CHAPTER SEVEN

Observing and Processing

STATIC GPS CONTROL OBSERVATIONS

The prospects for the success of a GPS project are directly proportional to the quality and training of the people doing it. The handling of the equipment, the on-site reconnaissance, the creation of field logs, and the inevitable last-minute adjustments to the survey design all depend on the training of the personnel involved for their success. There are those who say the operation of GPS receivers no longer requires highly qualified survey personnel. That might be true if effective GPS surveying needed only the pushing of the appropriate buttons at the appropriate time. In fact, when all goes as planned, it may appear to the uninitiated that GPS has made experienced field surveyors obsolete. But when the unavoidable breakdowns in planning or equipment occur, the capable people, who seemed so superfluous moments before, suddenly become indispensable.

Equipment

Conventional equipment. Most GPS projects require conventional surveying equipment for spirit-leveling circuits, offsetting horizontal control stations and monumenting project points, among other things. It is perhaps a bit ironic that this most advanced surveying method also frequently has need of the most basic equipment. The use of brush hooks, machetes, axes, etc., can sometimes salvage an otherwise unusable position by removing overhead obstacles. Another strategy for overcoming such hindrances has been developed using various types of survey masts to elevate a separate GPS antenna above the obstructing canopy.

Flagging, paint, and the various techniques of marking that surveyors have developed over the years are still a necessity in GPS work. The pressure of working in unfamiliar terrain is often combined with urgency. Even though there is usually not a moment to spare in moving from station to station, a GPS surveyor frequently does not have the benefit of having visited the particular points before. In such situations, the clear marking of both the route and the station during reconnaissance is vital.

Despite the best route marking, a surveyor may not be able to reach the planned station, or, having arrived, finds some new obstacle or unanticipated problem that can only be solved by marking and occupying an impromptu offset position for a session. A hammer, nails, shiners, paint, etc. are essential in such situations.

In short, the full range of conventional surveying equipment and expertise have a place in GPS. For some, their role may be more abbreviated than it was formerly, but one element that can never be outdated is good judgment.

Safety equipment. The high-visibility vests, cones, lights, flagmen, and signs needed for traffic control cannot be neglected in GPS work. Unlike conventional surveying operations, GPS observations are not deterred by harsh weather. Occupying a control station in a highway is dangerous enough under the best of conditions, but in the midst of a rainstorm, fog, or blizzard, it can be absolute folly without the proper precautions. And any time and trouble taken to avoid infraction of the local regulations regarding traffic management will be compensated by an uninterrupted observation schedule.

Weather conditions also affect travel between the stations of the survey, both in vehicles and on foot. Equipment and plans to deal with emergencies should be part of any GPS project. First aid kits, fire extinguishers, and the usual safety equipment are necessary. Training in safety procedures can be an extraordinary benefit, but perhaps the most important capability in an emergency is communication.

Communications. Whether the equipment is handheld or vehicle mounted, two-way radios and cell phones are used in most GPS operations. However, the line of sight that is no longer necessary for the surveying measurements in GPS is sorely missed in the effort to maintain clear radio contact between the receiver operators. A radio link between surveyors can increase the efficiency and safety of a GPS project, but it is particularly valuable when last-minute changes in the observation schedule are necessary. When an observer is unable to reach a station or a receiver suddenly becomes inoperable, unless adjustments to the schedule can be made quickly, each end of all of the lines into the missed station will require reobservation.

The success of static GPS hinges on all receivers collecting their data simultaneously. However, it is more and more difficult to ensure reliable communication between receiver operators in geodetic surveys, especially as their lines grow longer.

One alternative to contact between surveyors is reliance on the preprogramming feature available on most GPS receivers today. This attribute usually allows the start - stop time, sampling rate, bandwidth, satellites to track, mask angle, data file name, and start position to be preset so that the operator need only set up the receiver at the appropriate station before the session begins. The receiver is expected to handle the rest automatically. In theory, this approach eliminates the chance for an operator error ruining an observation session by missing the time to power-up or improperly entering the other information. Theory falls short of practice here, and even if the procedure could eliminate those mistakes, entire categories of other errors remain unaddressed. Some advocate actually leaving receivers unattended in static GPS. This idea seems unwise on the face of it.

High-wattage, private-line FM radios are quite useful when line of sight is available between them or when a repeater is available. The use of cell phones may eliminate the communication problem in some areas, but probably not in remote locations. Despite the limitations of the systems available at the moment, achievement of the best possible communication between surveyors on a GPS project pays dividends in the long run.

GPS equipment. Most GPS receivers capable of geodetic accuracy are designed to be mounted on a tripod, usually with a tribrach and adaptor. However, there is a trend toward bipod- or range-pole-mounted antennas. An advantage of these devices is that they ensure a constant height of the antenna above the station. The mismeasured height of the antenna above the mark is probably the most pervasive and frequent blunder in GPS control surveying.

The tape or rod used to measure the height of the antenna is sometimes built into the receiver, and sometimes a separate device. It is important that the H.I. be measured accurately and consistently in both feet and meters, without merely converting from one to the other mathematically. It is also important that the value be recorded in the field notes and, where possible, also entered into the receiver itself.

Where tribrachs are used to mount the antenna, the tribrach's optical centering should be checked and calibrated. It is critical that the effort to perform GPS surveys to an accuracy of centimeters not be frustrated by inaccurate centering or H.I. measurement. Since many systems measure the height of the antenna to the edge of the ground plane or to the exterior of the receiver itself, the calibration of the tribrach affects both the centering and the H.I. measurement. The resetting of a receiver that occupies the same station in consecutive sessions is an important source of redundancy for many kinds of GPS networks. However, integrity can only be added if the tribrach has been accurately calibrated.

The checking of the carrier phase receivers themselves is also critical to the control of errors in a GPS survey, especially when different receivers or different models of antennas are to be used on the same work. The zero baseline test is a method that may be used to fulfill equipment calibration specifications where a three-dimensional test network of sufficient accuracy is not available. As a matter of fact, the simplicity of this test is an advantage. It is not dependent on special software or a test network. This test can also be used to separate receiver difficulties from antenna errors.

Two or more receivers are connected to one antenna with a *signal, or antenna, splitter*. The antenna splitter can be purchased from specialty electronics shops and are also available online. An observation is done with the divided signal from the single antenna reaching both receivers simultaneously. Since the receivers are sharing the same antenna, satellite clock biases, ephemeris errors, atmospheric biases and multipath are all canceled. In the absence of multipath, the only remaining errors are attributable to random noise and receiver biases. The success of this test depends on the signal from one antenna reaching both receivers, but the current from only one receiver can be allowed to power the antenna. This test checks not only the precision of the receiver measurements, but also the processing software. The results of the test should show a baseline of only a few millimeters.

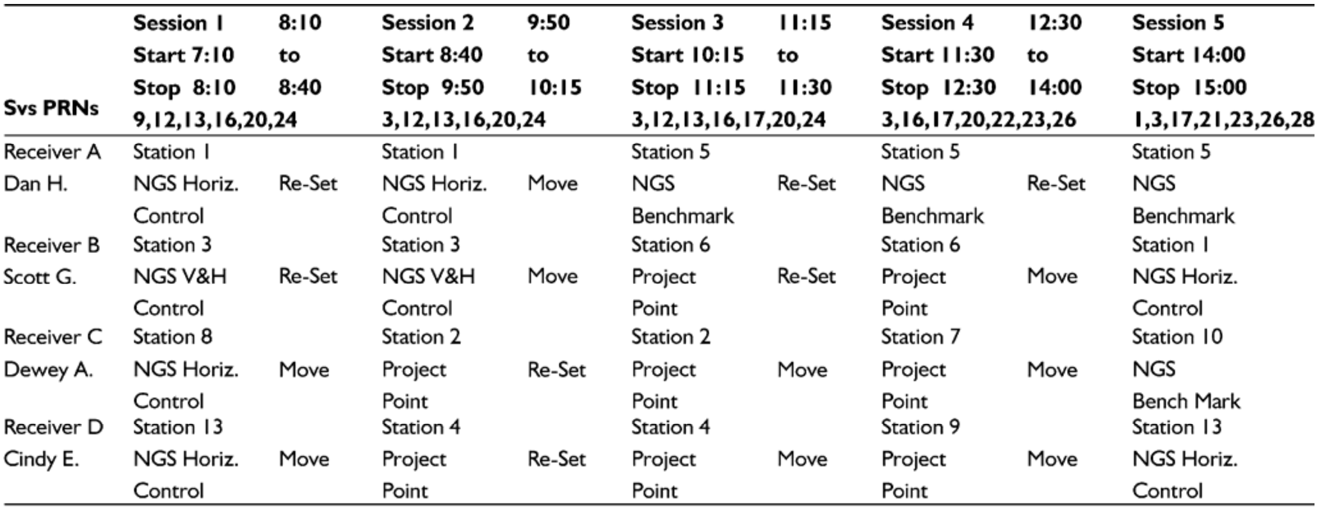
Information is also available on NGS calibration baselines throughout the United States. You can learn more by visiting the NGS site at http://www.ngs.noaa.gov/

Auxiliary equipment. Tools to repair the ends of connecting cables, a simple pencil eraser to clean the contacts of circuit boards, or any of a number of small implements have saved more than one GPS observation session from failure. Experience has shown that GPS surveying requires at least as much resourcefulness, if not more, than conventional surveying.

