Effective Use of the ConnDOT GPS Base Station

February 2003

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16. Abstract

This report presents the findings of an investigation of factors affecting GPS position accuracy using the ConnDOT base station. An empirical study was performed to evaluate the accuracy of carrier-phase Global Positioning System (GPS) as a function of: number of control points used, distance to control, observation time and number of frequencies observed. To facilitate the study, a 19-station control network was developed in Southeastern Connecticut and surveyed to High Accuracy Reference Network (HARN) standards using dual frequency, carrier-phase GPS. The network was controlled using existing HARN stations in Connecticut, Massachusetts and Rhode Island. GPS observations were subsequently taken independently and processed in various ways to measure the effect of the control variables on the positional accuracy obtained. Results showed the ability of carrier-phase GPS to deliver high accuracy results both vertically and horizontally in reasonable times, especially when using two GPS frequencies and having three base stations surrounding the study area.

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Global Positioning System, GPS, Geodetic Control, GPS Accuracy, GPS Observation Times, Base Station, Surveying, ConnDOT

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

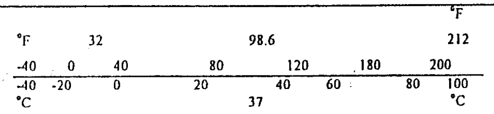
NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F



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UConn Professor John Silander and graduate student John Michelson graciously allowed us to use their antenna mount site for a base station site for this project.

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The GPS equipment used for the project came from three sources; the CCSU Civil Engineering Technology Department, the UConn Civil and Environmental Engineering Department, and ConnDOT's Central Surveys. The CCSU and UConn equipment was purchased with State of Connecticut Department of Economic Opportunity, Yankee Ingenuity, Elias Howe equipment grants awarded in consecutive years to each of the Principal Investigators. The computational software used was part of an educational grant by Trimble Navigation, Ltd.

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I. INTRODUCTION

The Connecticut Department of Transportation (ConnDOT) operates a GPS base station from their headquarters in Newington, CT, which is centrally located for Connecticut users (Figure 1). The base station is known as the Oliver H. Paquette base and is abbreviated as OHP Base. Depending on which of two antennas are mounted on the post, which is fixed in position on the roof of the headquarters building, ConnDOT's Geodetic Section can provide base station GPS observations for mapping quality, geodetic quality, or both types of users simultaneously. The latter capability is accomplished by inserting a signal splitter in the antenna cable (Figure 2). Note that mapping quality observations are also referred to as "code" observations and geodetic quality observations are also known as survey quality observations or "carrier" observations.

The authors were commissioned by the ConnDOT Joint Highway Research Advisory Council (JHRAC) to provide an empirical study of the accuracy of coordinate positions users may expect when using the ConnDOT base station for differential GPS operations. The study as initially conceived was to look at coordinate accuracies with respect to distance from the base station, length of observation session, and number of local "known" stations used in conjunction with the base station. The authors decided to add a second base station at the University of Connecticut, and use the USCG Montauk Point, Long Island base station as a third (Figure 3). Note that the distances between the three project base stations are:

OHP to UCON	25.5 miles
UCON to MNP1	55.3 miles
MNP1 to OHP	61.0 miles.

Coordinate position accuracies using various combinations of the three base stations, which effectively surround the project area, and observations at local "known" stations were examined and analyzed. This report for current and potential GPS users discusses the results of the study and makes recommendations for achieving the desired accuracies of a variety of users.

The method chosen to provide this information about accuracies attainable, and methods required to obtain these accuracies, was to establish a large number of High Accuracy Reference Network (HARN) quality points, well distributed geographically, over southeastern Connecticut. Experimental observations were then made on all of these points, using standard satellite signal reception methods, to obtain coordinated positions to compare with the previously established HARN coordinates. This study concentrates on survey quality signal receptions. The HARN quality network observations were processed first to determine the quality of base line solution between stations using the broadcast ephemeris. Those base lines which did not resolve to acceptable quality solutions were reobserved. Finally, all base line solutions were of acceptable quality. The HARN network was then reprocessed using the precise ephemeris. The precise ephemeris is obtained from the USCG via the Internet. The Internet site is operated by the NGS. The final product of this computation was a NAD 83/92, Order B, HARN network, the highest quality network obtainable within the project and equipment constraints (one part in a million) (previously available NAD 83 first order control in Connecticut is one part in one hundred thousand).

The experimental observation sets were processed using the broadcast ephemeris, as is most commonly the case with ordinary GPS use. The processing yielded coordinates for each of the control stations for observation times of 5, 10, 15, 30, 45, 60, and 90 minutes for various combinations of base stations for both one frequency (L1) and dual frequency (L1 and L2) observations. The computations allowed analysis and charting of the difference in coordinate position from the HARN coordinates based on 1.) observation time, 2.) distance from base station(s), 3.) number of base stations, and 4.) number of receiving frequencies. The authors used spreadsheet software to compute the positional variances and plotted graphs showing the relationships between positional error and the four variables listed above.

Armed with charts for two full sets of observations at 19 stations, relating positional error and the four variables, the analysis of the data was a daunting exercise. Conclusions regarding the four variables' effect on positional accuracy were made and are reported in detail in the conclusions section.

Definitions of terms which may not be immediately familiar to readers are found in the Appendix (page 22). Also located in the Appendix is a list of acronyms used in this report and in common use among GPS professionals (page 23).

II. PROJECT DESCRIPTION

II.A. Project Initiation

The project began in 1994 with a conference between project personnel and ConnDOT Central Surveys personnel about station selection for the GPS observations. It was anticipated that the project observations would be useful to Central Surveys in their maintenance of the Connecticut Coordinate Grid System (CGS) if the stations were chosen wisely. The first thought was that existing CGS stations should be used as project stations. Consequently ConnDOT personnel used their personal recollections of points and station descriptions to select CGS stations in southeastern Connecticut for reconnaissance by project personnel. The primary criteria for final project point selection were monument condition and GPS signal access suitability.

II.B. Point Reconnaissance

Using compass/clinometer instruments, steel tapes, plumb bobs, shovels, and magnetic locator, project personnel visited each of the CGS stations to determine their suitability as project GPS points. The CGS station visits yielded several different characteristics for the stations, namely:

1. CGS points destroyed
2. CGS points destroyed but had nearby reference marks that were suitable as project GPS points
3. CGS points and/or reference marks recovered, but unsuitable for GPS observations
4. CGS points and/or reference marks recovered but only marginally suitable for GPS observations
5. CGS points recovered and quite suitable for GPS observations.

Table 1 is a list of the CGS stations, azimuth marks, and reference marks used for the project experimental control stations (page 24).

Obstruction drawings were made for each of the suitable and marginally suitable points and were entered into the mission-planning portion of the GPS processing software. Sample obstruction data field charts and GPS planning software drawings are included in the appendix (Figures 4 and 5).

II.C. Project Point Selection

Those points suitable and marginally suitable for GPS observation were plotted in their proper CGS coordinate positions and examined for suitability as project points based on a simultaneous evaluation of two factors, 1.) their GPS observation suitability and 2.) the desirability of spacing for the project. Sixteen points were selected to comprise the control network. Three points were added later in the project when we decided there were not enough points close to the ConnDOT base station (Figure 3).

III. NETWORK OBSERVATIONS

III.A. Communications Problems

One of the first problems encountered in the project was observations not going smoothly, in spite of good planning, and the consequent need to reobserve the session. If an adequate means of communicating between stations was available this problem could often be avoided. Typical problems included 1.) not getting the receiver set up and observing at the prescribed time and 2.) not receiving signals from the minimum required number of satellites. The first method of communicating between stations in an observation station that was tried was using powerful two-way radios. Two problems were associated with the two-way radios: 1.) some two-way radio transmissions interfere with the GPS radio signals and 2.) some of the project control stations are too far apart for communication with even the most powerful two-way radios. Our experience was that the two-way radio transmission completely blocked the satellite signals, thereby interrupting the observation session each time the two-way radio transmitter was keyed. This was the case even when the transmitting frequency was outside those listed in the Trimble report as offending frequencies. Equipment vendors report that the newer chips in the GPS receivers eliminate this problem, but those using older receivers must still make sure that two-way radio communications do not block their GPS radio waves.

Cellular telephones proved to be a good means of communicating between project observation stations, once certain problems with them were ironed out. The cellular telephone problems encountered were: 1.) batteries that did not last long enough for a day's worth of observations and communications, 2.) battery charger malfunctions, and 3.) coverage range of the cellular telephone company. These problems can generally be avoided by purchasing the right telephones and batteries and selecting the right cellular telephone company.

III.B. HARN Specifications

Order "A" HARN specifications require setting special new types of monuments and observing satellite radio wave signals at each station longer than we felt was necessary to obtain the control network accuracy required for this project.

Order "B" HARN specifications were generally followed in establishing the project control network. Order "B" specifications are for a one part in one million (1:1,000,000) accuracy standard. We did not do atmospheric condition monitoring and did not include the required number of vertical control points (benchmarks) in our network because we felt we would obtain the required network control accuracy for the project without them. We would like to integrate more benchmarks into the network in the future to see if any significant difference in coordinated position of the 19 stations is effected by the densification of vertical control points.

III.C. Equipment

Equipment used for field observations consisted of Trimble Navigation, Ltd. 4000SSE dual frequency geodetic receivers and geodetic antennas with ground planes. Receivers and antennas used were from the pool of 11 receivers owned by the University of Connecticut (UConn) (4), Central Connecticut State University (CCSU)(3), and ConnDOT (4).

IV. HARN CONTROL SELECTION

Published coordinate values on the CGS are in the process of being upgraded from the North American Datum of 1927 (NAD27) to the improved North American Datum of 1983 (NAD83). ConnDOT's Central Surveys continues to make the field survey measurements to densify the monumented network and the lengthy and complex computations required to publish coordinates for the entire CGS. In the middle of the five-year recomputation process the National Geodetic Survey (NGS) decided that a further improvement of NAD83 was possible and so created a refined NAD83 datum known as NAD83/92. We decided to use the best available datum, NAD83/92, for our project. Although it would be a horrendous task for Central Surveys to recompute the portion of the CGS already upgraded to NAD83, using new GPS observations and either NAD83/92 or NAD83 values for the HARN control stations fairly easily yields coordinate values on either datum for the 19 stations in the project control network. The NAD83 values were supplied to Central Surveys for potential use in their CGS network.

IV.A. NGS Control Stations to "Surround" the Project Area

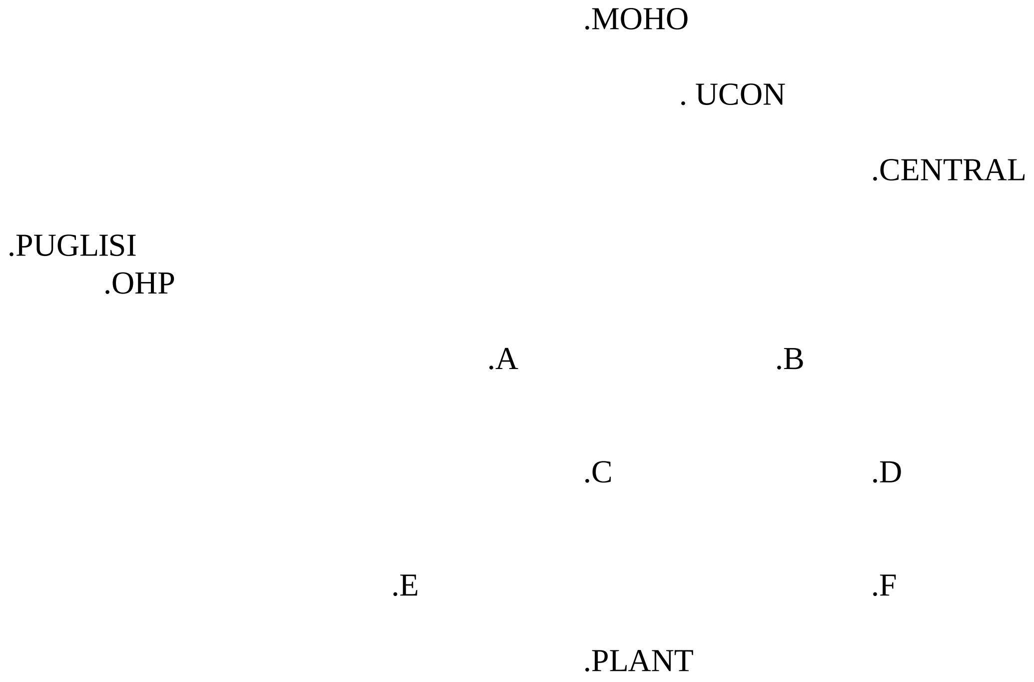
To assign NAD83/92 values to our network, control stations with NAD83/92 values, surrounding our network, had to be determined. The NGS supplied us with descriptions, coordinates, and elevations of all NGS control points in Connecticut and surrounding states. Four control points were found that satisfactorily surrounded our network; two in Connecticut, one in Massachusetts, and one in Rhode Island. The station names are Puglisi, Plant, Mount Holyoke, and Central (Figure 3). The distances between the HARN stations are:

Puglisi to Mount Holyoke	43.6 miles
Mount Holyoke to Central	62.4 miles
Central to Plant	46.2 miles
Plant to Puglisi	41.8 miles.

