracy of one centimeter or better. Moreover, these station positions can be continuously monitored. The use of GPS reference stations is already the dominant method of relating points to the coordinate system when using range observations for positioning.

Concept of GPS CORS Network

GPS differential positioning can be performed using two types of observables broadcast by the GPS satellites--range observables and carrier phase observables. Generally, range observables are now used to support navigation activities and positioning of points where accuracies of one or more meters are required and carrier phase observables are used where accuracies of a centimeter to a few decimeters are required. Combining the two observables will be increasingly important in the future and achievable accuracies using range observables can be expected to improve. Broadly speaking the current use of GPS reference stations to support differential positioning can be broken into three categories.

-Broadcasting range correctors in real time to support navigation and for real time differential positioning of fixed receivers.

-Making available range correctors and range observables to support after-the-fact computation of positions of moving vehicles and fixed receivers.

Providing carrier phase observables after the fact to support very precise carrier phase differential positioning of moving vehicles and fixed receivers.

GPS field receivers and reference station instrumentation have often been customized to satisfy one requirement to the exclusion of others. For example, there are many GPS field receivers that are designed to record only the range observable and use range information from a base station to compute correctors and obtain a position. As might be expected there are GPS base stations which record only the range observables to provide base station information for such receivers. Often these base stations can service only field receivers that are produced by the same manufacturers as the base station. Such a situation is a natural evolution in the early development of the GPS technology. This is particularly true since the cost of a single purpose instrument has been considerably less than a multipurpose instrument and there was little reason for individual users to spend funds for a capability that was not required for their own use.

However, GPS technology has evolved to the point where a single reference station receiver can record and make available all of the observables required for all applications and the cost of such a receiver is modest. Moreover, the uses of differential GPS in the Federal government and elsewhere is expanding rapidly. It is increasingly realized that support of multiple single- purpose GPS reference station networks is not a viable economic alternative at the Federal level. Recently a number of studies have been undertaken to address this situation. The General Accounting Office (GAO) has just completed a review of the situation. They concluded that while the establishment of single use GPS reference station networks was understandable, as GPS technology was initially developed, the time for multiuse reference networks had arrived. They felt the cooperative effort that will be discussed later in this paper was a good start but that coordination need to be more formalized at higher levels within the government, particularly to assure that navigation and positioning requirements were integrated.

The Department of Transportation (DOT) which, by joint agreement with the Department of Defense (DOD) is serving as the focal point for civil applications of GPS, is also moving to address the question of multiple-use GPS reference stations. A study had been initiated by DOT aimed at defining what is the nature of a GPS reference network that could meet all Federal civil needs. This study will be completed by the end of this month (September 1994). Also, the DOT is moving to assure close coordination with those civil agencies whose primary interest in GPS is positioning, in contrast to the primary DOT focus which is navigation. As a part of a DOD-DOT study completed in December 1993, it was decided that DOT would set up a management structure to support their civil GPS responsibilities. A part of this management structure would be a GPS Interagency Advisory Council supporting the DOT Executive Committee, the top level committee in DOT responsible for civil GPS management. Recently, Secretary of Interior Babbitt, in his capacity as head of the Federal Geographic Data Committee (FGDC) wrote to Secretary Pena, DOT, recommending that the Federal Geodetic Control Subcommittee (FGCS) of the FGDC serve as this Advisory Council. Secretary Pena accepted this recommendation. This will assure close coordination throughout the Federal government in the development of a common GPS reference station network to meet both navigation and positioning requirements.

<u>Cooperative Network Implementation</u>

The strategy adopted within the Federal government for the implementation of a single multiuse network of GPS reference stations to meet GIS and other positioning needs is to build upon the stations being implemented to support marine and air navigation. A more detailed description of the GPS reference station networks being established by the USCG and FAA in terms of their marine and air navigation applications are given in other papers presented at this meeting. Because marine and air navigation applications of reference stations have a special requirement to satisfy reliability and safety considerations, it was natural to use navigation reference stations as the basis for meeting other GPS reference station needs with less stringent reliability requirements such as those involving GIS applications.

NGS recognized several years ago that within a few years GPS CORS would be a primary method of providing access to a national coordinate system. The need for interagency cooperation to achieve this end was also realized. Thus, as the USCG began to develop plans for its differential GPS (DGPS) reference station network; NGS and USGS initiated discussions to determine if this network could be used to meet a part of the GPS CORS requirements. Initially, it was unclear as to whether this was feasible, but as GPS receiver technology improved and receiver costs decreased, it became technically feasible and economically possible for the USCG stations to serve multiuse. The USCG has worked closely with NGS to assure that the specifications for their receiver would result in their ability to meet NGS requirements, in particular that the receivers would be dual frequency and would provide carrier phase, as well as range, observables. A 1994 USCG/NGS agreement provides that USCG will make available the data from the receivers of their network and that NGS will make these observables available to after-the-fact positioning users as resources and requirements dictate. NGS also agreed to position the GPS antennas at the USCG sites relative to the NAD 83 coordinate system.

Establishment of approximately 50 stations by the USCG is well underway. Most of the sites of the USCG network have been selected and implementation of facilities at the sites has begun. Placement of GPS receivers at the sites is scheduled to begin in November 1994 with most sites operational by the end of 1995. As of September 1, 1994, NGS had established monumented points at 22 of the USCG sites and performed GPS observations to position these monuments. This was done in support of preliminary positioning activities at the sites by the USCG.

