The Establishment of a GPS Continuously Operating Reference Station System as a Framework for the National Spatial Reference System

William Strange & Lt. Neil Weston, *NOAA*

BIOGRAPHY

William Strange is the Chief Geodesist of the National Geodetic Survey of the National Oceanic and Atmospheric Administration. He has been employed at the National Geodetic Survey since 1977. His educational background is in geology, geophysics and mathematics. Prior to joining the National Geodetic Survey, Mr. Strange worked in the area of satellite geodesy in industry and academia. He is currently directing the implementation of the GPS continuously operating reference station system in his organization.

Neil D. Weston received his M.Sc. degree in Physics from the University of South Florida in 1992. He did his master thesis research program on laser optics, quantum electronics and remote spectral sensing. He is currently working on the GPS continuously operating reference station system at the National Geodetic Survey.

ABSTRACT

Working cooperatively with other Federal agencies, the National Ocean Service (NOS), NOAA, is implementing a national Global Positioning System (GPS) reference station system to support after-the-fact GPS data reduction. The Continuously Operating Reference Station (CORS) network will make extensive use of data from GPS stations to be established and operated by other Federal agencies in support of marine and air navigation. The U.S. Coast Guard has agreed to provide to NOS the code range and carrier phase data from the 40 to 50 stations they will establish by the end of 1995. The Federal Aviation Administration anticipates making the data available from their Wide Area Augmentation Stations (WAAS). NOS is currently operating five prototype stations. Data from these stations are being used to develop procedures during the implementation of the central data facility which is currently underway in Silver Spring, Maryland.

The system will have a 5-second sampling rate with data transmitted to the central facility either by INTERNET or the FTS 2000, X.25 Packet Service. At the central facility, data will be converted to the RINEX 2 format and placed in hourly files. The files will be available for direct access over the INTERNET and will be on line for 21 days. Data will also be archived and made available on CD-ROM. It is intended that this network will serve as the primary Federal reference station network to be operated in support of GPS positioning activities.

INTRODUCTION

Webster's New Collegiate Dictionary defines navigation as "---- the science of getting ships, aircraft, or spacecraft from place to place; especially the method of determining position, course, and distance traveled." Today we would add to this definition land vehicles. Essential to "getting from place to place" is a common coordinate system relative to which the positions of the moving vehicle, its desired path, destination and obstructions and other attributes along its path are defined. An attribute of particular importance is the variation with horizontal position of height, the height of the moving vehicle, of the solid earth, and of man made obstructions. Thus the common coordinate system must be three dimensional. The primary responsibility of the National Geodetic Survey (NGS) is to define and provide users access to a common, three dimensional, earth fixed, coordinate system.

The NGS fulfills its coordinate system responsibility through implementation of a National Spatial Reference System (NSRS). In the past, the NSRS consisted almost entirely of monumented reference points

whose horizontal positions and/or elevations above sea level were known. Today the NSRS has four components; monumented reference points, GPS reference stations, GPS satellite orbits, and a very precise gravimetric geoid. Increasingly, GPS reference stations and GPS satellite orbits are providing the fundamental framework for accessing the NSRS for both navigation and positioning users.

The advent of GPS has lead to a much closer coordination and cooperation between the navigation and positioning communities. To a large extent this is due to the fact that the navigator and surveyor, as well as others performing positioning, are using the same technology, GPS, and often the same observational data to achieve their objectives. It is also the result of improved navigational accuracy provided by GPS, leading to the need for greater three dimensional positional accuracy of navigational related attributes (eg. runway end points, ship channels, roadways).

One important component of this coordination is the use of the same set of GPS reference stations to meet both navigation and positioning/surveying requirements. Currently, the total sum of navigation and positioning/surveying GPS requirements can be conveniently divided into those requirements which are satisfied by the use of broadcast code range correctors and those which are satisfied by after-the-fact computations using code range and/or carrier phase data from the GPS reference stations. The GPS Continuously Operating Reference Station (CORS) system being developed by NGS as a part of the NSRS is designed to satisfy requirements of users performing after-the-fact computations.

BACKGROUND

GPS was developed as a navigation system to provide real time positioning of moving vehicles using the code range data broadcast by the GPS satellites. The current GPS constellation is capable of providing 10 to 15 meter navigational accuracy using the uncorrupted Precise Positioning Service (PPS) code range signal in the point positioning mode. In the corrupted Standard Positioning Service (SPS) mode available to civil users, navigational accuracies of about 100 meters are available using point positioning. To achieve improved navigational accuracy, GPS reference station data is used to compute and broadcast correctors in real time. With these correctors, it is possible to negate the corrupting effect introduced into SPS. Indeed, using reference station data, it is possible in many situations to achieve navigational accuracy at the one meter or better level, which is better than that provided by PPS point positioning. In the navigation community, the use of reference station correctors is usually referred to as differential GPS (DGPS) or as Augmented GPS.

