CHAPTER SIX

GPS Surveying Techniques

STATIC GPS SURVEYING

If a static GPS control survey is carefully planned, it usually progresses smoothly. The technology has virtually conquered two stumbling blocks that have defeated the plans of conventional surveyors for generations. Inclement weather does not disrupt GPS observations, and a lack of intervisibility between stations is of no concern whatsoever, at least in post-processed GPS. Still, GPS is far from so independent of conditions in the sky and on the ground that the process of designing a survey can now be reduced to points-per-day formulas, as some would like. Even with falling costs, the initial investment in GPS remains large by most surveyors' standards. However, there is seldom anything more expensive in a GPS project than a surprise.

Planning

New standards. The Federal Geodetic Control Committee (FGCC) has written provisional accuracy standards for GPS relative positioning techniques. The older standards of first, second, and third order are classified under the group C in the new scheme. In the past, the cost of achieving first-order accuracy was considered beyond the reach of most conventional surveyors.

Besides, surveyors often said that such results were far in excess of their needs anyway. The burden of the equipment, techniques, and planning that is required to reach its 2σ relative error ratio of 1 part in 100,000 was something most surveyors were happy to leave to government agencies. But the FGCC's proposed new standards of B, A, and AA are respectively 10, 100 and 1000 times more accurate than the old first-order. The attainment of these accuracies does not require corresponding 10-, 100- and 1000-fold increases in equipment, training, personnel, or effort. They are now well within the reach of private GPS surveyors both economically and technically.

New design criteria. These upgrades in accuracy standards not only accommodate control by static GPS; they also have cast survey design into a new light for many surveyors. Nevertheless, it is not correct to say that every job suddenly requires the highest achievable accuracy, nor is it correct to say that every GPS survey now demands an elaborate design. In some situations, a crew of two, or even one surveyor on-site may carry a GPS survey from start to finish with no more planning than minute-to-minute decisions can provide even though the basis and the content of those decisions may be quite different from those made in a conventional survey.

In areas that are not heavily treed and generally free of overhead obstructions, the now-lower C group of accuracy may be possible without a prior design of any significance. But while it is certainly unlikely that a survey of photocontrol or work on a cleared construction site would present overhead obstructions problems comparable with a static GPS control survey in the Rocky Mountains, even such open work may demand preliminary attention. For example, just the location of appropriate vertical and horizontal control stations or obtaining permits for access across privately owned property or government installations can be critical to the success of the work.

The lay of the land. An initial visit to the site of the survey is not always possible. Today online mapping browsers are making virtual site evaluation possible as well. Topography as it affects the line of sight between stations is of no concern on a static GPS project, but its influence on transportation from station to station is a primary consideration. Perhaps some areas are only accessible by helicopter or other special vehicle. Initial inquiries can be made. Roads may be excellent in one area of the project and poor in another. The general density of vegetation, buildings, or fences may open general questions of overhead obstruction or multipath. The pattern of land ownership, relative to the location of project points may raise or lower the level of concern about obtaining permission to cross property.

Maps. Maps, both digital and hard-copy, are particularly valuable resources for preparing a static GPS survey design. Local government and private sources can sometimes provide appropriate mapping, or it maybe available online. Other mapping that may be helpful is available from various government agencies: for example, the U.S. Forest Service in the Department of Agriculture; the Department of Interior's Bureau of Land Management, Bureau of Reclamation, and National Park Service; The U.S. Fish and Wildlife Service in the Department of Commerce; and the Federal Highway Administration in the Department of Transportation are just a few of them. Even county and city maps should be considered since they can sometimes provide the most timely information available.

Depending on the scope of the survey, various scales and type of maps can be useful. For example, a GPS survey plan may begin with the plotting of all potential control and project points on a map of the area. However, one vital element of the design is not available from any of these maps: the *National Spatial Reference System, NSRS* stations.

NGS Control

NGS control data sheets. It is important to understand the information available on NGS datasheets. A rectangular search based upon the range of latitudes and longitudes can now be performed on the NGS internet site. It is also possible to do a radial search, defining the region of the survey with one center position and a radius. You may also retrieve individual data sheets by the Permanent Identifier, *PID*, control point name, which is known as the *designation*, survey project identifier or USGS quad. It is best to ask for the desired horizontal and vertical information within a region that is somewhat larger than that which is contained by the boundaries of the survey. The internet address for NGS Data Sheets is http://www.ngs.noaa.gov/cgi-bin/datasheet.prl. There is a huge amount of information about survey monuments on each individual sheet.

NGS also provides a very convenient GIS map interface called *NGS Survey Control Map* from data sheets may be retrieved http://www.ngs.noaa.gov/ims/NgsMap2/viewer.htm

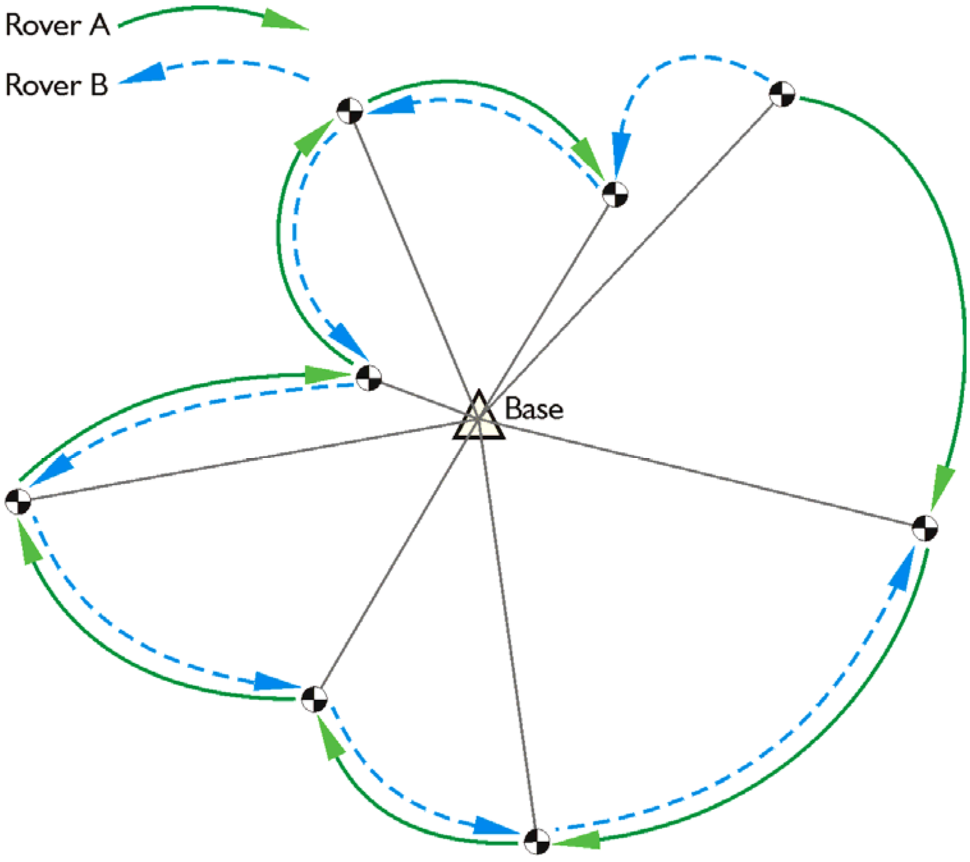


FIGURE 6.1

The information available from an NGS control sheet is valuable at the earliest stage of a GPS survey. See Figure 6.1 . In addition to the latitude and longitude, the published data include the state plane coordinates in the appropriate zones. The coordinates facilitate the plotting of the station's position on the project map.

The first line of each datasheet includes the retrieval date. Then the station's category is indicated. There are several, and among them are, Continuously Operating Reference Station, Federal Base Network Control Station and Cooperative Base Network Control Station.

This is followed by the station's designation, which is its name, and it's Permanent Identifier, *PID*. Either of these may be used to search for the station in the NGS database .The PID is also found all along the left side of each data sheet record and is always 2 upper case letters followed by 4 numbers.

The State, County and USGS 7.5 minute quad name follow. Even though the station is located in the area covered by the quad sheet, it may not actually appear in the map.

Under the heading, "Current Survey Control," you will find the latitude and longitude of the station in NAD 83 and its height in NAVD 88. Adjustments to NAD 27 and NGVD 29 datums are a thing of the past. However, these old values may be shown under, *Superseded Survey Control*. Horizontal values may be either, *Scaled*, if the station is a benchmark or *Adjusted*, if the station is indeed a horizontal control point.

When a date is shown in parentheses after NAD83 in the data sheet it means that the position has been readjusted since. Often these new adjustments are due to the stations inclusion in a State High Accuracy Reference Network, *HARN*, effort. There is more information on these cooperative projects in Chapter Five.

There are 13 sources of vertical control values shown on NGS data sheets. Here are a few of the categories. There is *Adjusted,* which are given to 3 decimal places and are derived from least squares adjustment of precise leveling. Another category is *Posted, which* indicates that the station was adjusted after the general NAVD adjustment in 1991. When a stations elevation has been found by precise leveling but non-rigorous adjustment, it is called *Computed*.

Stations vertical values are given to 1 decimal place if they are from GPS observation, *GPS Obs*, or vertical angle measurements, *Vert Ang*. And they have no decimal places if they were scaled from topographic map, *Scaled,* or found by conversion from NGVD29 values using the program known as *VERTCON*.

When they are available earth-centered earth-fixed, *ECEF*, coordinates are shown. These are right-handed system, 3D Cartesian coordinates. They are the same type of X, Y and Z coordinates presented in Chapter Five. These values are followed by the quantity which, when added to an astronomic azimuth, yields a geodetic azimuth, it is known as *the Laplace correction*.

It is important to note that NGS uses a clockwise rotation regarding the Laplace correction. The ellipsoid height per the NAD83 ellipsoid is shown followed by the geoid height where the position is covered by NGS's GEOID program. Please see Chapter Five for a more complete discussion of these values.

Survey Order and Class. Here the new accuracy standards mentioned earlier come into play. On NGS data sheets each adjusted control station will be assigned a horizontal, vertical (orthometric) and vertical (ellipsoid) order and class, where they apply.

Regarding horizontal control stations first-, second- and third- order continue to be published under group C. However, these designations are now augmented by AA-, A- and B-order stations as well. Horizontal AA-order stations have a relative accuracy of 3 mm +/- 1:100,000,000 relative to other AA-order stations. Horizontal A-order stations have a relative accuracy of 5 mm +/- 1:10,000,000 relative to other A-order stations. Horizontal B-order stations have a relative accuracy of 8 mm +/- 1: 1,000,000 relative to other A- and B-order stations.

Order and class continue to be published in first-, second- and third- order for orthometric vertical control stations. Under the orders, class 0 is sometimes used. First-order, class 0 is used for station whose tolerance is 2.0 mm or less. Second-order, class 0 is used for station whose tolerance is 8.4 mm or less. Third-order, class 0 is used for station whose tolerance is 12.0 mm or less. Posted bench marks are given a distribution rate code from a to f, respectively, to indicate their reliability from 0mm per km to 8 mm or more per km. Ellipsoid vertical control stations are also given order categories by NGS from first- to fifth- and each with a class 1 and 2, but the idea has not yet been adopted by the FGCC.

Photographs of the station may also be available in some cases. When the datasheet is retrieved online one can use the link provided to bring them up. Also, the geoidal model used is noted.

Coordinates. NGS data sheets also provide State Plane and UTM coordinates, the latter only for horizontal control stations. State Plane Coordinates are given in either U.S. Survey Feet or International Feet and UTM coordinates are given in meters. Azimuths to the primary azimuth mark are clockwise from north and scale factors for conversion from ellipsoidal distances to grid distances. This information may be followed by distances to reference objects. Coordinates are not given for azimuth marks or reference objects on the data sheet.

The Station Mark. Along with mark setting information, the type of monument and the history of mark recovery, the NGS data sheets provide a valuable *to-reach* description. It begins with the general location of the station. Then starting at a well-known location, the route is described with right and left turns, directions, road names, and the distance traveled along each leg in kilometers. When the mark is reached the monument is described and horizontal and vertical ties are shown. Finally there may be notes about obstructions to GPS visibility and etc.

Significance of the information. The value of the description of the monument's location and the route used to reach it is directly proportional to the date it was prepared and the remoteness of its location. The conditions around older stations often change dramatically when the area has become accessible to the public. If the age and location of a station increases the probability that it has been disturbed or destroyed then reference monuments can be noted as alternatives worthy of on-site investigation. However, special care ought to be taken to ensure that the reference monuments are not confused with the station marks themselves.

Control from Continuously Operating Networks

The requirement to occupy physical geodetic monuments in the field can be obviated by downloading the tracking data available online from appropriate *continuously operating reference stations, CORS* where their density is sufficient. These stations also know as *Active Stations* comprise fiducial networks that support a variety of GPS applications. While they are frequently administered by governmental organizations, some are managed by public-private organizations and some are commercial ventures. The most straightforward benefit of CORS is the user's ability to do relative positioning without operating his own base station by depending on that role being fulfilled by the networks reference stations.

While CORS can be configured to support DGPS and RTK applications, as in *Real-Time Networks*, most networks constantly collect GPS tracking data from known positions and archive the observations for subsequent download by users from the Internet.

In many instances the original impetus of a network of CORS was geodynamic monitoring as illustrated by the *GEONET* established by *the Geographical Survey Institute, GSI*, in Japan after the Kobe earthquake. Networks that support the monitoring of the International Terrestrial Reference System, ITRS have been created around the world by the *International GNSS Service, IGS*, which is a service of the International Association of Geodesy and the

Federation of Astronomical and Geophysical Data Analysis Services originally established in 1993. And the *Southern California Integrated GPS Network, SCIGN* is a network run by a government-university partnership.

