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PRECISION PRODUCTS

Practical GPS Surveying

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Introduction

Surveying with GPS can be extremely productive, but it has also been known to cause bouts of depression and loathing. The goal in writing this primer is to guide surveyors in the practical use of GPS for surveying tasks, as well as to outline the pitfalls and provide tips on how to avoid them. We will try to keep our tour as light as possible. We will do our best to leave out long equations loaded with Greek letters, nor will we include deeply technical discussions of the physics and mechanics of GPS. A bibliography of books on GPS and GPS Surveying accompanies this guide for those who want more information.

The GPS System

To start, let's go over some GPS fundamentals that you should know in order to use it productively. GPS was conceived as a navigation system. By knowing the positions of the satellites and measuring the distance between its antenna and four or more satellites, a single GPS receiver can compute its three dimensional position, speed, and direction of travel. Errors inherent in the system dilute the repeatable horizontal accuracy of the computed position to a level of 20 to 100 meters. That is, your actual position will be somewhere within a circle which has a radius measuring from 20 to 100 meters. Vertical accuracy is not as good, and is reckoned to be 2 to 2.5 times worse than horizontal accuracy. In addition to the standard error budget, the U.S. government is introducing artificial errors into the system under a program which is obscurely titled Selective Availability or SA. With SA in effect, 100 meter accuracy is the best you can expect at this time for an autonomous GPS receiver. Fortunately, there are ways to greatly reduce the standard error budget and errors imposed by SA.

The navigation range measurements described above are achieved by using two parts of the GPS broadcast: The navigation message, which contains a week-long almanac of satellite positions, and the Coarse Acquisition code (C/A-code), which is used to calculate the distance between a GPS receiver and the satellites. Think of code ranging as a stopwatch measurement. The C/A-code allows us to measure the time it takes the signal to arrive at our receiver from the satellite. We know that the speed of the signal is very close to the speed of light. By knowing the time it takes for the signal to arrive at our receiver, we can calculate the distance the signal has traveled from the satellite. With this information, and knowing the positions of the satellites, the receiver can calculate its own position. In other words, the receiver essentially is performing a resection from known monuments, which are the satellites.

The typical recreational hand-held or GIS-grade receiver normally uses code measurements to compute positions. Recreational receivers normally operate autonomously, and we can expect only 100 meter accuracy in this mode. This level of accuracy is good enough for navigation and will certainly allow your survey crew to get to a job site without wasting time. GIS applications normally require accuracy at the level of one meter or better. This kind of accuracy can be achieved through the use of differential corrections, which can be applied to the receiver's range calculations in real-time or after the fact. The trade-off for better accuracy is the need for more equipment.

Differential correction techniques require the use of an extra GPS receiver. The extra receiver, usually called a base-station, is placed on an established benchmark, the coordinates of which are programmed into the base station receiver. Put simply, by comparing the programmed coordinates with the coordinates derived from the GPS broadcast, the base station calculates range corrections for each satellite it is tracking in order to match the satellite position to the programmed position. These range corrections can be used by any receiver which is tracking the same satellites as the base station. Since the errors will change over time, each correction is tagged with a sequence number. Real-time range corrections are applied by using a communications link between the base station and the receivers in the field, allowing us to use corrected positions as we go. Because the corrections are time-tagged, they can also be applied after the fact using post-processing software, which eliminates the trouble and expense of a communications link. However, even when using the best navigation code receivers with differential corrections, the finest precision we can hope for is submeter. To get survey-grade accuracy with GPS, we must use a different measurement tool. We must change from the stop watch to a measuring tape.

Our survey tape measure is the underlying signal upon which the C/A-code and the navigation message are modulated. This underlying signal is called the carrier. Just like your electronic distance measuring (EDM) unit, some GPS receivers can measure a distance by determining the number of wavelengths of a certain frequency that exist between two points. The basic frequency used by most GPS receivers is called the L1 frequency; it is transmitted at 1575.42 MHz. This means that there are about 1.5 billion cycles, or wavelengths, every second. The wavelength, or the distance represented by one cycle of this frequency, is about 19 centimeters. This 19 centimeter wavelength is the basic unit of our survey tape measure.

Using a survey analogy, the receiver is the head chainman and reads the add portion of the tape for the fractional measurement. That is, the receiver determines the fractional portion of a single wavelength, and this measurement is the millimeter portion of our total measurement. But unlike your conventional EDM, with one clock and a reflected signal, the GPS receiver has no way of counting how many whole wavelengths there are behind this fractional measurement. It can't tell what the rear chainman is holding. For this reason, various processing techniques are used to determine the number of whole cycles associated with the fractional measurement. After it makes the initial fractional measurement, the receiver does keep track of the change in range (the change in the number of cycles) from measurement to measurement. This information, in conjunction with the changing positions of the satellites, enables the processing software to determine the whole number of cycles associated with the original fractional measurement. Having done this, the software then differences the measurements made to all the visible satellites between two receivers, and solves for the vector between them. It is this differencing step that provides the accuracy of GPS survey measurements. The processing in effect removes all the common errors in the satellites and in the receiver measurements. Our measurement between survey points is quite precise even though it is indirect.

So what does all this mean? It means that you need to have a sufficient number of measurements from a sufficient number of satellites to achieve centimeter accuracy in your GPS survey measurements. If you don't, you won't. What is a sufficient number? It varies. But don't worry. We won't leave you completely frustrated. The guidelines in the following pages will help you to determine how much time is needed to make a sufficient number of measurements, and how many satellites are necessary for each of our GPS measurement techniques. A good rule of thumb is...with GPS, you can't have too much or too many.

Comparing Conventional and GPS Surveys

As this is intended as a guide for the surveyor new to GPS, the first thing we'll do is explain a little about what exactly a GPS measurement consists of, and we'll also compare conventional survey methods to GPS survey methods. GPS is simply an EDM device that does not need direct line of sight between survey points. Instead, a GPS receiver needs to have a direct line of sight to a sufficient number of satellites. With GPS we want to look up, not out. Keep in mind that GPS is not the solution for every survey task. Like any other tool, it has advantages and disadvantages. It is simply one of the many tools that should be in the surveyor's toolbox.