Positioning users of GPS reference station data differ from navigation users in one or more of the following ways:

1. They are positioning stationary receivers, not moving platforms.
2. They are computing positions after-the-fact rather than real time.
3. They are using observed data rather than broadcasted correctors.
4. They are using carrier phase data rather than code range data.

Where positioning users require the location of their stationary receivers in nearly real time with an accuracy at the meter to several tens of meters accuracy, they can use the same broadcast correctors used for navigation. However, because they are stationary, these users have the option of using algorithms which average a number of observations taken over several seconds or minutes to improve accuracy. For these users "real time" does not mean a position obtained instantaneously from data taken at a single measurement epoch. Rather, "real time" means a position available a few seconds after completion of observations taken over a short time period and involving a number of measurement epochs. Other members of the positioning community who require meter to several tens of meters accuracy do not require near real time positioning. Many Geographic Information System (GIS) users are in this category. These users obtain their observations over some finite time period at stationary locations and take the data back to the office for computations. These users employ code range observations from a reference station to compute correctors and perform their data reductions. Many GPS reference stations have been set up to support this type of activity. These stations usually provide single frequency (CA code) code range data.

From the beginning of GPS, the surveying and earth science community which is interested in positioning at the millimeter to a few centimeter level have used GPS carrier phase data rather than code range data. This community has always employed differential positioning in conjunction with carrier phase data. Although fixed GPS reference stations have been used, the bulk of this carrier phase differential positioning has been performed by using as a reference station, a GPS receiver whose antenna is temporarily set up over a known monumented point for the duration of an observing session.

Surveying and earth science users have almost exclusively obtained results using post processing of the carrier phase data. While most differential positioning using carrier phase data has involved positioning of a stationary point, there has been significant use of carrier phase data to perform after-the-fact positioning of moving platforms. A notable example of this has been the positioning of aircraft performing aerial photogrammetry.

A recent development in after-the-fact use of GPS reference station data has been a non-positional application. It has been found that once the positions of GPS reference stations are known to a few centimeters, tropospheric delay information as a function of time can be derived and used to estimate water content of the troposphere, an important input parameter to weather and climate models.

What is the CORS System

The CORS System is designed to perform four functions:

1. To assure that all navigation and positioning in the United States is performed using a common coordinate system.
2. To provide positioning users with the code range and carrier phase data from GPS reference stations for after-the-fact positioning.
3. To permit multiuse of GPS reference stations established by different groups.
4. To promote GPS reference station standards which will facilitate multiuse.

The CORS System will have four components.

1. An observation station component.
2. A data transmission component.
3. A central facility component.
4. A data distribution component.

The CORS system will take carrier phase and code range data from dual frequency receivers operating at sites around the nation. The data will be transmitted to a central data facility using either INTERNET or a telephone packet service employing the X.25 protocol. At the central facility, the data will be formatted into a receiver independent exchange format, RINEX 2, and quality controlled. Also, the receiver antenna position will be computed and monitored. Positions will be made available in the North American Datum of 1983 (NAD 83) and IERS Terrestrial Reference Frame (ITRF) coordinate systems. The data and station position information will be available over the INTERNET. Most of the data will be obtained at a 5 second sampling rate and placed in hourly files which will be available within 10 minutes after the hour. Some data will be obtained at a 30 second sampling rate and placed in daily files which will be available within a few hours of the beginning of the next day. The current implementation allows access to data up to three weeks old via INTERNET. Data will be archived on CD-ROM's and can be obtained in this form after production.

The Observation Station Component

Very few GPS reference stations will be established specifically to support the CORS System. Rather, stations established to support particular navigation, positioning, and meteorological/climatological applications will be incorporated in CORS and, thereby, made multi-purpose. This is in agreement with General Accounting Office (GAO) recommendations and will minimize costs to the Federal government for GPS reference station operation.

The largest group of stations that will be made a part of the CORS system in the short term will be the 40 to 50 station network currently being established by the U.S. Coast Guard (USCG) to support marine navigation. These stations will be established along the Atlantic, Pacific, and Gulf Coasts of the coterminous 48 states, Alaska, Hawaii, Puerto Rico and in the Great Lakes region. The USCG has begun the implementation of this network and anticipates completion of the coterminous 48 state network in 1995 with completion of the entire network in 1996. NGS and the USCG have signed an agreement to provide data from these stations for CORS. In return NGS will provide the positioning for all the stations. The station positioning activity is currently underway. Several stations are now becoming fully operational and NGS is in the final stages of completing the capability of receiving 5 second data over the X.25 packet service. It is anticipated that data from this network will begin to come available by April 1995. The first stations to become available will be those along the North Atlantic Coast of the United States.