Despite the original motivation for the establishment of a CORS network the result has been a boon for high-accuracy GPS positioning. The data collected by these networks is quite valuable to GPS surveyors around the world. Surveyors in the US can take advantage of the CORS network administered by the National Geodetic Survey, NGS. The continental NGS system is has two components, the Cooperative CORS and the National CORS. Together they comprise a network of hundreds of stations which constantly log dual-frequency GPS data and make the data available in the *receiver independent exchange format, RINEX* format.

NGS Continuously Operating Reference Stations. NGS manages the National CORS system to support post-processing GPS data. Information is available online at http://www.ngs.noaa.gov/CORS/. Both code and carrier phase GPS data from receivers at these stations throughout the United States and its territories are archived in Silver Springs Maryland and Boulder Colorado. That data can then be conveniently downloaded in its original form from the internet free of charge for up to 30 days after its collection. It is also available later, but after it has been decimated to a 30-second format.

The Cooperative CORS system supplements the National CORS system. The NGS does not directly provide the data from the cooperative system of stations. Its stations are managed by participating university, public and private organizations that operate the sites. The partners are listed at this address http://www.ngs.noaa.gov/CORS/Organizations/Organizations.html. NGS provides links to that data from their web page.

NGS CORS datums. Nearly all coordinates provided by NGS for the CORS sites are available in NAD83 (CORS96) epoch 2002.0 and the international reference frame ITRF00. The epoch means that the published NAD 83 coordinate represents the stations position on January 1, 2002. To compute it's location at another date one would need to apply the stations velocity, which NGS provides.

Some CORS stations coordinates are not in NAD83(CORS96). Since the islands in the Pacific move at a rate of centimeters per year relative to the North American tectonic plate to which NAD83 (CORS96) is tied, the coordinates of the CORS there are presented in NAD 83 (PACP00) or NAD 83 (MARP00). Another exception occurs in Alaska where the coordinates of the CORS are available in NAD83 (CORS96) but epoch 2003.00 rather than 2002.0.

The coordinates of CORS stations are also published in ITRF00 and as mentioned in Chapter 5. WGS84(G1150) is the same as ITRF00. However, these positions differ from NAD83. The ITRF00 coordinates are also accompanied by velocities since they are moving with respect to NAD83. NGS uses the epoch 1997.0, that is January 1, 1997, for its ITRF00 positions. Again, provided velocities can be used to calculate the stations position at a different date using the *Horizontal Time Dependent Positioning , HTDP*, utility available at http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.html

NGS CORS Reference Points. At a CORS site NGS provides the coordinates of the L1 phase center and the Antenna Reference Point, ARP. Generally speaking it is best to adopt the position that can be physically measured, that means the coordinates given for the ARP. It is the coordinate of the part of the antenna from which the phase center offsets are calculated which is usually the bottom mount.

As mentioned in Chapter 4, the phase centers of antennas are not immovable points. They actually change slightly, mostly as the elevation of the satellite's signals change. In any case, the phase centers for L1 and L2 differ from the position of the ARP both vertically and horizontally, please see http://www.ngs.noaa.gov/ANTCAL. NGS provides the position of the phase center on average at a particular CORS site. As most post-processing software will, given the ARP, provide the correction for the phase center of an antenna, based on antenna type, the ARP is the most convenient coordinate value to use.

NGS CORS Precise Orbits. A significant improvement in positioning is available by using the post computed precise orbital data that can be downloaded from the *User Friendly CORS, UFCORS,* portion of the NGS site http://www.ngs.noaa.gov/CORS/. This service will provide the best orbital information available at the time of the download.

The orbits preferred on the NGS CORS site are produced in cooperation with the IGS. The most accurate is known as the precise orbit which is usually available in ~12 days. Only after a full GPS week's worth of data is available can the precise orbit be completed. There are also rapid orbits which are available within ~24 hours. With a 5cm orbital integrity and 1/10th of a nansecond clock accuracy it is only slightly less reliable than the precise orbit data itself. Ultra-rapid data which are available within ~6 hours. These are a bit less reliable than the precise orbits.

International GNSS Service (IGS). Like NGS IGS also provides CORS data. However it has a global scope illustrated by the organizations online map at http://igscb.jpl.nasa.gov/network/maps/allmaps.html. The information on the individual stations can be accessed by clicking on the map. There are variable upload rates for the IGS CORS sites. While http://itrf.ensg.ign.fr/ITRF_solutions/2000/sol.php provides the ITRF00 Cartesian coordinates and velocities for the IGS sites not all the sites are available on all IGS servers. IGS data organized by GPS week is available at ftp://igscb.jpl.nasa.gov/igscb/product/ and further explanation of IGS data products and formats can be found at http://igscb.jpl.nasa.gov/index.html.

The *Scripps Orbit and Permanent Array Center, SOPAC* is a convenient access point for IGS data. A virtual map of all GPS networks available there can be found at http://sopac.ucsd.edu/maps/. The data archive is available at http://sopac.ucsd.edu/dataArchive/

Project Design

Horizontal Control. When geodetic surveying was more dependent on optics than electronic signals from space, horizontal control stations were set with station intervisibility in mind, not ease of access. Therefore it is not surprising that they are frequently difficult to reach. Not only are they found on the tops of buildings and mountains, they are also in woods, beside transmission towers, near fences, and generally obstructed from GPS signals. The geodetic surveyors that established them could hardly have foreseen a time when a clear view of the sky above their heads would be crucial to high-quality control.

In fact, it is only recently that most private surveyors have had any routine use for NGS stations. Many station marks have not been occupied for quite a long time. Since the primary monuments are often found deteriorated, overgrown, unstable, or destroyed, it is important that surveyors be well acquainted with the underground marks, R.M.'s and other methods used to perpetuate control stations.

Obviously, it is a good idea to propose reconnaissance of several more than the absolute minimum of three horizontal control stations. Fewer than three makes any check of their

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

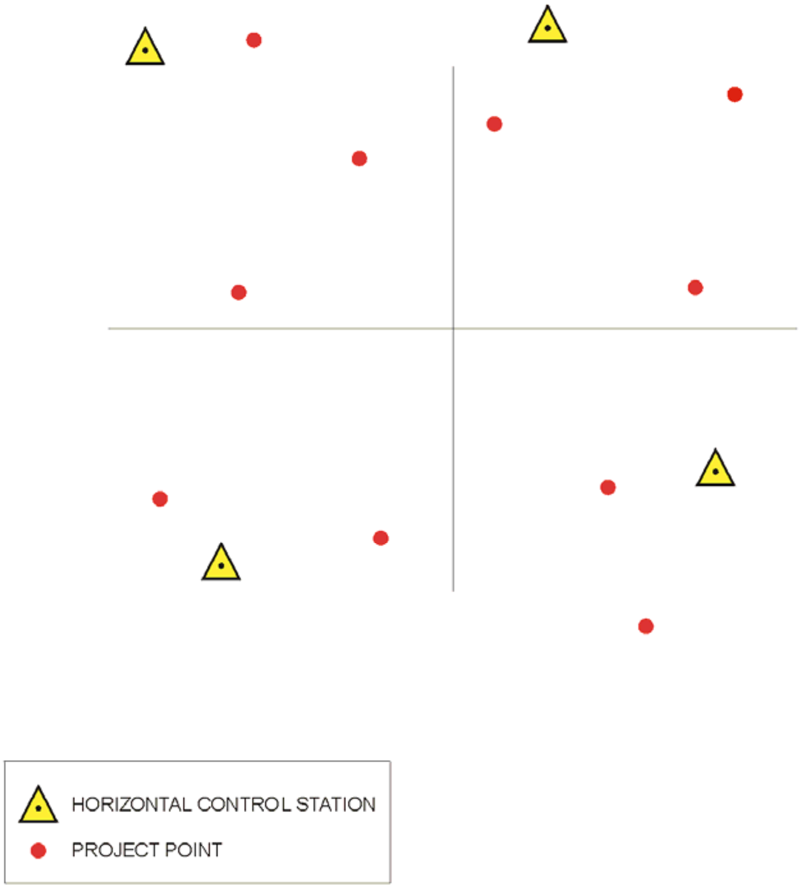
```
DATABASE = Sybase ,PROGRAM = datasheet, VERSION = 7.49
1        National Geodetic Survey,   Retrieval Date = JULY 26, 2007
 KK1696 ***********************************************************************
 KK1696  CBN         - This is a Cooperative Base Network Control Station.
 KK1696  DESIGNATION -  JOG
 KK1696  PID         -  KK1696
 KK1696  STATE/COUNTY-  CO/DOUGLAS
 KK1696  USGS QUAD   -  PARKER (1994)
 KK1696
 KK1696                         *CURRENT SURVEY CONTROL
 KK1696  ___________________________________________________________________
 KK1696* NAD 83(1992)-  39 34 05.17515(N)    104 52 18.24505(W)     ADJUSTED
 KK1696* NAVD 88     -      1796.4    (meters)    5894.     (feet)  GPS OBS
 KK1696  ___________________________________________________________________
 KK1696  X           -  -1,263,970.458 (meters)                    COMP
 KK1696  Y           -  -4,759,798.603 (meters)                    COMP
 KK1696  Z           -   4,042,268.499 (meters)                    COMP
 KK1696  LAPLACE CORR-           -5.62  (seconds)                  DEFLEC99
 KK1696  ELLIP HEIGHT-        1779.200 (meters)         (10/21/02) GPS OBS
 KK1696  GEOID HEIGHT-          -17.19  (meters)                   GEOID03
 KK1696
 KK1696  HORZ ORDER  -  B
 KK1696  ELLP ORDER  -  FIFTH     CLASS I
 KK1696
 KK1696.The horizontal coordinates were established by GPS observations
 KK1696.and adjusted by the National Geodetic Survey in May 1992.
 KK1696
 KK1696.The orthometric height was determined by GPS observations and a
 KK1696.high-resolution geoid model.
 KK1696
 KK1696.Photographs are available for this station.
 KK1696
 KK1696.The X, Y, and Z were computed from the position and the ellipsoidal ht.
 KK1696
 KK1696.The Laplace correction was computed from DEFLEC99 derived deflections.
 KK1696
 KK1696.The ellipsoidal height was determined by GPS observations
 KK1696.and is referenced to NAD 83.
 KK1696
 KK1696.The geoid height was determined by GEOID03.
 KK1696
 KK1696;                   North         East     Units Scale Factor Converg.
 KK1696;SPC CO C     -   497,563.455   968,386.196   MT  0.99996908   +0 23 46.5
 KK1696;SPC CO C     - 1,632,422.77  3,177,113.71   sFT  0.99996908   +0 23 46.5
 KK1696;UTM  13      - 4,379,830.656   511,017.352   MT  0.99960149   +0 04 54.1
 KK1696
 KK1696!             -  Elev Factor  x  Scale Factor =   Combined Factor
 KK1696!SPC CO C     -   0.99972095  x   0.99996908  =   0.99969003
 KK1696!UTM  13      -   0.99972095  x   0.99960149  =   0.99932255
```

Figure 6.2

Vertical Control. Those stations with a published accuracy high enough for consideration as vertical control are symbolized by an open square or circle on the map. Those stations that are sufficient for both horizontal and vertical control are particularly helpful and are designated by a combination of the triangle and square (or circle).

A minimum of four vertical control stations are needed to anchor a GPS network. A large project should have more. In general, the more high-order benchmarks available the better. Vertical control is best located at the four corners of a project.

Orthometric elevations are best transferred by means of classic spirit leveling. When vertical control is too far removed from the project or when the benchmarks are obstructed, if project efficiency is not drastically impaired, such work should be built into the project plan. When the distances involved are too long, two independent GPS measurements may suffice to connect a benchmark to the project. However, it is important to recall the difference between the ellipsoidal heights available from a GPS observation and the orthometric elevations yielded by a level circuit. Further, third-order level work is not improved by beginning at a first-order benchmark. When spirit levels are planned to provide vertical control positions, special care may be necessary to ensure that the precision of the conventional work is as consistent as possible with the rest of the GPS survey (Figure 6.3).



FGCC GEOMETRIC CONTROL STANDARDS				
GROUP	AA	A	B	C
ORDER	AA	A	B	1,2-I & II,3
PPM	0.01	0.1	1.0	10,20,50,100
BASE (CM)	0.03	0.5	0.8	1 2 3 5
Minimum number of NGRS Horizontal Control Stations	4	3	3	2

FIGURE 6.3

Route surveys require vertical control at the beginning and the end. They should be bridged with benchmarks on both sides of the line at intervals from 5 to 10 km.

Preparation

Plotting project points. A solid dot is the standard symbol used to indicate the position of project points. Some variation is used when a distinction must be drawn between those points that are in place and those that must be set. When its location is appropriate, it is always a good idea to have a vertical or horizontal control station serve double duty as a project point. While the precision of their plotting may vary, it is important that project points be located as precisely as possible even at this preliminary stage.

The subsequent observation schedule will depend to some degree on the arrangement of the baselines drawn on the map to connect the plotted points. Also, the preliminary evaluation of access, obstructions, and other information depends on the position of the project point relative to these features.

Evaluating access. When all potential control and project positions have been plotted and given a unique identifier, some aspects of the survey can be addressed a bit more specifically. If good roads are favorably located, if open areas are indicated around the stations, and if no station falls in an area where special permission will be required for its occupation, then the preliminary plan of the survey ought to be remarkably trouble-free. However, it is likely that one or more of these conditions will not be so fortunately arranged.

The speed and efficiency of transportation from station to station can be assessed to some degree from the project map. It is also wise to remember that while inclement weather does not disturb GPS observations whatsoever, without sufficient preparation it can play havoc with surveyor's ability to reach points over difficult roads or by aircraft.

