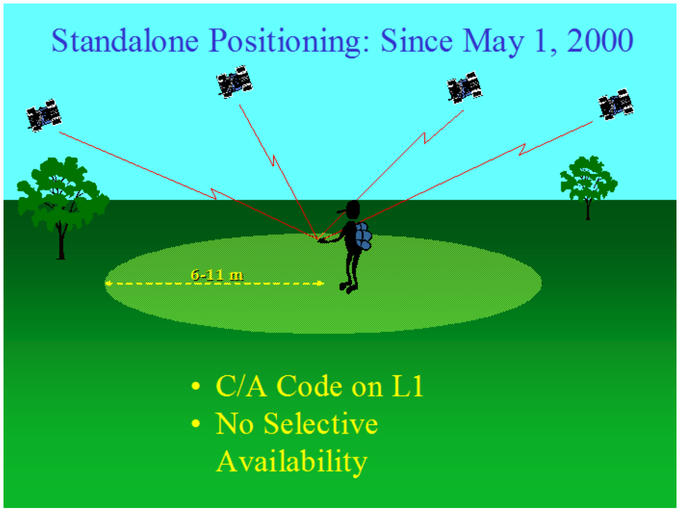
GPS Surveying Methods

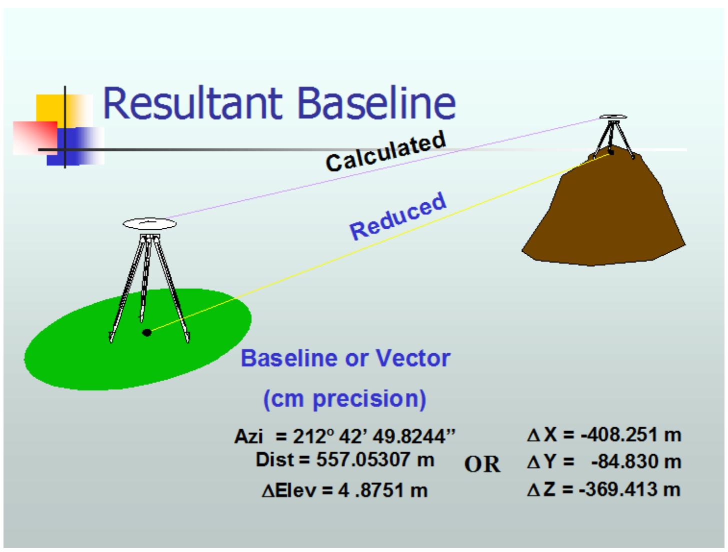
Reading:

Introduction

In Topic 2 (a) the fundamentals of GPS were discussed, including the space, control, and user segment; the L1 and L2 GPS signal structure; psuedorange distances; carrier phase range distances; and error sources. These concepts form the basis of the GPS system, what information is actually being sent from the satellites, how a distance from a GPS satellite to the GPS unit is calculated, and some of the potential error sources in the received signals.



It was also discussed that Selective Availability (SA) was turned off in May of 2000. This allowed for a "standalone" or "autonomous" position for a GPS unit to be between 6 – 11 meters. This position is created from the pseudoranges that are created from the Coarse/Acquisition (C/A) code. This standalone position can be transformed and projected to the user's coordinate system, however, the final coordinates are not acceptable for applications that require a high degree of accuracy in the results.



In order to produce more accurate coordinates from the data collected by GPS units, relative positions between the GPS units and, therefore, the occupied points need to be produced. These **relative positions** are produced from the information collected by two GPS units occupying different points simultaneously. The produced result is called a "baseline" between the two points. The baseline is either an azimuth, distance and delta elevation or a DX, DY, and DZ of the Earth Centered Earth Fixed (ECEF) coordinates of the two points. See the picture above. Note: in GPS surveys a baseline is not an observed measurement. It is a calculated and then reduced result. The observed measurements are the psuedoranges and the carrier phase ranges.

In order to produce high accuracy coordinates from GPS produced baselines, appropriate GPS surveying methodologies have to be followed. Additionally, for some of the methods, requirements on the postprocessing of the data should also be followed. The GPS surveying methods can be split into two main categories: Static GPS and Differential GPS (DGPS). The rest of this lesson will describe the Static GPS surveying method and the next lesson will discuss DGPS surveying methods.