To meet requirements for their inland waterways navigation, the U.S. Army Corps of Engineers (COE) has arranged for the USCG to establish five stations along the Mississippi River that are essentially identical to the USCG sites. These stations, near the cities of Vicksburg, Memphis, St. Louis, Rock Island, and St. Paul, are to be established in 1995. Additional inland waterways COE stations are anticipated. It is expected that data from these stations will be made available as a part of the CORS system.

The Federal Aviation Administration (FAA) has begun development of their Wide Area Augmentation

System (WAAS) to support aircraft navigation. Twenty to thirty GPS reference stations will be established over the next 2 to 3 years as a part of the WAAS program. These stations will be CORS compatible and will provide data to the CORS system. NGS has begun the positioning of monuments at the WAAS sites in support of this activity. The FAA is currently investigating the establishment of several hundred GPS reference stations at airports to support category II and III landings. The recently completed study for the Department of Transportation (DOT) recommended that, if such stations are established, they should be CORS compatible.

For several years, the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) have operated GPS reference stations in support of earth, ocean, and atmospheric science applications; computation of precise GPS orbits;, and coordinate system definition. These stations currently obtain data at a 30 second sampling rate with the data becoming available over the INTERNET daily. Ten of these stations within the United States are co-located with other space systems that are fundamental to the definition of the ITRF and NAD 83 coordinate systems. These stations are being included as a part of the CORS system to support realization and maintenance of the coordinate systems.

The Oceanic and Atmospheric Research (OAR) component of NOAA has begun operation of several GPS reference stations to demonstrate the value of using GPS derived water vapor information in weather and climatological models. Data from three of these stations is currently being included in the CORS system. This data is being taken at a 30 second sampling rate and is available daily. The potential exists over the next few years for the use of data from several hundred GPS reference stations to support meteorological/climatological applications.

The above discussion demonstrates the very large number of stations which have the potential for their data to be taken into the CORS system, placed in a common format, referenced to a common coordinate system, and made available for users performing after-the-fact positioning. There is, therefore, no need for establishment of large numbers of additional stations to support the CORS system. Indeed, only two stations have been established to support development of procedures and no more are planned. Data from these two stations and several existing NOAA stations are currently being used to develop the central data facility software.

Data Transfer Components

Currently two methods of data transfer from observing station to the central data facility are being used. One method is the use of the INTERNET; the other is the use of the FTS 2000 telephone packet service employing the X.25 packet data system. When using the INTERNET, the data is stored in files on personal computers at the sites. Files are downloaded automatically over the INTERNET to the central data facility at regular intervals, either hourly in the case of a 5 second sampling rate or daily in the case of a 30 second sampling rate. The advantage of this mode of operation is that several days of observations are stored at the site. Thus, if there is a problem at the central data facility, there can be delayed retrieval of the data. The disadvantage is that there are several pieces of equipment at the site that can, and do, malfunction. Thus this method of data transfer is not viable for stations of a national network which are not located at a facility with available computer knowledgeable personnel.

The X.25 packet data system offers an attractive alternative to the INTERNET. This is particularly true in the case of the USCG stations since the Coast Guard has already installed X.25 capability at their stations to handle their communication needs, and there is sufficient capacity to allow us to use this existing capability. Using the X.25 packet system, data is transferred over telephone lines directly to the central data facility as soon as a GPS measurement is made. There are no personal computers or data storage devices on site. Data arrives at the central facility within a fraction of a second after it is taken. The primary impact of X.25 data transfer is that it places a special requirement on the central data facility for reliability. If for any reason the central data facility goes down there is no retention of data at the stations. For the entire time that the central data facility is down data from all stations coming in on X.25 is permanently lost.

The Central Data Facility, Archiving and Distribution

The central data facility will perform five primary functions:

1. Conversion of data to a common format.
2. Quality control of the data.
3. Determination and monitoring of station positions.
4. Creation of files for distribution.
5. Data archiving.

With a 5 second sampling rate, each station will produce about 5 megabytes of data per day in compressed format. With a network of at least 100 stations, this will require handling on the order of 0.5 gigabytes of data per

day. This is not an unreasonable amount of data but it does require that the data handling procedures at the central facility be nearly completely automated. The data flow for data taken at 5 second sampling rate can be summarized as follows. Data is first placed in hourly files, one file for each station. Data taken in over the INTERNET is already in hourly files. Data taken in over the X.25 packet system is taken from the packet assembler/disassembler (PAD) as it arrives and placed in the proper files. At the end of each hour the files are closed and are ready for processing.