The GPS measurement is a three-dimensional vector from mark to mark. It contains distance, direction and difference in height between our survey points. Generally the software will report the vector as the difference in the earth-centered earth-fixed X,Y,Z coordinates of the survey points. A GPS vector can also be defined using a local E,N,U system or a geodetic Distance, Azimuth, Height format. The receiver makes its measurements between its antenna's electrical phase centers, and we use the measured antenna heights to correct the measurement down to the survey marks. What does that tell us? It tells us that the antenna height is a very important part of our measurement. In conventional surveying we often separate our measurements into horizontal (angle and distance) and vertical (elevation) parts. However, a GPS measurement is fully three-dimensional, and we cannot separate the parts. The vertical component affects the horizontal and vice versa, which is why it is critical to use fixed-height antenna poles for performing all GPS work. Conventional tripods are fine for static work, but the operator must be extremely careful to measure and record the antenna height correctly at each setup. A fixed-height pole needs to be checked only periodically for wear and tear, or if there is a change in the antenna being used. Using a fixed-height antenna pole will help to eliminate the possibility of antenna height errors in our measurements.

Conventional survey measurements involve a relative angle and a distance. It is this relative direction, or dependence on a backsight, that causes our conventional survey vectors to be strung together between the beginning and ending points as a traverse. Closure errors in a conventional survey traverse are typically removed by equally distributing the angular closure error and then prorating the remaining errors based on the lengths of the traverse legs. This method assumes that the errors occur systematically and evenly throughout the traverse, which in reality is seldom the case. But without any information other than our closure error, we can assume nothing else. If you have ever tried to adjust a series of dependent traverses using the compass rule, you'll have seen that the closure errors start to increase significantly after as few as two traverses. This occurs because the errors have been prorated instead of being dealt with where they actually occurred.

On the other hand, GPS vectors are independent of any backsight requirements, and you can put them together in any format you want. Ideally, you should put your GPS vectors together in strong interlocking networks that will allow you to make multiple measurements to each of your points. These multiple measurements will allow you to identify and deal with any vectors that contain a significant error (blunder). If there are no significant errors, the residual errors (random errors) will be adjusted using the least-squares method, which will provide you with the most accurate adjusted positions possible. If you link your GPS vectors like a conventional traverse between two points, your stations will be adjusted just like a conventional traverse would be, and you will lose the strength and accuracy of the least-squares method. Traditional static multiple-receiver sessions have provided us with the building blocks to create strong networks. With the advent of real-time kinematic (RTK) capability and a more radial approach to GPS surveying, we have overlooked some of the advantages of the strong network structure used in multiple-receiver static sessions. We need to take care to use techniques that will yield the most accurate and confident positions possible with these radial GPS survey methods. In short, as GPS surveyors, we want to think network, not traverse. We want to use the power of good network design and the least-squares method to provide us with the accuracy and confidence we need. And when it is not possible to have a good network structure, such as with dynamic or static radial surveys, we want to provide enough checks and redundancy to give us confidence in the accuracy of our points.

GPS surveying is by nature radial, that is to say, we are making sideshots relative to a base station. In post-processed dynamic applications, we can utilize multiple base stations in the processing to provide redundancy and confidence, but most real-time applications use only one base station. Radial surveys should never be used to establish control positions. They can, however, be very useful for general surveying tasks such as topography, photo control, site grading, lot stakeout, etc. Remember that a dynamic GPS position is a lot like a traverse side-shot. You have no solid check unless you visit the point twice. Therefore, it is a good practice to visit your radial points twice, and even better to move the base receiver to a different control station before the second visit.

The Dual Height Demon

Traditionally the major stumbling block in using GPS for surveying has been its shortcomings in establishing elevation. The basic problem is that it is impossible to directly measure elevation differences with GPS. With GPS, we can directly measure ellipsoidal height differences only. To directly measure elevation differences, we need to use a surveyor's level. That said, it is possible to place very good GPS-derived elevations on our survey points with the help of a good geoid model. This dual height system has been one of the hardest concepts for new users to grasp, and we'll try to explain it as simply as possible.

Elevation is defined as the height of a point above a gravity surface. Historically we have used the concept of mean sea level to describe the zero point, or datum, for elevation. Today in the United States, we are using a surface defined by gravity values because of the difficulty in describing a mean sea level from coast to coast. This gravity surface is irregular because it varies depending on the strength of the pull of gravity in an area. The surface of a potato is a good model for a world-wide gravity surface. Under the influence of the pull of gravity, water seeks its lowest level (sea level). That is, water flows downhill from a lower to a higher gravity, as it seeks this level. The only way to accurately measure the difference in height above this undulating gravity surface is to use a spirit level and differential leveling.

Ellipsoid height is the height of a point above a reference ellipsoid. GPS positions are referenced to the WGS84 ellipsoid. The center of this reference ellipsoid coincides with the center of the mass of the earth, which is also the origin point of the earth-centered earth-fixed X,Y,Z Cartesian coordinate system. We can easily determine the ellipsoid height of a point by determining its distance from the center of the earth and subtracting the radius of the ellipsoid from it. We can very accurately determine the ellipsoid height differences between points using GPS, but because of the absolute positioning errors inherent in the system, we need to reference these differences to points of known ellipsoidal height, just as we have to reference our spirit levels to some benchmark.

The fundamental problem is that these two height systems are completely separate. We can't directly measure heights in one system with the tools of the other system. We can, however, model the undulations of the geoid surface and extrapolate the separation between this surface and the surface of the WGS84 ellipsoid, These differences can then be used to derive elevations from our ellipsoid heights. Currently in the United States we have a very good model of the undulating surface of the geoid which is referenced to our WGS 84 ellipsoid surface within about a decimeter of absolute accuracy. If we use this model and tie our GPS measurements to points of known elevation, we can provide very good GPS-derived relative elevations for our new survey points in many areas of the country. There are places where the model is not sufficiently accurate (for example, much of the Rocky Mountains) to measure elevations with survey precision, but in many places it is quite possible to achieve relative elevation measurements with centimeter accuracy.

One of our tasks as surveyors is to find good benchmarks to which we can reference our model, and to find and use a sufficient number of them to accurately align the two surfaces. If we have only one benchmark, or if our benchmarks are distributed in a line, we will not be able to properly align the geoid with the ellipsoid, and we could have unacceptable errors in our GPS-derived elevations. These errors will increase as we get farther away from our controlling elevations. We should have a bare minimum of three well spaced control benchmarks if we want to use GPS to derive elevations, although the recommended minimum number is four. Having four benchmarks allows us some redundancy and provides us with some indication of the accuracy of our control benchmarks.