The health of the batteries are a constant concern in GPS. There is simply nothing to be done when a receiver's battery is drained but to resume power as soon as possible. A back-up power source is essential. Cables to connect a vehicle battery, an extra fully-charged battery unit, or both should be immediately available to every receiver operator.

Papers. The papers every GPS observer carries throughout a project ought to include emergency phone numbers; the names, addresses, and phone numbers of relevant property owners; and the combinations to necessary locks. Each member of the team should also have a copy of the virtual or hard copy project map, any other maps that are needed to clarify position or access, and, perhaps most important of all, the updated observation schedule.

The observation schedule for static GPS work will be revised daily based upon actual production (Table 7.1). It should specify the start-stop times and station for all the personnel during each session of the upcoming day. In this way, the schedule will not only serve to inform every receiver operator of his or her own expected occupations, but those of every other member of the project as well. This knowledge is most useful when a sudden revision requires observers to meet or replace one another.

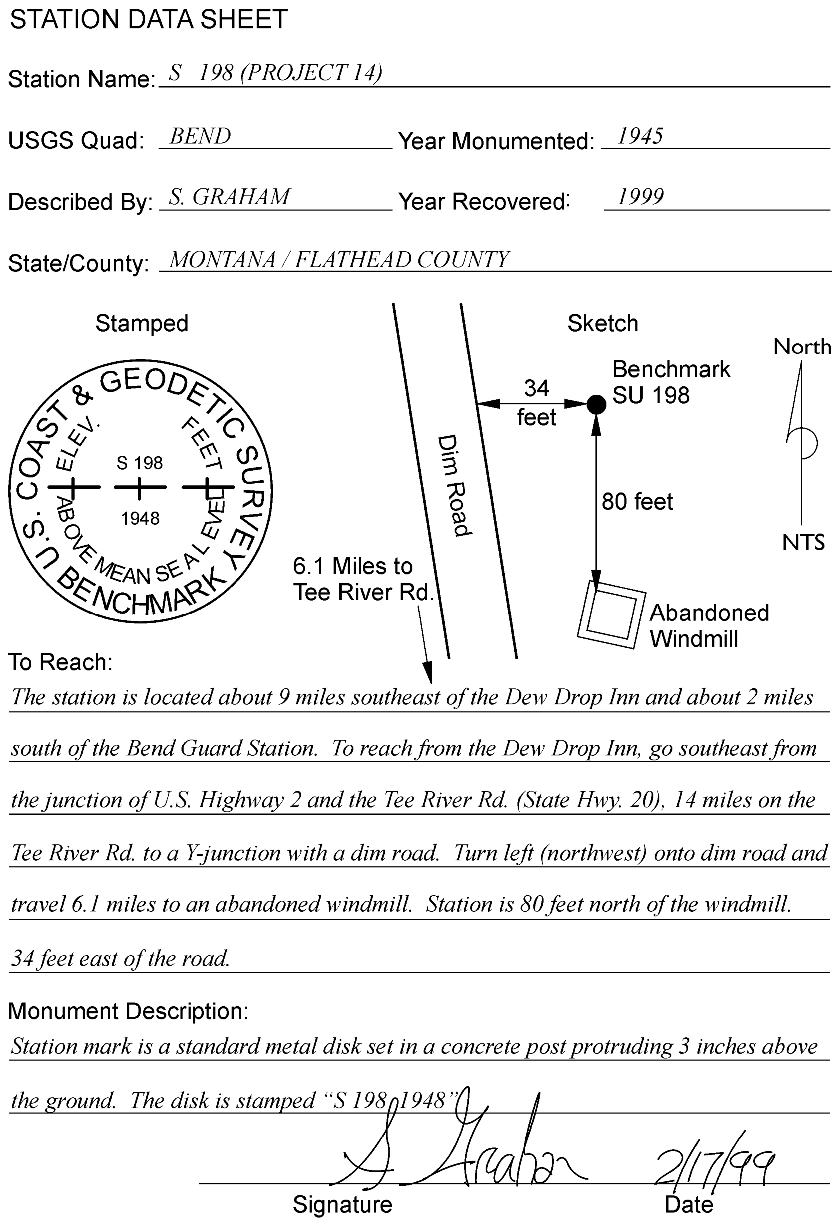


	Session 1	**8:10**	**Session 2**	**9:50**	**Session 3**	**11:15**	**Session 4**	**12:30**	**Session 5**
	Start 7:10	**to**	**Start 8:40**	**to**	**Start 10:15**	**to**	**Start 11:30**	**to**	**Start 14:00**
	Stop 8:10	**8:40**	**Stop 9:50**	**10:15**	**Stop 11:15**	**11:30**	**Stop 12:30**	**14:00**	**Stop 15:00**
Svs PRNs	**9,12,13,16,20,24**		**3,12,13,16,20,24**		**3,12,13,16,17,20,24**		**3,16,17,20,22,23,26**		**1,3,17,21,23,26,28**
Receiver A	Station 1		Station 1		Station 5		Station 5		Station 5
Dan H.	NGS Horiz.	Re-Set	NGS Horiz.	Move	NGS	Re-Set	NGS	Re-Set	NGS
	Control		Control		Benchmark		Benchmark		Benchmark
Receiver B	Station 3		Station 3		Station 6		Station 6		Station 1
Scott G.	NGS V&H	Re-Set	NGS V&H	Move	Project	Re-Set	Project	Move	NGS Horiz.
	Control		Control		Point		Point		Control
Receiver C	Station 8		Station 2		Station 2		Station 7		Station 10
Dewey A.	NGS Horiz.	Move	Project	Re-Set	Project	Move	Project	Move	NGS
	Control		Point		Point		Point		Bench Mark
Receiver D	Station 13		Station 4		Station 4		Station 9		Station 13
Cindy E.	NGS Horiz.	Move	Project	Re-Set	Project	Move	Project	Move	NGS Horiz.
	Control		Point		Point		Point		Control

TABLE 7.1

Station Data Sheet

The principles of good field notes have a long tradition in land surveying, and they will continue to have validity for some time to come. In GPS, the ensuing paper trail will not only fill subsequent archives; it has immediate utility. For example, the station data sheet is often an important bridge between on-site reconnaissance and the actual occupation of a monument.



STATION DATA SHEET

Station Name: S 198 (PROJECT 14)

USGS Quad: BEND Year Monumented: 1945

Described By: S. GRAHAM Year Recovered: 1999

State/County: MONTANA / FLATHEAD COUNTY

To Reach:

The station is located about 9 miles southeast of the Dew Drop Inn and about 2 miles south of the Bend Guard Station. To reach from the Dew Drop Inn, go southeast from the junction of U.S. Highway 2 and the Tee River Rd. (State Hwy. 20), 14 miles on the Tee River Rd. to a Y-junction with a dim road. Turn left (northwest) onto dim road and travel 6.1 miles to an abandoned windmill. Station is 80 feet north of the windmill. 34 feet east of the road.

Monument Description:

Station mark is a standard metal disk set in a concrete post protruding 3 inches above the ground. The disk is stamped "S 198 1948"

S Graham 2/17/99

Signature Date

FIGURE 7.1

Though every organization develops its own unique system of handling its field records, most have some form of the station data sheet. The document illustrated in Figure 7.1 is merely one possible arrangement of the information needed to recover the station.

The station data sheet can be prepared at any period of the project, but perhaps the most usual times are during the reconnaissance of existing control or immediately after the monumentation of a new project point. Neatness and clarity, always paramount virtues of good field notes, are of particular interest when the station data sheet is to be later included in the final report to the client. The overriding principle in drafting a station data sheet is to guide succeeding visitors to the station without ambiguity. A GPS surveyor on the way to observe the position for the first time may be the initial user of a station data sheet. A poorly written document could void an entire session if the observer is unable to locate the monument. A client, later struggling to find a particular monument with an inadequate data sheet, may ultimately question the value of more than the field notes.

Station name. The station name fills the first blank on the illustrated data sheet. Two names for a single monument is far from unusual. In this case the vertical control station, officially named S 198, is also serving as a project point, number 14. But two names purporting to represent the same position can present a difficulty. For example, when a horizontal control station is remonumented a number 2 is sometimes added to the original name of the station and it can be confusing. For example, it can be easy to mistake station, "Thornton 2," with an original station named, "Thornton," that no longer exists. Both stations may still have a place in the published record, but with slightly different coordinates. Another unfortunate misunderstanding can occur when inexperienced field personnel mistake a reference mark, R.M., for the actual station itself.