The first processing step consists of converting the data, which may be from one of several different types of receivers, to a common format. The common format used will be the receiver independent exchange (RINEX) format, version 2. The RINEX files are then checked by a quality evaluation program developed by the University NAVSTAR Consortium (UNAVCO). Relevant portions from the output of this program will be appended to the RINEX files for use by the user in evaluating the data. The hourly RINEX files will then be available for access via the INTERNET. The hourly files will be available for access within 10 to 15 minutes after the hour. Currently data is available over the INTERNET using anonymous FTP or the World Wide Web with Mosaic.

In addition to placing data on line for INTERNET access, files are prepared for CD-ROM production. Once sufficient data is available a CD-ROM is produced. If 100 stations were providing data, a CD-ROM would need to be produced each day. CD-ROM's would serve as an archiving medium and as a data distribution medium for those having applications such as in earth science where a large percentage of the data is to be analyzed. The user can then process days or weeks after-the-fact.

Data from CORS stations is of little value unless accurate station positions are known. The quantities of value to the user are the position of the GPS receiver antenna L1 phase center and the offsets between the L1 and L2 phase centers. Different users require different coordinate systems. Therefore, the antenna positions are provided in both the ITRF 1993 and NAD 83 coordinate systems. The user is then free to select the coordinate system which best fits his purpose.

Implementation Considerations

In order to make the CORS system fully usable, consideration must be given to several factors which will serve to provide the needed infrastructure. Three of the more important factors are; development of universal ability to use the RINEX 2 format, provision of antenna phase center models, and access to 1 second sampling rate data.

For a common reference station network to be successful it is essential that users be able to utilize data from the network regardless of the type of receiver or the reduction software being employed by the user. The RINEX format was developed by scientific and academic users to facilitate data interchange. Only recently has this format begun to come into general use with many types of hardware and software provided by GPS receiver manufacturers. It is essential to work with GPS industry to assure that the ability to use the RINEX format becomes universal and that there is general agreement as to what constitutes an acceptable RINEX format. This effort is currently underway.

Another aspect of mixing data from different GPS equipment types is the need to account for variations in the antenna phase center patterns of different GPS antennas. The phase center of any GPS antenna varies as a function of the azimuth and elevation angle of the satellite broadcasting the signal. The primary variation of interest is that associated with a change in elevation angle. When combining data from receivers using common antenna types, no substantive problems arise. However, when mixing antenna types, systematic errors can occur in the determination of the vertical coordinate if the software used for data reduction does not have the ability to model variations of the phase center location as a function of elevation angle. The information required to place the capability to model phase center variations into reduction software now exists. However, it has not generally been included in reduction software. Algorithms to allow inclusion of this capability are currently nearing completion. These algorithms will be made available to others who develop GPS reduction software in order to make this capability available as soon as possible.

Although data taken with a 5 second sampling rate meets the needs of a large number of users, there are users who have a need for GPS reference station data taken at a 1 second sampling rate. These include users who are using carrier phase data to perform post-mission positioning of aircraft to the few centimeter level in support of aerial photogrammetry. Also, users who are attempting to obtain sub meter accuracy using hand held, code range, receivers have expressed a need for 1 second sampling rate. Methods of satisfying these requirements are currently being explored. There are many problems in handling data at a 1 second sampling rate. The shear volume of data, 25 megabytes per station per day, could create handling problems. More importantly, significant cost increases would accrue in transmitting the data and there would need to be modifications at the receiving stations. Currently the USCG and their X.25 lines do not have sufficient capacity to handle 1 second data rates. There are several groups investigating the ability to

interpolate data with sufficient accuracy. NGS will work with all groups to determine the most effective method of providing 1 second data where it is needed.

CONCLUSION

The CORS system will compliment GPS reference station activities, such as those of the USCG, FAA, and COE, which will support navigation and positioning through the broadcasting, in real time, code range correctors. Through the CORS system, GPS code range and carrier phase data will be made available to users for post processing applications. Also, by providing positioning for all stations relative to a common coordinate system, the CORS activity will assure that all navigation and positioning activities produce compatible results. By providing for a common data format on a national basis, and developing the ability to combine data from differing hardware, the CORS system will facilitate the cost effective integration of observations taken by differing groups. Finally, by bringing together into a single data base, observations taken by different groups, the CORS activity will encourage multiple use of the GPS reference stations operated by the Federal government.