The base stations at ConnDOT headquarters (OHP) and UConn (UCON) had to be integrated into the project HARN network also since UCON was a new station and OHP had only NAD83 coordinate values. In order to create the required base line ties between the project network, the OHP and UCON base stations, and the four HARN stations, nine GPS receivers were required and personnel were required to operate each receiver. Four UConn receivers, three CCSU receivers, and two ConnDOT receivers were used, and since there were not enough project personnel to operate all the receivers, Central Surveys field personnel operated their receivers plus some of the UConn and CCSU receivers.

IV.B. HARN Observations

The observations to tie the project base stations and network stations to the NGS HARN stations were done on two different days consisting of three observation sessions each. Six project network stations where multiple base lines intersected were chosen for this purpose. The sketch and explanation below will help readers understand how the observation ties to the six network stations, with the desired base line redundancy, were accomplished with four receivers.



Day one observations had three two-hour sessions with receivers at Puglisi, MOHO, Central, Plant, and OHP for all sessions and receivers at the following combinations of stations for

Session One:	A,B,C,D
Session Two:	C,D,E,F
Session Three:	A,B,E,F

Day two observations came later in the project, after we decided to work with three base stations, rather than with one base station and other local controlling stations. Day two observations were essentially the same as day one observations with the substitution of base station UCON for base station OHP.

Figure 6 shows the resulting baselines drawn to scale.

The two-hour sessions for days one and two were planned considering the need to move the four receivers at project network stations twice and to have the moves coincide with periods of low satellite availability and/or high positional dilution of precision (PDOP).

Communications for the two days of HARN observations were with the four project cellular telephones plus one of the student worker's personal cellular telephone and the Central Surveys office telephone, since stations Puglisi and OHP were close to the Central Surveys office. This is obviously not one telephone per station, but with some predetermined plans in the event any of the stations without telephones had problems, or needed to be contacted, and some improvised leap frog calls when some of the telephones were out of range for certain other telephones; the observation sessions were accomplished, essentially as planned.

HARN observations within the project control network were made generally at three stations at a time and occasionally simultaneously at four stations. Observation sessions were planned so that all base lines were observed at least once, but most were observed multiple times to provide the redundant measurements desired to ensure network accuracy. Observations were made by the project principal investigators and graduate student, and several undergraduate student workers in whatever combinations were available. Occasional observations were also made by GPS independent study students from UConn and CCSU.

Some early observations had to be discarded and reobserved due to poor mission planning or lack of mission planning, or due to the lack of good communication tools for the observers. Once good cellular telephone communications and good mission planning procedures, using individual station obstruction drawings, were established, project HARN network observations went smoothly.

All base lines were processed preliminarily, as described in section V, to verify that they were of acceptable quality. A few base lines did not meet the established criteria, so were reobserved and reprocessed until all base lines were of acceptable quality.

The computational software indicates the type of base line solution achieved. Only fixed integer solutions were accepted (“ionosphere free fixed” for baselines longer than 10 kilometers, “L1-only fixed” for shorter baselines). Float solutions, in which the integer ambiguity is not fixed, were not acceptable. If processing yielded only a float solution, the baseline observation data would be examined and reprocessed using modified parameters and/or controls. If a fixed integer solution still could not be obtained, the baseline would be reobserved. A discussion of various types of base line solutions is included in the appendix. See page 27. The computational software used also provides an analysis of the quality of the base line computed as well as residual plots for each satellite observed. Two computed quantities are provided as a quality measure for the baselines: "Ratio" and "Reference Variance". The ratio compares the best integer solution to the second best solution. A high ratio implies that the correct solution was obtained while a low value indicates uncertainty in the solution. The reference variance compares the actual variance in the solution to an estimated value. The lower the reference variance the better. These two measures were used to flag suspect fixed solutions for further evaluation. The residual plots were very useful in analyzing problem solutions. If the signal from a particular satellite was noisy or otherwise problematic, the residuals will tend to be high. Oftentimes, removing one problematic satellite observation from the solution, resulted in dramatic improvements to the baseline solution.

As we began to do some of the processing of the HARN network, it became evident to us that we had not selected enough network stations close to the OHP base station. Through additional interaction with ConnDOT Geodetic Section personnel and additional field reconnaissance, we were able to identify three new stations to add to the network. Once observations were made at the new stations, simultaneously with observations at some of the originally chosen stations, it was felt that we had a suitable network. We were ready to complete the processing and begin the dual set of new observations to evaluate the effect of several parameters on accuracy of computed position of the 19 network stations.

As we proceeded with the creation of our HARN network, discussed this project and their proposed new multiple base station project with ConnDOT Geodetic Section personnel, and thought about the later independent observations of the individual stations, we decided that working with three permanent base stations that surround the project area would better simulate the future GPS operating conditions in Connecticut than working with the OHP base station and one or more local stations whose positions are known. Consequently, we decided to establish a new base station at the University of Connecticut (UCON) and use the United States Coast Guard (USCG) Continuously Operating Reference Station (CORS) at Montauk Point (MNP1) as the third base station. See Figure 3, page 21. Integrating the UCON station into the HARN network has been discussed and shown in the earlier sketches of the network. Integration of the Montauk station into our HARN network should have been easy, since observation data from that station is available over the Internet. We should have been able to simply add that data to some of our observation sessions to ensure that we had good, redundant baseline data connecting our HARN with the CORS station. At this point in time, before there was widespread knowledge about the CORS/HARN shift, we discovered the discrepancy between CORS and HARN coordinates. We decided to consolidate the Montauk observations into our observation network to create our own NAD83/92 coordinates for the Montauk base station. An additional complication in using the observations from Montauk Point is that the base station is an Ashtech receiver while the receivers we are using are Trimble receivers. The Montauk observations are posted to the Internet in RINEX (receiver independent exchange) format for use in the Trimble processing software. The Montauk station was added to the HARN primarily by obtaining Montauk observations at times when our network coastline stations CORN, COOK, PLANT, AND STONINGTON were being observed and creating processing baselines between Montauk and the coastline stations. The final sketch representing the network ties to HARN and project base stations is shown below.

.MOHO

. UCON
.CENTRAL

.PUGLISI

.OHP
.A .B

.C .D.

.E.CORN .COOK .PLANT .F.STONINGTON

.MONTAUK

Figure 7 shows the project base station-HARN tie-in baselines drawn to scale.

V. PROCESSING HARN OBSERVATIONS

The first level of processing was of each session, using the broadcast ephemeris which provides the predicted positions of the satellites for any time. For each of these sessions we ensured that all base lines solutions were fixed integer solutions and that the base lines had acceptable ratios and reference variances. If there were other observations of the discarded base lines that had acceptable solutions, the base line was not reobserved. If the discarded base line had not been acceptably observed as part of another observation session, it was reobserved. When all base lines had acceptable solutions, we moved on to the next processing level, using the precise ephemeris, which can be thought of as an "as-built" of the satellite positions for a given time; it is based on actual positions of the satellites as determined by several tracking stations located across the globe.

The broadcast ephemeris is automatically collected by the GPS receivers. The precise ephemeris may be obtained from NGS using their new “user-friendly CORS” utility. It is generally available within two days of the observation date.

The processing was done in four sections first, then, when we were satisfied with the data used in these sessions, all of the acceptable data was processed simultaneously to obtain the final coordinate and elevation values for our experimental 19 station HARN. In this phase of the processing we used only independent base lines.

For each processing section we used the processing software's analytical capabilities to observe what portion of time each SV was being received effectively by each observation station. Were there cycle slips from the SV, or were there extensive periods when the SV signals were not being received by the station? See Figure 8, page 37. If there were significant problems with the signal receptions from a particular SV then its signals were removed and the processing was redone. We would like to have been able to simply remove the portion of the SV signals that were problematic from the processing session, but the software does not have that flexibility. Consequently, long periods of good observations from a particular SV had to be discarded if there were significant periods of poor signals during an observation session. If the SV removal resulted in too few satellites being received during a session or caused PDOP problems, we went back to the field and re-observed the affected session.

The first processing section contained the four existing HARN stations which surrounded the network, OHP base, and the six network stations used to tie the network to the HARN.

The second processing section contained the four existing HARN stations which surrounded the network, UCON base, and the six network stations used to tie the network to the HARN.

The third processing section contained all of the observation sessions within the 19 station network, including all of the re-observation sessions. None of the HARN or base station observations were included in this section.

The fourth processing section contained all of the observation sessions required to integrate the Montauk base station into the HARN

Satisfied that all the observations in the four sections described above were good observations, we were ready to process all of the observations simultaneously, ensure that we had good relationships between all baselines, and finally, compute coordinates and elevations for the 19 stations to be used for experimental observations and for the three base stations to be used as fixed control during the experimental observations. The coordinates and elevations were to be computed by adjusting the observation baselines while holding the four HARN stations fixed in X, Y, and Z. The four observation sections checked well individually and the combined sessions yielded acceptable results. We did note that there was more adjustment in the long base lines to HARN stations CENTRAL and MOHO than we liked, particularly vertically. Consequently, in order to minimize adjustment in the eastern Connecticut network that we wished to work within, we decided to make our network adjustment holding only the two HARN stations in close proximity to the 19 station network we wished to work with, PLANT and PUGLISI, fixed in position (X, Y, Z). This adjustment yielded the best available HARN coordinates and elevations for the three base stations and 19 network stations we wished to use for our experimental observations. The NAD83/92 HARN stations we used to establish the coordinates and elevations for our network are part of a 1/1,000,000 control network, while the NAD83 coordinates available for NGS stations in Connecticut and for the OHP base station are part of only a 1/100,000 control network. Loop closure checking within our network insured that we had a 1/1,000,000 network to use for our experimental observations.

VI. EXPERIMENTAL SINGLE SESSIONS

With a good HARN quality network ready to observe on, we began our experimental observations. Having learned our lesson about mission planning well, we used the mission planning software, including the individual station obstruction drawings in the analysis, and planned when we could make 90 minute observations at each station. There were a couple of stations with a lot of obstructions for which this was impossible and we had to settle for 60 minute observations. It was interesting to try to have the poor observation times coincide with travel time between stations. Depending on travel distance between stations and the obstructions around the stations, we were able to do three or four stations per day. On a long day, for example, we were able to observe all of the coastline stations, STONINGTON, PLANT, COOK, and CORN. We were able in this instance to observe the coastline stations in both the order listed above, east to west, and in the reverse order, west to east. This allowed us to be sure that the satellites forming the observation constellation for the two sets of observations were different. We decided to make two independent sets of observations of the 19 stations in the network and to make sure that the satellite, or SV, configuration was different for the two observation sessions at each station.

Positions computed for each station were similar for each of the observation sessions, and the SV configurations were different for the observation sessions, so conclusions drawn from the positions achieved in the experimental observations are valid.