Static GPS - Baselines

Baselines

The first method developed for GPS surveying was the Static GPS method and includes Static and Fast Static GPS surveys. This method involves the collection of GPS data from two or more GPS units for a specified period of time during one or more observation session. In other words, the GPS units are “static” while the data is being collected. This allows for the integer ambiguities to be accurately resolved. One definition of Static GPS is: *Carrier phase ranging technique where the integer ambiguities are resolved from an extended observation period through a change in satellite geometry.*

So, in Static GPS surveying, the observation sessions will have more than one GPS unit collecting data simultaneously for a specified period of time. From that data, the integer ambiguities can be accurately resolved during postprocessing and accurate baselines can be produced.

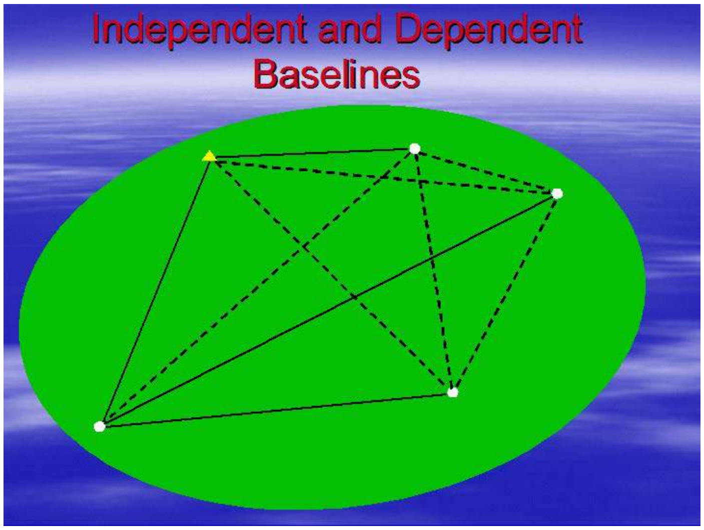
Independent and Dependent Baselines

Before describing the design (planning) of a Static GPS survey, the concepts of independent and dependent baselines needs to be understood.

The number of baselines that can be produced from an observation session is dependent on the number of GPS units collecting data simultaneously during that session. The total number of baselines that can be produced from a session is (N)(N-1)/2, where N is the number of GPS units collecting data for a session. So, if there are 3 GPS units collecting data simultaneously, the total number of baselines that can be produced from that session is (3)(2)/2 = 3. Similarly, if there are 5 GPS units collecting data simultaneously, the total number of baselines that can be produced from that session is (5)(4)/2 = 10.

An ***independent baseline*** is a baseline produced from a Static GPS survey observation session that provides no redundancy when combined with the other selected baselines from that session. In other words, there are no closed loops produced from the independent baselines from a session. For example, if you had three GPS units collecting data for an observation session and they were occupying Station 1, Station 2, and Station3, the possible sets of independent baselines for that session are:

- Station 1 – Station 2, Station 2 – Station 3
- Station 1 – Station 2, Station 1 – Station 3
- Station 1 – Station 3, Station 2 – Station 3



A ***dependent baseline*** is a baseline produced from a static GPS survey observation session that produces redundancy when combined with the other selected baselines from that session. In other words, it creates a closed loop.

The picture to the left shows a Static GPS session that has five GPS units. The bold lines show the selected independent baselines for the session and the dashed lines show the resultant dependent baselines.

As described above, the total number of baselines able to be produced from a Static GPS observation session is (N)(N-1)/2, where N is the number of GPS units collecting data during the session. The number of independent baselines from that session is (N-1). So, if you have five GPS units collecting data for a session, the total number of independent baselines for that session is (5 – 1) = 4.

The total number of dependent baselines for a session is the number of baselines that are not independent. This means that the number of dependent baselines is (N)(N-1)/2 – (N-1). So, if you have five GPS units collecting data for a session the total number of dependent baselines is (5)(4)/2 – (4) = 6.

The idea of independent baseline is important for the planning of a Static GPS survey.