The taking of rubbings and/or close-up photographs are widely recommended to avoid such blunders regarding stations names or authority.

Rubbings. The illustrated station data sheet provides an area to accommodate a rubbing. With the paper held on top of the monument's disk, a pencil is run over it in a zig-zag pattern producing a positive image of the stamping. This method is a bit more awkward than simply copying the information from the disk onto the data sheet, but it does have the advantage of ensuring the station was actually visited and that the stamping was faithfully recorded. Such rubbings or close-up photographs are required by the provisional FGCC *Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques* for all orders of GPS surveys.

Photographs. The use of photographs is growing as a help for the perpetuation of monuments. It can be convenient to photograph the area around the mark as well as the monument itself. These exposures can be correlated with a sketch of the area. Such a sketch can show the spot where the photographer stood and the directions toward which the pictures were taken. The photographs can then provide valuable information in locating monuments, even if they are later obscured. Still, the traditional ties to prominent features in the area around the mark are the primary agent of their recovery.

Quad Sheet Name. Providing the name of the appropriate state, county, and USGS quad sheet helps to correlate the station data sheet with the project map. The year the mark was monumented, the monument description, the station name, and the "to-reach" description all help to associate the information with the correct official control data sheet and, most importantly, the correct station coordinates.

To-reach descriptions. The description of the route to the station is one of the most critical documents written during the reconnaissance. Even though it is difficult to prepare the information in unfamiliar territory and although every situation is somewhat different, there are some guidelines to be followed. It is best to begin with the general location of the station with respect to easily found local features.

The description in Figure 7.1 relies on a road junction, a guard station, and a local business. After defining the general location of the monument, the description should recount directions for reaching the station. Starting from a prominent location, the directions should adequately describe the roads and junctions. Where the route is difficult or confusing, the reconnaissance team should not only describe the junctions and turns needed to reach a station; it is wise to also mark them with lath and flagging, when possible. It is also a good idea to note gates. Even if they are open during reconnaissance, they may be locked later. When turns are called for, it is best to describe not only the direction of the turn, but the new course too. For example, in the description in Figure 7.1 the turn onto the dim road from the Tee River Road is described to the,"left (northwest)." Roads and highways should carry both local names and designations found on standard highway maps. For example, in Figure 7.1 Tee River Road is also described as State Highway 20.

The "to-reach" description should certainly state the mileages as well as the travel times where they are appropriate, particularly where packing-in is required. Land ownership, especially if the owner's consent is required for access, should be mentioned. The reconnaissance party should obtain the permission to enter private property and should inform the GPS observer of any conditions of that entry. Alternate routes should be described where they may become necessary. It is also best to make special mention of any route that is likely to be difficult in inclement weather.

Where helicopter access is anticipated, information about the duration of flights from point to point, the distance of landing sites from the station, and flight time to fuel supplies should be included on the station data sheet.

Flagging and describing the monument. Flagging the station during reconnaissance may help the observer find the mark more quickly. On the station data sheet, the detailed description of the location of the station with respect to roads, fence lines, buildings, trees, and any other conspicuous features should include measured distances and directions. A clear description of the monument itself is important. It is wise to also show and describe any nearby marks, such as R.M.s, that may be mistaken for the station or aid in its recovery. The name of the preparer, a signature, and the date round out the initial documentation of a GPS station.

Visibility Diagrams

Obstructions above the mask angle of a GPS receiver must be taken into account in finalizing the observation schedule. A station that is blocked to some degree is not necessarily unusable, but its inclusion in any particular session is probably contingent on the position of the specific satellites involved.

Date: *February 17, 1999*

STATION VISIBILITY DIAGRAM

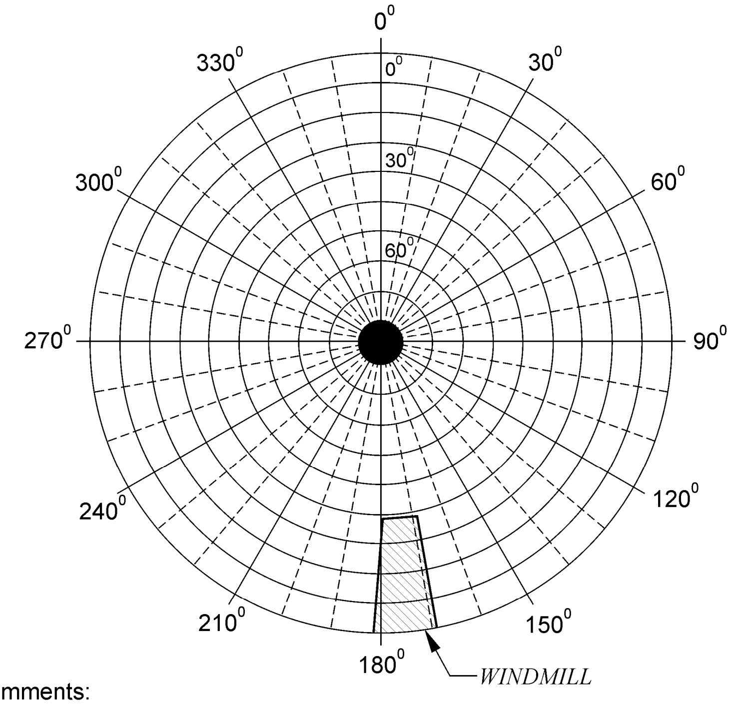
Station Name: *S 198 (PROJECT 14)*

USGS Quad: *BEND*

Latitude: *$47^{0}52'39''$*

Described By: *S. GRAHAM*

Longitude: *$115^{0}00'48''$*



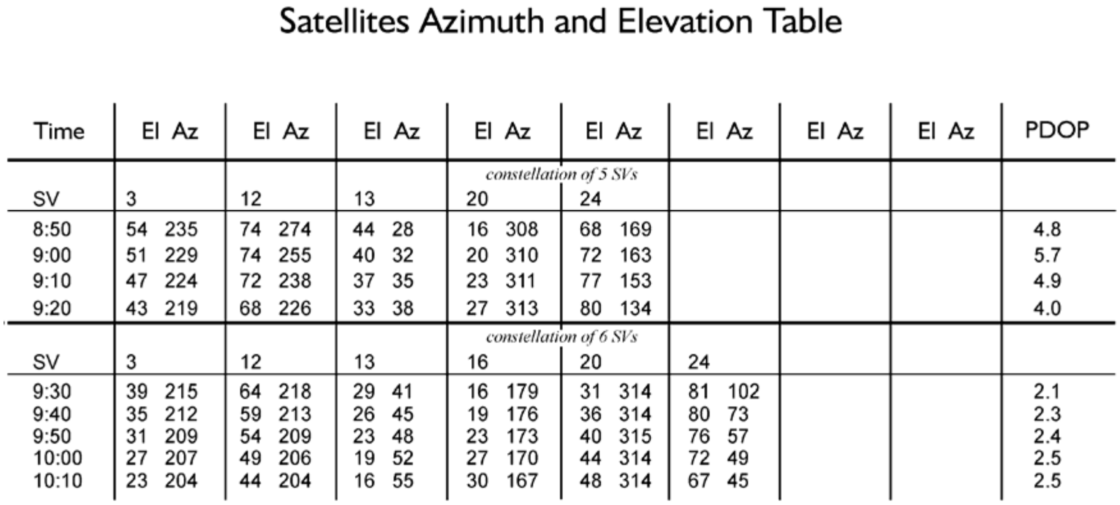
Comments:

OBSTRUCTION FROM ABANDONED WINDMILL SOUTH OF THE STATION AS SHOWN. WINDMILL BASE IS CROSS-MEMBER STEEL.

FIGURE 7.2

An example. The diagram in Figure 7.2 is widely used to record such obstructions during reconnaissance. It is known as a *station visibility diagram*, a *polar plot* or a *skyplot*. The concentric circles are meant to indicate 10° increments along the upper half of the celestial sphere, from the observer's horizon at 0° on the perimeter, to the observer's zenith at 90° in the center. The hemisphere is cut by the observer's meridian, shown as a line from 0°in the north to 180° on the south. The prime vertical is signified as the line from 90° in the east to 270° in the west. The other numbers and solid lines radiating from the center, every 30° around the perimeter of the figure, are azimuths from north and are augmented by dashed lines every 10°.

Drawing obstructions. Using a compass and a clinometer, a member of the reconnaissance team can fully describe possible obstructions of the satellite's signals on a visibility diagram. By standing at the station mark and measuring the azimuth and vertical angle of points outlining the obstruction, the observer can plot the object on the visibility diagram. For example, a windmill base is shown on in Figure 7.2 as a cross-hatched figure. It has been drawn from the observers horizon up to 37° in vertical angle from 168°, to about 182° in azimuth at its widest point. This description by approximate angular values is entirely adequate for determining when particular satellites may be blocked at this station.