Planning offsets. If control stations or project points are located in areas where the map indicates that topography or vegetation will obstruct the satellite's signals, alternatives may be considered. A shift of the position of a project point into a clear area may be possible where the change does not have a significant effect on the overall network. A control station may also be the basis for a less obstructed position, transferred with a short level circuit or traverse. Of course, such a transfer requires availability of conventional surveying equipment on the project. In situations where such movement is not possible, careful consideration of the actual paths of the satellites at the station itself during on-site reconnaissance may reveal enough windows in the gaps between obstructions to collect sufficient data by strictly defining the observation sessions.

Planning azimuth marks. Azimuth marks are a common requirement in GPS projects. They are almost always a necessary accompaniment to static GPS stations when a client intends to use them to control subsequent conventional surveying work. Of course, the line between the station and the azimuth mark should be as long as convenience and the preservation of line-of-sight allows.

It is wise to take care that short baselines do not degrade the overall integrity of the project. Occupations of the station and its azimuth mark should be simultaneous for a direct measurement of the baseline between them. Both should also be tied to the larger network as independent stations. There should be two or more occupations of each station when the distance between them is less than 2 km.

While an alternative approach may be to derive the azimuth between a GPS station and its azimuth mark with an astronomic observation, it is important to remember that a small error, attributable to the deflection of the vertical, will be present in such an observation. The small angle between the plumb line and a normal to the ellipsoid at the station can either be ignored or removed with a Laplace correction.

Obtaining permissions. Another aspect of access can be considered when the project map finally shows all the pertinent points. Nothing can bring a well-planned survey to a halt faster than a locked gate, an irate landowner, or a government official that is convinced he should have been consulted, previously. To the extent that it is possible from the available mapping, affected private landowners and government jurisdictions should be identified and contacted. Taking this precaution at the earliest stage of the survey planning can increase the chance that the sometimes long process of obtaining permissions, gate keys, badges, or other credentials has a better chance of completion before the survey begins.

Any aspect of a GPS survey plan derived from examining mapping, virtual or hardcopy, must be considered preliminary. Most features change with time, and even those that are relatively constant cannot be portrayed on a map with complete exactitude. Nevertheless, steps toward a coherent workable design can be taken using the information they provide.

Some GPS Survey Design Facts

Though much of the preliminary work in producing the plan of a GPS survey is a matter of estimation, some hard facts must be considered, too. For example, the number of GPS receivers available for the work and the number of satellites above the observer's horizon at a given time in a given place are two ingredients that can be determined with some certainty.

Software assistance. Most GPS software packages provide users with routines that help them determine the satellite *windows*, the periods of time when the largest numbers of satellites are simultaneously available. Now that the GPS system is operational and a full constellation of satellites are on orbit, observers are virtually assured of 24-hour coverage. This assurance is a welcome relief from the forced downtime in the early days of GPS. However, the mere presence of adequate satellites above an observer's horizon does not guarantee collection of sufficient data. Therefore, despite the virtual certainty that at least four satellites will be available, evaluation of their configuration as expressed in the position dilution of precision (PDOP) is still crucial in planning a GPS survey.

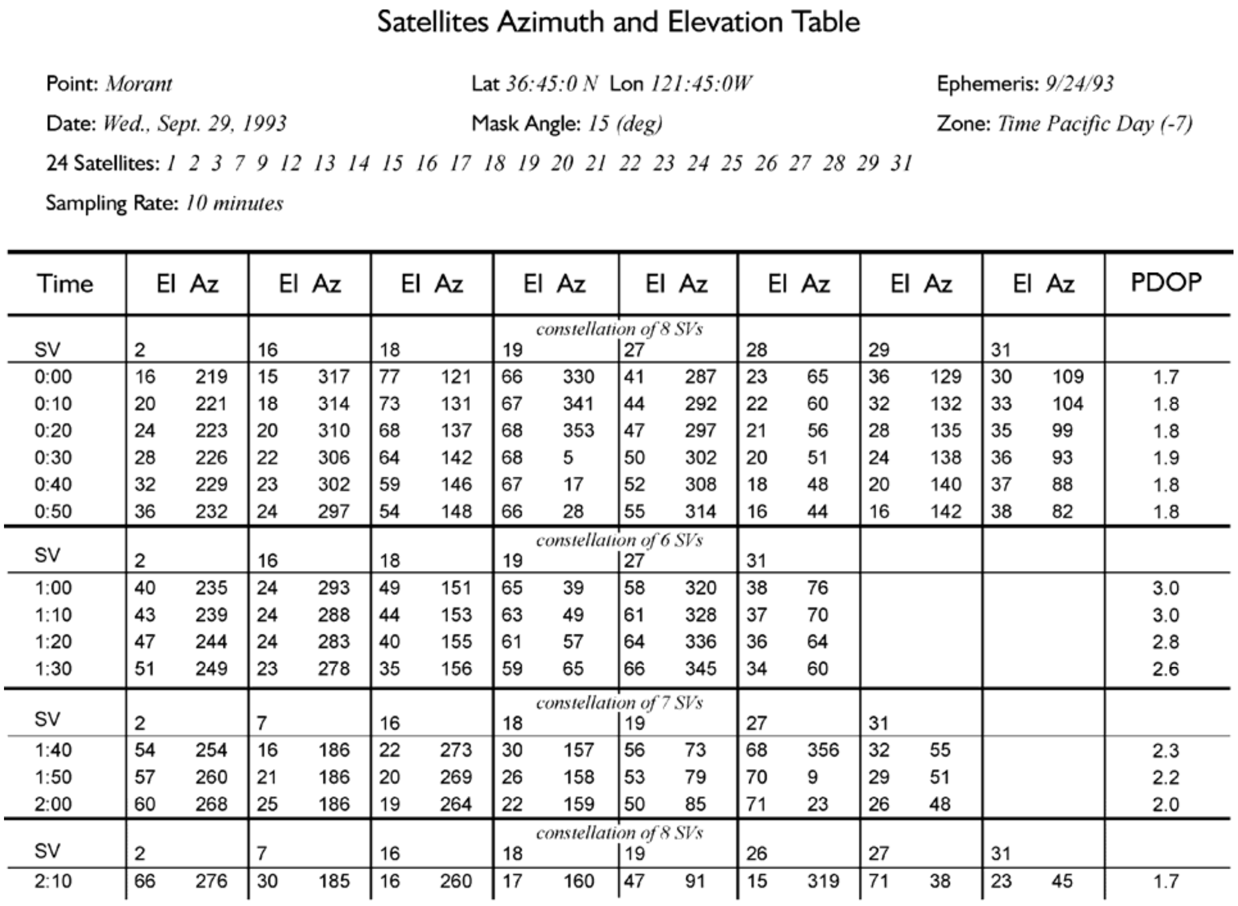
PDOP. In GPS, the receiver's position is derived from the simultaneous solution of vectors between it and at least four satellites. The quality of that solution depends, in large part, on the distribution of the vectors. For example, any position determined when the satellites are crowded together in one part of the sky will be unreliable, because all the vectors will have virtually the same direction. Given the ephemeris of each satellite, the approximate position of the receiver, and the time of the planned observation, a computer can predict such an unfavorable configuration and indicate the problem by giving the PDOP a large number. The GPS survey planner, on notice that the PDOP is large for a particular period of time, should consider an alternate observation plan.

On the other hand, when one satellite is directly above the receiver and three others are near the horizon and 120° in azimuth from one another, the arrangement is nearly ideal for a four-satellite constellation. The planner of the survey would be likely to consider such a window. However, more satellites would improve the resulting position even more, as long as they are well distributed in the sky above the receiver. In general, the more satellites, the better. For example, if the planner finds eight satellites will be above the horizon in the region where the work is to be done and the PDOP is below 2, that window would be a likely candidate for observation.

There are other important considerations. The satellites are constantly moving in relation to the receiver and to each other. Satellites rise and set and the PDOP is constantly changing. Within all this movement, the GPS survey designer must have some way of correlating the longest and most important baselines with the longest windows, the most satellites, and the lowest PDOP. Most GPS software packages, given a particular location and period of time, can provide illustrations of the satellite configuration.

Polar plot. One such diagram is a plot of the satellite's tracks drawn on a graphical representation of the upper half of the celestial sphere with the observer's zenith at the center and perimeter circle as the horizon. The azimuths and elevations of the satellites above the specified mask angle are connected into arcs that represent the paths of all available satellites. The utility of this sort of drawing has lessened with the completion of the GPS constellation. In fact, there are so many satellites available that the picture can become quite crowded and difficult to decipher.

Another printout is a tabular list of the elevation and azimuth of each satellite at time intervals selected by the user.



Satellites Azimuth and Elevation Table

Point: *Morant* **Lat** *36:45:0 N* **Lon** *121:45:0W* **Ephemeris:** *9/24/93*

Date: *Wed., Sept. 29, 1993* **Mask Angle:** *15 (deg)* **Zone:** *Time Pacific Day (-7)*

24 Satellites: *1 2 3 7 9 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 31*

Sampling Rate: *10 minutes*

Time	El	Az	El	Az	El	Az	El	Az	El	Az	El	Az	El	Az	El	Az	PDOP
							constellation of 8 SVs										
SV	2		16		18		19		27		28		29		31		
0:00	16	219	15	317	77	121	66	330	41	287	23	65	36	129	30	109	1.7
0:10	20	221	18	314	73	131	67	341	44	292	22	60	32	132	33	104	1.8
0:20	24	223	20	310	68	137	68	353	47	297	21	56	28	135	35	99	1.8
0:30	28	226	22	306	64	142	68	5	50	302	20	51	24	138	36	93	1.9
0:40	32	229	23	302	59	146	67	17	52	308	18	48	20	140	37	88	1.8
0:50	36	232	24	297	54	148	66	28	55	314	16	44	16	142	38	82	1.8
							constellation of 6 SVs										
SV	2		16		18		19		27		31						
1:00	40	235	24	293	49	151	65	39	58	320	38	76					3.0
1:10	43	239	24	288	44	153	63	49	61	328	37	70					3.0
1:20	47	244	24	283	40	155	61	57	64	336	36	64					2.8
1:30	51	249	23	278	35	156	59	65	66	345	34	60					2.6
							constellation of 7 SVs										
SV	2		7		16		18		19		27		31				
1:40	54	254	16	186	22	273	30	157	56	73	68	356	32	55			2.3
1:50	57	260	21	186	20	269	26	158	53	79	70	9	29	51			2.2
2:00	60	268	25	186	19	264	22	159	50	85	71	23	26	48			2.0
							constellation of 8 SVs										
SV	2		7		16		18		19		26		27		31		
2:10	66	276	30	185	16	260	17	160	47	91	15	319	71	38	23	45	1.7

TABLE 6.1

An example. The position of point Morant in the Table 6.1 needed expression to the nearest minute only, a sufficient approximation for the purpose. The ephemeris data were 5 days old when the chart was generated by the computer, but the data were still an adequate representation of the satellite's movements to use in planning. The mask angle was specified at 15°, so the program would consider a satellite set when it moved below that elevation angle. The zone time was Pacific Daylight Time, 7 hours behind Coordinated Universal Time, UTC. The full constellation provided 24 healthy satellites, and the sampling rate indicated that the azimuth and elevation of those above the mask angle would be shown every 10 minutes.

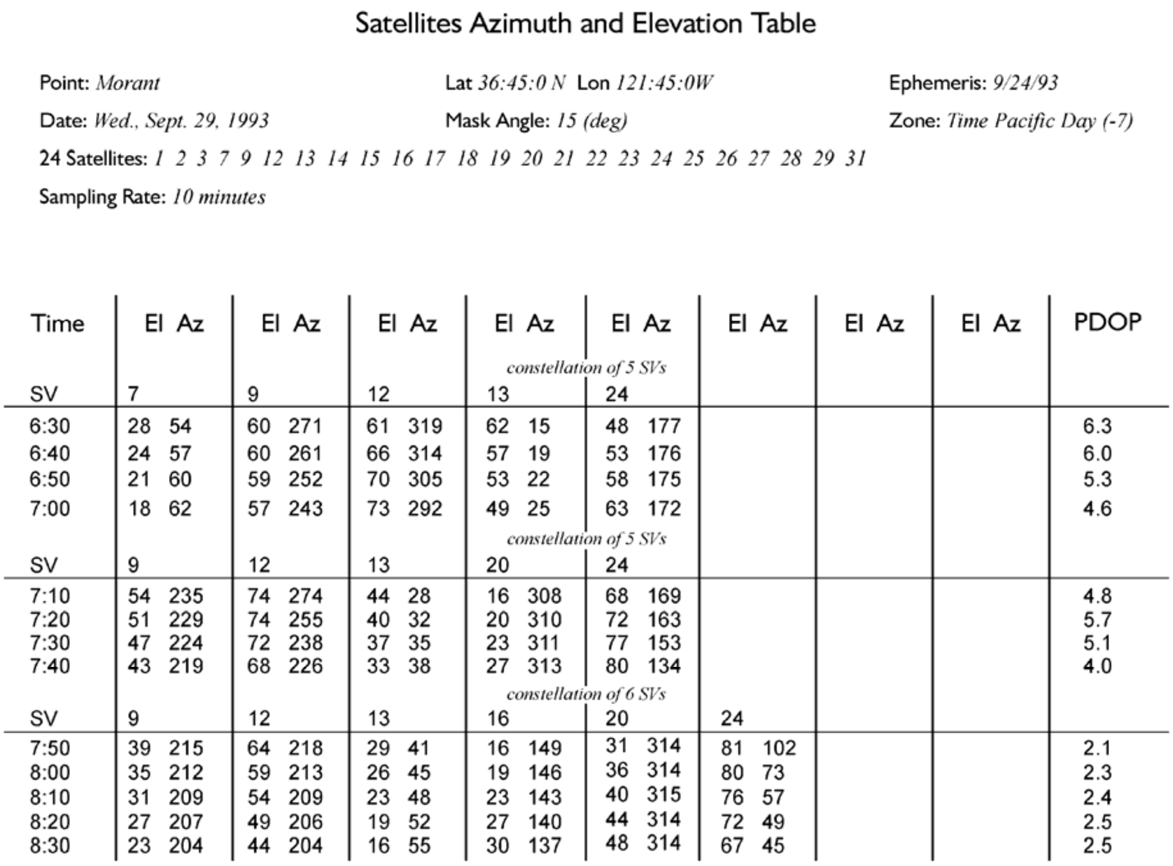
At 0:00 hour satellite PRN 2 could be found on an azimuth of 219° and an elevation of 16° above the horizon by an observer at 36°45'Nφ and 121°45'Wλ. The table indicates that PRN 2 was rising, and got continually higher in the sky for the 2 hours and 10 minutes covered by the chart. The satellite PRN 16 was also rising at 0:00 but reached its maximum altitude at about 1:10 and began to set. Unlike PRN 2, PRN 16 was not tabulated in the same row throughout the chart. It was supplanted when PRN 7 rose above the mask angle and PRN 16 shifted one column to the right. The same may be said of PRN 18 and PRN 19. Both of these satellites began high in the sky, unlike PRN 28 and PRN 29. They were just above 15° and setting when the table began and set after approximately 1 hour of availability. They would not have been seen again at this location for about 12 hours.