Static GPS Survey - Planning

One of the most important aspects of a Static GPS Survey is the survey plan. The plan is the overall design of the survey including the occupied stations and occupied time frame for each GPS unit being used for the survey as well as "mission planning", which includes reviewing the potential satellites in view and their PDOP for the area of the survey before the survey.

Step one: The first step for the planning of a Static GPS survey is to research the control in the area of the survey. The research should include the County records (records of survey and corner records), other municipality records, State records from the Department of Transportation and the Department of Water Resources to name a couple, NGS datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), and any other entity that may have control information that would help with the planning of the survey as well as recovering the control before the survey. Note: the quality of the control that a GPS surveyor will select for a project is contingent on the standards and specifications for that project. Standards and specifications will be discussed at length in a later lesson in this topic.

Step Two: The second step is to plot the selected control and the stations to be surveyed on a map so that the relative positioning of the stations can be viewed. This map will then be used in the planning process to ensure that the Static GPS survey plan is complete and meets all of the requirements for the standards and specifications.

Step Three: Nearly all, if not all, GPS processing software contains a tool for “mission planning”. This tool allows the planner of a GPS survey to know what times during the day the GPS satellite constellation will have enough satellites in view and the appropriate PDOP levels. The planner should make use of the mission planning tool to ensure that the appropriate observation criteria on the satellites for the required accuracy level of the survey results are present. The observation criteria will also be discussed in the standards and specifications lesson. This information will then be used to set up the observation schedule.

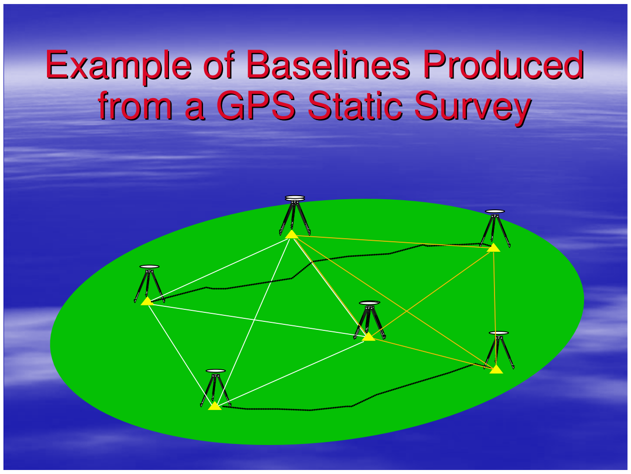
Step Four: The fourth step is to plan the observation sessions. The recommended way to do this is to have a spreadsheet for the observation sessions that has rows for each observation session and columns that are for each GPS unit and the desired independent baselines for each session. Note: for each session the time of the session is to be placed in the first column, the station to occupy for a particular GPS unit is to be placed in the corresponding columns and the desired independent baselines for the session in the last column. Below is an example of the Static GPS survey observation plan spreadsheet.

Static GPS Survey Observation Plan

Session	Unit 1	Unit 2	Unit 3	Unit 4	Independent Baselines
Session 1: Time	*Occupied Point*				
Session 2: Time					
Session 3: Time					
Session 4: Time					
Session 5: Time					
Session 6: Time					
Session 7: Time					
Session 8: Time					
Session 9: Time					
Session 10: Time					
Session 11: Time					