The USCG stations, located along the coasts of the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Great Lakes, will not provide sufficient CORS coverage inland. However, much of the additional coverage can be achieved by making use of GPS reference stations being established by the FAA to support air navigation and by the COE to support river navigation. The COE has an agreement with the USCG for establishment along rivers of reference stations identical to the USCG stations. It is anticipated that, as a minimum, stations will be established along the Mississippi, Ohio, and Missouri Rivers. Until such time as these systems are in place, the COE is operating temporary systems using dual frequency receivers along the Mississippi at Vicksburg, Memphis, and St. Louis. NGS has recently completed the

computation of NAD 83 positions for these three stations.
The FAA is currently proceeding toward implementation of their Wide Area Augmentation System (WAAS) which will involve the establishment of the order of 30 GPS reference stations to support provisions of range correctors for aircraft navigation. The FAA is also working closely with NGS to assure that their WAAS stations will be able to satisfy NGS CORS needs for after-the-fact range and carrier phase observables, as well as satisfying their primary WAAS navigation objectives. As was the case with the USCG and COE stations, NGS has an agreement with FAA to provide positions for the WAAS sites. A component of this positioning activity, the establishment and high accuracy positioning of monumented stations at the WAAS sites is already underway.

Operation of Prototype Network

To develop software and procedures, both at the CORS sites and at a central data facility, NGS began in early 1994 to operate a limited number of prototype stations and to put in place a central data facility.
The initial prototype station was established at the National Institute of Science and Technology (NIST) facility in Gaithersburg, Maryland. The receiver used is a Trimble 4000SSE. Data are recorded on site on the hard disk of a 486 personal computer. The 5-second data are recorded in 1-hour files. Each hour a personal computer at the central facility at Silver Spring, Maryland, automatically accesses the computer at the NIST site and downloads the latest hour's data. Initially, the access was via modem and downloading of the data produced in an hour required about 5 minutes. INTERNET access is now being used and about 2.6 seconds is required to retrieve each hour's data. As backup, 5 days of data are retained on the hard disk at the site. At the central facility, each hourly data set is reformatted by the receiving personal computer (currently a 90 Mhz pentium-based computer) from receiver format to the Receiver Independent Exchange (RINEX) format version 2 and placed on the hard disk of a Hewlett Packard (HP) workstation which supports INTERNET access through anonymous FTP and MOSAIC. To minimize storage, the data are compressed. Supporting programs are maintained that allow the user to uncompress the data and to combine several sequential hourly files into a single file. The central computer facilities currently being used as a data server for INTERNET access are temporary. An HP 715 with 6.8 gigabytes of hard disk space expandable to 12.6 gigabytes is currently being acquired.
Current plans call for keeping on line 20 days of data for each station. This will require 100 megabytes of data per station to be on line. With ancillary data (e.g., weather data), the central facility will be able to support 50 to 100 stations. Once data are taken off line, it will be archived on CD Rom's. NGS has recently acquired the equipment necessary to produce CD ROM masters. The data will probably be further compressed before it is archived, with perhaps a 30-second sampling retained.
In order to monitor data quality and to assure the stability of

the GPS antennas at the stations, NGS will perform monitoring of interstation differential positions on a daily basis. That is, using 24 hours of data, two base lines will be computed from each station to other stations of the network. The stability of the interstation vectors will serve to evaluate the stability of the station antennas, while the observational residuals will provide a measure of data quality. NGS currently has a computer program which will automatically compute interstation vectors using a 24-hour data set. This program, developed for another application, is being adopted to provide the required CORS results.

Conclusions

Efforts are now well underway toward the development of a GPS CORS network that will meet at the Federal level the coordinate system referencing required to support GIS development. By providing range and carrier phase information from these stations the full spectrum of GIS positioning activities will be supported, ranging from positioning at the few centimeter level to positioning at the meters level and including the after-the-fact positioning of photogrammetric aircraft producing orthophotography. In addition to direct positioning relative to its stations, the CORS network will also serve as a means of positioning CORS established by state and local government agencies and private industry. Some challenges still exist in realizing a fully integrated system. The most important of these are the putting in place of a system for delivering the data to the maximum number of users and the bringing into being of data form at standardization with respect to both hardware and software.

The use of INTERNET, which is now being adopted at the central data facility for data distribution, is clearly the way of the future for data distribution. However, in the short run, it may be necessary to have groups with INTERNET capability take down the data from the central facility, and make it available on a local or regional basis over a modem from a computer bulletin board for those not having access to INTERNET.

The common formats for GPS data that have been generally accepted by the positioning community are Radio Technical Commission for Marine Services 104 for real time broadcast of GPS observations or correctors and RINEX for data for use in an after-the-fact reduction mode. However, not all current hardware and/or reduction software are compatible with these formats. Considerable effort will be required to bring about compatibility.

Movement toward resolving these problems at the Federal level will begin with a Workshop to be held on November 15-16, 1994, involving all interested Federal agencies, which will concentrate on data distribution and format problems. This meeting, to be held in Silver Spring, Maryland, will be sponsored by a Working Group of the FGCS. It will be followed by other meetings and discussions involving state and local governmental users, private surveying and positioning groups, and GPS equipment and software providers.

An integrated GPS CORS network can be expected to become a reality over the next 2 to 3 years. This network will be a major contributor to the development of a seamless GIS system on a national scale.