This chart indicated changes in the available constellation from eight space vehicles, *SVs*, between 0:00 and 0:50, six between 1:00 and 1:30, seven from 1:40 to 2:00 and back to eight at 2:10. The constellation never dipped below the minimum of four satellites, and the PDOP was good throughout. The PDOP varied between a low of 1.7 and a high of 3.0. Over the interval covered by the table, the PDOP never reached the unsatisfactory level of 5 or 6 which is when a planner should avoid observation.

Choosing the window. Using this chart, the GPS survey designer might well have concluded that the best available window was the first. There was nearly an hour of eight-satellite data with a

PDOP below 2. However, the data indicated that good observations could be made at any time covered here, except for one thing: it was the middle of the night. When a small number of satellites were available in the early days of GPS, the discomfort of such observations were ignored from necessity. With a full constellation, the loss of sleep can be avoided, and the designer may look at a more convenient time of day to begin the field work.

Ionospheric delay. It is worth noting that the ionospheric error is usually smaller after sundown. In fact, the FGCC specifies two-frequency receivers for daylight observations that hope to meet AA-, A-, and B-order accuracy standards, due, in part, to the increased ionospheric delay during those hours. There are provisions for compensation by modeling the error with two-frequency data from other sources where only single-frequency receivers are available. However, the specification illustrates the importance of considering atmospheric error sources.



Satellites Azimuth and Elevation Table

Point: *Morant* **Lat** *36:45:0 N* **Lon** *121:45:0W* **Ephemeris:** *9/24/93*
Date: *Wed., Sept. 29, 1993* **Mask Angle:** *15 (deg)* **Zone:** *Time Pacific Day (-7)*
24 Satellites: *1 2 3 7 9 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 31*
Sampling Rate: *10 minutes*

Time	El Az	El Az	El Az	El Az	El Az	El Az	El Az	El Az	PDOP
				constellation of 5 SVs					
SV	7	9	12	13	24				
6:30	28 54	60 271	61 319	62 15	48 177				6.3
6:40	24 57	60 261	66 314	57 19	53 176				6.0
6:50	21 60	59 252	70 305	53 22	58 175				5.3
7:00	18 62	57 243	73 292	49 25	63 172				4.6
				constellation of 5 SVs					
SV	9	12	13	20	24				
7:10	54 235	74 274	44 28	16 308	68 169				4.8
7:20	51 229	74 255	40 32	20 310	72 163				5.7
7:30	47 224	72 238	37 35	23 311	77 153				5.1
7:40	43 219	68 226	33 38	27 313	80 134				4.0
				constellation of 6 SVs					
SV	9	12	13	16	20	24			
7:50	39 215	64 218	29 41	16 149	31 314	81 102			2.1
8:00	35 212	59 213	26 45	19 146	36 314	80 73			2.3
8:10	31 209	54 209	23 48	23 143	40 315	76 57			2.4
8:20	27 207	49 206	19 52	27 140	44 314	72 49			2.5
8:30	23 204	44 204	16 55	30 137	48 314	67 45			2.5

TABLE 6.2

An example. Table 6.2, later in the day, covers a period of two hours when a constellation of five and six satellites was always available. However, through the first hour, from 6:30 to 7:30, the PDOP hovered around 5 and 6. For the first half of that hour, four of the satellites - PRN 9, PRN 12, PRN 13, and PRN 24 - were all near the same elevation. During the same period, PRN 9 and PRN 12 were only approximately 50° apart in azimuth, as well. Even though a sufficient constellation of satellites was constantly available, the survey designer may well have considered only the last 30 to 50 minutes of the time covered by this chart as suitable for observation.

There is one caution, however. Azimuth-elevation tables are a convenient tool in the division of the observing day into sessions, but it should not be taken for granted that every satellite listed is healthy and in service. For the actual availability of satellites and an update on atmospheric conditions, it is always wise to call the recorded message on the United States Coast Guard hotline at (703) 313-5907 or online you can check *GPS Status Message* at http://www.navcen.uscg.gov/ftp/GPS/status.txt before and after a project. In the planning stage, the call can prevent creation of a design dependent on satellites that prove unavailable. Similarly, after the field work is completed, it can prevent inclusion of unhealthy data in the post-processing.

Supposing that the period from 7:40 to 8:30 was found to be a good window, the planner may have regarded it as a single 50-minute session, or divided it into shorter sessions. One aspect of that decision was probably the length of the baseline in question. In static GPS, a long line of 30 km may require 50 minutes of six-satellite data, but a short line of 3 km may not. If the planned survey was not done by static GPS, but instead with rapid-static, a 10-minute session may have been sufficient. Therefore, another aspect of the decision as to how the window was divided probably depended on the anticipated GPS surveying technique. A third consideration was probably the approximation of the time necessary to move from one station to another.

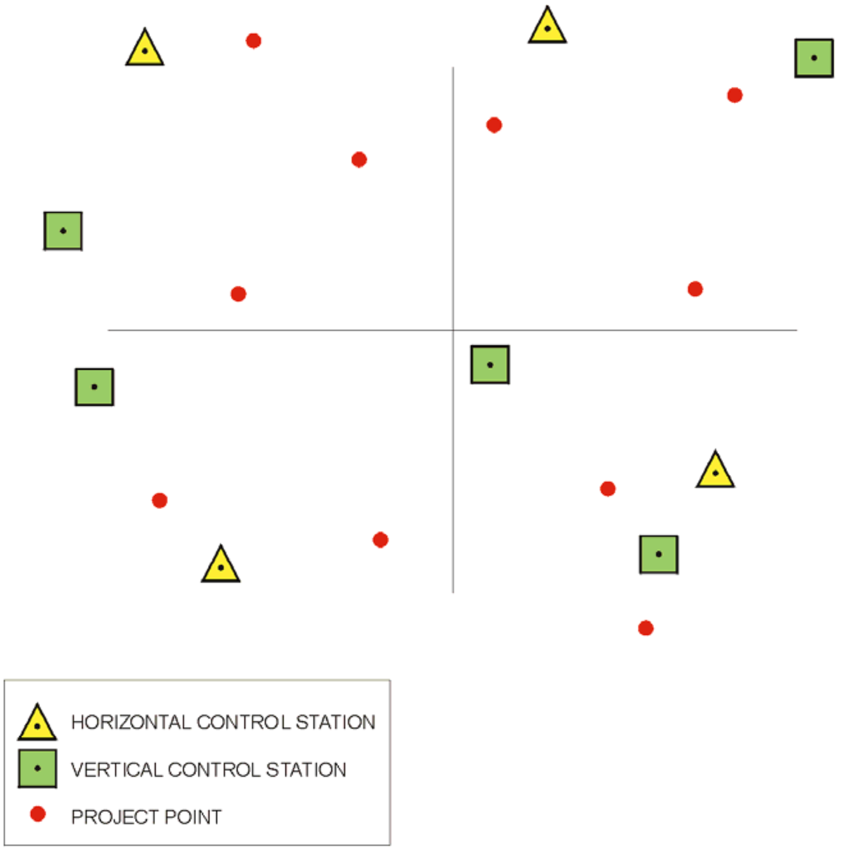
Naming the variables. The next step in the GPS survey design is drawing the preliminary plan of the baselines on the project map. Once some idea of the configuration of the baselines has been established, an observation schedule can be organized. Toward that end, the FGCC has developed a set of formulas provided in appendix F of their provisional *Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques*. Those formulas will be used here.

For illustration, suppose that the project map (Figure 6.5) includes horizontal control, vertical control, and project points for a planned GPS network. They will be symbolized by m. There are four dual-frequency GPS receivers available for this project. They will be symbolized by r. There will be five observation sessions each day during the project. They will be symbolized by d. To summarize:

m = total number of stations (existing and new) = 14

d = number of possible observing sessions per observing day = 5

r = number of receivers = 4 dual frequency



FGCC GEOMETRIC CONTROL STANDARDS	GROUP ORDER PPM BASE (CM)	AA AA 0.01 0.03	A A 0.1 0.5	B B 1.0 0.8	C 1,2-I & II,3 10,20,50,100 1 2 3 5
Minimum number of NGRS Horizontal Control Stations		4	3	3	2
Minimum number of NGRS Vertical Control Stations		5	5	5	4

FIGURE 6.4

The design developed from this map must be preliminary. The session for each day of observation will depend on the success of the work the day before. Please recall that the plan must be provisional until the baseline lengths, the obstructions at the observation sites, the transportation difficulties, the ionospheric disturbances, and the satellite geometry are actually known. Those questions can only be answered during the reconnaissance and the observations that follow. Even though these equivocations apply, the next step is to draw the baselines measurement plan.

Drawing the Baselines

Horizontal control. A good rule of thumb is to verify the integrity of the horizontal control by observing baselines between these stations first. The vectors can be used to both corroborate the accuracy of the published coordinates and later to resolve the scale, shift, and rotation parameters between the control positions and the new network that will be determined by GPS.

These baselines are frequently the longest in the project, and there is an added benefit to measuring them first. By processing a portion of the data collected on the longest baselines early in the project, the degree that the sessions could have been shortened without degrading the quality of the measurement can be found. This test may allow improvement in the productivity on the job without erosion of the final positions (Figure 6.5).

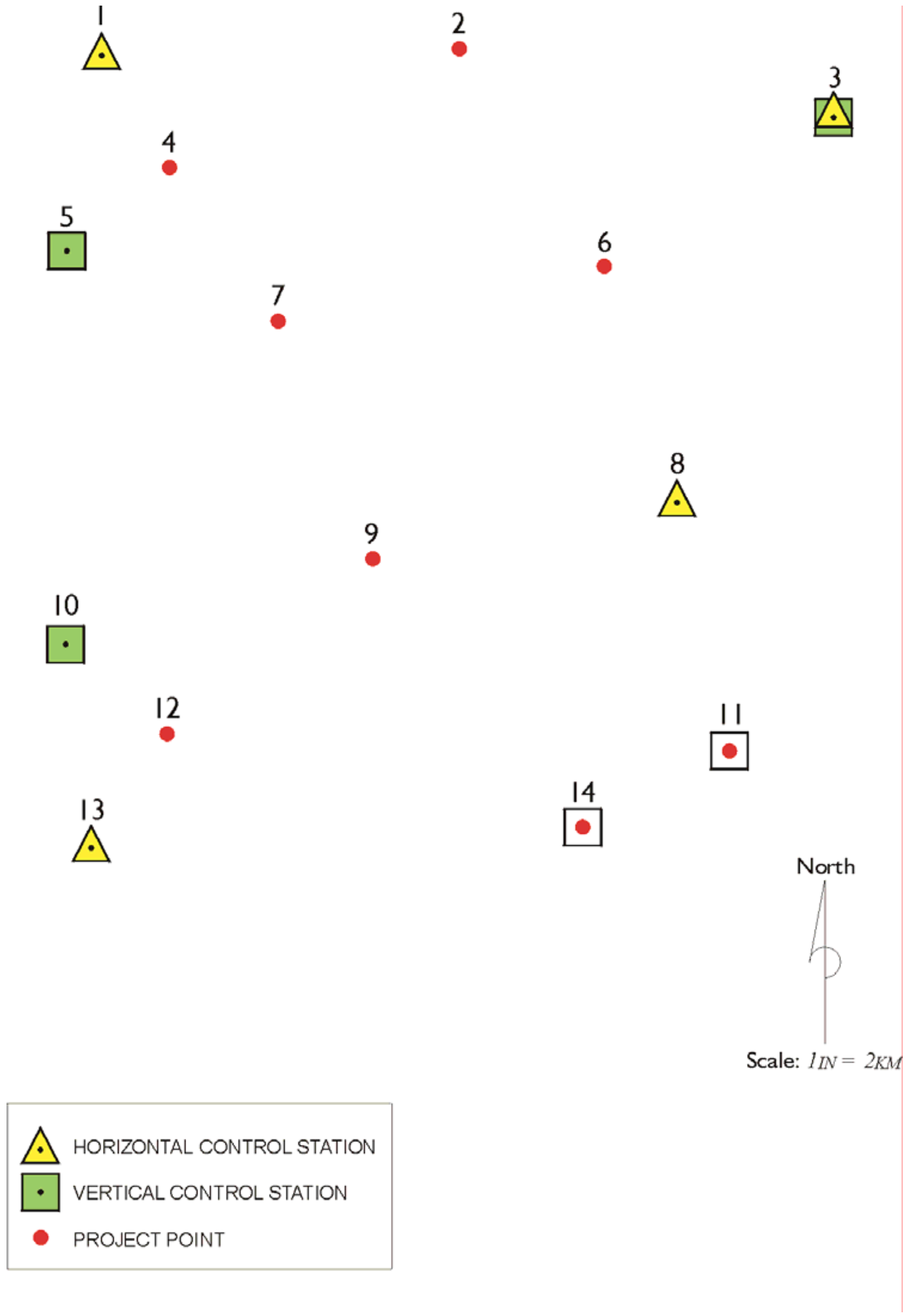


FIGURE 6.5

Julian Day in naming sessions. The table at the bottom of Figure 6.6 indicates that the name of the first session connecting the horizontal control is 49-1. The date of the planned session is given in the Julian system. Taken most literally, Julian dates are counted from January 1, 4713 B.C. However, most practitioners of GPS use the term to mean the day of the current year measured consecutively from January 1. Under this construction, since there are 31 days in January, Julian day 49 is February 18 of the current year. The designation 49-1 means that this is to be the first session on that day. Some prefer to use letters to distinguish the session. In that case, the label would be 49-A.