The parameters affecting position accuracy we wished to evaluate were distance from base station, number of base stations used, number of receiving frequencies (L1 alone or L1 and L2), and observation time. Early processing required to evaluate these parameters was for observation times of 2, 3, 5, 7, 10, 15, 30, 45, 60, and 90 minutes for L1 alone and for L1 and L2. This processing was done for seven base station combinations: OHP alone; UCON alone; MNP1 alone; OHP and UCON; OHP and MNP1; UCON and MNP1; and OHP, UCON, and MNP1. Examples of the charts used to examine these processing results are included in the appendix (Figures 9 and 10). Note that after we processed a few stations it became evident that processing for less than 30 minutes for L1 observations yielded no usable coordinates or elevations. A computation was made for 10 minutes to demonstrate this, then computations were made for 30, 60, and 90 minutes for analysis. Later processing for L1 and L2 observations was for 5, 10, 15, 30, 45, 60, and 90 minutes. This processing was done for OHP alone, OHP and UCON, and OHP, UCON, and MNP1.

A spreadsheet was used to calculate the horizontal and vertical variation in computed position of each station from the HARN control position. Finally, graphs of the parameters were created to allow analysis of the effect of the four accuracy parameters. Samples of these spreadsheet and graphs are included in the appendix and will be referred to individually in the Section VII, "Analysis of Results of Position Accuracy Computations."

Using one base station and receiving on L1 alone, observation for 60 minutes was required to yield 2 centimeter horizontal position accuracy for distances up to 10 kilometers. Two centimeter vertical accuracy for distances up to 10 kilometers also required 60 minute observation. Receiving on L1 and L2 and using one base station, 2 centimeter horizontal position accuracy for distances up to 20 kilometers was achieved with observations of only 20 minutes (Figure 11). Vertical accuracy with one base station varied so that no comparable statement can be made.

Observations using two base stations and dual frequency receivers shows that 2 centimeter horizontal position accuracy was not achieved when distances from the OHP base stations exceeded 40 kilometers (Figure 11), and 2 centimeter vertical accuracy with one base station varied so that no comparable statement can be made.

For observation of points within a triangle formed by three base stations separated from each other by no more than 98 kilometers, distance from base stations does not seem to be a factor for horizontal position or vertical accuracy. This is fortunate as it would be a difficult parameter to analyze. Controlling the computed horizontal and vertical position accuracies with three base stations required 60 minutes of observation for 2 centimeter horizontal position accuracy, with no results worse than 3.5 centimeters (Figure 16A), and 60 minutes of observation for 3 centimeter vertical accuracy receiving on L1 anywhere within the three base station triangle. Receiving on L1 and L2 reduced the observation times to 15 minutes for 1 centimeter horizontal position accuracy and 15 minutes for 1 centimeter vertical accuracy, with no median results worse than 3.5 centimeters horizontally and 4 centimeters vertically (Figures 16A and 12).

VII. ANALYSIS OF RESULTS OF POSITION ACCURACY COMPUTATIONS

The position accuracy factors we chose to evaluate are interdependent. Discussions of one factor will thus often include discussions of other factors. The interdependence of the factors did, however, influence the order in which we chose to discuss them and in some cases caused us to decide to eliminate some observations from consideration. As the individual factors are discussed, we will indicate situations where findings about one factor are considered irrelevant because of findings about another factor.

VIIA. Position Accuracy Factors

We will discuss four factors which affect differentially corrected GPS position accuracy achieved at a point when using a base station or multiple base stations. The factors are:

1. Single vs. Dual Frequency Observations
2. Number of Base Stations
3. Duration of Observation
4. Distance from Base Station

VII.A.1. Single vs. Dual Frequency Considerations

A look at Figures 9 and 10 will be useful in considering the positional accuracy effect of single vs. dual frequency GPS observations. The results of the computations from these observations are typical of those found throughout the 19 station experimental network. These observations are for station Stonington (STON). The three numbers in the upper left hand corner in the box with the station name are the NAD 83/92 HARN quality coordinates (Northing and Easting) and ellipsoid height in meters. For the coordinates we have shown only the units place and four decimal places to avoid a lot of needless writing of numbers. The numbers in each box are the computed values of the coordinates and ellipsoid height for the observation time and base station combination listed.

It is obvious that we do not approach 2 centimeter accuracy in either horizontal or vertical position for observations of less than 30 minutes when observing on only the L1 frequency. Yet when observing with both the L1 and the L2 frequency, we approach 2 centimeter accuracy in both horizontal and vertical position after only 5 minutes of observation. Although dual frequency receivers cost more than single frequency receivers, the cost differential is not enough to not warrant purchasing dual frequency and thereby saving about a half hour of observation time at every station for which coordinates or elevations are desired. We will consequently limit the major portion of our discussion of the other three accuracy factors to observations with dual frequency receivers.

VII.A.2. Number of Base Stations

Examination of Figures 11 and 12 illustrates the telling point about the number of base stations used very well. We have chosen to examine horizontal and vertical errors found in 20 minute observations on a plot of error versus distance from the OHP base station for one, two, and three base stations held fixed in horizontal and vertical position. From these graphs we can see that horizontally and vertically, the error increases with distance from the base station when one or two base stations are used, but that the error is essentially unchanged from 0 to 80 kilometers with three base stations. That median error is a very acceptable 1 centimeter. Note that for the 20 minute observation data chosen as an example, for one base station, observations further than 20 kilometers from OHP cannot produce position accuracy better than 2 centimeters horizontally. For two base stations, the distance from OHP can extend to 40 kilometers for 2 centimeter horizontal accuracy.

The number of base stations is also a factor in the required observation time, as will be discussed in the next section. In addition to the positive interactions observations from three base stations (surrounding the project area) have with distance and time factors, these observations provide very valuable quality checks of the base lines in the least squares adjustments made by the position computational GPS software. These checks are unavailable if only one base station is used and are of limited reliability with two base stations.

VII.A.3. Duration Considerations

Figure 13 shows the median horizontal error for all dual frequency observations for various observation times. Note that there is no consideration of distance from base station in these graphs. We can see that using one base station, and a minimum observation time of 20 minutes, errors range from 2 to over 3 centimeters, with slight improvement over time. This approaches acceptable quality geodetic work. Using the same 20 minute minimum observation time and using two base stations, the results improve to errors ranging from about one to just under 2 centimeters, once again seeming to improve with time. With three base stations, however, from 5 minutes to 90 minutes, the error hovers right around an acceptable error of 1 centimeter, with once again some improvement over time. The improvement here is academic, since the 5 minute error is within the acceptable range.

A close look at some of the graphs we have produced reveals that there is some variation in errors from station to station, yielding some scatter in the individual points from which the smooth exponential curves fit to the data are drawn. Figures 14 through 16A are designed to allow us to think about this a bit. These graphs look at median, minimum, and maximum errors versus time for one, two, and three base stations. An important observation from these graphs is that the variation between the median, minimum, and maximum errors is very significantly minimized when using three base stations. For observations where the results must always be within the centimeter range, three base stations must be used. Note on Figure 14 that errors of 2 to 3 decimeters were experienced even when the observations were in the 30 to 60 minute range with only one base station and for two base stations the errors observed were in the 1 to 2 decimeter range. With three base stations, however, the maximum errors were generally in the 4 to 6 centimeter range. Figures 12 and 19 clearly show the improvement in distribution of horizontal and vertical error respectively with increased observation time.

VII.A.4. Distance Considerations

We may revisit Figures 11 and 12 to consider the effect of distance on the horizontal and vertical position accuracy achieved from GPS observations. In Section VIIA.2, Number of Base Stations, we made the following statements. "Note that for the 20 minute observation data chosen as an example, for one base station, observations further than 20 kilometers from OHP cannot produce position accuracy better than 2 centimeters horizontally. For two base stations, the distance from OHP can extend to 40 kilometers for 2 centimeter horizontal accuracy, but only to 25 kilometers for 2 centimeter horizontal accuracy." Note again that for the entire range of distances from OHP (0 to 80 kilometers), the position error for points "surrounded" by the three base stations is essentially a constant 1 centimeter. Similar graphs were produced for other observation times and yielded slightly different results. For example, for a 5 minute observation, 2 centimeter horizontal accuracy can be expected for only up to 17 kilometers with one base station and 30 kilometers with two. Three base stations yield 1 to 2 centimeter accuracy from 0 to 80 kilometers in 5 minutes. These results are all slightly worse than for the 20 minute observation, which is expected, but show similar results regarding the relationship between distance from base station and positional accuracy.

VIII. CONCLUSIONS AND RECOMMENDATIONS

GPS is an excellent geodetic control survey tool, when used properly. When improperly used, erroneous horizontal and vertical positions of control points can be proliferated and used to their great detriment by the unsuspecting surveyor or mapper and their clients. GPS can be used effectively and properly or it can be misused. Effective, proper use can be very profitable while improper use can simply minimize the available business profit or time savings, or it can cause a large sequence of problems having domino-like effect on many subsequent users of inaccurate control points.

GPS is very accurate. Inaccuracies can result from problems with the tools GPS receivers interact with, such as the tribrachs and tripods the receivers are mounted on to be positioned over control points. It is essential to keep the tribrachs calibrated and the tripods tight.

The importance of mission planning cannot be overstressed. GPS observations when the proper number of or configuration of satellites are not available are worthless and can be easily avoided by proper mission planning.

Mission planning comprises more than obstruction drawings and number of satellite and PDOP plots. Missions can be aborted at cost of time and money for other failures, such as not having enough GPS receiver batteries charged for the planned observation time, failing to have the cellular telephone or two-way radio batteries charged, not having a tribrach in the GPS receiver case, not having a tripod in the truck, sending an operator to a station that he or she has not seen before and consequently cannot find, or failing to ensure that the base station you are planning to use will be operating when you want to use it.

When observations at multiple stations must be coordinated, communications between the operators at the stations are essential. Cellular telephones have proven to be very effective, particularly when distances between stations are greater than the range of two-way radios. Two-way radios should be used cautiously because of the potential for interference with GPS satellite radio signals.

Dual frequency geodetic receivers allow much shorter observation times than single frequency receivers for centimeter accuracy horizontal and vertical. The higher cost of the dual frequency receivers can easily be recouped in a short time by their greater production.

Whenever possible, GPS observations should be conducted within an area surrounded by at least three base stations. This eliminates effects of time and distance on the accuracy of horizontal and vertical positions achieved from GPS observations. Centimeter accuracy is achieved in observations of 20 minutes or less. For situations where lesser accuracy is required, observations can be shorter. Five centimeter accuracy can be achieved in 5 minutes of observation.

The foresight of Central Surveys personnel in proposing a nine-station base station network for Connecticut provides a tremendous benefit to all future GPS users in Connecticut. Once the nine base stations are in place, GPS users will be able to complete control surveys anywhere in Connecticut with the requisite minimum of three base stations.

IX. APPENDIX

IX.A.