Definition of the terms Static and Dynamic for GPS Surveying

Let's clear the air a little bit and define the survey techniques that we are going to talk about. The jargon of GPS surveying has been inflated by manufacturers trying to individualize similar techniques by using different names for them. We are going to simplify this and use only two names: Static and Dynamic. Included in the list of names used for the various GPS survey techniques are static, rapid static, fast static, short static, pseudo-kinematic, pseudo-static, repeat occupation, kinematic, stop-and-go kinematic, and last but not least, real-time kinematic.

A static survey involves two or more receivers which are collecting data on different points for a sufficient amount of common time in order to resolve the vector(s) between them to the centimeter or millimeter level. The receivers are turned on at the beginning of the measurement session and off at the end of the session. Each receiver has a separate file for each occupation, and no data is collected while moving between survey sites. Static, rapid static, fast static and short static all refer to the classic static technique. Only the occupation time varies. Here we have to jump back into a discussion of GPS fundamentals. The satellites broadcast data on two frequencies, which are dubbed L1 and L2. Remember that we said the speed of the GPS signal is close to, but not equal to, the speed of light. This is because the speed and path of the signal are affected by the earth's atmosphere. The ionosphere is especially troublesome because its composition can change rapidly, which in turn changes the amount of error it contributes to the range measurements. However, the ionospheric effect is different for different frequencies. By correlating the effect of the ionosphere on the L1and L2 frequencies, we can mathematically eliminate ionospheric errors within just a few minutes. This is one of the advantages of using a dual frequency receiver; that is, a receiver that can track L1 and L2. Single frequency receivers can also solve for ionospheric errors in real time, but it takes them longer, in some cases much longer, to do it. Dual frequency capability is the basic requirement for achieving short occupation times, but with the number of satellites now available, and with better receivers and better processing algorithms, occupation times have also been reduced for most single frequency receivers used in surveying.

Pseudo-kinematic, pseudo-static and repeat occupation all refer to the same single frequency surveying technique. This technique is an attempt to obtain the efficiency of dual frequency short static occupations by repeating short observations of the same points. The observations are separated by some time interval (usually the time span of a standard static session) that allows for a sufficient change in satellite geometry to fix our distance measurements at the centimeter level. It's like a long static observation, but the part in the middle is ignored. Instead, during the middle part, you are occupying other sites the same way. With "pseudo" or repeat occupation methods, the receiver usually stays turned on when moving between survey sites. The software ignores the data collected while moving and uses only the data gathered by the receivers while occupying the survey points. These "pseudo" techniques are really just variations of the static technique. That is to say, only the data gathered while occupying the survey station is used in the processing. The techniques mentioned at the beginning of this paragraph are variations of the static technique.

Dynamic techniques require the use of the moving or trajectory data. The term kinematic traditionally has been used to describe dynamic GPS surveying. The term kinematic refers to both true kinematic, where only the trajectory is of interest, and to stop-and-go kinematic, where points along the trajectory are the items of interest. Real-time kinematic (RTK) simply relegates kinematic data processing to the receiver during data collection, providing information relating to the quality of field measurements while you are taking the measurement. This eliminates the need for post-processing, thus enabling you to do point stakeout as you go. A word of caution: Real-time kinematic adds a whole new dimension of radio-related problems to the art of dynamic GPS surveying. True to the old adage, you don't get anything for free.

Dynamic GPS surveying techniques allow for very short observations on survey points, but they require some form of initialization in order to achieve the centimeter accuracy quickly. Once initialized, you must maintain lock to a sufficient number of satellites to maintain the centimeter accuracy both while moving and while on the survey points. If during the survey lock is lost on too many satellites at the same time, you will have to reinitialize the survey. How you reinitialize the survey depends on the type of receiver you are using. A dual frequency receiver can reinitialize just by collecting sufficient clean data, while a single frequency receiver will have to be reinitialized by occupying a known survey point, or with some other technique using a known baseline. All these attributes apply equally to real-time surveys as well as post-processed surveys. The requirements for dynamic surveying make it suitable only to areas of open terrain. It is best suited for prairies, deserts, and bodies of water. In areas with trees and tall buildings, its use is extremely limited.

In summary, all of the confusing terms for the techniques cited above can be broken down into static or dynamic categories. With static methods only the common-time data gathered at our survey points is used to resolve the vectors between our survey points. With dynamic methods, the data collected while the receiver is moving is of equal importance. After initializing to achieve centimeter accuracy, the trajectory data allows this accuracy to be sustained while moving from point to point. In this way, only very short periods need be spent at the survey points. With Dual-frequency receivers we can simply use the moving data to solve or re-solve centimeter accuracy, allowing initialization 'on-the-fly,' and removing the need to initialize on a previously known vector. On-the-fly (OTF) techniques have made real-time kinematic a viable survey productivity tool in reasonably open terrain, as well as permitting the realistic use of dynamic centimeter positioning in aircraft and boats. Dynamic GPS is suitable for survey use only in open areas, even when using dual frequency receivers with OTF capability. If there are a lot of obstructions between the receiver and the satellites in the area you wish to survey, you will be better off using your total station tool rather than dynamic GPS. Using the right tool for a particular environment or task is the key. The more tools you have and the more flexible you are in selecting and using them, the more efficient you will be in accomplishing your survey tasks. No single tool is right for all uses.

Static GPS Surveying

Static GPS is the original technique used in GPS survey positioning. It is reliable and accurate. Historically it has been done using multiple receivers to build strong networks of points that facilitate the use of least-squares adjustment techniques to provide extremely accurate positions with confidence. This is the strength of static GPS. The disadvantage is that it takes longer to position a point than if we use dynamic methods. It's the old trade off: Speed and efficiency versus accuracy and confidence. We will want to use static GPS methods when we're establishing new control points.

Control

The first thing we should do in preparing for a static GPS survey is to find out where the control is, who established the control, and how it was established. We recommend that you use only good quality control established by GPS methods for your horizontal needs, and good high-order bench marks to control your vertical. Know your source. The best place to find good control is in the National Geodetic Survey's database. CD's containing all the control in a region are available for a modest fee. When you have selected the control you would like to use, you need to verify that it is capable of being used for GPS occupations. A benchmark set vertically in the face of building is not going to work, and a triangulation station set under a large Oak tree will also be a problem. In these cases, if you don't have other control options available, you will have to set eccentric stations which can be occupied by your GPS system.