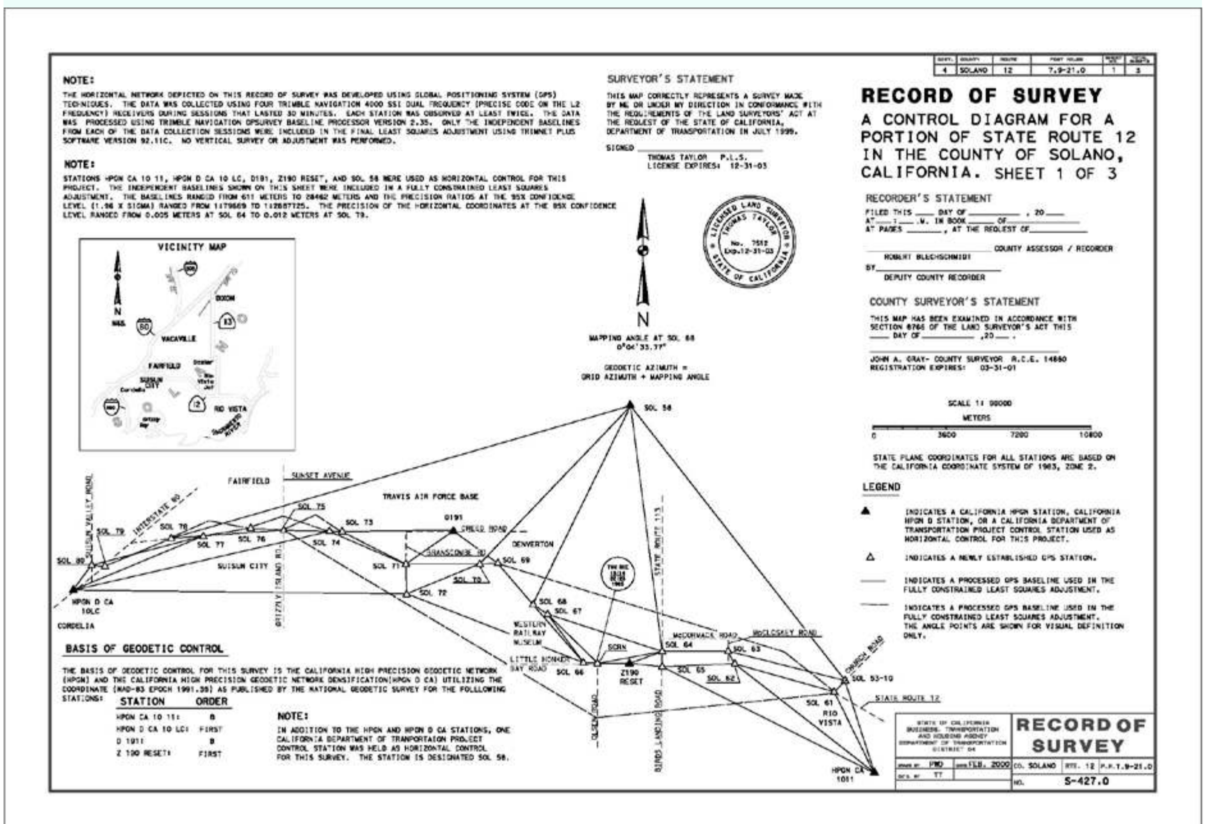
Project XYZ Located at ____________________

While completing the observation plan spreadsheet the desired independent baselines for each session as the session is planned should be placed on the map that contains the control and the stations to be surveyed. The picture to the left is an example of the desired baselines to be produced for six stations. Suppose the Static GPS survey was using four GPS units. How many observation sessions would it take to get the eleven desired independent baselines shown?



Note: there are closed loops in the diagram. This is an important point in planning a Static GPS survey. It is desirable to have closed loops of three to five sides produced from the independent baselines from different sessions. Also, a good “strength of figure” is desirable.

The following Record of Survey depicts the results of a Static GPS survey that followed the above planning steps. The solid triangles are the researched control stations used, the other triangles are the new stations in the survey, and the lines between the stations are the independent baselines used from the Static GPS survey observation plan. Note: some of the control is external to the survey and in different “quadrants” with respect to the survey area. This is a good rule of thumb to follow and is also a requirement in most specifications. Also note the good strength of figure, which is also called good network geometry.



There should also be redundancy built into the observation design. This includes number of occupations of each station and the number of repeat baselines to be included in the network adjustment. These numbers also depend on the specification being used for a particular survey.

There are no hard fast rules for the method of designing the observation plan. I.e. there is no best observation design, at present, to observe the independent baselines to achieve efficiency in the overall survey. There are some ideas currently out there, however, there are literally hundreds of ways to design a plan for any static GPS survey. In other words, it is like an art creating a Static GPS survey observation plan. Because of this, it is recommended for the planner to try different schemes until one is found that works effectively for him/her.