Satellites Azimuth and Elevation Table

Time	El Az	El Az	El Az	El Az	El Az	El Az	El Az	El Az	PDOP
				constellation of 5 SVs					
SV	3	12	13	20	24				
8:50	54 235	74 274	44 28	16 308	68 169				4.8
9:00	51 229	74 255	40 32	20 310	72 163				5.7
9:10	47 224	72 238	37 35	23 311	77 153				4.9
9:20	43 219	68 226	33 38	27 313	80 134				4.0
				constellation of 6 SVs					
SV	3	12	13	16	20	24			
9:30	39 215	64 218	29 41	16 179	31 314	81 102			2.1
9:40	35 212	59 213	26 45	19 176	36 314	80 73			2.3
9:50	31 209	54 209	23 48	23 173	40 315	76 57			2.4
10:00	27 207	49 206	19 52	27 170	44 314	72 49			2.5
10:10	23 204	44 204	16 55	30 167	48 314	67 45			2.5

TABLE 7.2

For example, suppose a 1-hour session from 9:10 to 10:10, illustrated in Table 7.2, was under consideration for the observation on station S 198. The station visibility chart might motivate a careful look at SV PRN 16. Twenty minutes into the anticipated session, at 9:30 SV 16 has just risen above the 15° mask angle. Under normal circumstances, it would be available at station S 198, but it appears from the polar plot that the windmill will block its signals from reaching the receiver. In fact, the signals from SV 16 will apparently not reach station S 198 until sometime after the end of the session at 10:10.

Working around obstructions. Under the circumstances, some consideration might be given to observing station S 198 during a session when none of the satellites would be blocked. However, the 9:10 to 10:10 session may be adequate after all. Even if SV 16 is completely blocked, the remaining five satellites will be unobstructed and the constellation still will have a relatively low PDOP. Still, the analysis must be carried to other stations that will be occupied during the same session. The success of the measurement of any baseline depends on common observations at both ends of the line. Therefore, if the signals from SV 16 are garbled or blocked from station S 198, any information collected during the same session from that satellite at the other end of a line that includes S 198 will be useless in processing the vector between those two stations.

But the material of the base of the abandoned windmill has been described on the visibility diagram as cross-membered steel, so it is possible that the signal from SV 16 will not be entirely obstructed during the whole session. There may actually be more concern of multipath interference from the structure than that of signal availability. One strategy for handling the situation might be to program the receiver at S 198 to ignore the signal from SV 16 completely if the particular receiver allows it.

The visibility diagram (Figure 7.2) and the azimuth-elevation table (Table 7.2) complement each other. They provide the field supervisor with the data needed to make informed judgments about the observation schedule. Even if the decision is taken to include station S 198 in the 9:10 to 10:10 session as originally planned, the supervisor will be forewarned that the blockage of SV 16 may introduce a bit of weakness at that particular station.

Approximate station coordinates. The latitude and longitude given on the station visibility diagram should be understood to be approximate. It is sometimes a scaled coordinate, or it may be taken from another source. In either case, its primary role is as input for the receiver at the beginning of its observation. The coordinate need only be close enough to the actual position of the receiver to minimize the time the receiver must take to lock onto the constellation of satellites it expects to find.

Multipath. The multipath condition is by no means unique to GPS. When a transmitted television signal reaches the receiving antenna by two or more paths, the resulting variations in amplitude and phase cause the picture to have ghosts. This kind of scattering of the signals can be caused by reflection from land, water, or man-made structures. In GPS, the problem can be particularly troublesome when signals are received from satellites at low elevation angles; hence the general use of a 15° to 20° mask angle. The use of choke ring antennas to mediate mulipath may also be considered.

It is also wise, where it is possible, to avoid using stations that are near structures likely to be reflective or to scatter the signal. For example, chain-link fences that are found hard against a mark can cause multipath by forcing the satellite's signal to pass through the mesh to reach the antenna. The elevation of the antenna over the top of the fence with a survey mast is often the best way to work around this kind of obstruction. Metal structures with large flat surfaces are notorious for causing multipath problems. A long train moving near a project point could be a potential problem, but vehicles passing by on a highway or street usually are not, especially if they go by at high speed. It is important, of course, to avoid parked vehicles. It is best to remind new GPS observers that the survey vehicle should be parked far enough from the point to avert any multipath. A good way to handle these unfavorable conditions is to set an offset point .

Point Offsets. An offset must, of course, stand far enough away from the source of multipath or an attenuated signal to be unaffected. However, the longer the distance from the originally desired position the more important the accuracy of the bearing and distance between that position and the offset becomes. Recording the tie between the two correctly is crucial to avoid misunderstanding after the work is completed. Some receivers allow input of the information directly into the observations recorded in the receiver or datalogger. However, during a control survey it is best to also record the information in a field book.

Offsets in GPS control surveying are an instance where conventional surveying equipment and expertise are necessary. Clearly the establishment of the tie requires a position for the occupation of the instrument, i.e. total station, and a position for the establishment of it orientation, i.e. an azimuth. It is best to establish three intervisible rather than two points- one to occupy and two azimuth marks. This approach makes it possible to add a redundant check to the tie. The positions on these two, or three, points may be established by setting monuments and performing static observations on them all. Alternatively azimuthal control may be established by astronomic observations.

Look for multipath. Both the GPS field supervisor and the reconnaissance team should be alert to any indications on the station visibility diagram that multipath may be a concern. Before the observations are done, there is nearly always a simple solution. Discovering multipath in the signals after the observations are done is not only frustrating, but often expensive.

Monumentation

The monumentation set for GPS projects varies widely and can range from brass tablets to aerial premarks, capped rebar or even pin flags. The objective of most station markers is to adequately serve the clients subsequent use. However, the time, trouble, and cost in most high-accuracy GPS work warrants the most permanent, stable monumentation.

Many experts predict that GPS will eventually make monumentation unnecessary. The idea foresees GPS receivers in constant operation at well-known master stations will allow surveyors with receivers to determine highly accurate relative positions with such speed and ease that monumentation will be unnecessary. The idea may prove prophetic, but for now monumentation is an important part of most GPS projects. The suitability of a particular type of monument is an area still most often left to the professional judgement of the surveyors involved.

The FGCC recommends the use of traditional metal disks set in rock outcroppings, bridge abutments, or other large structural elements where possible. A three-dimensional rod mark is approved as an alternative by the federal committee. It is described in detail in appendix H of *Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning*

Techniques.

Logistics

Scheduling. Once all the station data sheets, visibility diagrams, and other field notes have been collected, the schedule can be finalized for the first observations. There will almost certainly be changes from the original plan. Some of the anticipated control stations may be unavailable or obstructed, some project points may be blocked, too difficult to reach or simply not serve the purpose as well as a control station at an alternate location. When the final control has been chosen, the project points have been monumented, and the reconnaissance has been completed, the information can be brought together with some degree of certainty that it represents the actual conditions in the field.

Now that the access and travel time, the length of vectors, and the actual obstructions are more certainly known, the length and order of the sessions can be solidified. Despite all the care and planning that goes into preparing for a project unexpected changes in the satellites orbits or health can upset the best schedule at the last minute. It is always helpful to have a backup plan.

The receiver operators usually have been involved in the reconnaissance and are familiar with the area and many of the stations. Even though an observer may not have visited the particular stations scheduled for him, the copies of the project map, appropriate station data sheets and visibility diagrams will usually prove adequate to their location.

Observation

When everything goes as planned a GPS observation is uneventful. However, even before the arrival of the receiver operator at the control or project point the session can get off-track. The simultaneity of the data collected at each end of a baseline is critical to the success of any measurement in GPS. When a receiver occupies a master station throughout a project there need be little concern on this subject. But most static applications depend on the sessions of many mobile receivers beginning and ending together.

Arrival. The number of possible delays that may befall an observer on the way to a station are too numerous to mention. With proper planning and reconnaissance, the observer will likely find that there is enough time for the trip from station to station and that sufficient information is on hand to guide him to the position, but this too cannot be guaranteed. When the observer is late to the station, the best course is usually to set up the receiver quickly and collect as much data as possible. The baselines into the late station may or may not be saved, but they will certainly be lost if the receiver operator collects no information at all. It is at times like these that good communication between the members of the GPS team are most useful. For example, some of the other observers in the session may be able to stay on their station a bit longer with the late arrival and make up some of the lost data. Along the same line, it is usually a good policy for those operators who are to remain on a station for two consecutive sessions to collect data as long as possible, while still leaving themselves enough time to reset between the two observation periods.

Set-up. Centering an instrument over the station mark is always important. However, the centimeter-level accuracy of static GPS gives the centering of the antenna special significance. It is ironic that such a sophisticated system of surveying can be defeated from such a commonplace procedure.   A tribrach with an optical plummet or any other device used for centering should be checked and, if necessary, adjusted before the project begins. With good centering and leveling procedures, an antenna should be within a few millimeters of the station mark. The FGCC's provisional specifications require that the antenna's centering be checked with a plumb bob at each station for surveys of the AA, A, and B orders.