Did we end up with enough control points? The bare minimum of control points to do a fully constrained three-dimensional adjustment is two horizontal and three vertical control points. We recommend a minimum of three horizontal and four vertical. This provides some redundancy and allows us to calculate some statistics that will give a better indication of the control accuracy. If your project is large, you may very well have more than the minimum number of control points available. Use them. More is better, but you wouldn't want to end up with a network that has more control than new stations.

Is our control well placed? It should lie outside of, or near the edges of our project. It should be well distributed geometrically. We don't want all the control on one side of the project. We don't want our vertical control all in a line. Our results can be distorted with poorly distributed control just as easily as with poor quality control. GPS surveying is not magic, but if we perform our observations well and control our adjustments properly, we will be able to achieve positional accuracy that is impossible to obtain using even the most rigorous conventional surveying methods.

We have determined the control we are going to use. Now we need to connect our new points to the control points in some coherent fashion. This is where a good game of leapfrog comes in handy. Start at one of the control points. Connect lines to, and between, all the points that will be occupied by the receivers in one session. If you only have two receivers, that's one line between two points. If you have four receivers, that's six lines between four points, or one session. Now, leaving at least one receiver as the pivot point, move (leapfrog) the other receivers to new points, and repeat the drawing of the lines. Continue leapfrogging in this fashion until you have connected all your new points and your control stations in nice strong network. There are two principles to remember in doing this:

1. Connect the dots
2. Measure the short lines

Following the first principle usually provides for fulfillment of the second. In other words, don't measure long lines that pass by intermediate points. Always try to connect adjacent points. More on network design appears later in this document.

As you can see, using four receivers will quickly provide us with a very strong network which has lots of redundancy for our least-squares adjustment. The use of only two receivers to achieve the same amount of redundancy would probably be cost-prohibitive from a time point of view. If you are using only two receivers you will need to provide some cost-effective number of cross ties to provide improved accuracy and confidence in your project positions. Please resist using GPS to simply traverse from control point to control point.

Observations

Okay, we have the plan of how our points are going to be connected. Now what? We need to establish a schedule for observing our stations. We need to verify that we can occupy the new positions with our GPS receivers, and we need to establish how much time we need to occupy them in order to ensure successful measurements. The occupation times needed to get good results will vary based on the type of receivers we have, the length of the baselines we are measuring, the amount of obstructions to satellite visibility at the sites, and the amount of other kinds of interference with our GPS signals. Interference can come in the form of multipath (reflected signals), ionospheric disturbance (solar storms), or nearby microwave transmitters. There are no guarantees, but you don't need a Philadelphia lawyer to figure it out. Look around your site. Does it look bad to you? If so extend your session. Remember that all receivers participating in the session will have to extend their observations also. Do both sites in a baseline look bad? If they do, extend the session even more. Recommended occupation times given for both single and dual frequency receivers assume clean environmental conditions. This brings up another important point: Good communications between operators allows the crew to be flexible in the observation schedule.

Once you have determined the length of each session, you will need to make a schedule for the operators. This schedule will include the stations to be occupied and the start and stop times of the sessions. The schedule will be made using our network plan as a guide, keeping in mind the travel time between survey points. We want to occupy our points in a sequence that provides a nice structure. Factors affecting the ease of travel will need to be taken into account, such as time of day and terrain. I've been on surveys where it took several hours to go between points a mile apart. Terrain factors may influence the structure of the network by causing you to reconfigure your basic network. Another important factor is satellite visibility. You should use your satellite visibility software to look for the optimal periods of time to make your observations. You may wish to shorten or lengthen sessions based on the number of satellites available. With the number of satellites now in operation, satellite visibility has become less important in the planning of sessions in areas where the terrain is reasonably open. However, it is still important in areas where there are numerous obstructions to the satellite signals.

The hard part is done. The operators have their schedules and away they go. Everyone sets up for the first session. They all find their correct marks. They set their antennas over the marks and carefully measure the antenna heights (if they are using a standard tripod, they should record at least two measurements taken from different sides of the antenna). The receivers are turned on, the site names are noted, and comments are logged. After the specified session time has expired, the receivers are turned off and the leapfrog receivers move to their new points. These steps are repeated until all the planned sessions have been recorded and all the points have been positioned. It's wonderful when it happens smoothly like that, but the reality is that our session plans will change because of things like washed-out roads and stalled vehicles, as well as incorrect antenna heights, signal interference, etc. If the crew has communications, they can usually make adjustments for the unexpected. If not, changes will have to be made at the end of the day for implementation the following day. Even the best laid plans will almost always change.

Housekeeping

Small things sometimes have big consequences. Good housekeeping is very important in a successful GPS survey. Things like battery maintenance and the availability of sufficient receiver memory can have profound effects on productivity. It is not fun to return from a day's work to find that nothing had been recorded because the receiver memory was full. Likewise, it is not fun to get to a pack-in station and find that the batteries are not sufficiently charged to complete your sessions, and you don't have any spares.

Another small factor that can cause problems is the receiver recording interval. If you are expecting to post-process short occupation static data, and the recording interval is set to 20 seconds instead of 5, you will be recording less data than you were counting on, and your occupation may not be successful. Also, if you wish to use dynamic GPS and occupy points for 5 or 10 seconds, you will have very poor results if your recording interval is set to 20 or 30 seconds. Make sure your recording interval is correct for the technique you're using, and that the recording intervals of all receivers in the session are set identically.

One of the most common mistakes that new GPS users make is to use a slightly different name on a repeat occupation of a point. An example would be calling a point C012 in one occupation and 012C in another. The computer can't tell that this is really the same point, and therefore two separate points will exist. Another naming problem would be to use the same name for two different points. This will cause the adjustment to "blow up". When the residual errors and statistics in an adjustment are huge, two points with the same name is usually the cause. We want to use one and only one name for each point in our survey. There should be a logical and consistent method for naming points, and all operators should be aware of it. It is not uncommon to have a point that can't be occupied, and an eccentric station will have to be set or an unscheduled point will have to be occupied. Bad stuff is going to happen, but we want to try to keep it to a minimum. Have a checklist for the crew to use. A morning checklist and an evening checklist might be appropriate. We all need reminders at times.