Independent lines. This project will be done with four receivers. The table shows that receiver A will occupy point 1; receiver B point 3; receiver C, point 8; and receiver D, point 13 in the first session. However, the illustration shows only three of the possible six base lines that will be produced by this arrangement. Only the *independent*, also known as *non-trivial*, lines are shown on the map. The three lines that are not drawn are called *trivial*, and are also known as *dependent lines*. This idea is based on restricting the use of the lines created in each observing session to the absolute minimum needed to produce a unique solution.

Whenever four receivers are used, six lines are created. However, any three of those lines will fully define the position of each occupied station in relation to the others in the session. Therefore, the user can consider any three of the six lines independent. But once the decision is made only those three baselines are included in the network. The remaining baselines are then considered trivial and discarded. In practice, the three shortest lines in a four-receiver session are almost always deemed the independent vectors, and the three longest lines are eliminated as trivial, or dependent. That is the case with the session illustrated.

Where *r* is the number of receivers, every session yields *r*-1 independent baselines. For example, four receivers used in 10 sessions would produce 30 independent baselines. It cannot be said that the shortest lines are always chosen to be the independent lines. Sometimes there are reasons to reject one of the shorter vectors due to incomplete data, cycle slips, multipath, or some other weakness in the measurements. Before such decisions can be made, each session will require analysis after the data has actually been collected. In the planning stage, it is best to consider the shortest vectors as the independent lines.

Another aspect of the distinction between independent and trivial lines involves the concept of error of closure, or loop closure. Loop closure is a procedure by which the internal consistency of a GPS network is discovered. A series of baseline vector components from more than one GPS session, forming a loop or closed figure, is added together. The closure error is the ratio of the length of the line representing the combined errors of all the vectors components to the length of the perimeter of the figure. Any loop closures that only use baselines derived from a single common GPS session will yield an apparent error of zero, because they are derived from the same simultaneous observations. For example, all the baselines between the four receivers in session 49-1 of the illustrated project will be based on ranges to the same GPS satellites over the same period of time. Therefore, the trivial lines of 13-1, 1-8, and 3-13 will be derived from the same information used to determine the independent lines of 1-3, 3-8, and 8-13. It follows that, if the fourth line from station 13 to station 1 were included to close the figure of the illustrated session, the error of closure would be zero. The same may be said of the inclusion of any of the trivial lines. Their addition cannot add any redundancy or any geometric strength to the lines of the session, because they are all derived from the same data. If redundancy cannot be added to a GPS session by including any more than the minimum number of independent lines, how can the baselines be checked? Where does redundancy in GPS work come from?

Redundancy. If only two receivers were used to complete the illustrated project, there would be no trivial lines and it might seem there would be no redundancy at all. But to connect every station with its closest neighbor, each station would be have to be occupied at least twice, and each time during a different session. For example, with receiver A on station 1 and receiver B on station 2, the first session could establish the baseline between them. The second session could then be used to measure the baseline between station 1 and station 4. It would certainly be possible to simply move receiver B to station 4 and leave receiver A undisturbed on station 1. However, some redundancy could be added to the work if receiver A were reset. If it were recentered, replumbed, and its H.I. remeasured, some check on both of its occupations on station 1 would be possible when the network was completed. Under this scheme, a loop closure at the end of the project would have some meaning.

If one were to use such a scheme on the illustrated project and connect into one loop all of the 14 baselines determined by the 14 two-receiver sessions, the resulting error of closure would be useful. It could be used to detect blunders in the work, such as mis-measured H.I.s. Such a loop would include many different sessions. The ranges between the satellites and the receivers defining the baselines in such a circuit would be from different constellations at different times. On the other hand, if it were possible to occupy all 14 stations in the illustrated project with 14 different receivers simultaneously and do the entire survey in one session, a loop closure would be absolutely meaningless.

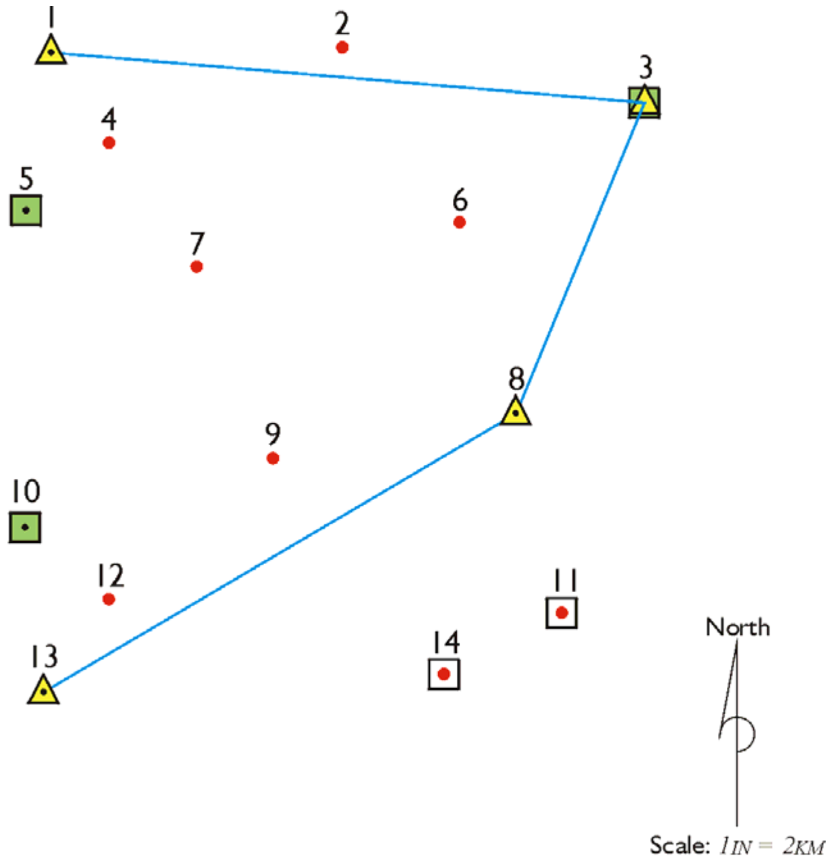
In the real world, such a project is not usually done with 14 receivers nor with 2 receivers, but with 3, 4, or 5. The achievement of redundancy takes a middle road. The number of independent occupations is still an important source of redundancy. In the two-receiver arrangement every line can be independent, but that is not the case when a project is done with any larger number of receivers. As soon as three or more receivers are considered, the discussion of redundant measurement must be restricted to independent baselines, excluding trivial lines.

Redundancy is then partly defined by the number of independent baselines that are measured more than once, as well as by the percentage of stations that are occupied more than once. While it is not possible to repeat a baseline without reoccupying its endpoints, it is possible to reoccupy a large percentage of the stations in a project without repeating a single baseline. These two aspects of redundancy in GPS - the repetition of independent baselines and the reoccupation of stations - are somewhat separate.

FGCC Standards for redundancy. To meet order AA geometric accuracy standards, the FGCC requires three or more occupations on 80 percent of the stations in a project. Three or more occupations are necessary on 40, 20, and 10 percent of the stations for A, B, and C standards, respectively. When the distance between a station and its azimuth mark is less than 2 km, both points must be occupied at least twice to meet any standard above 2nd order. All vertical control stations must be occupied at least twice for all orders of accuracy. Two or more occupations are required for all horizontal control station in order AA - the percentage requirements for repeat occupations on horizontal control stations drops to 75, 50, and 25 percent for A, B and C respectively. For new project points, reoccupation is mandated on 80, 50 and 10 percent of the stations in the project for A, B, and C, respectively.

The standards for repeat measurements of independent baselines in the FGCC provisional specifications note that an equal number of N-S and E-W vectors should be remeasured in a network. Of the independent baselines, 25 percent should be repeated in a project to meet order AA geometric accuracy standards. The standards require 15, 5 and 5 percent for orders A, B, and C respectively.

Unless a project is to be *blue-booked*, that is, submitted to the NGS for inclusion in the national network, or there is a contractual obligation, there is usually no need to meet the letter of the specifications listed above. They are offered here as an indication of the level of redundancy that is necessary for high-accuracy GPS work.



Session	Receivers				Independent Lines	Trivial Lines
	A	B	C	D		
49-1	1	3	8	13	1-3 3-8 8-13	13-1 1-8 3-13

Session	Receivers				Independent Lines	Trivial Lines
	A	B	C	D		

FIGURE 6.6

Figure 6.6 shows one of the many possible approaches to setting up the baselines for this particular GPS project. The survey design calls for the horizontal control to be occupied in session 49-1. It is to be followed by measurements between two control stations and the nearest adjacent project points in session 49-2. As shown in the table at the bottom of Figure 6.7, there will be redundant occupations on stations 1 and 3. Even though the same receivers will occupy those points, their operators will be instructed to reset them at a different H.I.s for the new session. A better, but probably less efficient, plan would be to occupy these stations with different receivers than were used in the first session.

Forming loops. As the baselines are drawn on the project map for a static GPS survey, or any GPS work where accuracy is the primary consideration, the designer should remember that part of their effectiveness depends on the formation of complete geometric figures. When the project is completed, these independent vectors should be capable of formation into closed loops that incorporate baselines from two to four different sessions. In the illustrated baseline plan, no loop contains more than ten vectors, no loop in more than 100 km long, and every observed baseline will have a place in a closed loop.

Finding the number of sessions. The illustrated survey design calls for 10 sessions, but the calculation does not include human error, equipment breakdown, and other unforeseeable difficulties. It would be impractical to presume a completely trouble-free project. The FGCC proposes the following formula for arriving at a more realistic estimate:

$$s = \frac{(m\cdot n)}{r} + \frac{(m\cdot n)(p-1)}{r} + k\cdot m$$

where

s = the number of observing sessions,
r = the number of receivers,
m = the total number of stations involved

But *n*, *p*, and *k* require a bit more explanation. The variable n is a representation of the level of redundancy that has been built into the network, based on the number of occupations on each station. The illustrated survey design includes more than two occupations on all but 4 of the 14 stations in the network. In fact, 10 of the 14 positions will be visited three or four times in the course of the survey. There are a total of 40 occupations by the 4 receivers in the 10 planned sessions. By dividing 40 occupations by 14 stations, it can be found that each station will be visited an average of 2.857 times. Therefore in the FGCC formula, the planned redundancy represented by factor *n* is equal to 2.857 in this project.

The experience of a firm is symbolized by the variable *p* in the formula. The division of the final number of actual sessions required to complete past projects by the initial estimation yields a ratio that can be used to improve future predictions. That ratio is the production factor, *p*. A typical production factor is 1.1.

A safety factor of 0.1, known as *k*, is recommended for GPS projects within 100 km of a company's home base. Beyond that radius, an increase to 0.2 is advised.

The substitution of the appropriate quantities for the illustrated project increases the prediction of the number of observation sessions required for its completion:

$$s = \frac{(mn)}{r} + \frac{(mn)(p-1)}{r} + km$$

$$s = \frac{(14)(2.857)}{4} + \frac{(14)(2.857)(1.1-1)}{4} + (0.2)(14)$$

$$s = \frac{40}{4} + \frac{4}{4} + 2.8$$

$$s = 10 + 1 + 2.8$$

$$s = 14 \text{ sessions (rounded to the nearest integer)}$$

In other words, the 2-day, 10-session schedule is a minimum period for the baseline plan drawn on the project map. A more realistic estimate of the observation schedule includes 14 sessions. It is also important to keep in mind that the observation schedule does not include time for on-site reconnaissance.

Ties to the vertical control. The ties from the vertical control stations to the overall network are usually not handled by the same methods used with the horizontal control. The first session of the illustrated project was devoted to occupation of all the horizontal control stations. There is no similar method with the vertical control stations. First, the geoidal undulation would be indistinguishable from baseline measurement error. Second, the primary objective in vertical control is for each station to be adequately tied to its closest neighbor in the network.

If a benchmark can serve as a project point, it is nearly always advisable to use it, as was done with stations 11 and 14 in the illustrated project. A conventional level circuit can often be used to transfer a reliable orthometric elevation from vertical control station to a nearby project point.