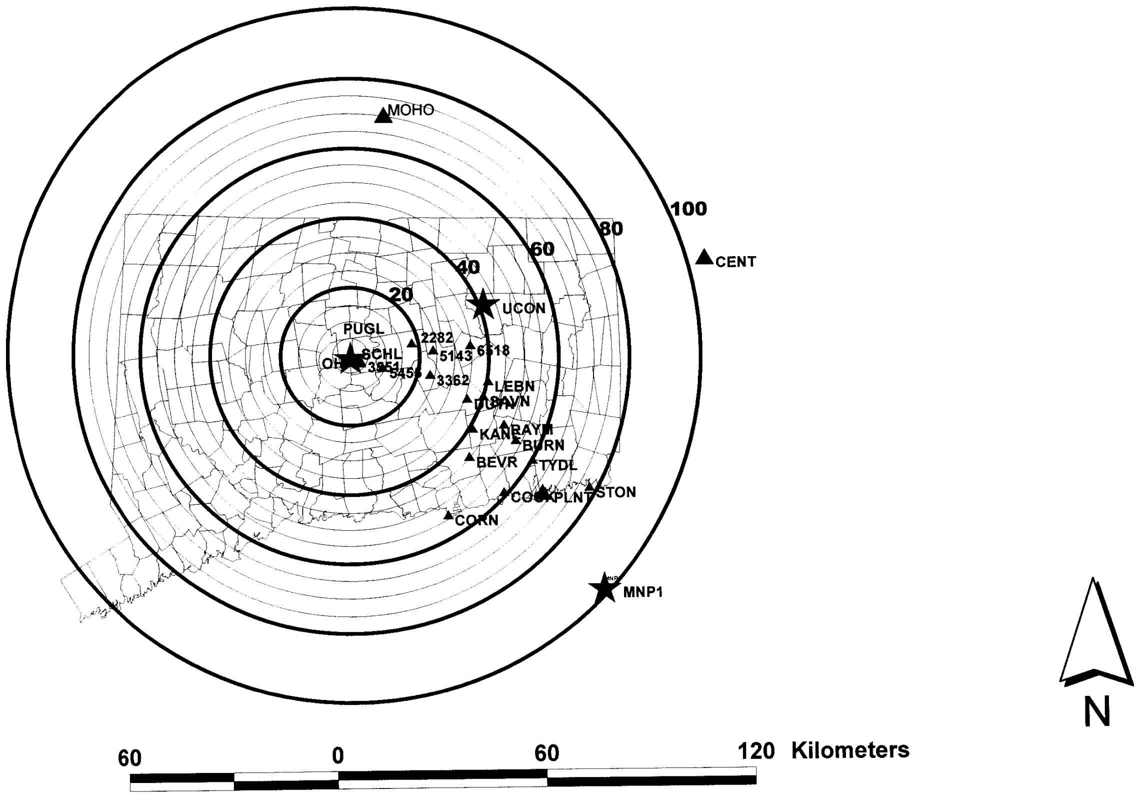


Figure 1. Oliver H. Paquette (OHP) Base Station in Connecticut
5 and 20 km Spacing Concentric Circles Centered on OHP Base

IX.B.

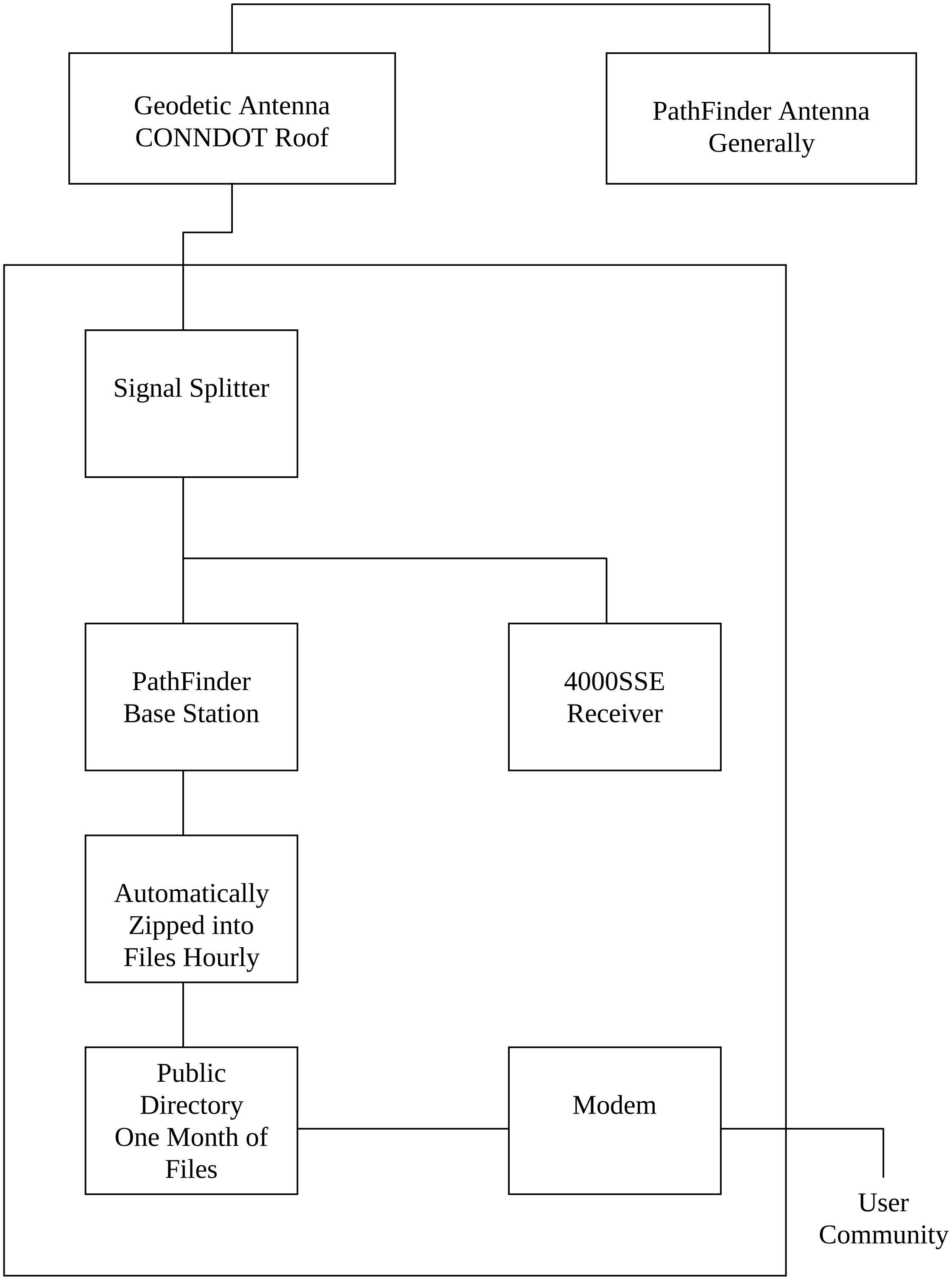


Figure 2. OHP Base Station Schematic

IX.C.

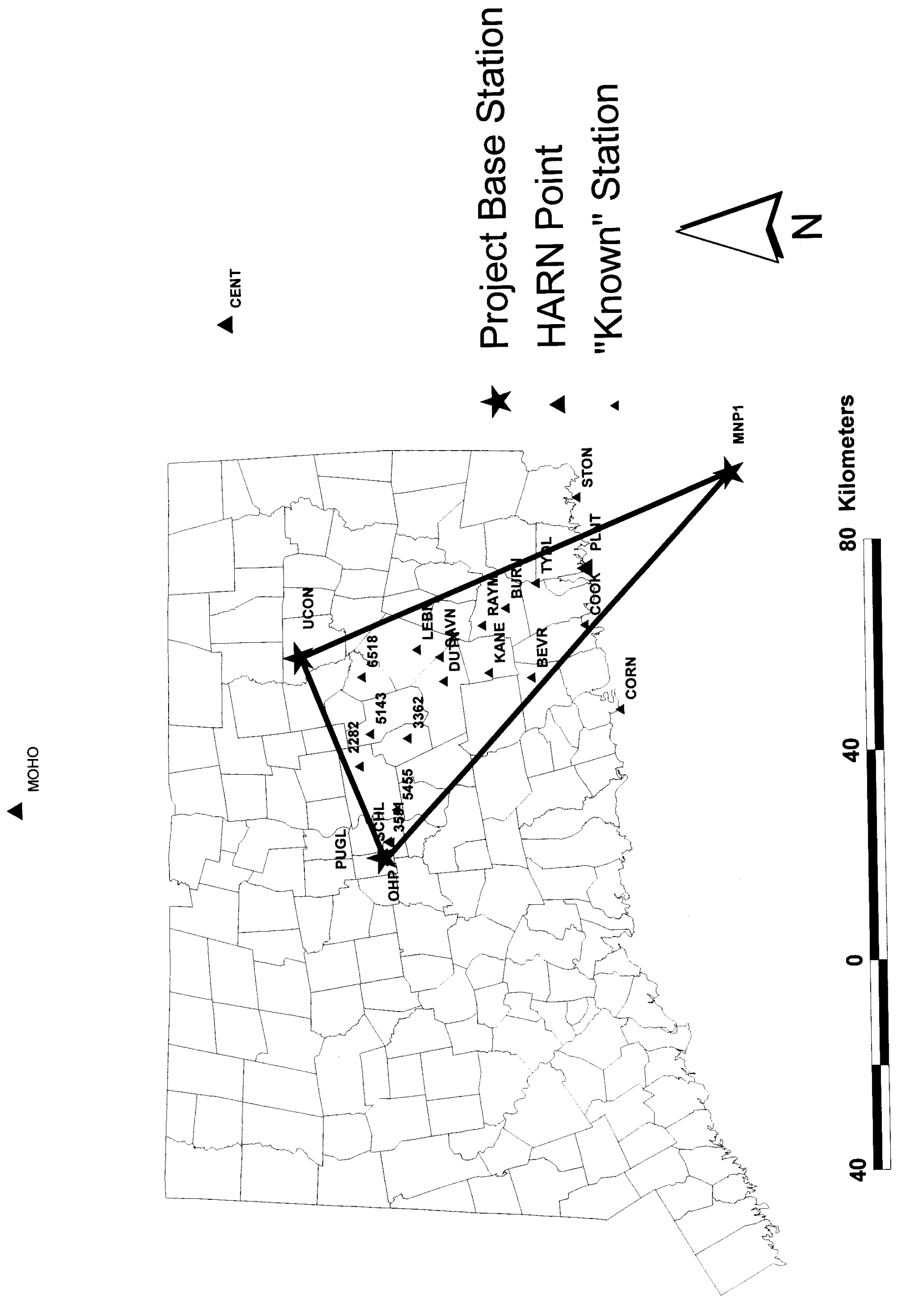


Figure 3. Project Area "Known" Stations, Base Stations and HARN Stations

IX.D.

GLOSSARY OF TERMS USED IN THIS REPORT

Base Station – a continuously operating GPS receiver referenced to a known point.

Broadcast Ephemeris – the ephemeris transmitted to the GPS user as part of the data message of the GPS signal (See also Ephemeris and Precise Ephemeris)

Differential Positioning – precise measurement of the relative positions of two receivers tracking the same GPS signals simultaneously

Ephemeris – the predictions of satellite position as a function of time (See also Broadcast Ephemeris and Precise Ephemeris)

Global Positioning System – a navigational/positioning system based on the US Department of Defense’s NAVSAT orbital satellite system.

HARN – High Accuracy Reference Network – A network of highly accurate monumented locations determined by the US National Geodetic Survey using an extensive network of GPS baselines.

Positional Accuracy – Closeness of position derived from test occupations at a point to the position of that point determined from the HARN-quality network

Precise Ephemeris – A “post-fit” ephemeris based on earth observation of actual satellite orbits (See also Ephemeris and Broadcast Ephemeris)

IX.E.