Dynamic GPS Surveying

Dynamic survey techniques are becoming increasingly popular. Everyone is talking about RTK surveying these days. Initialization and re-initialization have been simplified with the advent of dual-frequency receivers and dual-system (GPS/GLONASS) single-frequency receivers. Antennas, multi-path reduction techniques, and processing algorithms have been improved to provide better performance under tree canopy. But "improved performance" does not mean centimeter accuracy. Under heavy tree canopy, the best we can hope for at this time, even with the most sophisticated receivers, is submeter performance. While dynamic GPS surveying can be very efficient and accurate in performing some survey tasks, we need to be aware of its shortcomings as well as its strengths. As great as it is in open areas, there are many places where it won't work well. Let's take at look at the process, as well as the good and the bad, of dynamic GPS surveying.

The Dynamic Process

In static GPS, we resolve the phase ambiguity (the rear chainman's reading) and get centimeter accuracy by collecting lots of data. In order to make a survey dynamic we need to occupy points for very short time periods while getting the same centimeter accuracy. To do that we must initialize our dynamic survey. This means we must solve for centimeter accuracy before we begin visiting any new survey points. The best way to do this is to place both the base and the mobile receiver on two known points, such as either end of a known baseline. The known baseline should have a direct GPS measurement between its end points. The software will use this known information to solve and fix the phase ambiguities from just few seconds of data collection. Once we have occupied the known baseline and achieved centimeter level accuracy, the mobile receiver can proceed to the points in the survey. As long as the mobile receiver maintains lock to four or more satellites, the receiver should maintain centimeter accuracy. This means that our trajectory, the data collected while moving, is also at the centimeter level of accuracy, and we can use dynamic GPS to do accurate profiles and cross sections. If the receiver fails to maintain lock on at least four satellites, you will have to reinitialize the survey. If you lose lock too many times, dynamic GPS quickly becomes as unproductive and frustrating as spinning your wheels in the mud. In open terrain it can be like sailing before the wind.

Set one receiver on the known base point. Set the other receiver (the mobile unit) on another known point relative to the base point. This is the other end of the initializing bar. To ensure the integrity of the initialization, you should use a tripod on both ends of the bar. A good recording interval for dynamic surveys, where we are interested only in the survey points and not the trajectory itself, is an interval of two to five-seconds. Turn the receivers on and enter the appropriate site ID's and the observation time. A five-minute observation is recommended when using the initializing bar. At the end of the input observation time, four question marks (????) will replace the entered site ID. These question marks tell the software that, from this time on, this is moving data. After the question marks have been entered by the logging software, the operator removes the antenna of the mobile receiver from the tripod (carefully, so as to remain locked on all the satellites), places it on the kinematic pole, and moves to the next point. Again, be very careful to keep the antenna vertical and avoid, as much as possible, any overhead obstructions to the satellites. On the new site, the operator enters the correct site ID for the point and waits to collect a few epochs of data on the point. After the prescribed time period, the program reenters question marks (????) in the site ID field, and the operator moves to the next survey point. This procedure is repeated until all new survey points have been visited. If the survey extends for more than 30 minutes, it is recommended that the operator reoccupy the initialization point, or another point known relative to the base point. This should also be done at the end of the survey. This gives us the ability to check our re-initializations and provides us with multiple initialization points for processing. Multiple rovers can be initialized and used in the same session.

Because of the radial nature of dynamic GPS surveying, it is recommended that repeat observations are made with enough time between them to allow a change in the satellite constellation. It is even better if these repeat occupations are performed using a different point for the base station.

Dynamic Advantages

One of the advantages of dynamic GPS surveying is that it provides us with a tool to very quickly position our survey points on the ground. If we also use real-time equipment, we have the ability to quickly stakeout points to pre-designed coordinates. The use of real-time has two other built-in benefits. We can tell exactly how much time we need on a point, and we can be sure that we have a good position when we return to the office. Keep in mind that the benefit of knowing exactly when we have enough time also applies to static methods. In areas with lots of obstructions, if you are using real-time equipment, you should think in terms of real-time static, rather than beating yourself up trying to use real-time dynamic methods. Stay on the point as long as it takes, but no longer.

Another advantage of dynamic GPS is that it allows us to very precisely position moving aircraft and boats. We can use dynamic GPS positioning to eliminate most, if not all, of the ground control in an aerial photogrammetry project. Dynamic GPS can also be used to perform high precision hydrographic surveys. In combination with a fathometer, dynamic GPS will provide us direct bottom elevations without having to worry about the tide level.

The primary advantage of dynamic GPS on land is speed. Static methods are more accurate. In the air and on the water, the primary advantage is accuracy. Dynamic GPS surveying is the most accurate way to position a moving vehicle. Now, with dual-frequency receivers and on-the-fly initialization techniques, both real-time and post-processed, dynamic GPS surveying is viable in a production sense. One cannot do static observations with moving targets, so single-frequency dynamic GPS is of little use in constantly moving vehicles likes boats and airplanes, where it is impossible to reinitialize without a stationary known baseline.

Not So Dynamic Disadvantages

The main disadvantage of dynamic GPS is that it requires good satellite visibility. It does not work well in forests, urban centers, and canyons. We need to have reasonably clean data from an absolute minimum of four satellites at all times in order to do centimeter level dynamic GPS surveys. Each time we fall below the minimum number of satellites, the survey must be reinitialized. With a single-frequency receiver, this means we have to occupy a point (it could be the last point just surveyed) that is known with respect to the base station. If we are fortunate enough to have dual-frequency receivers, we only need to move to where we have good satellite visibility and wait until the receiver reacquires centimeter accuracy. This "on-the-fly" initialization is the primary benefit of using dual-frequency receivers in dynamic GPS surveys.

Another disadvantage of dynamic GPS for the surveyor is that it's a radial technique. Unless we revisit points or we set up additional base stations and post-process the data, we have a sideshot--a single positioned point with no redundancy. At this writing, I am not aware of any commercial real-time GPS survey system that uses multiple base stations. Most of the time everything works well and we get excellent results. But GPS measurements are just another kind of measurement, and like any other measurement, sometimes they are inaccurate. So what should you, the prudent surveyor, do? Check your work. This is as true for GPS surveying as is for conventional surveying. As we said before, GPS is similar to an EDM. It is not magic. In many cases dynamic GPS provides a better solution than using a conventional total station, however there are also lots of cases where the total station might be more suitable. Don't forget about the other tools in you toolbox.