REAL TIME KINEMATIC, RTK AND DIFFERENTIAL GPS, DGPS

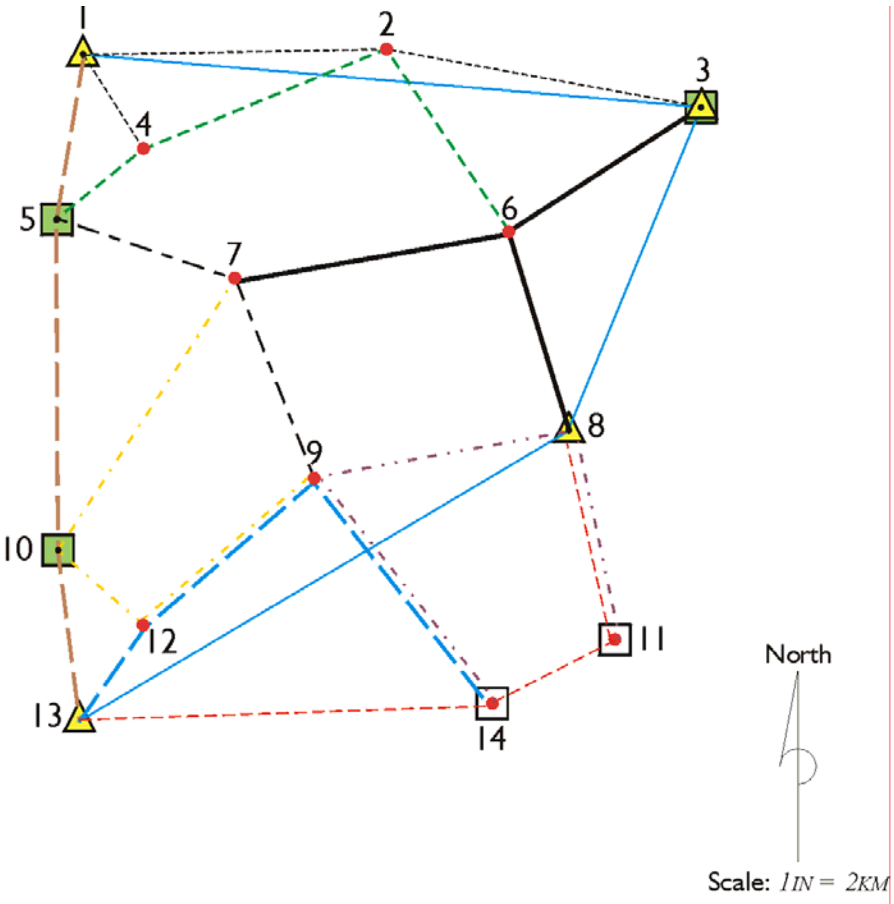
Most, not all, GPS surveying relies on the idea of differential positioning. The mode of a base or reference receiver at a known location logging data at the same time as a receiver at an unknown location together provide the fundamental information for the determination of accurate coordinates. While this basic approach remains today, the majority of GPS surveying is not done in the static post-processed mode just described. Post-processsing is most often applied to control work. Now, the most commonly used methods utilize receivers on reference stations that provide correction signals to the end user via a data link sometimes over the internet, radio signal or cell phone and often in real-time.

In this category of GPS surveying work there is sometimes a distinction made between code-based, DGPS, and carrier based, RTK, solutions. In fact, most systems use a combination of code and carrier measurements so the distinction is more a matter of emphasis rather than an absolute difference.

The General Idea

Errors in satellite clocks, imperfect orbits, the trip through the layers of the atmosphere, and many other sources contribute inaccuracies to GPS signals by the time they reach a receiver. These errors are variable, so the best to way to correct them is to monitor them as they happen. A good way to do this is to set up a GPS receiver on a station whose position is known exactly, a base station. This base station receiver's computer can calculate its position from satellite data, compare that position with its actual known position, and find the difference and presto, error corrections. It works well, but the errors are constantly changing so a base station has to monitor them all the time, at least all the time the rover receiver or receivers are working. While this is happening the rovers move from place to place collecting the points whose positions you want to know relative to the base station, which is the real objective after all. Then all you have to do is get those base station corrections and the rover's data together somehow. That combination can be done over a data link in real-time, or applied later in post-processing.

Both RTK and DGPS have been built on the foundation of the idea that, with the important exceptions of multipath and receiver noise, GPS error sources are correlated. In other words, the closer the rover is to the base the more the errors at the ends of the baseline match. The shorter the baseline, the more the errors are correlated. The longer the baseline the less the errors are correlated.



Session	Receivers				Independent Lines	Trivial Lines
	A	B	C	D		
49-1	1	3	8	13	1-3 3-8 8-13	13-1 1-8 3-13
49-2	1	3	2	4	1-2 2-3 1-4	1-3 3-4 2-4
49-3	5	6	2	4	5-4 4-2 2-6	5-6 2-5 4-6
49-4	5	6	7	9	5-7 7-9 6-7	5-6 6-9 5-9
49-5	5	1	10	13	1-5 5-10 10-13	1-10 1-13 5-13

Session	Receivers				Independent Lines	Trivial Lines
	A	B	C	D		
50-1	10	12	7	9	7-10 10-12 9-12	7-12 9-10 7-9
50-2	14	12	13	9	9-12 12-13 9-14	13-14 12-14 9-13
50-3	14	8	13	11	13-14 14-11 11-8	13-8 8-14 13-11
50-4	14	8	11	9	14-9 8-9 8-11	9-11 8-14 14-11
50-5	7	6	3	8	6-8 6-7 3-6	3-8 3-7 7-8

FIGURE 6.7

Radial GPS. In both RTK and DGPS surveying radial GPS has become the typical surveying style. There are advantages to the approach. (Figure 6.7). The advantage is a large number of positions can be established in a short amount of time with little or no planning. The disadvantage is that there is little or no redundancy in positions derived from this approach since all the baselines originate from the same control station. Redundancy can be incorporated, but it requires repetition of the observations. One way to do it is to occupy the project points, the unknown positions, successively with more than one rover. It is best if these successive occupations are separated by at least 4 hours and not more than 8 hours so the satellite constellation can reach a significantly different configuration.

Another more convenient but less desirable approach is to do a second occupation almost immediately after the first. The roving receiver's antenna is blocked or tilted until the lock on the satellites is interrupted. It is then re-oriented on the unknown position a second time for the repeat solution. This does offer a second solution, but from virtually the same constellation.

A third way to achieve redundancy is to occupy each point with the same rover but utilizing a different base station. This approach allows a solution to be available from two separate control stations. Obviously, this can be done with re-occupation of the project points after one base station has been moved to a new control point, or a two base stations can be up and running from the very outset and throughout of the work as would be the case using two CORS stations. It is best if there are both two occupations on each point and each of the two utilize different base stations.

More efficiency can be achieved by adding additional roving receivers. However, as the number of receivers rises, the logistics become more complicated, and a survey plan becomes necessary. Also, project points that are simultaneously near one another but far from the control station should be directly connected with a baseline to maintain the integrity of the survey. Finally, if the base receiver loses lock and it goes unnoticed, it will completely defeat the radial survey for the time it is down.

The Correction Signal. The agreed upon format first designed for communication between the base station and rovers used in marine navigation is known as ***RTCM.*** In 1985, *the Radio Technical Commission for Maritime Services, RTCM, Special Committee, SC-104,* created a standard that is still more used than any proprietary formats that have come along since. It was originally designed to accommodate a slow data rate with a configuration somewhat similar to the navigation message. It is important to note that RTCM is *open*, in other words it is a general purpose format and is not restricted to a particular receiver type. It works across platforms and the pseudorange correction is made up of a sequence of different message types

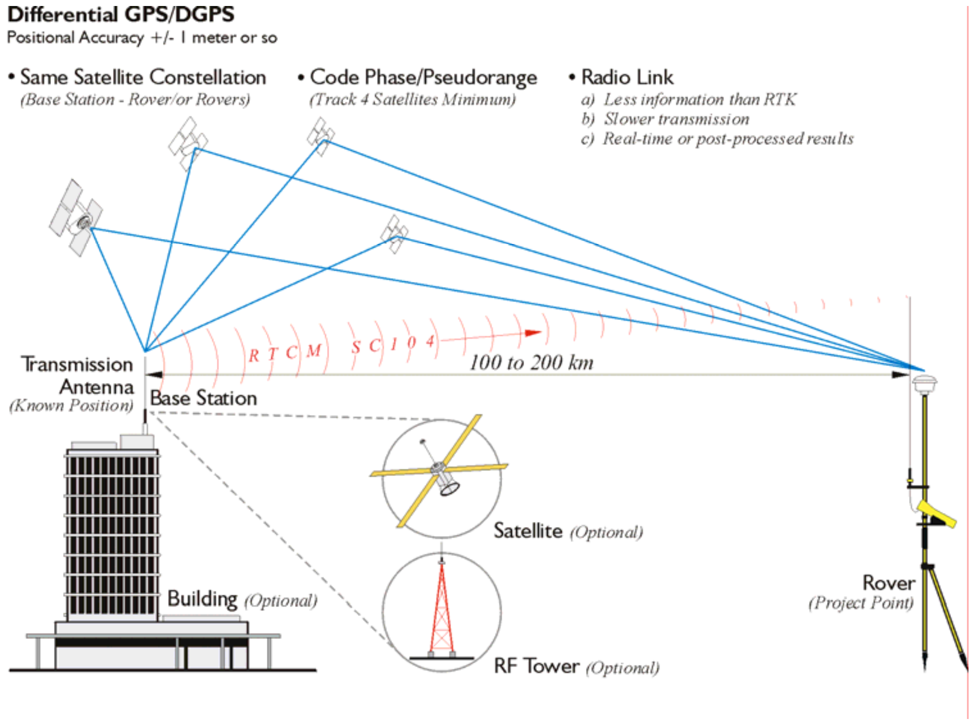


FIGURE 6.8

The term DGPS is most often used to refer to differential GPS that is based on pseudoranges, aka code phase. Even though the accuracy of code phase applications was given a boost with the elimination of Selective Availability, SA, in May 2000 consistent accuracy better than 5 meters or so still requires reduction of the effect of correlated ephemeris and atmospheric errors by differential corrections. Though the corrections could be applied in post-mission processing services that supply these corrections most often operate in real-time.

Real-time. Usually, pseudorange corrections, rather than coordinate corrections, are broadcast from the base to the rover or rovers for each satellite in the visible constellation. Rovers with an appropriate *input/output, I/O,* port that can receive the correction signal and calculate coordinates. The real-time signal comes to the receiver over a data link. It can originate at a project specific base station or it can come to the user through a service of which there are various categories. Some are open to all users and some are by subscription only. Coverage depends on the spacing of the beacons, aka transmitting base stations, their power, interference and etc. Some systems require two-way, some one-way, communication with the base stations. Radio systems, geostationary satellites, low-earth-orbiting satellites and cellular phones are some of the options available for two-way data communication. In any case, most of the wide variety of DGPS services were not originally set up to augment surveying and mapping applications of GPS they were established to aid GPS navigation.

Local and Wide Area DPGS. As mentioned earlier the correlation between most of the GPS biases becomes weaker as the rover gets farther from the base. The term *Local Area Differential GPS, LADGPS*, is used when the baselines from a single base station to the roving receivers using the service are less than a couple of hundred kilometers.

The term *Wide Area Differential GPS, WADGPS* is used when the service uses a network of base stations and distributes correction over a larger area, an area that may even be continental in scope. Many bases operating together provide a means by which the information from several of them can be combined to send a normalized or averaged correction tailored to the rover's geographical position within the system. Some use satellites to provide the data link between the service provider and the subscribers. Such a system depends on the network of base stations receiving signals from the GPS satellites and then streaming that data to a central computer at a control center. There the corrections are calculated uploaded to a geo-stationary communication satellite. Then the communication satellite broadcasts the corrections to the service's subscribers.

While some services that broadcast RTCM corrections by satellite and others use tower mounted transmitters. In all cases, the base stations are at known locations and their corrections are broadcast to all rovers that are equipped to receive their particular radio message carrying real-time corrections in the RTCM format. An example of such a DGPS service originated as an augmentation for marine navigation.

Maritime DGPS. Both the *United States Coast Guard, USCG,* and the *Canadian Coast Guard, CCG* instituted DGPS services to facilitate harbor entrances, ocean mapping, marine traffic control as well as navigation in inland waterways. Their system base stations beacons broadcast GPS corrections along major rivers, major lakes, the east coast and the west coast. The sites use marine beacon frequencies of 255-325 kHz which has the advantage of long range propagation that can be several hundreds of kilometers. Access to the broadcasts is free and over recent years the service has become very popular outside of its maritime applications particularly among farmers engaged in GPS aided precision agriculture. Therefore, the system has been extended beyond waterways across the continental US and is now known as the *Nationwide DGPS* or *NDGPS*. There are currently 86 base stations. Of these 39 are USCG sites, 38 are *Department of Transportation, DOT* sites and 9 are *Corps of Engineers* sites.

Wide Area Augmentation System, WAAS. Another US DGPS service initiated in 1994 cooperatively by the *Department of Transportation, DOT* and the *Federal Aviation Administration, FAA* is known as WAAS. It is available to users with GPS receivers equipped to receive it. The signal is free and its reliability is excellent. While the official horizontal accuracy is 7.6 m, its capability to actually deliver approximately 1m horizontally makes it a possible alternative to Wide Area DGPS. It utilizes both satellite based, also known as *SBAS,* and ground based augmentations and was initially designed to assist aerial navigation from take-off, en route through landing. Reference stations on the ground send their data via processing sites to two Ground Earth Stations that upload differential corrections and time to geostationary satellites, *Inmarsat III's*, devoted to transmission of GPS differential corrections to users.