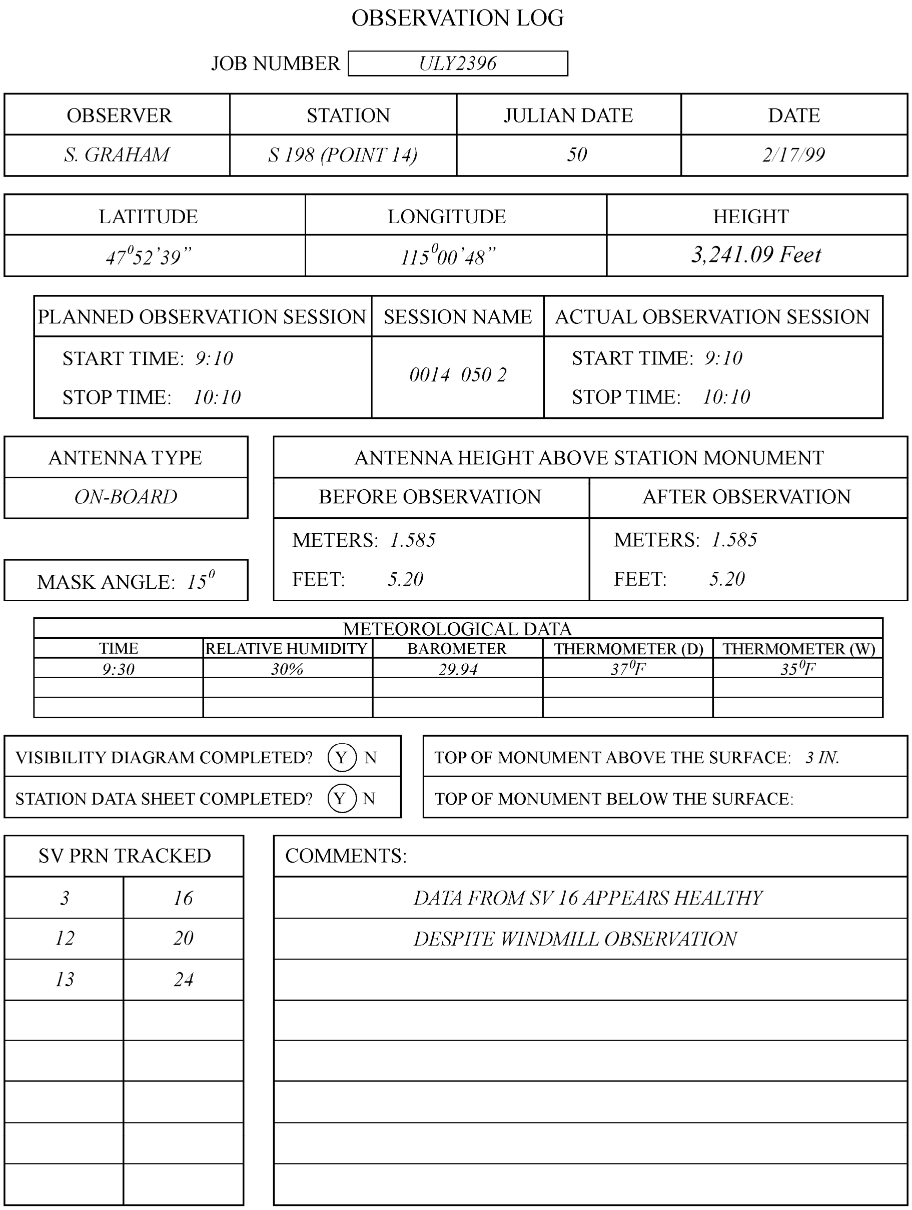
Unfortunately, the centering of the antenna over the station does not ensure that its phase center is properly oriented. The contours of equal phase around the antenna’s electronic center are not themselves perfectly spherical. Part of their eccentricity can be attributed to unavoidable inaccuracies in the manufacturing process. To compensate for some of this offset, it is a good practice to rotate all antennas in a session to the same direction. Many manufacturers provide reference marks on their antennas so that each one may be oriented to the same azimuth. That way they are expected to maintain the same relative position between their physical and electronic centers when observations are made.

The antenna's configuration also affects another measurement critical to successful GPS surveying: the height of the instrument. The frequency of mistakes in this important measurement is remarkable. Several methods have been devised to focus special attention on the height of the antenna. Not only should it be measured in both feet and meters, it should also be measured immediately after the instrument is set-up and just before tearing it down to detect any settling of the tripod during the observation.

Height of instrument. The measurement of the height of the antenna in a GPS survey is often not made on a plumb line. A tape is frequently stretched from the top of the station monument to some reference mark on the antenna or the receiver itself. Some GPS teams measure and record the height of the antenna to more than one reference mark on the ground plane. These measurements are usually mathematically corrected to plumb.

The care ascribed to the measurement of antenna heights is due to the same concern applied to centering. GPS has an extraordinary capability to achieve accurate heights, but those heights can be easily contaminated by incorrect H.I.s.

Observation logs. Most GPS operations require its receiver operators to keep a careful log of each observation. Usually written on a standard form, these field notes provide a written record of the measurements, times, equipment, and other data that explains what actually occurred during the observation itself. It is difficult to overestimate the importance of this information. It is usually incorporated into the final report of the survey, the archives, and any subsequent effort to blue-book the project. However, the most immediate use of the observation log is in evaluation of the day's work by the on-site field supervisor.



OBSERVATION LOG

JOB NUMBER *ULY2396*

OBSERVER	STATION	JULIAN DATE	DATE
S. GRAHAM	*S 198 (POINT 14)*	*50*	*2/17/99*

LATITUDE	LONGITUDE	HEIGHT
$47^0 52'39''$	$115^0 00'48''$	*3,241.09 Feet*

PLANNED OBSERVATION SESSION	SESSION NAME	ACTUAL OBSERVATION SESSION
START TIME: *9:10* STOP TIME: *10:10*	*0014 050 2*	START TIME: *9:10* STOP TIME: *10:10*

ANTENNA TYPE
ON-BOARD

MASK ANGLE: 15^0

ANTENNA HEIGHT ABOVE STATION MONUMENT	
BEFORE OBSERVATION	AFTER OBSERVATION
METERS: *1.585* FEET: *5.20*	METERS: *1.585* FEET: *5.20*

METEOROLOGICAL DATA				
TIME	RELATIVE HUMIDITY	BAROMETER	THERMOMETER (D)	THERMOMETER (W)
9:30	*30%*	*29.94*	37^0F	35^0F

VISIBILITY DIAGRAM COMPLETED? [✓ Y] N	TOP OF MONUMENT ABOVE THE SURFACE: *3 IN.*
STATION DATA SHEET COMPLETED? [✓ Y] N	TOP OF MONUMENT BELOW THE SURFACE:

SV PRN TRACKED	
3	*16*
12	*20*
13	*24*

COMMENTS:
DATA FROM SV 16 APPEARS HEALTHY
DESPITE WINDMILL OBSERVATION

FIGURE 7.3

An observation log may be organized in a number of ways. The log illustrated in Figure 7.3 is one method that includes some of the information that might be used to document one session at one station. Of course, the name of the observer and the station must be included, and while the date need not be expressed in both the Julian and Gregorian calendars that information may help in quick cataloging of the data. The approximate latitude, longitude, and height of the station are usually required by the receiver as a reference position for its search for satellites. The date of the planned session will not necessarily coincide with the actual session observed. The observer's arrival at the point may have been late, or the receiver may have been allowed to collect data beyond the scheduled end of the session.

There are various methods used to name observation session in terminology that is sensible to computers. A widely used system is noted here. The first four digits are the project point’s number. In this case it is point 14 and is designated 0014. The next three digits are the Julian day of the session, in this case it is day 50, or 050. Finally, the session illustrated is the second of the day, or 2. Therefore, the full session name is 0014 050 2.

Whether onboard or separate, the type of the antenna used and the height of the antenna are critical pieces of information. The relation of the height of the station to the height of the antenna is vital to the station’s later utility. The distance that the top of the station's monument is found above or below the surface of the surrounding soil is sometimes neglected. This information can not only be useful in later recovery of the monument, but can also be important in the proper evaluation of photo-control panel points.

Weather. The meteorological data is useful in modeling the atmospheric delay. This information is required at the beginning, middle, and end of each session of projects that are designed to satisfy the FGCC's provisional specifications for the AA and A orders of accuracy. Under those circumstances, measurement of the atmospheric pressure in millibars, the relative humidity, and the temperature in degrees Centigrade are expected to be included in the observation log. However, the general use is less stringent. The conditions of the day are observed, and unusual changes in the weather are noted.

A record of the satellites that are actually available during the observation and any comments about unique circumstances of the session round out the observation log.