Networks and Least Squares Adjustments

Surveying with GPS provides us with precise vectors, but not perfect vectors.   We can improve the accuracy and confidence in our measurements by using adjustment procedures. Historically surveyors have used traverse methods to go from point A to point B (or from point A returning to point A), and have used some sort of proportional adjustment, such as Compass, Transit, or Crandall, to adjust out the traverse closure error. This method is reasonably good for small simple traverses, but in large surveys with interconnected traverses this method falls short, and we can end up with very poor closures by using proportional methods. For sets of interconnecting traverses, the use of the least squares method is necessary. The traditional static method of making GPS measurements using multiple receivers provides us with what is essentially a series of interconnected traverses, or sessions. Because of this, the least squares method has always been the preferred adjustment technique.

The least squares method adjusts the position of a point so that the differences between measurements made to it are as small as possible. If a particular measurement does not fit with the other measurements, its movement will be greater and its residual values will be higher, indicating more error. If this error is large enough it may be flagged as a statistical outlier, and we may want to remove the measurement from our survey. The ability to remove poorly fitting vectors from our adjustment depends on the level of redundancy we have built into our network. The more redundancy we have in our network measurements, the more flexibility we will have in removing poor fitting vectors from our network without having to return to the field for repeat observations. The more redundancy we have in our network measurements, the more accurate our points will be, and the higher our confidence will be in those positions. When planning a survey for a least squares adjustment, keep in mind the importance of connecting the dots and measuring the short lines.

There is a third principle to consider: More is usually better. Notice I use the qualifier usually. At some point in any project it is ineffective and uneconomic to make additional measurements. This will vary from project to project depending on the accuracy requirements and the end use of the points surveyed. If you follow the two basic principles you should not need to add more measurements.

Designing a Network

This section is intended to give some guidelines for designing a strong survey network. We will begin with a general discussion of the strength of components of the network, then discuss two different methods of network design, followed by some examples of problems that may be experienced.

Geometric Strength of Figure

The geometric strength of a figure may best be thought of as a scaffold structure and its relative structural strength. The strongest figures are an equilateral triangle or a double braced quadrilateral (Figure 1). Lattices composed of these figures would be analogous to a network.

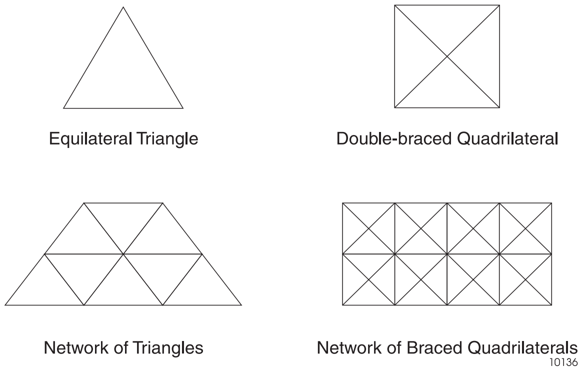

Figure 1

With a survey control network, as with a scaffold structure, the more acute the angles are, the weaker the structure. While this was more crucial to triangulation than trilateration or GPS measurements, the principles are still valid. The more rigidity a network has, the more confident you can be that the adjusted positions are precise.

Not only is strength of the individual geometric figures important, but the manner in which they interconnect and relate to each other in the network is vital. Consider the example in Figure 2:

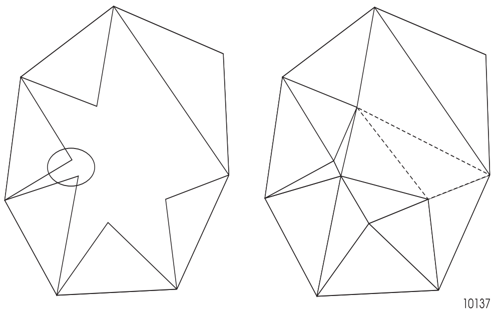

Figure 2

In Figure 2, the network on the left is composed of geometrically strong figures, but their interconnections are poorly structured, especially in the circled area, where two stations that are close together are not directly connected. Would you stand on a scaffold built this way? You wouldn’t want to rely on the positions computed in a network structured like this. The structure above may be improved significantly by adding some lines as shown on the right. The dashed lines probably would not be required, even though they provide added strength.

As you can see, the additional lines strengthened the network considerably. In cadastral surveying, many states have enacted minimum standards legislation requiring all boundary lines to be measured directly, as opposed to performing a radial survey and inversing the lines. A radial survey is dependent upon a single observation that may or may not contain significant error. And although a traverse along a boundary would have similar potential for error, detection of such an error would be simpler. With networks, the additional redundancy provides not only integrity (strength), it also allows for a statistical analysis of where errors have occurred through the use of least squares adjustments.

Don't think of this redundancy as extra work. It isn't. Redundancy is needed to detect and eliminate errors. In measuring an angle, a single observation can be grossly erroneous, which is why the techniques of "wrapping" angles (with a transit) and "turning" multiple sets (with theodolites) were developed. The same is true of distance measurements. Chained measurements were commonly repeated, and the accuracy of EDM measurements may be increased by measuring a line from both ends. No matter how precise the equipment may be, the true accuracy of the measurements is unknown without sufficient redundancy.

Effects of Known Control on Network Geometry

Location of known ("fixed" or "control") stations will affect the quality of the network, usually in a positive manner. If you have a sufficiently strong network before the knowns are added to the adjustment, you may detect "bad" control (erroneous coordinates). Also, in situations where redundant measurements are extremely expensive (such as one composed of stations that may be reached only by helicopter), proper location of known stations may reinforce an otherwise weak network. As an example, consider Figure 3:

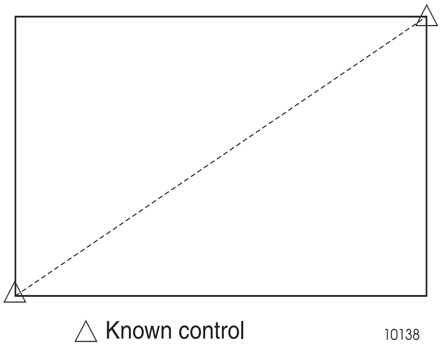

Figure 3

Figure 3 is not a network, nor would two known stations be enough to perform a fully constrained adjustment, but you can see that the figure is made rigid by "fixing" the two known positions. Without at least two fixed points, this is not a rigid structure.

[It's not a good procedure to rely on known control to shore up a poorly designed network. Poor control can distort otherwise good measurements. Again, the best procedure is to design a network structure that is rigid by itself, containing as many known stations as possible. Sufficient control allows poorly fitting known stations to be rejected or deweighted.]