Another WAAS is planned for the *European Geostationary Navigation Overlay Service, EGNOS.* This system will augment GPS and GLONASS using three geostationary and a network of ground stations. The Japanese are planning a similar WAAS known by the acronym *MSAS*.

Latency. It takes some time for the base station to calculate corrections and it takes some time for it to put the data into packets in the correct format and transmit them. Then the data makes its way from the base station to the rover over the data link. It is decoded and must go through the rover's software. The time this takes is called the *latency* of the communication between the base station and the rover**.** It can be as little as a quarter of a second or as long as a couple of seconds. And since the base stations corrections are only accurate for the moment they were created, the base station must send a range rate correction along with them. Using this rate correction, the rover can *back date* the correction to match the moment it made that same observation.

Identical Constellation. DGPS requires that all receivers collect pseudoranges from the same constellation of satellites. It is vital that the errors corrected by the base station are common to the rovers. The rover must share its selection of satellites with the base station; otherwise it would be necessary to create differential corrections for all the combinations of all the available satellites. That could get unmanageable in a hurry, for example, with just four satellites above the observer's horizon there can be more than 80 such combinations.

GIS Applications for DGPS. Aerial navigation, marine navigation, agriculture, vehicle tracking and construction are all now using DGPS. DGPS is also useful in land and hydrographic surveying, but perhaps the fastest growing application for DGPS is in data collection, data updating and even in-field mapping for Geographic Information Systems, GIS.

GIS data has long been captured from paper records such as digitizing and scanning paper maps. Photogrammetry, remote sensing and conventional surveying has also been data sources for GIS. More recently, data collected in the field with DGPS has become significant in GIS.
GIS data collection with DGPS requires the integration of the position of features of interest and relevant attribute information about those features. Whether a hand-held datalogger, an electronic notebook or a pen computer are used the attributes to be collected are defined by the data dictionary designed for the particular GIS.

In GIS it is frequently important to return to a particular site or feature to perform inspections or maintenance. DGPS with real-time correction makes it convenient to load the position or positions of features into a datalogger, and navigate back to the vicinity. But to make such applications feasible, a GIS must be kept current. It must be maintained. A receiver configuration including real-time DGPS, sufficient data storage and graphic display allows easy verification and updating of existing information.

DGPS allows the immediate attribution and validation in the field with accurate and efficient recording of position. In the past many GIS mapping efforts have often relied on ties to street centerlines, curb-lines, railroads and etc. Such dependencies can be destroyed by demolition or new construction. But, meter level positional accuracy even in obstructed environments such as urban areas, amid high-rise building is possible with DGPS. In other words, with DGPS the control points are the satellites themselves, therefore it can provide reliable positioning even if the landscape has changed. And its data can be integrated with other technologies, such as laser range-finders, etc. in environments where DGPS is not ideally suited by to the situation.

Finally, loading GPS data into a GIS platform does not require manual intervention. GPS data processing can be automated, the results are digital and can pass into a GIS format without redundant effort, reducing the chance for errors.

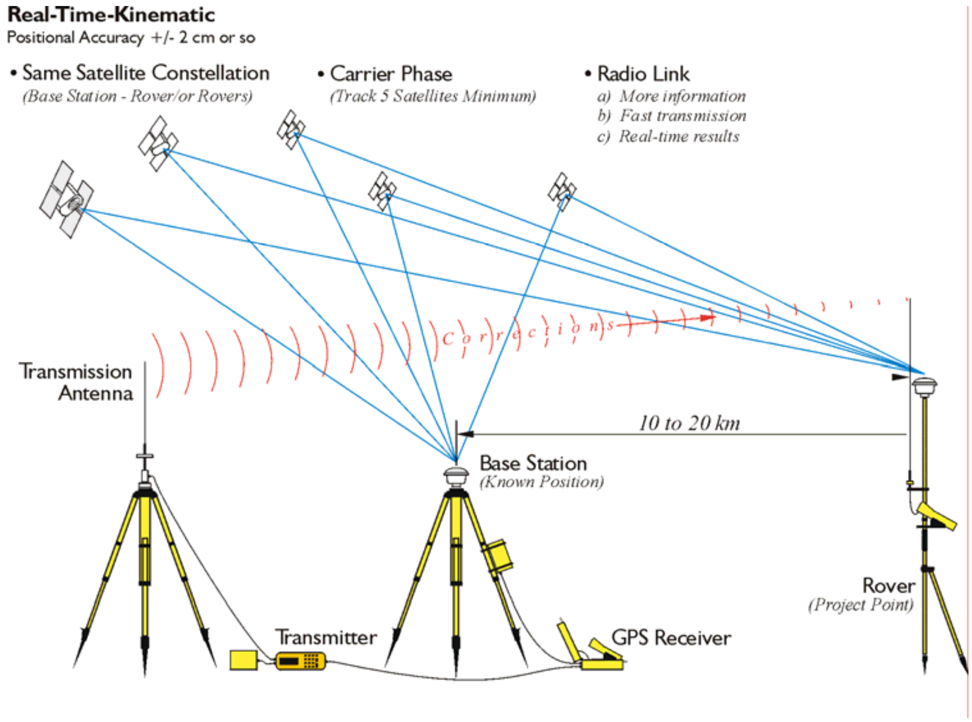


FIGURE 6.9

Kinematic surveying, also known as stop-and-go kinematic surveying is not new. The original kinematic GPS innovator, Dr. Benjamin Remondi developed the idea in the mid-1980s. RTK is a method that can offer positional accuracy nearly as good as static carrier phase positioning, but RTK does it in real-time. Today, RTK has become routine in development and engineering surveys where the distance between the base and roving receivers can most often be measured in thousands of feet. RTK is capable of delivering accuracy within a few centimeters. RTK is a GPS method that definitely uses carrier phase observations corrected in real-time and therefore it depends on the fixing of the integer cycle ambiguity.

Fixing the Integer Ambiguity in RTK. The earliest processing software was capable of making C/A-code pseudorange, L1 carrier phase and usually half wavelength L2 carrier phase measurements. These techniques tended to require long static occupations up to an hour or more. With that amount of data the software could estimate the integer ambiguity rather well and then round the results to the nearest integer. In this era kinematic GPS was not used often. Later both receiver hardware and data processing algorithms improved and by the 1990s both rapid static positioning and RTK positioning systems began using "on-the-fly" (OTF) integer ambiguity resolution.

Many RTK systems resolve the integer ambiguity, *on-the-fly*. *On-the-fly* refers to a method of resolving the carrier phase ambiguity very quickly. The method requires a dual-frequency GPS receiver capable of making both carrier phase and precise pseudorange measurements. The receiver is not required to remain stationary.

Here is one way it can be done. A search area is defined in the volume of the possible solutions, but that group is narrowed down quite a bit by using pseudoranges. If the number of integer combinations to be tested is greatly reduced with precise pseudoranges the search can be very fast. The possible solutions in that volume are tested statistically, according to a minimal variance criterion, and the best one is found. This candidate is verified, i.e. compared with the second best candidate. The process can take less than 10 seconds under the best circumstances where the receivers are tracking a large constellation of satellites, the PDOP is small, the receivers are dual-frequency, there is no multipath and the receiver noise is low. This technique relies on dual frequency information. Observations on L1 and L2 are combined into a widelane, which has an ambiguity of about 86 cm, and the integer ambiguity is solved in a first pass. This information is used to determine the kinematic solution on L1. Therefore, it is a good idea to restrict RTK to situation where there is good correlation of atmospheric biases at both ends of the baseline. In other words, RTK is best used when the distance between the base and rover is less than 20 km; this is usually not a problem.

Today the development of GPS receivers with virtually instantaneous carrier phase-based positioning has become feasible on a routine basis. Not only that, but these techniques of integer ambiguity resolution, validation and quality control, are being further improved to apply to GPS, GLONASS and Galileo data processing.

Radio License. RTK often requires a radio link between the base station and the rover, and the modems at each end must be tuned to the same frequency. The usual configuration operates at 4800 baud or faster. The units communicate with each other along a direct line-of-sight. Most radios connected to RTK GPS surveying equipment operate between UHF 400-475 MHz or VHF 170-220 MHz, and emergency voice communications also tend to operate in this same range, which can present problems from time to time.

The transmitter at the base station is usually the larger and more powerful of the two radios. However, the highest wattage radios, 35 Watts or so, cannot be legally operated in some countries. Lower power radios, from ½ W to 2 W are sometimes used in such circumstances. The radio at the rover has usually lower power and smaller. The *Federal Communications Commission, FCC* is concerned with some RTK GPS operations interfering with other radio signals, particularly voice communications. It is important for GPS surveyors to know that voice communications have priority over data communications.

The FCC requires cooperation among licensees that share frequencies. Interference should be minimized. For example, it is wise to avoid the most typical community voice repeater frequencies. They usually occur between 455_460 MHz and 465_470 MHz. Part 90 of the Code of Federal Regulations, 47 CFR 90, contains the complete text of the FCC Rules including the requirements for licensure of radio spectrum for private land mobile use. The FCC does require application be made for licensing a radio transmitter. Fortunately, when the transmitter and rover receivers required for RTK operations are bought simultaneously radio licensing and frequency selection are often arranged by the GPS selling agent. Nevertheless, it is important that surveyors do not operate a transmitter without a proper license. Please remember that the FCC can levee fines for several thousand dollars for each day of illegal operation. More can be learned by consulting the FCC Wireless Fee Filing Guide http://wireless.fcc.gov/feesforms/feeguide/ and http://wireless.fcc.gov/feesforms/feeguide/services/landmobile.pdf.

There are also other international and national bodies that govern frequencies and authorize the use of signals elsewhere in the world. In some areas certain bands are designated for public use, and no special permission is required. For example, in Europe it is possible to use the 2.4 GHz band for spread spectrum communication without special authorization with certain power limitations. Here in the United States the band for spread spectrum communication is 900 MHz.

Cell Phone. There is an alternative to the radio link method of RTK; the corrections can be carried to the rover using a cell phone. The cell phone connection does tend to ameliorate the signal interruptions that can occur over the radio link, and it offers a somewhat wider effective range in some circumstances. With the cell phone connected to the receiver via a serial cable or Bluetooth^{TM} technology. The use of cell phones in this regard is frequently a characteristic of *Real-Time Network, RTN* solutions, more about that in a moment.

Typical RTK. A typical RTK set-up includes a base station and rover or rovers. They can be single- or dual-frequency receivers with GPS antennas, but dual- frequency receivers are usual. The radio receiving antennas for the rovers will either be built into the GPS antenna or separate units. It is usual that the radio antenna for the data transmitter and the rover are omnidirectional whip antennas, however at the base it is usually on a separate mast and has a higher gain than those at the rovers.

The position of the transmitting antenna affects the performance of the system significantly. It is usually best to place the transmitter antenna as high as is practical for maximum coverage and the longer the antenna- the better its transmission characteristics. It is also best if the base station occupies a control station that has no overhead obstructions, is unlikely to be affected by multipath and is somewhat away from the action if the work is on a construction site. It is also best if the base station is within line of sight of the rovers. If line of sight is not practical as little obstruction as possible along the radio link is best.

The data radio transmitter consists of an antenna, a radio modulator and an amplifier. The modulator converts the correction data into a radio signal. The amplifier increases the signal's power, which determines how far the information can travel. Well, not entirely, the terrain and the height of the antenna have something to do with it too. RTK work requires a great deal of information be successfully communicated from the base station to the receivers. The base station transmitter ought to be VHF, UHF or spread spectrum -frequency hopping or direct to have sufficient capacity to handle the load. UHF spread spectrum radio modems are the most popular for DGPS and RTK applications. The typical gain on the antenna at the base is 6 dB. But while DGPS operations may need no more than 200 bps, bits-per-second, updated every 10 seconds or so, RTK requires at least 2,400 bps updated about every ½ second or less. Like the power of the transmission, the speed of the link between the base and rover, *the datarate,* can also be a limiting factor in RTK performance

As mentioned earlier RTK is at its best when the distance between the base station and the rovers is less than 20 km, under most circumstances, but even before that limit is reached the radio data link can be troublesome. In areas with high radio traffic it can be difficult to find an open channel. It is remarkable how often the interference emanates from other surveyors in the area doing RTK as well. That is why most radio data transmitters used in RTK allow the user several frequency options within the legal range.

It is vital, of course, that the rover and the base station are tuned to the same frequency for successful communication. The receiver also has an antenna and a demodulator. The demodulator converts the signal back to an intelligible form for the rover's receiver. The data signal from the base station can be weakened or lost at the rover from, reflection, refraction, atmospheric anomalies, or even being too close. A rover that is too close to the transmitter may be overloaded and not receive the signal properly, and, of course, even under the best circumstances the signal will fade as the distance between the transmitter and the rover grows too large.

The Vertical Component in RTK. The output of RTK can appear to be somewhat similar to that of optical surveying with an EDM and a level. The results can be immediate and with similar relative accuracy. Nevertheless, it is not a good idea to consider the methods equivalent. RTK offers some advantages, and some disadvantages when compared with more conventional methods. For example, RTK can be much more productive since it is available 24 hours a day and is not really by weather conditions. However, when it comes to the vertical component of surveying RTK and the level and certainly not equal.

GPS can be used to measure the differences in ellipsoidal height between points with good accuracy. However, unlike a level - unaided GPS cannot be used to measure differences in orthometric height. Or, as stated in Chapter Five, "orthometric elevations are not directly available from the geocentric position vectors derived from GPS measurements." The accuracy of orthometric heights in GPS is dependent on the veracity of the geoidal model used and the care with which it is applied.