Daily Progress Evaluation

The planned observation schedules of a large GPS project usually change daily. The arrangement of upcoming sessions are often altered based on the success or failure of the previous day’s plan. Such a regrouping follows evaluation of the day’s data.

This evaluation involves examination of the observation logs as well as the data each receiver has collected. Unhealthy data, caused by cycle slips or any other source, are not always apparent to the receiver operator at the time of the observation. Therefore a daily quality control check is a necessary preliminary step before finalizing the next day’s observation schedule.

Some field supervisors prefer to actually compute the independent baseline vectors of each day’s work to ensure that the measurements are adequate. Neglecting the daily check could leave unsuccessful sessions undiscovered until the survey was thought to be completed. The consequences of such a situation could be expensive.

RTK AND DGPS OBSERVATIONS

Some components of static GPS control methods are useful in RTK and DGPS work just as they are described above. However, there are some, such as station diagrams, observations logs and to-reach descriptions that would rarely if ever be necessary in high-production dynamic work. And finally, there are aspects, though handled a bit differently in both categories of work have utility in each. One such technique is offsetting points to avoid multipath and signal attenuation.

Point Offsets. The need to offset points is much more prevalent in DGPS and RTK surveying. However, the methods of dealing with it are more varied. DGPS and RTK surveying generally have lower accuracy requirements than does static control work, and therefore the establishment of the tie between the offset and the originally desired position need not be so stringent. However, when circumstances arise that require a particularly accurate tie the same conventional surveying procedures mentioned for static point offsets may be useful.

The offset point must be established far enough from the original position to avoid an obstructed signal, but close enough to prevent unacceptable positioning error. While the calculation of the allowable vertical and horizontal measurement errors can be done trigonometrically, the measurements themselves will be different than those for an offset point in a static survey. For example, rather than a total station point and an azimuth point, a magnetic fluxgate digital compass and laser may be used to measure the tie from the offset point to the original point. It is worth noting that magnetic declination must be accommodated and metal objects avoided when doing magnetic work. A declination calculator is available online at http://www.ngdc.noaa.gov/seg/geomag/jsp/Declination.jsp. And also such internal compasses should be carefully checked before they are relied upon.

The length of the tie may be measured by an external laser, a laser cabled directly into the GPS receiver, or even a tape and clinometer. Lasers are much more convenient since they can be used to measure longer distances more reliably and taping requires extra field crew members. And rather than recording the bearing and distance in a field book for post-processing in DGPS or RTK the information is usually stored directly in the data collector. In fact, often the receiver's real-time processor can combine the measured distance and direction-the *sideshot*- with the receiver's position and calculate the coordinate of the originally desired position on-the-fly.

Dynamic Lines. A technique unique to RTK and DGPS and used especially in mobile GPS application is the creation of dynamic lines. The GPS receiver typically moves along a route to be mapped logging positions at pre-determined intervals of time or distance. These points can then be joined together to create a continuous line. Obstructions along the route present a clear difficulty for this procedure. Points may be in error, or lost completely due to multipath or signal attenuation. Also, in choosing the epoch interval the capacity of the receiver's memory must be considered, especially when long lines are collected. If the interval chosen is too short the receiver's storage capacity may be overwhelmed. If the interval is too long important deflections along the way may be missed.

Where it is impossible or unsafe to travel along the line to be collected in the field the dynamic line may be collected with a consistent offset. This technique is especially useful in the collection roads and railroads where it is possible to estimate the offset with some certainty due to the constant width of the feature. It is also possible, of course, to collect routes with individual discrete points with short occupations where that approach recommends itself.

Planning. Multipath and signal attenuation are particularly troublesome for the dynamic GPS of DGPS and RTK work. While the visibility diagrams mentioned earlier are not directly applicable it is nevertheless prudent to plan the work so that at least five GPS satellites are available above the mask angle in the area where data is to be collected. It also may be useful to lower the mask angle and/or reduce the signal-to-noise ratio, *SNR* when conditions warrant it. There are, of course, trade offs to such strategies that may involve a reduction in positional integrity. The balance between accuracy and productivity is always a consideration.

A Few RTK Procedures

As mentioned earlier redundancy in RTK work can be achieved by occupying each newly established position twice and it is best if the second occupation is done using a different base station than was used to control the first. The control points occupied by base stations should not be too close to one another. A minimum of 300 meters is a good rule of thumb. Each time the base is set up and before it is taken down it is best to do a check shot on at least one known control point to verify the work. And in order to ensure that the GPS constellation during the second occupation differs substantially from that of the first it is best if the second occupation takes place not less than 4 hours and not more than 8 hours later or earlier than the first.

To ensure that the centering is correct during the short occupations of RTK it is best if a bipod is used with a fixed height rod to eliminate the possibility of incorrect height of instrument measurement corrupting the results. Concerning heights, if orthometric heights in real-time are desired a geoidal model is required and it is best if it is the most recent. However, please note that work retraced with a different geoidal model than was used initially will likely show vertical differences at the re-occupied points.

Some rover configurations facilitate *in-fill* surveys. In others words, when the correction signals from the base station fail to reach the rover the collected data is stored in the memory of the receiver for post-processing after the work is completed.

Site Calibration. The area of interest, that is the project area, covered by an RTK survey is usually relatively small and defined. Typically a *site calibration* is performed to prepare such a GPS project to be done using plane coordinates. A site calibration establishes the relationship between geographical coordinates - latitude, longitude and ellipsoidal height- with plane coordinates - northing, easting and orthometric heights across the area. In the final analysis the relationship is expressed in three dimensions; translation, rotation and scale. Because of the inevitable distortion that a site calibration must model one of the prerequisites for such a *localization* is the enclosure of the area by the control stations that will be utilized during the work.

In the horizontal plane the method of using plane coordinates on an imaginary flat reference surface with northings and eastings, or *x*- and *y*- coordinates assumes a flat earth. That is incorrect of course but a viable simplification if the area is small enough and the distortion is negligible. Such local tangent planes fixed at discrete points, control points, by GPS site calibration have been long used by land surveyors. Such systems demand little if any manipulation of the field observations and once the coordinates are derived they can be manipulated by straightforward plane trigonometry. In short Cartesian systems are simple and convenient.

However, there are difficulties as the area grows as mentioned in Chapter 5. For example, typically each of these planes has a unique local coordinate system derived from its own unique site calibration. The axes, the scale and the rotation of each one of these individual local systems will not be the same as those elements of its neighbor's coordinate system. Therefore, when a site calibration is done and a local flat plane coordinate system is created it is important to keep all of the work in that system inside limits created by the control points used in its creation. In the simplest case, a single point calibration, a flat plane is brought tangent to the Earth at one point, but a more typical approach is the utilization of three or four points enclosing the area of interest to be covered by the independent *local coordinate system.* Working outside of the limits created by those points should be avoided as it involves working where the distortion has not been modeled.

It might be said that a site calibration is a *best fit* of a plane onto a curved surface. It distributed the inevitable distortion in both the horizontal and vertical planes. The vertical aspect is particularly important. It is called upon to adjust the measured GPS ellipsoid heights to a desired local vertical datum. Therefore, it must account for undulations in the geoid because the separation between the ellipsoid and geoidal models is seldom if ever consistent over the project area. The separation is not consistent and usually can be modeled approximately as a trend across the area of interest so that the site calibration typically produces an inclined plane in the vertical aspect. Toward that end the set of control points used to establish the site calibration must have both geographical coordinates - latitude, longitude and ellipsoidal height- and plane coordinates - northing, easting and orthometric heights in the desired local system. It is best if these control points are from the NSRS when possible that enclose the project and are distributed evenly around its boundary.

PROCESSING

Post-Processing GPS Static Control Surveys

In many ways, processing is the heart of a GPS operation. Some processing should be performed on a daily basis during a GPS project. Blunders from operators, noisy data, and unhealthy satellites can corrupt entire sessions. And left undetected, such dissolution can jeopardize an entire survey. But with some daily processing, these weaknesses in the data can be discovered when they can still be eliminated with a timely amendment of the observation schedule.

But even after blunders and noisy data have been removed from the observation sets, GPS measurements are still composed of fundamentally biased ranges. Therefore, GPS data-processing procedures are really a series of interconnected computerized operations designed to remove these more difficult biases and extract the true ranges.

The biases originate from a number of sources; imperfect clocks, atmospheric delays, cycle ambiguities in carrier phase observations, and orbital errors. If a bias has a stable, well-understood structure, it can be estimated. In other cases, dual-frequency observations can be used to measure the bias directly, as in the ionospheric delay, or a model may be used to predict an effect, as in tropospheric delay. But one of the most effective strategies in eradicating biases is called *differencing*.