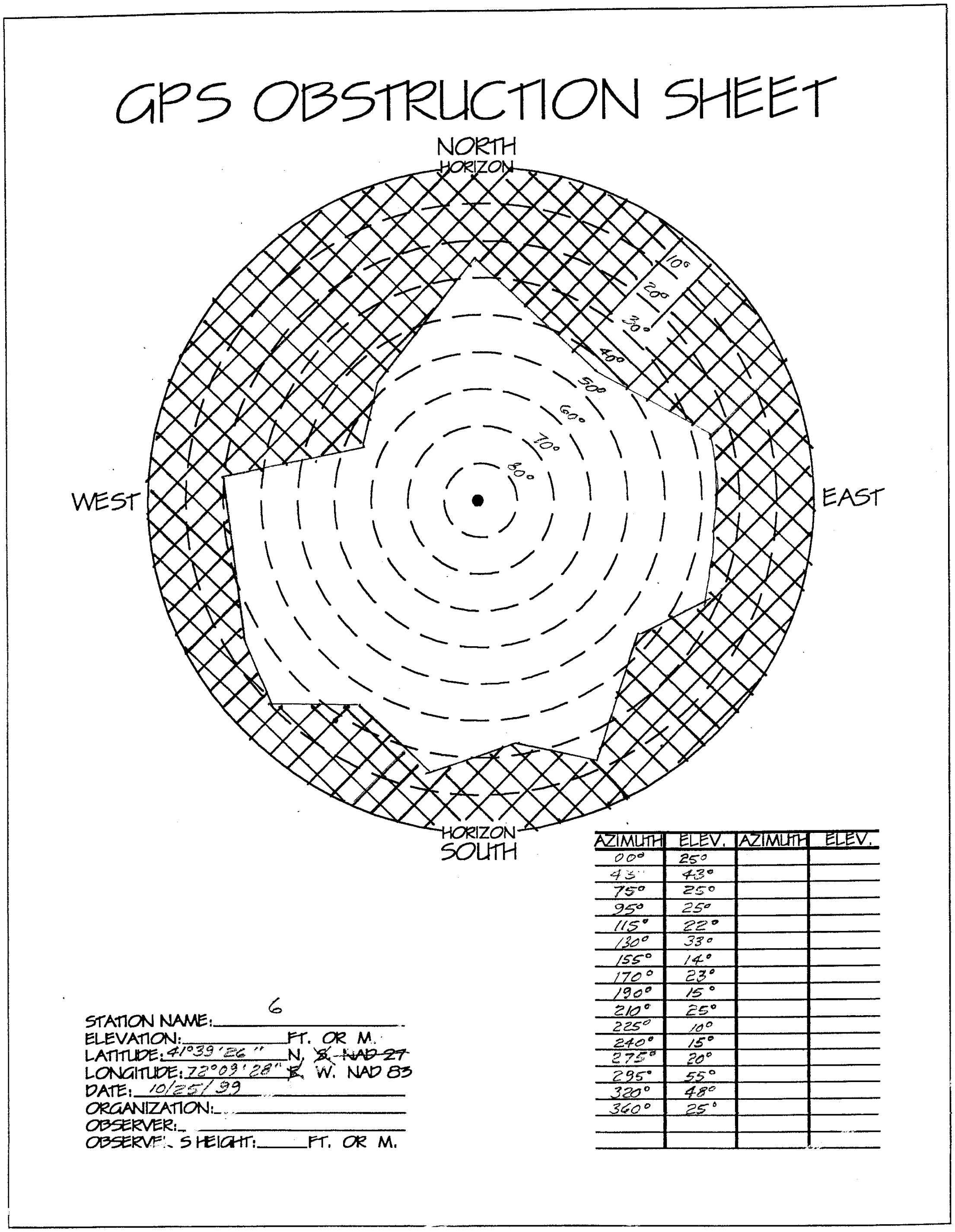
ACRONYMS USED IN THIS REPORT

CCSU	Central Connecticut State University
CGS	Connecticut Grid System or Connecticut Coordinate System
ConnDOT	Connecticut Department of Transportation
CORS	Continuously Operating Reference Station (GPS)
DOP	Dilution of Precision (from many causes in GPS work, see PDOP)
GPS	Global Positioning System
JHRAC	Joint Highway Research Advisory Council (ConnDOT and UConn Civil and Environmental Engineering Department)
HARN	High Accuracy Reference Network
MNP1	The four character name for the USCG CORS base station at Montauk Point, Long Island, NY
NAD	North American Datum (year specific, NAD 27 coordinates do not mix with NAD 83 coordinates in the traditional apples and oranges example way)
NAD 27	North American Datum of 1927 (used exclusively of late until, 1983, still used in the majority of cases today, although we are slowly converting to NAD 83)
NAD 83	North American Datum of 1983 (uses an upgraded spheroid from NAD 27)
NAD 83/92	North American Datum of 1983 upgraded in 1992
NGS	National Geodetic Survey
OHP or OHP Base	The Oliver H. Paquette Base Station at ConnDOT headquarters in Newington, CT
PDOP	Positional Dilution of Precision (one of the many potential causes of error in GPS work. This one is caused by the relative position of the satellites, or space vehicles, to the receiving GPS antenna)
RINEX	Receiver Independent Exchange Format
SV	Space Vehicle. One of the constellation of Navstar satellites that comprise the GPS
UCON	The four character name for the base station created for this project. It is located on the roof of the Life Sciences Building Annex.
UConn	The University of Connecticut
USCG	United States Coast Guard

IX.F.

Table 1. CGS Stations, Azimuth Marks, and Reference Marks Used for Project Control Network

Station Name	Four Character Abbreviation	Point Used
2282	2282	Station
3362	3362	Station
3551	3551	Station
5143	5143	Station
5455	5455	Station
6518	6518	Station
Beaver	BEVR	Reference Mark 2
Burns	BURN	Station
Cook	COOK	Reference Mark 1
Cornfield	CORN	Station
Dutton	DUTN	Station
Kane	KANE	Station
Lebanon	LEBN	Station
Plant	PLNT	Station
Raymond Hill	RAYM	Azimuth Mark
Savin	SAVN	Station
Schoolhouse	SCHL	Station
Stonington	STON	Reference Mark 1
Tydol	TYDL	Station



GPS OBSTRUCTION SHEET

AZIMUTH	ELEV.	AZIMUTH	ELEV.
00°	25°		
43°	43°		
75°	25°		
95°	25°		
115°	22°		
130°	33°		
155°	14°		
170°	23°		
190°	15°		
210°	25°		
225°	10°		
240°	15°		
275°	20°		
295°	55°		
320°	48°		
360°	25°		

STATION NAME: 6
ELEVATION: ______ FT. OR M.
LATITUDE: 41°39'26" N, ~~S~~ ~~NAD 27~~
LONGITUDE: 72°09'28" ~~E~~, W. NAD 83
DATE: 10/25/99
ORGANIZATION: ______
OBSERVER: ______
OBSERVER'S HEIGHT: ______ FT. OR M.

Figure 4. Sample Obstruction Drawing, Field Observation Chart

IX.H

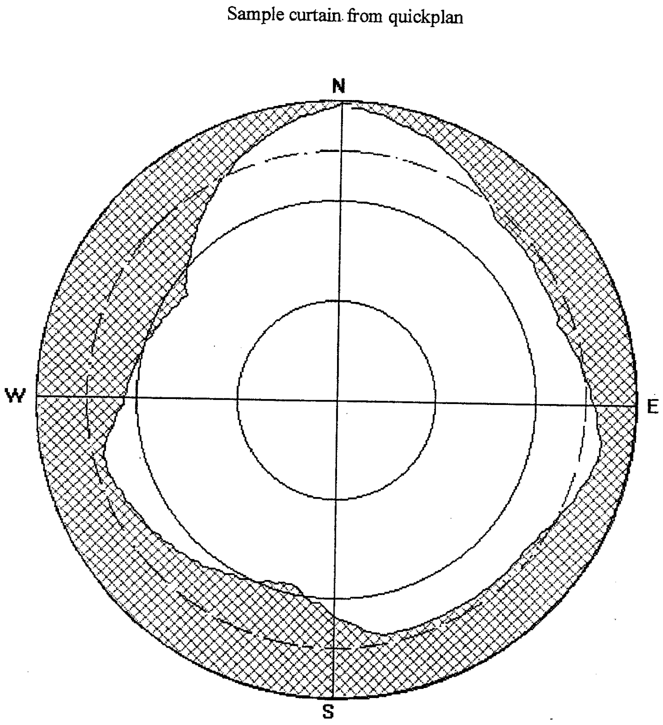


Figure 5. Sample Obstruction Drawing, Software Plotting

IX.I.

4.2 Quality Information in the GPS Baseline Processing Report

The *GPS Baseline Processing Report* provides six important pieces of information to help you evaluate each baseline:

- Solution type
- Ratio
- Reference variance
- RMS
- Station and combined tracking summaries
- SV residual plots

Each of these items is discussed in more detail, with an emphasis on how to use them to evaluate the quality of the processed baselines. Consider all six indicators when determining whether or not a particular baseline solution is valid.

4.2.1 Solution Type

The Baseline Processor progresses through an ordered sequence of solutions for each baseline or occupation, based on the types of observations available and the current settings of several processing controls. Processing typically begins with a code solution, followed by a triple-difference and several double-difference carrier-phase solutions. The final pass solution is the best that can be obtained by the processor with the given set of observations and controls. The processing steps are a bit more involved for dual frequency processing than for single frequency processing. (The following sections describe the types of final pass carrier phase solutions that may be generated by the processor when working with dual frequency and single frequency data.)

Base Line Solutions Discussion

With dual-frequency data, the processor works with different combinations of the observables to provide the optimal solution. The "Wide Lane" solution is based on the L1–L2 combination, which produces an effective wavelength of 86 centimeters. Because of the long wavelength, it is generally easier to resolve the integer ambiguties.

An alternative combination is the "Narrow Lane," which is derived from a combination of L1+L2, or an effective wavelength of about 11 centimeters. Because of the short wavelength, it offers a more precise solution, but there is an increased risk of fixing the wrong integers. Each of these solution types may contribute to an optimal solution.

The Baseline Processor first estimates the Wide Lane ambiguities followed by the Narrow Lane ambiguities to obtain an Iono Free Fixed final pass solution. If the Narrow Lane search is not successful, an Iono Free Float solution is generated.

Note – You can specify a different final solution type using Processing Styles. For more information, see GPS Processing Styles, page 2-6.

Iono Free versus L1 Only solutions

The Iono Free Fixed solution is the optimum solution under the widest range of conditions. These solutions contain no ionospheric biases, and fixed ambiguities give the best overall results.

An Iono Free Fixed solution on short baselines, however, can be a weak solution. Avoid using such solutions for short baselines. The Trimble Geomatics Office software automatically identifies short baselines and selects the appropriate final solution type.

An Iono Free Float solution on baselines longer than 30 km may be a very good solution, but make sure to verify it. On very long baselines an Iono Free Float solution may be the best you can achieve. Longer occupation times result in better Iono Free Float solutions since the unbiased Iono Free observable allows the solution to converge toward the correct geometric result. In fact, Iono Free Float solutions on very long lines, occupied for several hours, can give excellent results.

For very short baselines (less than 5 km), an L1-only final pass (derived from the dual-frequency ambiguities) typically is the final solution; for very long baselines (more than 200 km using broadcast ephemeris, 2000 km using precise ephemeris) an Iono Free Float final pass may be the final solution, as follows:

- *Very Short Baselines*

  For short baselines of a few kilometers in length, an L1-only final pass is generated instead of Iono Free Fixed. This final L1-only solution, however, is generated using the dual frequency data to help derive the L1 ambiguities. For baselines in the range of approximately 5 km or less, the L1 Fixed solution is generally preferable because there is less noise in the solution.

  The value used as the cutoff for L1-only solutions can be set using Processing Styles.

- *Very Long Baselines*

  For very long baselines (several hundred to several thousand kilometers), select a Float solution type to generate an Iono Free Float solution using the dual-frequency data. As mentioned previously, long occupation times on very long lines can give excellent Iono Free Float solutions.

  The value used as the cutoff for float solutions for very long baselines can be set using Processing Styles. Separate criteria can be set for the use of broadcast and precise ephemeris.

Float solutions

When processing single-frequency data, the Baseline Processor generates an L1 Fixed final pass solution if L1 ambiguities can be successfully determined. If the L1 search is not successful, however, an L1 Float solution is generated. An L1 Float solution for a very short line may arise from too brief an occupation or unusually noisy observations. For baselines of 10 to 15 km and more, it can become increasingly difficult to obtain reliable L1 Fixed solutions due to the sensitivity of single frequency observations to ionospheric delays.

L1 Float solutions generally are weaker than fixed integer solutions. For standard survey applications it is recommended that you avoid using L1 Float solutions. You should either reprocess your data or reobserve these baselines in the field.

The decision to produce a fixed integer solution is controlled by the ratio cutoff specified internally by the Baseline Processor. The cutoff is set internally by the processor to 1.5. When the computed ratio is less than this ratio cutoff value, float solutions are produced.

Trimble Geomatics Office

WAVE Baseline Processing Software User Guide

Version 1.0

Part Number 39685-00-ENG

Revision A

November 1999

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IX.J.