Fortunately, ever improving geoid models have been, and still are, available from NGS. Since geoidal heights can be derived from these models, and ellipsoidal heights are available from GPS it is certainly feasible to calculate orthometric heights. In the past these calculations were done exclusively in post-processed network adjustments. Today, more and more manufacturers are finding ways to include a geoid model in their RTK systems. However, it is important to remember that without a geoid model RTK will only provide differences in ellipsoid heights between the base station and the rovers.

It is not a good idea to presume that the surface of the ellipsoid is sufficiently parallel to the surface of the geoid and ignore the deviation between the two. They may depart from one another as much as a meter in 4 or 5 kilometers.

Some Practical RTK Suggestions

Typical Satellite Constellations. In RTK, generally speaking, the more satellites that are available the faster the integer ambiguities will be resolved. In the United States there are usually 6 satellites or so above an observer's horizon most of the time. And there are likely to be approximately 8 satellites above an observer's horizon about a third of the time, more only seldom. For baselines under 10 km an 8 satellite constellation should be quite adequate for good work under most circumstances.

Dual Frequency Receiver. A dual-frequency receiver is a real benefit in doing RTK. Using a dual-frequency receiver instead of a single-frequency receiver is almost as if there were one and a half more satellites available to the observer.

Setting up a Base Station. Set up the base station over a known position first, before configuring the rover After the tripod and tribrach are level and over the point, attach the GPS antenna to the tribrach and, if possible, check the centering again.

Set up the base station transmitter in a sheltered location at least 10 feet from the GPS antenna, and close to the radio transmitter's antenna. It is best if the air flow of the base station transmitter's cooling fan is not restricted. The radio transmitter's antenna is often mounted on a range pole attached to a tripod. Set the radio transmitter's antenna as far as possible from obstructions and as high as stability will allow.

The base station transmitter's power is usually provided by a deep-cycle battery. Even though the cable is usually equipped with a fuse, it is best to be careful to not reverse the polarity when connecting it to the battery. It is also best to have the base station transmitter properly grounded, and avoid bending or kinking any cables.

After connecting the base station receiver to the GPS antenna, to the battery and the data collector, if necessary, carefully measure the GPS antenna height. This measurement is often the source of avoidable error, both at the base station and the rovers. Many surveyors measure the height of the GPS antenna to more than one place on the antenna, and it is often measured in both meters and feet for additional assurance.

Select a channel on the base station transmitter that is not in use, and be sure to note the channel used so that it may be set correctly on the rovers as well.

After the RTK survey. When the RTK work is done it is best to review the collected data from the data logger. Whether or not fixed height rods have been used it is a good idea to check the antenna heights. Incorrect antenna heights are a very common mistake. Another bulwark against blunders is the comparison of different observations of the same stations. If large discrepancies arise there is an obvious difficulty. Along the same line it is worthwhile to check for discrepancies in the base station coordinates. Clearly if the base coordinate is wrong the work created from that base is also wrong. Finally, look at the residuals of the final coordinates to be sure they are within reasonable limits. Remember that multipath and signal attenuation can pass by the observer without notice during the observations, but will likely affect the residuals of the positions where they occur.

Comparing RTK and DGPS

Multipath in RTK and DGPS. While most other errors in GPS discussed earlier can be mediated, or cancelled, due to the relatively short distance between receivers the same cannot be said for multipath.

Environments that have the highest incidence of multipath, such as downtown city streets, are the places where RTK and DGPS called upon most often. Yet in these techniques the position is computed over a very few epochs, there is little if any of the averaging of errors from epoch to epoch available in other applications. Therefore, in RTK the affect of multipath is rather direct, and even if it distorts the results only slightly, it may be too much in some situations. In principle, multipath affects carrier observations the least. It is a bit worse for P-code pseudoranges. And in the observable used in most DGPS, C/A-code pseudoranges, multipath affects the results the most. But receiver manufacturers have created ingenious technologies to minimize the multipath effects in DGPS pseudoranges. Therefore, it is entirely possible to find that it is in the RTK carrier phase application that multipath contributes the largest bias to the error budget

Initialization. As mentioned, RTK relies on the carrier phase and the integer ambiguity must be solved. In other words, the method requires some time for initialization, usually at the start of day. Initialization is also required any time after which the continuous tracking of all available satellite signals stops for even the briefest length of time. After tracking of the same GPS satellites begins at the base station and the roving receiver or receivers, there is usually a short wait is required for initialization to be accomplished. With many dual frequency RTK receivers, capable of reinitializing On-the-Fly initialization can happen very quickly. Some receivers might require a return to a known coordinated position for re-initialization. On the other hand, DGPS relies on pseudoranges; its immediate initialization is a clear advantage over some RTK systems. But DGPS can only provide meter accuracy, whereas RTK offers centimeter-level positional accuracies.

Base Station. Concerning base stations, in both RTK and DGPS, a base station on a coordinated control position must be available. Its observations must be simultaneous with those at the roving receivers and it must observe the same satellites.

It is certainly possible to perform a differential survey in which the position of the base station is either unknown, or based on an assumed coordinate, at the time of the survey. However, unless only relative coordinates are desired, the position of the base station must be known. In other words, the base station must occupy a control position, even if that control is established later.

Utilization of the DGPS techniques requires a minimum 4 satellites for three-dimensional positioning. RTK ought to have at least 5 satellites for initialization. Tracking 5 satellites is a bit of insurance against losing one abruptly; also it adds considerable strength to the results. While cycle slips are always a problem it is imperative in RTK that every epoch contains a minimum of four satellite data without cycle slips. This is another reason to always track at least 5 satellites when doing RTK. Both methods most often rely on real-time communication between the base station and roving receivers. But RTK base station corrections are generally more complex than those required in DGPS.

RTCM Version 3. For DGPS there are more sources of real-time correction signals all the time. There are commercial providers and earth-bound systems. Originally sources offered code-phase corrections in the RTCM SC-104 format appropriate to DGPS. However, when it became clear in 1994 that including carrier phase information in the message could improve the accuracy of the system RTCM Special Committee 104 added four new message types to Version 2.1 to fulfill the needs of RTK. Still proprietary message formats were more widely used in RTK work than in DGPS so further improvements were made along the same line in Version 2.2 which became available in 1998. And the changes continue, in 2007 the Radio Technical Commission for Maritime Services Special Committee 104 published its Version 3 for Differential Global Navigation Satellite System, GNSS, services. It is called RTCM 10403.1 documents concerning the details of this standard are available at www.rtcm.org

The GPS constellation along with the Russian GLONASS system and the European Galileo system are currently known together as the *Global Navigation Satellite Systems, GNSS.* It is likely that more systems will become included under the GNSS concept in the future. It is also likely that more accuracy of autonomous positions will be available from GNSS than GPS alone. However, in GNSS, as with GPS, even better accuracies can be achieved by broadcasting corrections from reference stations at precisely known locations. And by utilizing RTCM 10403.1 it is not only possible to use receivers from different manufacturers together, but also to incorporate signals from satellites other than GPS. Perhaps the term DGPS will be expanded to become *DGNSS.*

Another aspect of RTCM 10403.1 is especially interesting as regards its support of Real-Time Network Services.

Real-Time Network Services

There is no question that RTK dominates the GPS surveying applications. It is applicable to much of engineering, surveying, air-navigation, mineral exploration, machine control, hydrography and a myriad of other areas that require centimeter-level accuracy in real-time. However, the requirements of setting up a GPS reference station on a known position, the establishment of an RF transmitter and all attendant components before a single measurement can be made are both awkward and expensive. This, along with the baseline limitation of short baselines, 10 to 20 kilometers for centimeter level work, has made RTK both more cumbersome and less flexible than most surveyors prefer.

In an effort to alleviate these difficulties services have arisen around the world to provide RTCM real-time corrections to surveyors by a different means. The pace of the development of these *Real-Time Networks, RTN,* both by governments and commercial interests, is accelerating. The services are sometimes free and sometimes require the arrangement of a subscription or the payment of a fee before the surveyor can access the broadcast corrections over a datalink via a modem such as a cell-phone or some other device. Nevertheless there are definite advantages including the elimination of individual base station preparation and the measurement of longer baselines without rapid degradation of the results. These benefits are accomplished by the services gleaning corrections from a whole network of continuously operating reference stations, CORS, rather than just a single base. In this way, quality control is facilitated by the ability to check corrections from one CORS with those generated from another and should a CORS go off-line or give incorrect values other CORS in the network can take up the slack little accuracy loss.

The central idea underlying RTN differential corrections is the combination of observations from several CORS at known positions used to derive a model of an entire region. So rather than being considered as isolated beacons with each covering its own segregated area- the CORS are united into a network. The data from the network can then be used to produce a virtual model of the area of interest and from this model *distance-dependent* biases such as ionospheric, tropospheric and orbit errors can be calculated. Once the roving receivers place within that network is established it is possible to predict the errors at that position with a high degree of certainty. And not only can the CORS network be used to model errors in a region more correctly but the multi-base solution also can improve redundancy. Solving several baselines that converge on a project point simultaneously rather than the relying on just one from a typical RTK set up adds more certainty to the resulting coordinate.

Implementing an RTN requires data management and communication. The information from the CORS must be communicated to the central master control station where all the calculations are done. There raw measurement data, orbits, etc must be managed as they are received in real-time from each of the CORS that make up the network. Along with the modeling of the distance-dependent errors all the integer ambiguities must be fixed for each CORS in real-time. This is probably the most significant data processing difficulty required of an RTN, especially considering that there are usually large distances between the CORS. To accomplish it post-computed ephemerides, antenna phase center corrections and all other available information is brought to bear on the solution such as tropospheric modeling, ionospheric modeling.

Modeling is subject to variation in both space and time. For example, ionospheric and orbit biases are satellite specific whereas tropospheric corrections can be estimated station by station. But the ionospheric, dispersive, biases change more rapidly than the tropospheric and orbit biases, which are non-dispersive. Therefore, ionospheric corrections must be updated more frequently than orbit and tropospheric corrections. And while it is best to keep the modeling for ionosphere within the limited area around three or so CORS, when it comes to tropospheric and orbital modeling the more stations used the better.

Finally, the pseudorange and/or carrier phase residuals must be determined for the L1 and/or L2, by using one of many techniques to interpolate the actual distance-dependent corrections for the surveyor's particular position within the network. Then the subsequent corrections must be communicated to the surveyor in the field which typically requires the transmission of a large amount of data. There is more than one way the appropriate correction can be determined for a particular position within an RTN. So far there is no clear best method. One approach is the creation of a *Virtual Reference Station, VRS,* and the attendant corrections. This approach requires a two-way communication link. Users must send their approximate positions to the master control center, usually via an NMEA string. The master control center returns corrections for an individual VRS via RTCM and then the baseline processing software inside the rover calculates its position using the VRS which seems to the receiver to be a single nearby reference station. Another method involves sending basic RTK type corrections. Or the system may broadcast raw data for all the reference stations.

Precise Point Positioning. Differential GPS whether real-time or post-processed is the foundation of nearly all surveying applications in the field. However, when precise GPS orbital information and clock data became broadly available a new technique arose that is not differential in the usual sense.

As mentioned earlier errors in satellite clocks and imperfect orbital information contribute substantial inaccuracies to GPS work, especially in autonomous positioning. And the corrections available from the Navigation Message are not adequate to reduce those biases sufficiently, but positions several orders of magnitude better than the broadcast corrections can support can be achieved with *Precise Point Positioning, PPP*. The technique often utilizes the precise GPS orbit and clock products available from international sources to correct data collected by dual frequency receivers to ameliorate the ionospheric delay. It is important to note that PPP is not a code-only solution but rather relies on code and phase observations. The sources for the precise orbit and clocks products include the *International GNSS service- IGS, the Jet Propulsion Laboratory-JPL* and *Natural Resources Canada- NRCan* among others. In fact, NRCan offers an on-line service known as *CSRS - Precise Point Positioning, CSRS-PPP* which permits users to submit their collected GPS data over the Internet for PPP processing GPS observations with the results can be returned in NAD83 or ITRF -http://www.geod.nrcan.gc.ca/ppp_e.php

On the downside, there can be a bit of lag time between the collection of the data and the availability of precise ephemeris and clock information from free sources and PPP can require a rather long initialization period, perhaps a half-hour. And since the method utilizes undifferenced observations PPP cannot rely on the concept that the carrier phase ambiguity, N, is an integer. The lack of certain knowledge that N must be an integer complicates the solution.

However, there are several advantages to PPP. A single GPS receiver is all that is required and there is no need to run a base station during the work. While an RTN also alleviates a surveyor from the responsibility of operating a second receiver, PPP removes the necessity to stay within the area covered by a network, a base station or a CORS. PPP can provide more consistency over large areas, generally speaking and offers a valuable solution where a control network is simply unavailable.

Summary. So here are the fundamental ideas that underlie some GPS surveying techniques. Most often, a fixed point with previously established coordinates is occupied by a one receiver, a base station. The first receiver, the base, provides the data to compute the differences between its known position and the unknown positions measured at the second, or roving receiver. Static GPS requires post-processing and is used for establishing control by GPS. With DGPS the corrections can either be applied in post-processing or in real-time. And while correlated systematic errors can be virtually eliminated with differential correction the biases such as multipath and receiver channel noise are certainly not. These errors have been much reduced in modern GPS receivers, but not completely defeated. Biases such as high PDOP can only be resolved with both good receiver design and care as to when and where the surveying is done.

Real-Time Kinematic is the method of choice for much of GPS work but the technique is being supported more and more by Real-Time Networks as opposed to dedicated individual base stations. And Precise Point Positioning, PPP, offers a centimeter or decimeter solution that does not rely on differential correction as it is usually defined, but rather precise ephemeris and clock data. Finally, all of these techniques will be improved as the Global Navigation Satellite System, GNSS, matures.