Correlation of biases. When two or more receivers observe the same satellite constellation simultaneously, a set of correlated vectors are created between the co-observing stations. Most GPS practitioners use more than two receivers. Therefore, most GPS networks consist of many sets of correlated vectors for every separate session. The longest baselines between stations on the earth are usually relatively short when compared with the more than 20,000-km distances from the receivers to the GPS satellites. Therefore, even when several receivers are set up on widely spaced stations, as long as they collect their data simultaneously from the same constellation of satellites, they will record very similar errors. In other words, their vectors will be correlated. It is the simultaneity of observation and the resulting correlation of the carrier phase observables that make the extraordinary GPS accuracies possible. Biases that are correlated linearly can be virtually eliminated by differencing the data sets of a session.

Quantity of Data

Organization is essential. One of the difficulties of GPS processing is the huge amount of data that must be managed. For example, when even one single-frequency receiver with a 1-second sampling rate tracks one GPS satellite for an hour, it collects about 0.15 Mb of data. However, a more realistic scenario involves four receivers observing six satellites for 3600 epochs. There can be 4 X 6 X 3600 or 86,400 carrier phase observations in such a session. In other words, a real-life GPS survey with many sessions and many baselines creates a quantity of data in the gigabyte range. Some sort of structured approach must be implemented to process such a huge amount of information in a reasonable amount of time.

File naming conventions. One aspect of that structure is the naming conventions used to head GPS receivers' observation files. Many manufacturers recommend a file naming format that can be symbolized by *pppp-ddd-s.yyf*. The first letters, (*pppp*), of the file name indicate the point number of the station occupied. The day of the year, or Julian date, can be accommodated in the next three places (*ddd*), and the final place left of the period is the session number (*s*). The year (*yy*), and the file type (*f*) are sometimes added to the right of the period.

Downloading

The first step in GPS data processing is downloading the collected data from the internal memory of the receiver itself into a PC or laptop computer. When the observations sessions have been completed for the day, each receiver, in turn, is cabled to the computer and its data transferred. Nearly all GPS systems used in surveying are PC-compatible and can accommodate post-processing in the field. But none can protect the user from a failure to back up this raw observational data onto some other form of semi-permanent storage.

Making room. Receiver memory capacity is usually somewhat limited, and older data must be cleared to make room for new sessions. Still, it is a good policy to create the necessary space with the minimum deletion and restrict it to only the oldest files in the receiver's memory. In this way the recent data can be retained as long as possible, the data can provide an auxiliary back-up system. But when a receiver's memory is finally wiped of a particular session, if redundant raw data are not available re-observation may be the only remedy.

Most GPS receivers record data internally. The Navigation message, meteorological data, the observables, and all other raw data are usually in a manufacturer-specific, binary form. They are also available in RINEX Receiver Independent Exchange Format. These raw data are usually saved in several distinct files. For example, the PC operator will likely find that the phase measurements downloaded from the receiver will reside in one file and the satellite's ephemeris data in another, etc. Likewise, the measured pseudorange information may be found in its own dedicated file, the ionospheric information in another, and so on. The particular division of the raw data files is designed to accommodate the suite of processing software and the data management system that the manufacturer has provided its customers, so each will be somewhat unique.

Control

All post-processing software suites require control. GPS static work often satisfies that requirement by inclusion of NGS monuments in the network design. In this approach the control stations are occupied by the surveyor building the network. There is an alternative. Continuously operating reference stations, CORS, already occupy many NGS control monuments and constantly collect observations, their data can be used to support carrier-phase static surveys as well as dynamic GPS work. The most direct method is to download the CORS data files posted on the Internet. The CORS data collected during the time of the survey can be combined with those collected in the field. They can be used to post-process the baselines and derive positions for the new points.

A difficulty arises when the density of the CORS in and around the project area is not adequate to support the required accuracy of the survey. This problem occurs in both dynamic and static GPS surveying applications. Real-Time Networks are a useful strategy for dealing with this control spacing issue in RTK and DGPS work as discussed in Chapter 6. However, in static control surveys outside of urban or highly developed areas the sparseness of CORS may obviate their use. Still, the situation is changing around the world. While there may be distances of up to 100km between CORS in the

US, GEONET in Japan has a spacing between stations of approximately 25 km and in Hong Kong the distance may be as little as 10km.

The First Position

Baseline processing is usually begun with a point position solution at each end from pseudoranges. These differential code estimations of the approximate position of each receiver antenna can be thought of as establishing a search area, a three-dimensional volume of uncertainty at each receiver containing its correct position. The size of this search area is defined by the accuracy of the code solution, which also affects the computational time required to find the correct position among all the other potential solutions.

Triple Difference

The next step, usually the triple-difference, utilizes the carrier phase observable. Triple differences have several features to recommend them for this stage in the processing. They can achieve rather high accuracy even before cycle slips have been eliminated from the data sets, and they are insensitive to integer ambiguities in general.

Components of a triple difference. A triple difference is created by differencing two double differences at each end of the baseline. Each of the double differences involves two satellites and two receivers. A triple difference considers two double differences over two consecutive epochs. In other words, triple differences are formed by sequentially differencing double differences in time. For example, two triple differences can be created using double differences at epochs 1, 2, and 3. One is double difference 2 minus double difference 1. A second can be formed by double difference 3 minus double difference 2.

Since two receivers are recording the data from the same two satellites during two consecutive epochs across a baseline, a triple difference can temporarily eliminate any concern about the integer cycle ambiguity, because the cycle ambiguity is the same over the two observed epochs. However, the triple difference cannot have as much information content as a double difference. Therefore, while receiver coordinates estimated from triple differences are usually more accurate than pseudorange solutions, they are less accurate than those obtained from double differences, especially fixed-ambiguity solutions. Nevertheless, the estimates that come out of triple-difference solutions refine receiver coordinates and provide a starting point for the subsequent double-difference solutions. They are also very useful in spotting and correcting cycle slips. They also provide a first estimate of the receiver's positions.

Double Difference

The next baseline processing steps usually involve two types of double differences, called the *float* and the *fixed* solutions.

The integer ambiguity. Double differences have both positive and negative features. On the positive side, they make the highest GPS accuracy possible, and they remove the satellite and receiver clock errors from the observations. On the other hand, the integer cycle ambiguity, sometimes known simply as *the ambiguity*, cannot be ignored in the double difference. In fact, the fixed double-difference solution, usually the most accurate technique of all, requires the resolution of this ambiguity.

The integer cycle ambiguity, usually symbolized by *N*, represents the number of full phase cycles between the receiver and the satellite at the first instant of the receiver's lock-on. N does not change from the moment of the lock is achieved, unless there is a cycle slip. Unfortunately, N is also an unknown quantity at the beginning of any carrier phase observation.

The float solution. Once again estimation plays a significant role in finding the appropriate integer value that will correctly resolve the ambiguity for component pairs in double differencing. In this first try, there is no effort to translate the biases into integers. It is sometimes said that the integers are allowed to float; hence the initial process is called the *float solution*. Especially when phase measurements for only one frequency, L1 or L2, are available, a sort of calculated guess at the ambiguity is the most direct route to the correct solution. Not just N, but a number of unknowns, such as clock parameters and point coordinates, are estimated in this geometric approach. However, all of these estimated biases are affected by unmodeled errors, and that causes the integer nature of N to be obscured. In other words, the initial estimation of N in a float solution is likely to appear as a real number rather than an integer.

However, where the data are sufficient, these floating real-number estimates are very close to integers- so close that they can next be rounded to their true integer values in a second adjustment of the data. Therefore, a second double difference solution follows. The estimation of N that is closest to an integer and has the minimum standard error is usually taken to be the most reliable and is rounded to the nearest integer. Now, with one less unknown, the process is repeated and another ambiguity can be fixed, and so on.

The fixed solution. This approach leads to the *fixed solution* in which N can be held to integer values. It is usually quite successful in double differences over short baselines. The resulting fixed solutions most often provide much more accurate results than were available from the initial floating estimates.

Cycle Slip Detection and Repair

However, this process can be corrupted by the presence of cycle slips. A cycle slip is a discontinuity in a receiver's continuous phase lock on a satellite's signal. The coded pseudorange measurement is immune from this difficulty, but the carrier beat phase is not. In other words, even when a fixed double-difference solution can provide the correct integer ambiguity resolution, the moment the data set is interrupted by a cycle slip that solution is lost.

There are actually two components to the carrier phase observable that ought not change from the moment of a receiver’s lock onto a particular satellite. First is the fractional initial phase at the first moment of the lock. The receiver is highly unlikely to acquire the satellite’s signal precisely at the beginning of a wavelength. It will grab on at some fractional part of a phase, and this fractional phase will remain unchanged for the duration of the observation. The other unchanged aspect of a normal carrier phase observable is an integer number of cycles. The integer cycle ambiguity is symbolized by N. It represents the number of full phase cycles between the receiver and the satellite at the first instant of the receiver's lock on. The integer ambiguity ought to remain constant throughout an observation as well. But when there is a cycle slip, lock is lost, and by the time the receiver reacquires the signal, the normally constant integer ambiguity has changed.