Static GPS Survey – Collection of GPS Data

Ok, after the new stations are set, the control has been researched and recovered, and the Static GPS survey observation plan has been created, the next step is the Static GPS survey itself. The following is a list for the GPS surveyor to use for collecting Static GPS survey data:

- The station sites should be visited before the survey to ensure ease of locating during the survey.
- The GPS equipment should be checked and calibrated before the survey. This includes checking and adjusting the leveling bubbles on the rods and the general shape of all the rest of the equipment.
- The batteries for the GPS equipment should be checked to ensure that there is enough power to complete the observation sessions.
- Each surveyor should have a method to contact the Party Chief or person who is in responsible charge during the survey in case a problem arises.
- Each surveyor should be provided with "observation session log sheets". These are sheets that are filled out for each observation session by each GPS surveyor that contain the name of the station, the beginning and ending HI of the antenna, the serial numbers of the antenna and GPS receiver, the beginning time for collecting data, the ending time of collecting the data, and any problems that were encountered while collecting data.
- The data collectors should be configured before the survey to ensure the appropriate observation limits are the same for each of them. This includes the limiting PDOP, the minimum number of satellites, and the elevation mask. Note: the elevation mask is the minimum elevation of a satellite above the horizon for collecting GPS data.
- The surveyor arrives at the station, diligently sets up the GPS equipment making sure that it is on the correct point and level, fills out the log sheet for that session, and notifies (if requested) the Party Chief or person in responsible charge that data is being collected.
- The surveyor should check the GPS equipment during the observation session to ensure that it hasn't moved or become not level, the appropriate number of satellites are in view, and the PDOP is in an acceptable range per specifications.
- Before picking up the equipment at the end of an observation session, the surveyor should also re-measure the HI to ensure its accuracy. Note: the HI is one of the only pieces of information that cannot be salvaged during postprocessing making its value imperative that it is correct and checked in the field.
- At the end of each day of a Static GPS survey the data should be downloaded and the observation session log sheets turned in.

Static GPS Survey - Baseline Processing

After the Static GPS survey is complete and the observation data has been downloaded, the data is then imported into a baseline processing program. Typically, within these programs the first step is to “check in” the observation data. When performing this task the surveyor should make sure the name of the station in the observation data is the same as that listed on the observation session log sheet for that data. Also, the HI should be checked from the observation data log sheet to make sure it was entered into the observation data correctly.

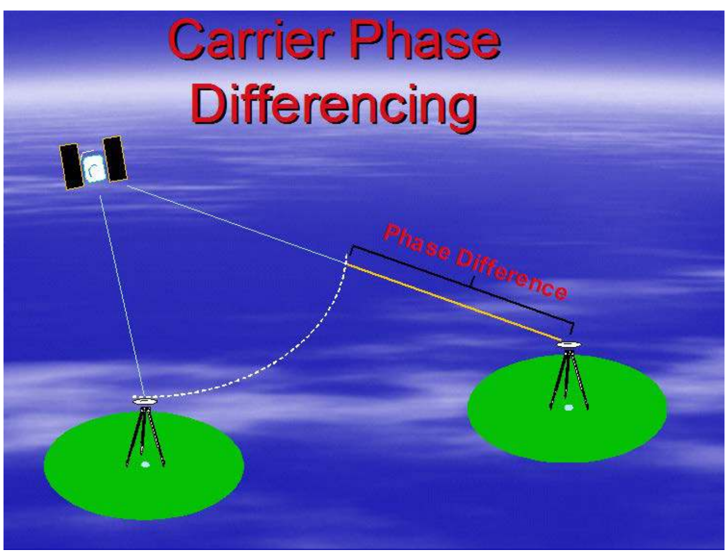
The next step is to include the appropriate ephemeris for the Static GPS survey. If you will recall from lesson 2 (a), some of the data sent on the L1 and L2 carrier signal is the navigation data for the satellites. The data of interest is called the “broadcast ephemeris”. The broadcast ephemeris may be used to produce baselines for some applications, however, the “precise ephemeris”, which contains more accurate navigation data for the satellites, can be downloaded from the Coast Guard’s web site shortly (within a week) of the end of the survey. The precise ephemeris is used to produce higher accuracy results. The appropriate ephemeris to use is described in the specifications for Static GPS surveys.