Loop Framework Method

Designing a GPS network boils down to one basic premise--think network, not traverse. We want to use the inherent strength of redundancy that a least-squares adjustment provides. The following pages outline the steps used in designing a network with the “non-trivial” loop method. The loop method starts out like a traverse method, but by including the other vectors observed along with the loop baselines, the result will be a nicely redundant network. If we use this method correctly, we will arrive at the most efficient set of observations for our network. To be acceptable to NGS for inclusion into the national network, we need to add sessions to account for triple occupation of 10 percent of the stations, double occupation of control (100 percent of vertical and 25 percent of horizontal), and double occupation of 5 percent of the baselines.

There has been some discussion as to whether or not trivial baselines should be included in a network. Notice that "trivial" (and “non-trivial”) have been placed in quotes. With independent processing of the baselines, none of the lines are trivial. Correlated, yes, but not trivial. If the baselines have been processed by software that uses all the data in a session at the same time, then some of the lines will indeed be trivial: they will result in zero closures. In a typical case like this, statistics would be reported only for the “non-trivial” lines. The "trivial" lines will simply be mathematical inverses between the end points of the “non-trivial” baselines, and these lines probably should not be used the network.

Factors which help contribute to the "non-trivialness" of independently processed session vectors are:

- Different satellite visibility between stations
- The effects of directional orientation on baseline results.

For a stronger network, we will use all of the independently processed baselines we possibly can. We want to avoid a network that looks like the one in Figure 11.

The steps

(Before starting, you might wish to try designing a network using your current method with the provided points in Figure 4)

1. Establish the framework loops.

   Using the points provided in Figure 5, connect the network stations in traverse loops. Each loop shall not exceed 10 baselines. Examples are shown in Figure 6 and Figure 8.

2. Layout the sessions (Connect the Dots).

   Determine the number of receivers to be used and add the "trivial" session lines, shading the areas enclosed by the sessions. Each session should include the appropriate number of loop vectors. The formula for "non-trivial" vectors is N-1 where N is the number of receivers used. With 4 receivers, as in our example, each session should contain 3 "non-trivial" vectors as shown in Figure 7 and Figure 9.

For basic surveys you may simply want to start with step two and connect the dots in session groups as you leapfrog from session to session between your control points. Between each session, one or two receivers will remain on point while the others move to new points for the next session. This is probably the quickest way to design your network, but may lead to one or two extra sessions. Remember to take into account terrain features and travel times when grouping your sessions and planning your moves

3. (Optional NGS)

   Make sure the criteria for repeat observations have been met. This is not really a third step, since it’s usually done during the second step. As you can see from Figure 12 and Figure 13, judicious planning can save time.

The criteria for NGS acceptance involves much more than a good network design. If you are planning on performing a "Bluebook" survey, please refer to the *Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques*, Version 5.0 May 11, 1988 (at least two reprints have occurred) put out by the Federal Geodetic Control Subcommittee.

A well-designed network will provide confidence that the adjusted positions will be the best positions possible. Also, well-designed networks help us to estimate job costs more accurately and easily. If we know the number of "non-trivial" baselines, i.e. the number of baselines in our loop framework, we know exactly how many sessions are required. Referring to Figure 8, we see that there are 30 baselines. With careful planning, we can complete the project with 10 sessions using 4 receivers (with N-1, or 3, "non-trivial" baselines per session).

These examples do not cover the effect that additional known stations would have on the network.

Design A Network Using 4 Receivers

Use your current method in Figure 4.

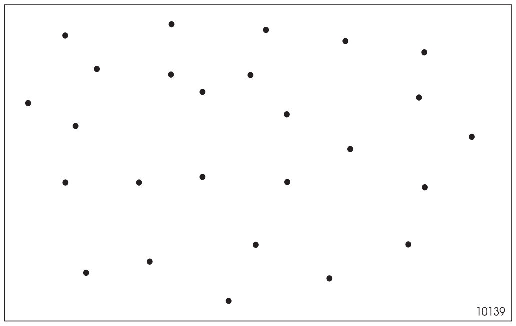

Figure 4

In Figure 5, start with loops of "non-trivial" baselines. Each loop should contain no more than 10 baselines and be no more than 100 kilometers in length. Each loop must contain baselines from more than one session Each session should also contain N-1 loop baselines, where N is the number of receivers participating in the sessions. For example, if 4 receivers are used, each session should contain 3 of the "non-trivial" loop baselines. Start by designing the loops first and then fill in the session’s "trivial" vectors.

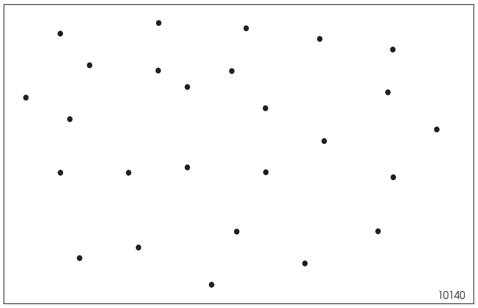

Figure 5

One possible loop framework solution is shown in Figure 3.

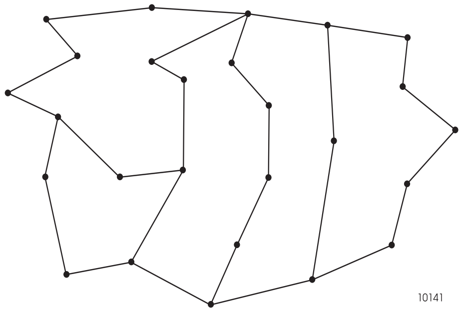

Figure 6

In Figure 7 we see a plan for 11 sessions based on the 5 loops created in Figure 6. The inefficient areas of this plan are circled, and are the result of using only one loop baseline in a session and having a baseline observed in two different sessions.

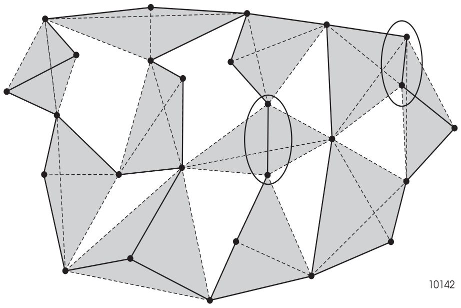

Figure 7

Try to avoid parallel loops while planning your loop framework. Long parallel runs with few cross ties make for a weaker structure and can compromise the quality of your least squares adjustment. The loop structure show below in Figure 8 is better than the one shown in Figure 6.