4.2.2 Ratio

The ratio is the relation between two variances generated in the integer search of the processor. Higher ratios indicate bigger differences between the variance of the best choice and the variance of the second best. In other words, the Baseline Processor is more confident in that one set of integers than those of the second best set.

- High ratios are good.
- Ratios are GPS quality indicators—not human quality indicators. (Antenna height errors are not reflected here.)
- Only fixed integer solutions have ratios.

The Baseline Processor only considers a solution to be a fixed solution if the ratio is greater than 1.5. Although this ratio cutoff is set internally by the processor, you can use the baseline acceptance criteria to flag or fail baselines with higher ratios.

Ratio and Variance Discussion

4.2.3 Reference Variance

The reference variance is a unitless number indicating how well the error encountered in the observed data fit the expected error. Before processing, the Baseline Processor estimates the expected error for each type of data. After processing, it compares the actual error in the solution (the residuals) to the expected error. If the two quantities were to be equal, the reference variance would be exactly 1.0, indicating that the processor was able to precisely predict the errors and model them in the solution.

Note – Evaluate ratios and reference variances together. Baselines with low ratios and high reference variances need to be checked.

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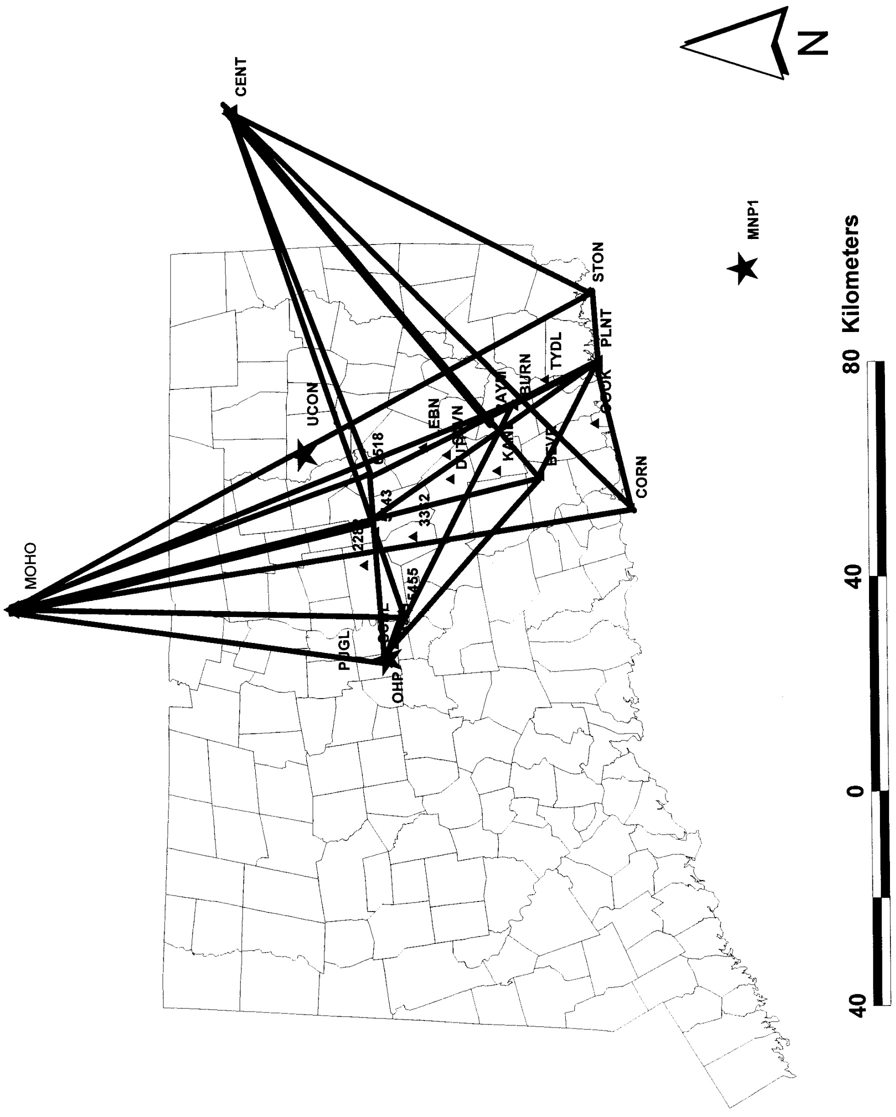


Figure 6. Project Network Baselines - Harn Tie-in

IX.L.

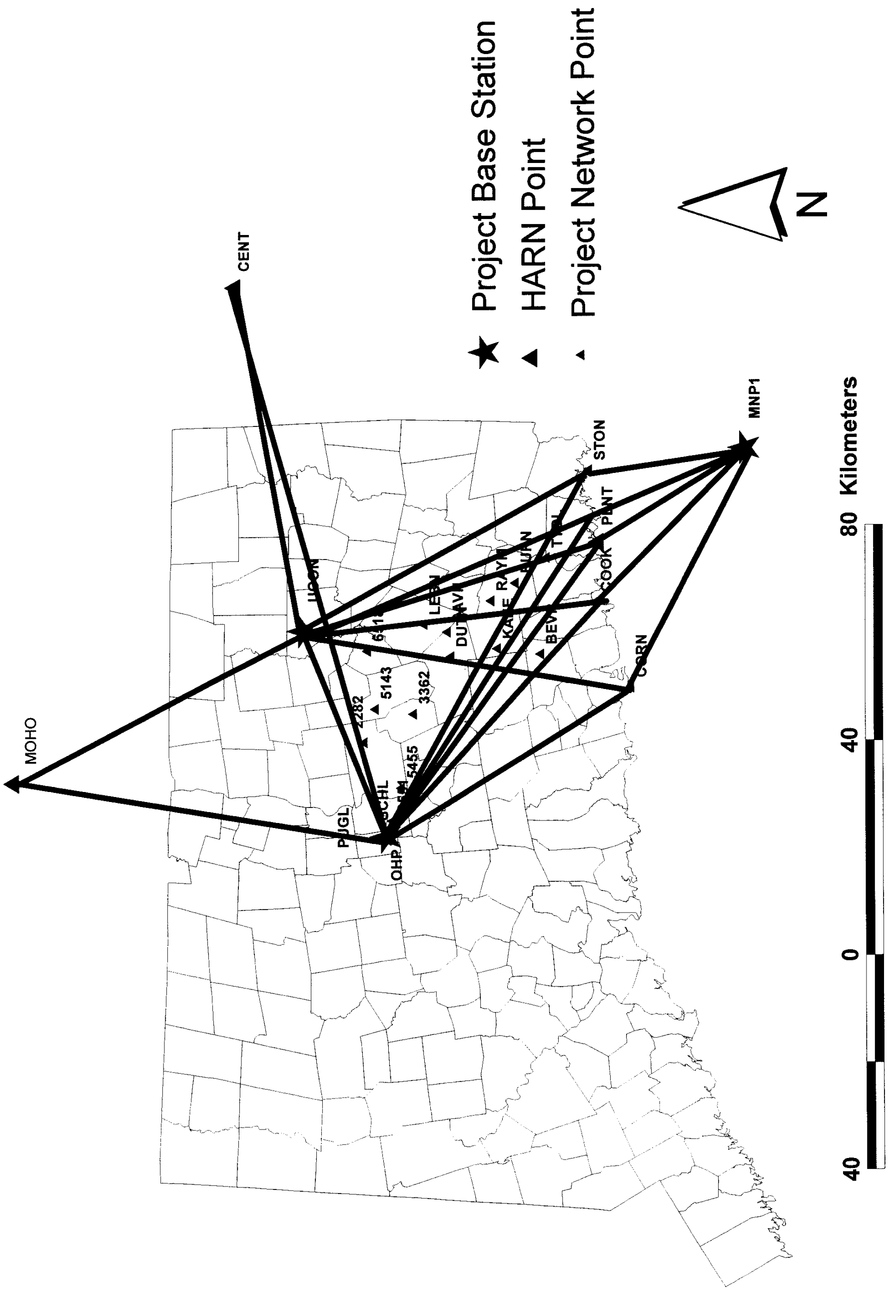


Figure 7. Project Base Station - Harn Tie-in Baselines

IX.M.

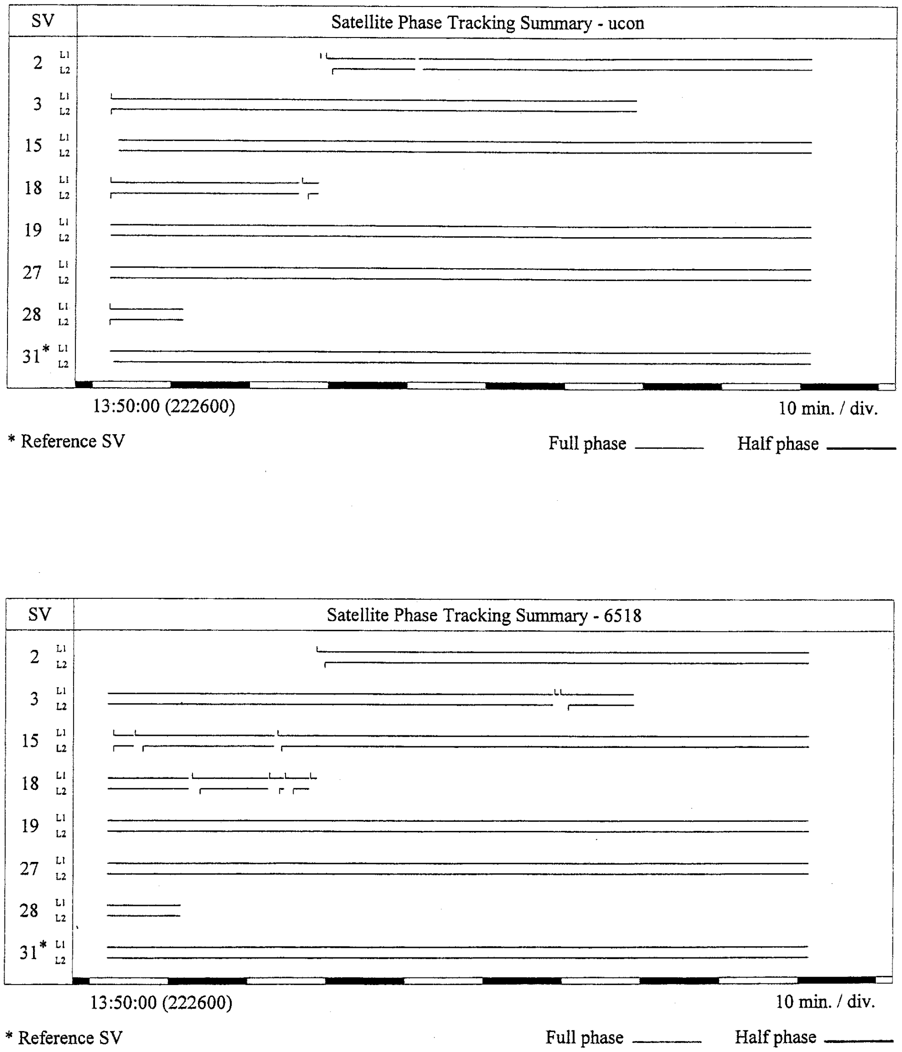
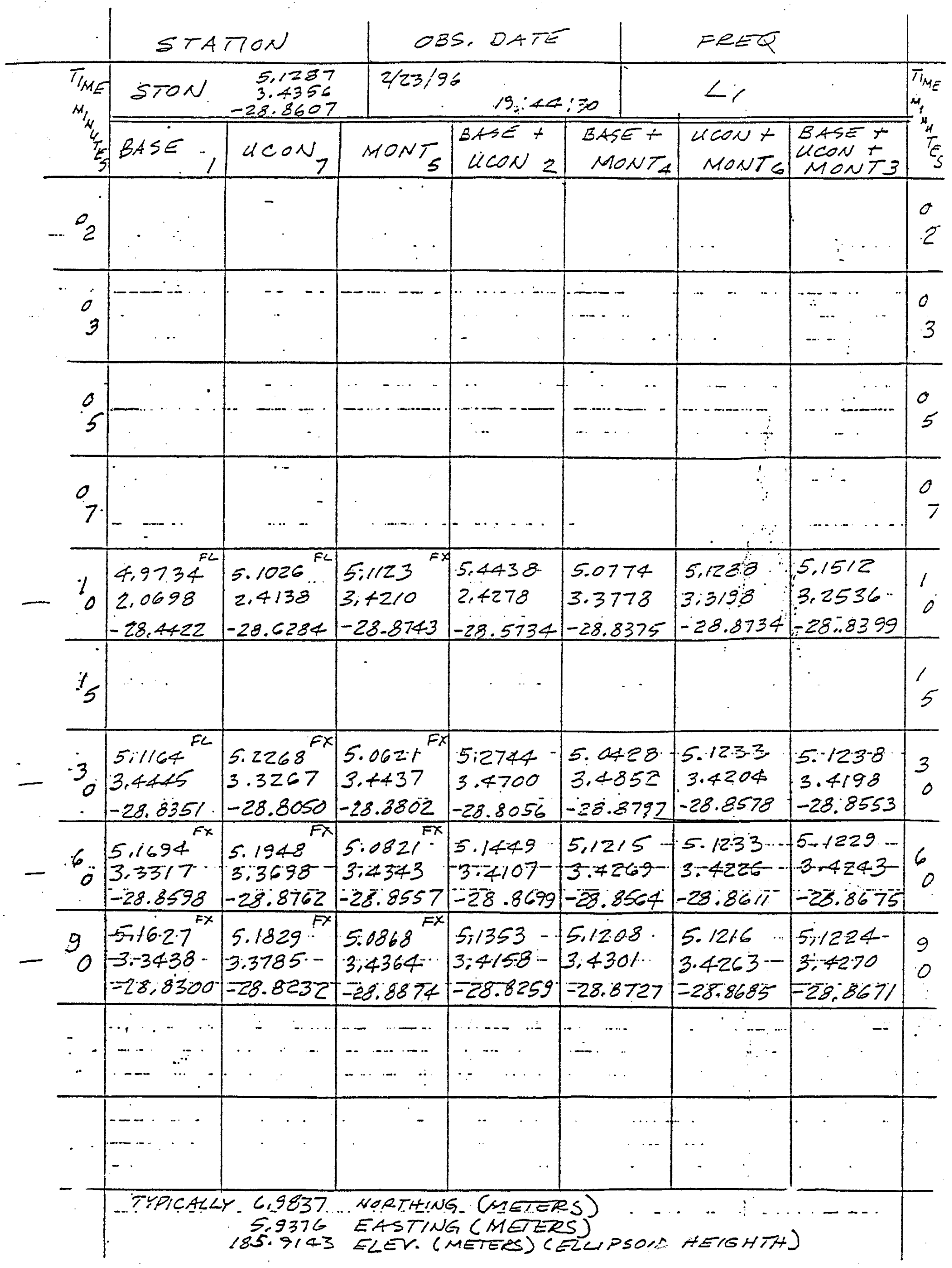