After the observation data has been checked in and the appropriate ephemeris has been loaded, the baseline processing configuration should be checked. Within the configuration the surveyor should make sure that a tropospheric model and an ionospheric model are selected. Also, values for the standard error for the measuring of the HI and the centering of the GPS equipment should be input. Typically the value for both is 0.03 foot (0.010 meter), however, the value may be different depending on the equipment and the set up conditions.

The baselines are now ready to be processed. So, what is happening during the processing of the baselines? The baseline processing software will first estimate the location of the receivers, then resolve the integer ambiguities, followed by computing the baselines. In order to understand how a baseline is processed the concept of ***differencing*** *(single, double, and triple)* will be discussed.

Baseline Processing - Differencing

Differencing is a term that represents several types of methods to get to a baseline solution of combined measurements. The most commonly used are the single difference, the double difference, and the triple difference.



A **single-difference**, which is also known as between-receivers difference, refers to the difference in the simultaneous carrier phase measurements from one GPS satellite as measured by two different GPS units. The single-difference solution allows for the removal of any error or bias in the satellite clock, however, doesn't remove any errors in the difference between the integer ambiguities or the difference between the receiver clock errors. The carrier phase single-difference is shown in the picture above.

A **double-difference**, also known as between-satellite difference, is a solution that eliminates the receiver clock errors. This term refers to the difference in the measurement of signals from two satellites as measured simultaneously at a single receiver.

A **triple-difference**, also known as receiver-satellite-time triple difference, is created from combining two double-differences. Each of the double-difference solutions contains two satellites and two receivers. This difference is derived from two different epochs. The triple-difference makes the elimination of cycle slips (a discontinuity in a receiver's lock on a satellite signal) easy and is used to find the integer ambiguities. This allows for highly accurate baselines to be produced between two receivers.

Baseline Processing – Continued

So, after the brief tangent describing differencing, the discussion will pick back up on the actual processing of the baselines.

At this point, the GPS observation data has been checked in and loaded into a baseline processor with the appropriate ephemeris. Additionally, the baseline processing configuration has been checked and/or established. It is at this point that the baselines are processed by the baseline processing software.

As stated above, the software will first estimate the location of the receiver, then resolve the integer ambiguity by utilizing the differencing methods, followed by computing the baseline from the results. In order to evaluate the quality of the baselines the surveyor should analyze several statistical indicators. They include: the type of baseline solution, the ratio, the reference variance, and the Root Mean squared (RMS).

There are several different **solution types** that can result from the processing of a baseline. The types of solutions are dependent on the distance between the two stations as well as the quality of the observed GPS data. The types include: wide lane – narrow lane solution, iono-free fixed solution, iono-free float solution, L1 fixed, and L1 float. The surveyor should discard, reprocess, or re-observe any baseline that has a float solution. The best solution for shorter baselines is L1 fixed and for longer baselines is iono-free fixed.

The **Ratio** is a unitless number that indicates the quotient of the variance of the second best solution type and the variance of the best solution type. The higher the number the better where the minimum value acceptable is 1.5.

The **Reference Variance** is a unitless number that relates the actual error in the resultant baseline to the expected error of the baseline. The ideal value is 1 and means the expected errors are the same as the actual error in the baseline. A value that is less than 1 means that the error in the processed baseline is better than the expected error, while a value that is greater than 1 means that the error in the processed baseline is worse than the expected error. The possible causes for a high reference variance include: multipath, "noisy" data, and unmodeled systematic error sources.

The **Root Mean Squared (RMS)** within a baseline solution is a value that indicates the quality and reliability of a satellite in the baseline solution. Ideally, the value of the RMS will be below 15 mm. If the value is higher than 15 mm then the surveyor should evaluate the satellite tracking data that is also produced during the baseline processing to determine if the baseline should be reprocessed without the information from a particular satellite.

Once the baseline processing is completed and all of the problems have been removed the baselines can then be loaded into a network adjustment processing program. Static GPS survey network adjustment programs are based on least squares adjustment concepts and the corresponding statistics. For the purposes of this lesson, the statistical indicators for a least squares adjustment will be discussed in terms of appropriate values to look for in an analysis and not the underlying theory.

Static GPs Survey – Network Adjustment

This is the point where the rubber meets the road, so to speak. The makeup of the GPS observed data is understood, a GPS observation plan has been produced, the ideas concerning collecting GPS data has been discussed, and concepts around how a baseline is processed and the statistical indicators on the baselines to analyze their quality has been discussed. Now we well turn our attention to the network adjustment of the Static GPS survey produced baselines.