Cycle slip causes. A power loss, a very low signal-to-noise ratio, a failure of the receiver software, a malfunctioning satellite oscillator, or any event that breaks the receiver’s continuous reception of the satellite’s signal causes a cycle slip. Most common, however, is an obstruction that is so solid it prevents the satellite signal from being tracked by the receiver. Under such circumstances, when the satellite reappears, the tracking resumes. The fractional phase may be the same as if tracking had been maintained, but the integer number of cycles is not.

Repairing cycle slips. Cycle slips are repaired in post-processing. Both their location and their size must be determined; then the data set can be repaired with the application of a fixed quantity to all the subsequent phase observations. One approach is to hold the initial positions of the stations occupied by the receivers as fixed and edit the data manually. This has proven to work, but would try the patience of Job. Another approach is to model the data on a satellite-dependent basis with continuous polynomials to find the breaks and then manually edit the data set a few cycles at a time. In fact, several methods are available to find the lost integer phase value, but they all involve testing quantities.

One of the most convenient of these methods is based on the triple difference. It can provide an automated cycle slip detection system that is not confused by clock drift and, once least-squares convergence has been achieved, it can provide initial station positions even using the unrepaired phase combinations. They may still contain cycle slips but can nevertheless be used to process approximate baseline vectors. Then the residuals of these solutions are tested, sometimes through several iterations. Proceeding from its own station solutions, the triple difference can predict how many cycles will occur over a particular time interval. Therefore, by evaluating triple-difference residuals over that particular interval, it is not only possible to determine which satellites have integer jumps, but also the number of cycles that have actually been lost. In a sound triple-difference solution without cycle slips, the residuals are usually limited to fractions of a cycle. Only those containing cycle slips have residuals close to one cycle or larger. Once cycle slips are discovered, their correction can be systematic.

For example, suppose the residuals of one component double difference of a triple-difference solution revealed that the residual of satellite PRN 16 minus the residual of satellite PRN 17 was 8.96 cycles. Further suppose that the residuals from the second component double difference showed that the residual of satellite PRN 17 minus the residual of satellite PRN 20 was 14.04 cycles. Then one might remove 9 cycles from PRN 16 and 14 cycles from PRN 20 for all the subsequent epochs of the observation. However, the process might result in a common integer error for PRNS 16, 17, and 20. Still, small jumps of a couple of cycles can be detected and fixed in the double-difference solutions.

In other words, before attempting double difference solutions, the observations should be corrected for cycle slips identified from the triple difference solution. And even though small jumps undiscovered in the triple difference solution, might remain in the data sets the double difference residuals will reveal them at the epoch where they occurred.

However, some conditions may prevent the resolution of cycle slips down to the one-cycle level. Inaccurate satellite ephemerides, noisy data, errors in the receiver’s initial positions, or severe ionospheric effects all can limit the effectiveness of cycle-slip fixing. In difficult cases, a detailed inspection of the residuals might be the best way to locate the problem.

Fixing the Integer Ambiguity and Obtaining Vector Solutions

When cycle slips have been finally eliminated, the ambiguities can be fixed to integer values. First, the standard deviations of the adjusted integers are inspected. If found to be significantly less than one cycle, they can be safely constrained to the nearest integer value. This procedure is only pertinent to double differences, since phase ambiguities are moot in triple differencing. The number of parameters involved can be derived by multiplying one less the number of receivers by one less the number of satellites involved in the observation. And for dual-frequency observations the phase ambiguities for L1 and L2 are best fixed separately. But such a program of constraints is not typical in long baselines where the effects of the ionosphere and inaccuracies of the satellite ephemerides make the situation less determinable.

In small baselines, however, where these biases tend to be virtually identical at both ends, integer fixing is almost universal in GPS processing. Once the integer ambiguities of one baseline are fixed, the way is paved for constraint of additional ambiguities in subsequent iterations. Then, step by step, more and more integers are set, until all that can be fixed have been fixed. Baselines of several thousand kilometers can be constrained in this manner.

With the integer ambiguities fixed, the GPS observations produce a series of vectors, the raw material for the final adjustment of the survey. The observed baselines represent very accurately determined relative locations between the stations they connect. However, the absolute position of the whole network is usually much less accurately known, although more accurate absolute positioning may be on the horizon for GPS. For now, there remains a considerable difference in the accuracy of relative and absolute positioning. A GPS survey is usually related to the rest of the world by translation of its Cartesian coordinates into ellipsoidal latitude, longitude, and height. Most users are less comfortable with the original coordinate results, given in the WGS84 coordinate system of the satellites themselves, than latitude, longitude, and height.

Least-squares Adjustment

There are numerous adjustment techniques, but least-squares adjustment is the most precise and most commonly used in GPS. The foundation of the idea of least-squares adjustment is the idea that the sum of the squares of all the residuals applied to the GPS vectors in their final adjustment should be held to the absolute minimum. But minimizing this sum requires first defining those residuals approximately. Therefore, in GPS it is based on equations where the observations are expressed as a function of unknown parameters, but parameters that are nonetheless given approximate initial values. This is the process that has been described above. Then by adding the squares of the terms thus formed and differentiating their sum, the derivatives can be set equal to zero. For complex work like GPS adjustments, the least-squares method has the advantage that it allows for the smallest possible changes to original estimated values.

The solution strategies of GPS adjustments themselves are best left to particular suites of software. Suffice it to say that the single baseline approach, that is, a baseline-by-baseline adjustment, has the disadvantage of ignoring the actual correlation of the observations of simultaneously occupied baselines. An alternative approach involves a network adjustment approach where the correlation between the baselines themselves can be more easily taken into account. And while the computations are simpler for the baseline-by-baseline approach, cycle slips are more conveniently repaired in network adjustment.

For the most meaningful network adjustment, the endpoints of every possible baseline should be connected to at least two other stations. Thereby, the quality of the work itself can be more realistically evaluated. For example, the most common observational mistake, the mis-measured antenna height, is very difficult to detect when adjusting baselines sequentially, one at a time, but a network solution spots such blunders more quickly.

For example, most GPS post-processing adjustment begins with a minimally constrained least-squares adjustment. That means that all the observations in a network are adjusted together with only the constraints necessary to achieve a meaningful solution. For example, the adjustment of a GPS network with the coordinates of only one station fixed. The purpose of the minimally constrained approach is to detect large mistakes, like a misidentifying one of the stations. The residuals from a minimally constrained work should come pretty close to the precision of the observations themselves. If the residuals are particularly large, there are probably mistakes, if they are really small the network itself may not be a strong as it should be.

This minimally constrained solution is usually followed by an over-constrained solution. In other word, a least-squares adjustment where the coordinate values of selected control station are held fixed.

It is important to note that the down side of least-squares adjustment is its tendency to spread the effects of even one mistake throughout the work. In other words, it can cause large residuals to show up for several measurements that are actually correct. And when that happens it can be hard to know exactly what is wrong. The adjustment may fail the *chi-square* test. That tells you there is a problem, unfortunately it cannot tell you where the problem is. The chi square test is based in probability, and it can fail because there are still unmodeled biases in the measurements. Multipath, ionosphere and troposphere biases, and etc. may cause it to fail.

Most programs look at the residuals in light of a limit at a specific probability, and when a particular measurement goes over the limit it gets highlighted. Trouble is you cannot always be sure that the one that got tagged is the one that is the problem. Fortunately, least-squares does offer a high degree of comfort once all the hurdles have been cleared. If the residuals are within reason and the chi-square test is passed, it is very likely that the observations have been adjusted properly.

Using a Processing Service

There are several services available to GPS surveyors. While they differ somewhat in their requirements they are all based on the same idea. Static GPS data collected in the field may be uploaded to a web site on the Internet by the hosting organization which will then return the final positions, often free of charge. Usually the user is directed to an ftp site where the results can be downloaded.

There can be advantages to the use of such a processing service. Aside from removing the necessity of having post-processing software in-house, there is the strength of the network solution available from of them. In other words, rather than the data sent in by the GPS surveyor being processed against a single CORS in the vicinity of the work, it is processed against a group of the nearest CORS. There are often three in the group. Such a network based solution improves the integrity of the final position markedly and may compensate for long baselines required by the sparseness of the CORS in the area of interest.

Among the online resources available for processing services is the National Geodetic Surveys *Online Positioning User Service, OPUS.* This service allows the user to submit RINEX files through NGS web page. They are processed automatically with NGS computers and software utilizing data from three CORS that may be user selected, http://www.ngs.noaa.gov/OPUS/. There are others. Among them are - the Scripps Orbit and Permanent Array Center, SOPAC *Scripps Coordinate Update Tool, SCOUT*, http://csrc.ucsd.edu/cgi-bin/SCOUT.cgi and the *Australian Online GPS Processing Service, AUSPOS* http://www.ga.gov.au/bin/gps.pl and the Jet Propulsion Laboratories, *Auto Gipsy, AG,* http://milhouse.jpl.nasa.gov/ag/ and