Figure 8. Sample Software Plot of SV Reception Quality

IX.N.



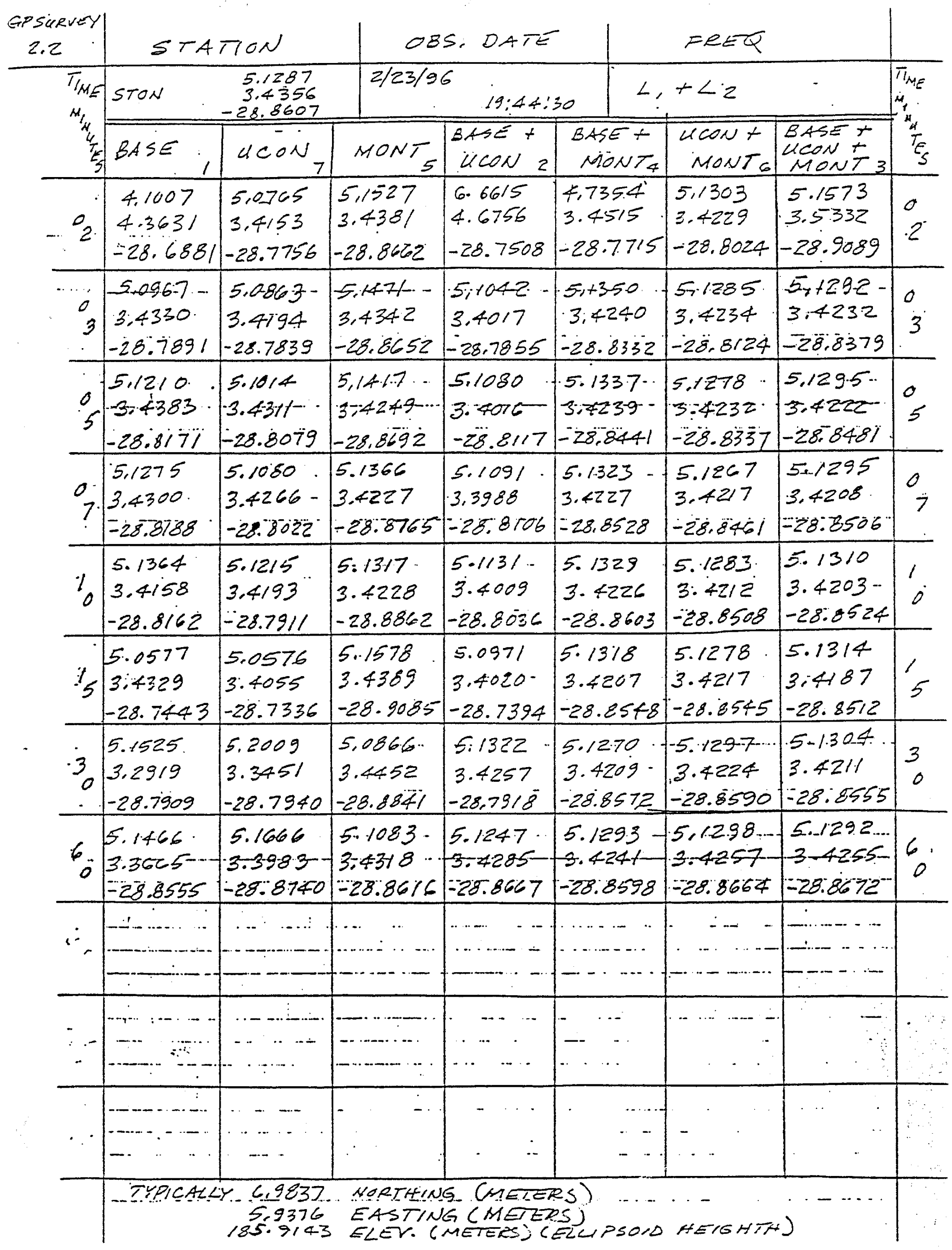
STATION		OBS. DATE	FREQ
STON	5.1287 3.4356 -28.8607	2/23/96 19:44:30	L1

TIME MINUTES	BASE 1	UCON 7	MONT 5	BASE + UCON 2	BASE + MONT 4	UCON + MONT 6	BASE + UCON + MONT 3	TIME MINUTES
02								02
03								03
05								05
07								07
10	FL 4.9734 2.0698 -28.4422	FL 5.1026 2.4138 -28.6284	FX 5.1123 3.4210 -28.8743	5.4438 2.4278 -28.5734	5.0774 3.3778 -28.8375	5.1288 3.3198 -28.8734	5.1512 3.2536 -28.8399	10
15								15
30	FL 5.1164 3.4445 -28.8351	FX 5.2268 3.3267 -28.8050	FX 5.0621 3.4437 -28.8802	5.2744 3.4700 -28.8056	5.0428 3.4852 -28.8797	5.1233 3.4204 -28.8578	5.1238 3.4198 -28.8553	30
60	FX 5.1694 3.3317 -28.8598	FX 5.1948 3.3698 -28.8762	FX 5.0821 3.4343 -28.8557	5.1449 3.4107 -28.8699	5.1215 3.4269 -28.8564	5.1233 3.4226 -28.8611	5.1229 3.4243 -28.8675	60
90	FX 5.1627 3.3438 -28.8300	FX 5.1829 3.3785 -28.8232	FX 5.0868 3.4364 -28.8874	5.1353 3.4158 -28.8259	5.1208 3.4301 -28.8727	5.1216 3.4263 -28.8685	5.1224 3.4270 -28.8671	90

TYPICALLY 6.9837 NORTHING (METERS)
5.9376 EASTING (METERS)
185.9143 ELEV. (METERS) (ELLIPSOID HEIGHTH)

Figure 9. Sample Processing Results Chart for L1 Observations

IX.O.