Least Squares

Before addressing the network adjustment concepts a brief discussion of least squares is required.

Least Squares is an adjustment algorithm that adjusts measurements in a network of observations simultaneously. Within a Static GPS survey the least squares adjustment is not actually performed on the observation data. The observation data or measurements are the carrier phase ranges to the satellites. The baselines are a produced result. However, for Static GPS surveys, the network adjustment applies the least squares concepts to the resultant baselines in the same way as it would be applied to direct measurement data.

Least squares adjustments have the benefits that it helps to ensure that there are no gross errors in the observation data and it models random errors. The criterions of a least squares adjustment are:

- The network must close geometrically as well as mathematically (statistically).
- The sum of the weighted squares of the residuals is minimized. Note: a residual is the difference in an observation from the mean of all observations to a particular station.

So, a least squares adjustment is an iterative calculation process that produces the "**best fit**" solution for a network of observations and the statistical results of that solution. The "best fit" solution is characterized by the minimization of the weighted squares of all of the residuals for the observations in a network. Note: a weight in statistics is a value that is directly associated with standard deviation (some people use the terms standard error and standard deviation interchangeably). The value for the weight of an observation is: 1/(standard deviation for that observation)^2.

The two key concepts to understand about a least squares adjustment are that it is a best fit solution of the data and that the network must close geometrically and mathematically. The student should study/review least squares adjustment via text books or a separate class on your own to obtain a more thorough understanding of the subject.

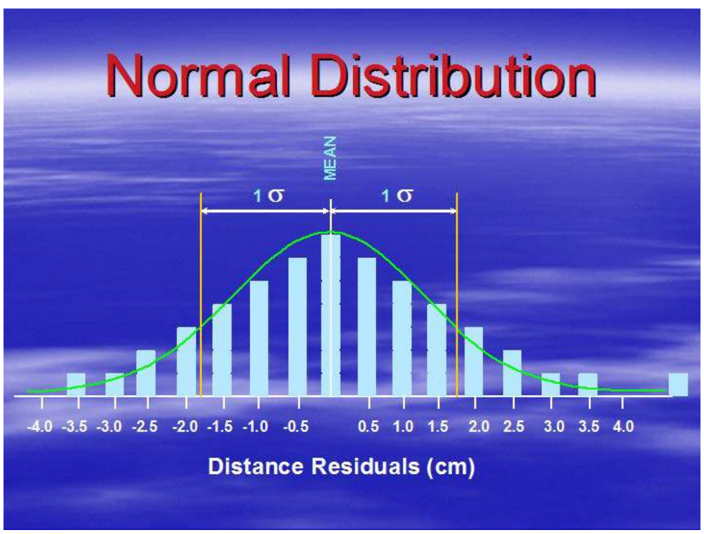
Network Adjustment

After the baselines from a Static GPS survey have been produced they are then incorporated into a network adjustment program that is based on the least squares adjustment algorithm. The steps in a network adjustment are:

- Perform a minimally constrained adjustment.
- Analyze the results of the minimally constrained adjustment.
- Make alterations, if necessary, to baselines included in the adjustment.
- Repeat the minimally constrained adjustment until all of the appropriate observation data is included.
- Perform a fully constrained adjustment.
- Analyze the fully constrained adjustment.
- Make decisions, as necessary, on the adjustment.
- Perform the final fully constrained adjustment.

Minimally Constrained Adjustment

The minimally constrained adjustment is used to check the internal quality of the measurement data, or in the case of a Static GPS survey, the internal quality of the baselines; to check for blunders; and to obtain accurate error estimates on the baselines. Basically, it is a check on the consistency of the data with respect to each other and to ultimately derive the statistical weights for the baselines.



Step one: The minimally constrained adjustment (in some circles it is known as a free adjustment) is performed by holding one latitude, one longitude, and one ellipsoid height fixed and then doing the adjustment. The adjustment results will produce statistical information based on a normal distribution. A normal distribution is characterized by a bell shaped curve. The picture to the left shows a normal distribution of distance residuals.