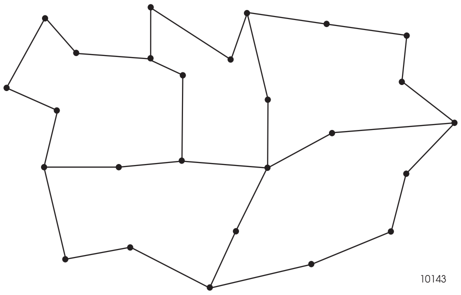

Figure 8

Based on this new loop structure, the sessions have been laid out more efficiently in Figure 9. The same stations have been observed using 10 sessions instead of the 11 shown in Figure 7.

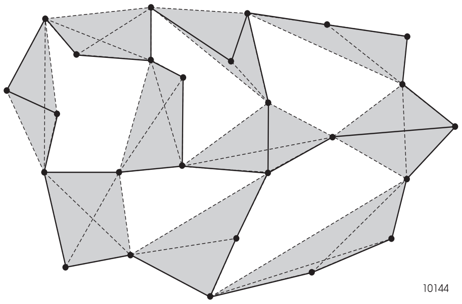

Figure 9

Notice that each session in Figure 9 has three “non-trivial” baselines used in the loop framework, and that each session is connected to at least 2 other sessions. Another interesting thing to notice is that the "holes"--the white areas--in Figure 9 are all four-sided or more while Figure 7 contains several that are only three-sided.

Compare Figure 8 to Figure 10. Which looks stronger to you? When using least-squares adjustments, redundancy is strength.

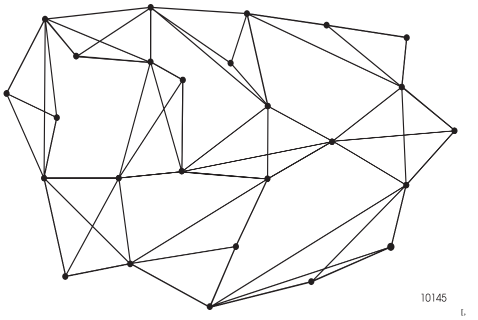

Figure 10

In Figure 8 only the “non-trivial” baselines have been included, while all baselines have been included in Figure 10. Using the so-called "trivial" baselines adds redundancy and strength to the solution, and if nothing else, using all observed vectors allows the deletion of poor baselines without any ill effects.

A Poor Network

Can you identify some of the problems with the following network of vectors?

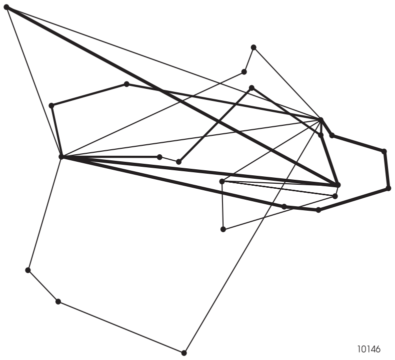

Figure 11

There are three fairly obvious problems with the network in Figure 11:

- The loops have poor cross-connections
- Most of the short distances have not been measured
- There are long ties that bypass closer stations

Figure 11 illustrates some of the problems that can result from "traverse thinking"; i.e., thinking within the context of a conventional traverse rather than thinking of network integrity.

NGS Specifications

Designing a network that will meet NGS specifications results in more sessions. In meeting the requirement of triple occupation for 10 percent of the stations, we should also, automatically, meet the 5% double baseline occupation requirement. In the example shown in Figure 12, there are a total of 13 sessions, three more than necessary for a good network. This is not efficient work. The network was laid out by starting with three stations to be occupied three times, and adding sessions to observe all of the loop baselines. It was also done without concern for where the control was located. We end up with extra triple occupied stations, extra double occupied lines, extra sessions--in short, extra time.

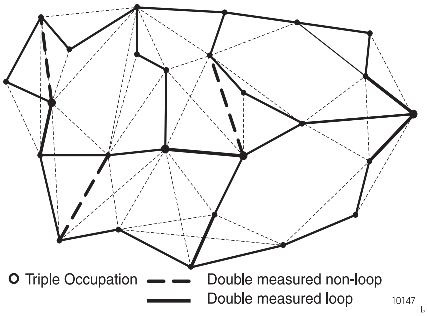

Figure 12

Figure 13 shows a better solution meeting NGS requirements.

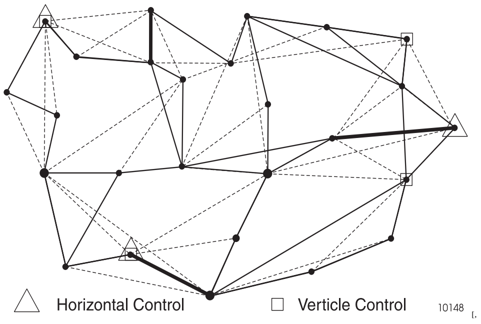

Figure 13

The network in Figure 13 has been laid out more efficiently, and the location of the control has been considered. Below are the criteria used, listed in descending order of concern:

1. Triple station occupation -
   10% (Need 3 stations, have 3)
2. Double station occupation -
   New stations - 30% (Need 8 stations, have 9)
   Vertical control - 100% (Need 4 stations, have 4)
   Horizontal control - 25% (Need 1 station, have 3)
3. Repeated baselines -
   5% of loop baselines (Need 2 baselines, have 3; include any azimuth pairs)

Practical net design and session planning

The preceding loop framework design method of designing networks will produce strong networks suitable for Blue booking (submittal for NGS acceptance), but probably contain more than is necessary for more common surveying needs, such as photogrammetric or cadastral control. Loop closures are rarely required outside of surveys submitted for NGS acceptance, and are somewhat of an anachronistic holdover from conventional surveying methods. Still, loop closures can be a useful network analysis tool.

If you adhere to the guidelines presented in the section entitled *Designing a Network*, you can design a stable network better suited to the needs of the average surveyor. Consider network geometry when planning sessions (observation periods). Use planning maps to design the network while planning your observations, paying close attention to the strength of geometric figure for each session. A simple schedule change can have a drastic effect on the strength of your net. Consider also the travel time between stations for all observers moving between sessions. This brings up an important point that we'll mention again: Good communications are necessary to efficient GPS surveying, and a timetable should be provided to field crews as a backup in case of a communications outage.

A Closing Reminder

CONNECT THE DOTS
MEASURE THE SHORT LINES

If you apply these two principles, your networks should always provide you with accurate positions that you can be confident in.

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