Several statistical indicators should be evaluated after a minimally constrained adjustment is performed. They are the Network Reference Factor or standard unit of weight, the

Tau criterion, and the chi-square test. These are all statistical indicators provided by the network adjustment software.

Step two: The **Network Reference Factor** (NRF) and the Tau criterion are based on the "Degree Of Freedom" (DOF) in an adjustment. The degree of DOF is a measure on the redundancy in the network. In other words, it is the number of observations minus the number of unknown (or held) coordinates. For example, if you had 10 stations in your network you would have 30 unknowns (for each station, latitude, longitude, and ellipsoid height). If you had 35 baselines in the adjustment you have 105 "observations" (azimuth, distance, and D ellipsoid height for each baseline). So, if you fixed one latitude, one longitude, and one ellipsoid height your number of unknown coordinates is 30 – 3 = 27. So, the degree of freedom for this case is 105 observations – 27 unknown coordinates = 78. Of course the DOF changes as more coordinates are fixed.

The NRF is a test used to determine if the predicted errors for the observations have been accurately estimated. These predicted errors are derived mainly from the minimally constrained adjustment. The NRF is a probability test of fit based on the square root of the sum of the weighted squares of the residuals, the DOF in the network, and a critical probability % (95%). Remember that minimization of the sum of the weighted squares of the residuals is the main least squares criterion. A NRF of 1 means that the predicted (a priori) errors match the post adjustment (a posteriori) errors, a NFR that is < 1 means that the predicted errors are greater than the adjustment errors, and a NFR that is > 1 means that the predicted errors are less than the adjustment errors.

Step three: The **Tau criterion** is a value based on the size, confidence level and DOF of the observation data set and is based on the normal distribution. If a standard residual (the residual of an observation divided by the standard deviation of that residual) of an observation is outside of the Tau criterion value then the observation is marked as an "**outlier**". An outlier is an observation that appears to be inconsistent with the other observation data. When an observation is flagged as an outlier it should be removed from the adjustment.

Step four: The **chi-squared test** is another statistical test to determine if the predicted errors have been correctly estimated. The adjustment will either pass or fail this test. If the test fails, a scalor will need to be applied to the estimated errors. Even if the test passes it is good practice to apply a scalor to the estimated errors.

Ok, so after holding one longitude, one latitude, and one ellipsoid height fixed and performing an adjustment, the NRF and chi-squared test are evaluated and the outliers are removed based on the tau criterion. The network is now ready for a fully constrained adjustment.

Fully Constrained Network Adjustment

Step one: The first step in a fully constrained network adjustment is to produce a scalor that will be applied to the estimated errors that will make the NRF equal to 1. This is an iterative process where the adjustment is performed and a scalor is produced. The scalor is then applied to the adjustment and a new scalor is produced. At this point the NRF is checked to see if it equals 1. If it doesn't equal one then the new scalor is applied and the process is repeated. This process is repeated until the NRF equal 1.

Step two: The second step is to fix all of the known control and perform the adjustment. If the NRF is high (typically > 4) then there is probably a problem with one or more of the control values. If this happens the control values should be taken out one or two at a time until the problem is located. It is the decision of the surveyor whether to eliminate the problem control values from the adjustment or to leave them in.

Once the final decision is made on what control to hold for the adjustment the final fully constrained adjustment is performed and the final values are produced.

Step three: Step three is simply performing a datum transformation and mapping projection to the adjustment results to produce the coordinates on the surveyed stations that are on the appropriate datum for the project. This subject was covered in Topic 1 of the Eighth Period.

Static GPS Survey Project Folder

The final step in a Static GPS survey is to produce the Static GPS survey project folder. Every organization has different criteria for the contents of the project folder. The following list is a suggestion for the contents of the folder:

- A narrative describing the purpose of the survey, the points set, the control held, and any problems that were encountered during the Static GPS survey process.
- A map of the project area including the points surveyed.
- "To reach" descriptions and sketches of the points set.
- Descriptions of the monuments set.
- A copy of the observation plan.
- Copies of all of the observation session log sheets.
- All of the files containing statistical information from the production of the baselines.
- All of the files containing statistical information from the network adjustment.
- The final values produced.