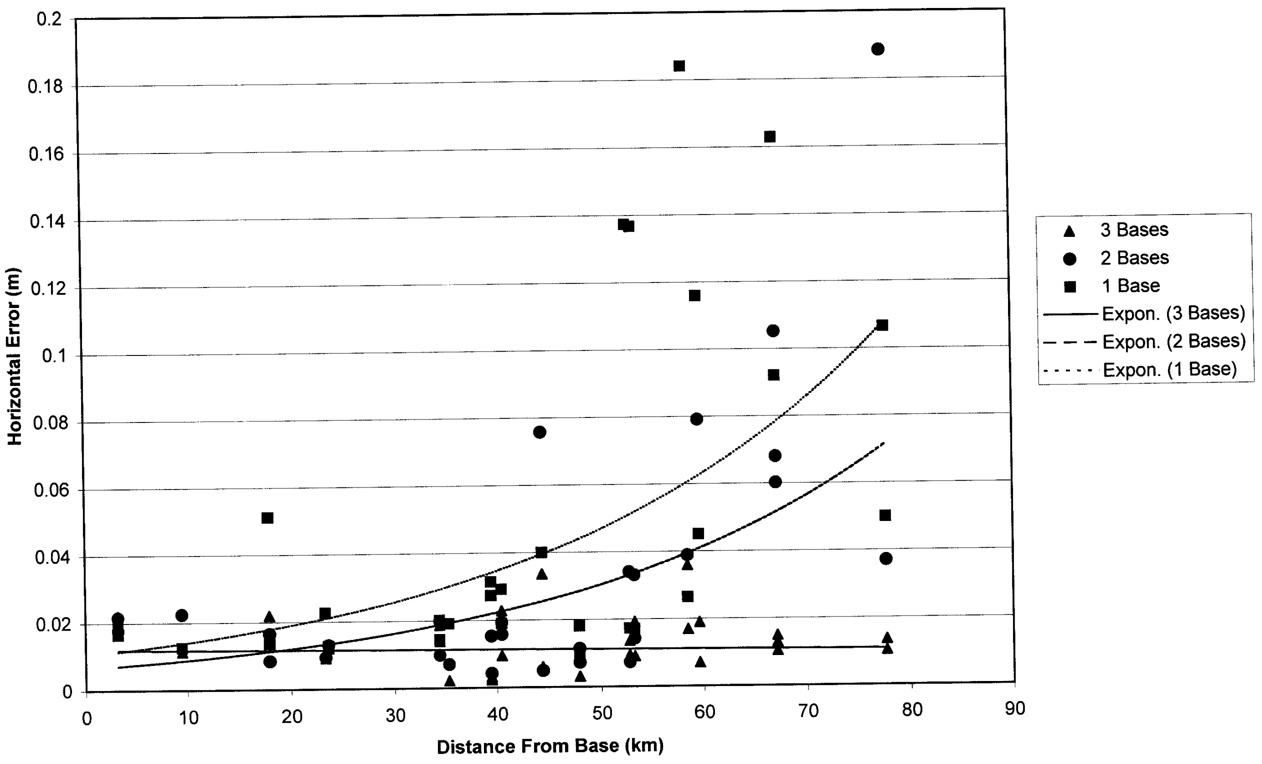


GPSURVEY 2.2	STATION	OBS. DATE	FREQ	
TIME	STON 5.1287 3.4356 -28.8607	2/23/96 19:44:30	L, + L 2	TIME

TIME MINUTES	BASE 1	UCON 7	MONT 5	BASE + UCON 2	BASE + MONT 4	UCON + MONT 6	BASE + UCON + MONT 3	TIME MINUTES
02	4.1007 4.3631 -28.6881	5.0765 3.4153 -28.7756	5.1527 3.4381 -28.8662	6.6615 4.6756 -28.7508	4.7354 3.4515 -28.7715	5.1303 3.4229 -28.8024	5.1573 3.5332 -28.9089	02
03	5.0967 3.4330 -28.7891	5.0863 3.4194 -28.7839	5.1471 3.4342 -28.8652	5.1042 3.4017 -28.7855	5.1350 3.4240 -28.8332	5.1285 3.4234 -28.8124	5.1292 3.4232 -28.8379	03
05	5.1210 3.4383 -28.8171	5.1014 3.4311 -28.8079	5.1417 3.4249 -28.8692	5.1080 3.4076 -28.8117	5.1337 3.4239 -28.8441	5.1278 3.4232 -28.8337	5.1295 3.4222 -28.8481	05
07	5.1275 3.4300 -28.8188	5.1080 3.4266 -28.8022	5.1366 3.4227 -28.8765	5.1091 3.3988 -28.8106	5.1323 3.4227 -28.8528	5.1267 3.4217 -28.8461	5.1295 3.4208 -28.8506	07
10	5.1364 3.4158 -28.8162	5.1215 3.4193 -28.7911	5.1317 3.4228 -28.8862	5.1131 3.4009 -28.8036	5.1329 3.4226 -28.8603	5.1283 3.4212 -28.8508	5.1310 3.4203 -28.8524	10
15	5.0577 3.4329 -28.7443	5.0576 3.4055 -28.7336	5.1578 3.4389 -28.9085	5.0971 3.4020 -28.7394	5.1318 3.4207 -28.8548	5.1278 3.4217 -28.8545	5.1314 3.4187 -28.8512	15
30	5.1525 3.2919 -28.7909	5.2009 3.3451 -28.7940	5.0866 3.4452 -28.8841	5.1322 3.4257 -28.7918	5.1270 3.4209 -28.8572	5.1297 3.4224 -28.8590	5.1304 3.4211 -28.8555	30
60	5.1466 3.3665 -28.8555	5.1666 3.3983 -28.8740	5.1083 3.4318 -28.8616	5.1247 3.4285 -28.8667	5.1293 3.4241 -28.8598	5.1298 3.4257 -28.8664	5.1292 3.4255 -28.8672	60

TYPICALLY 6.9837 NORTHING (METERS)
5.9376 EASTING (METERS)
185.9143 ELEV. (METERS) (ELLIPSOID HEIGHTH)

Figure 10. Sample Processing Results Chart for L1 and L2 Observations



L1 & L2 - Horizontal Error

Figure 11. 20 Minute Observation. Horizontal Error vs. Distance from Base Station for Various Combinations of Base Stations

IX.Q.

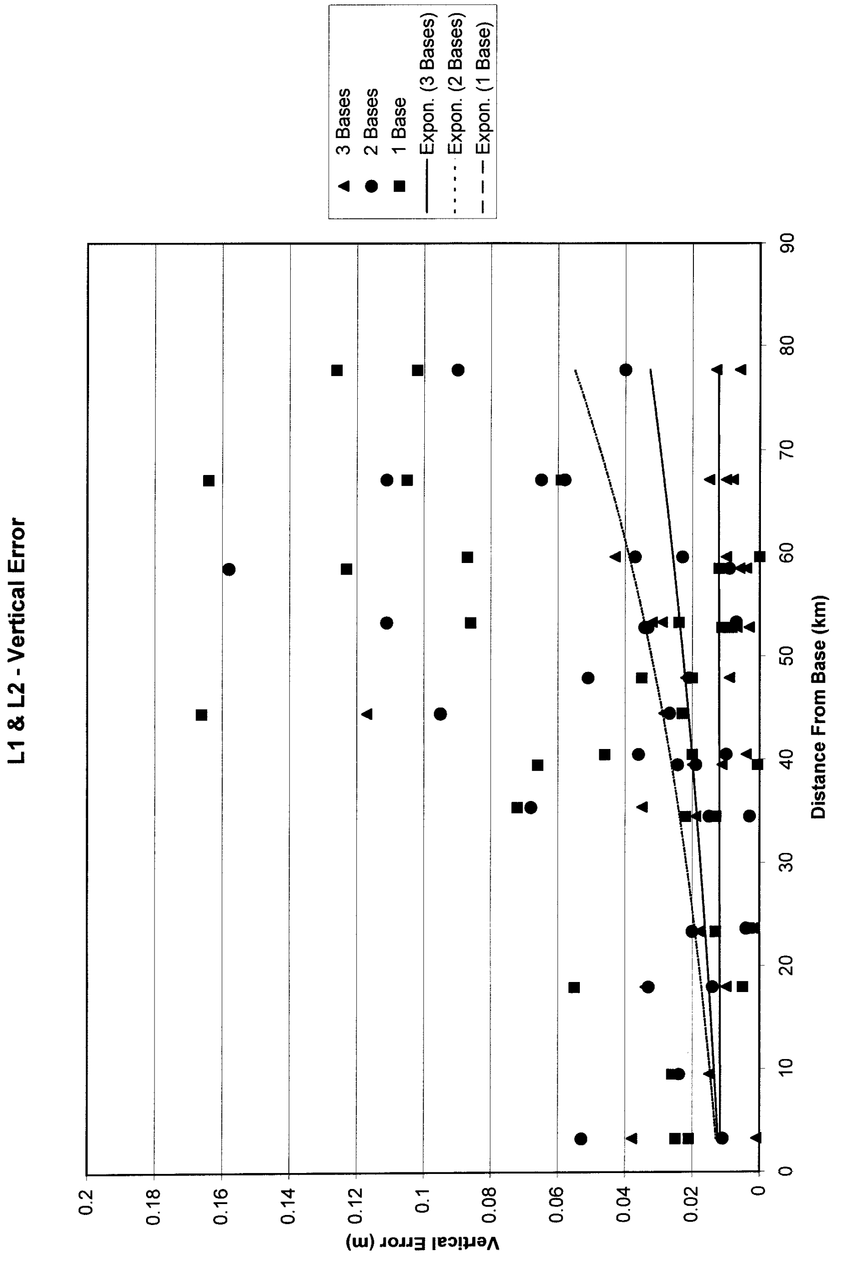


Figure 12. 20 Minute Observation. Vertical Error vs. Distance from Base Station for Various Combinations of Base Stations

IX.R.

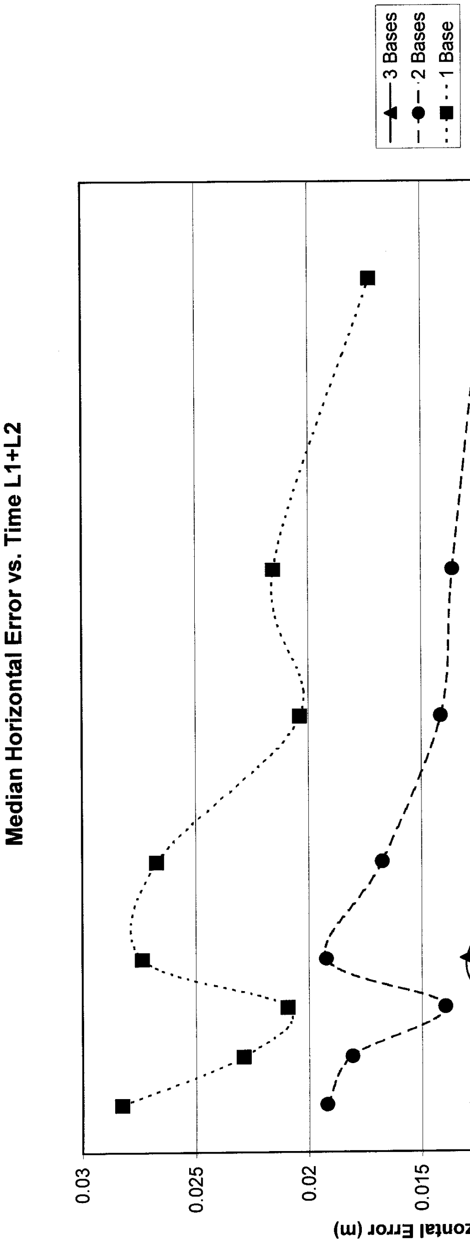


Figure 13. Median Horizontal Error vs. Observation Time for Various Combinations of Base Stations

IX.S.

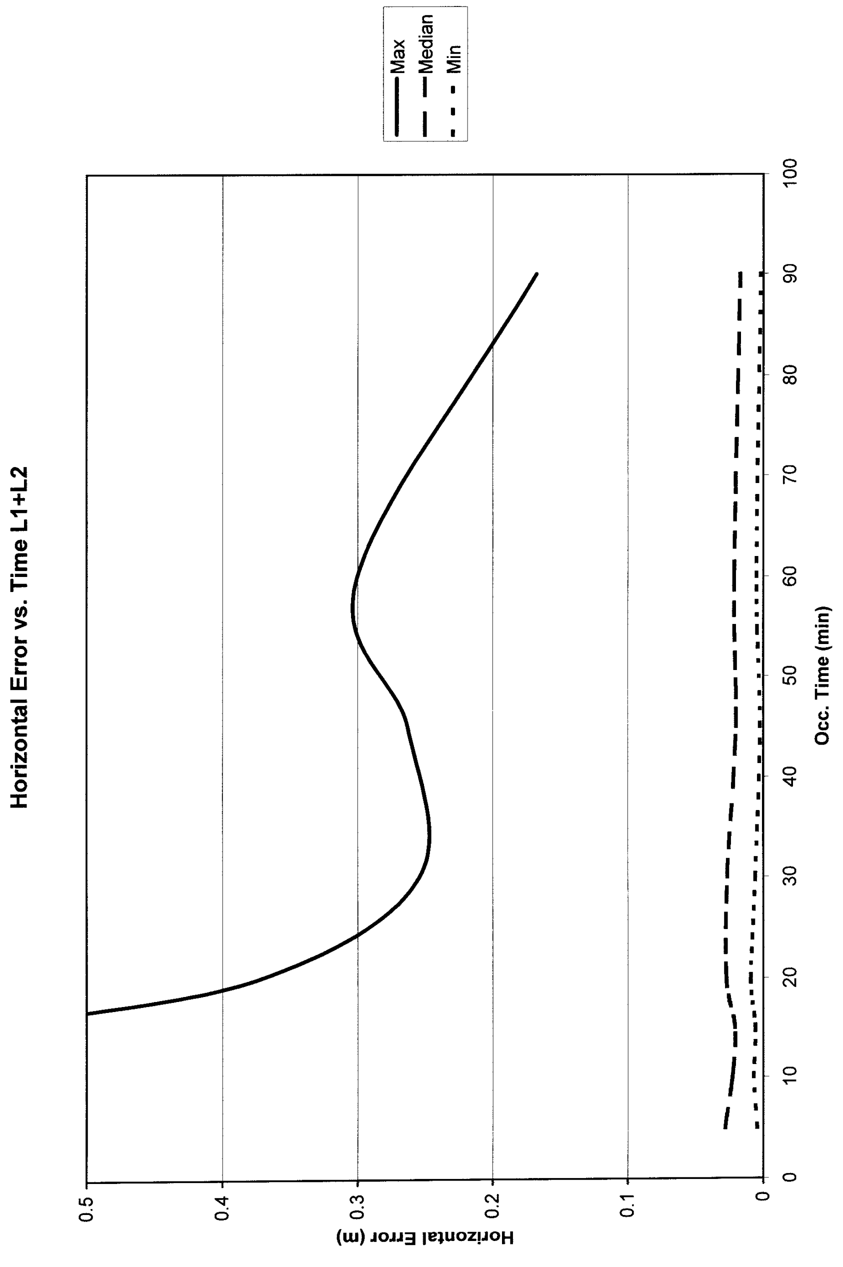


Figure 14. Horizontal Error vs. Observation Time for OHP Base Alone

IX.T.

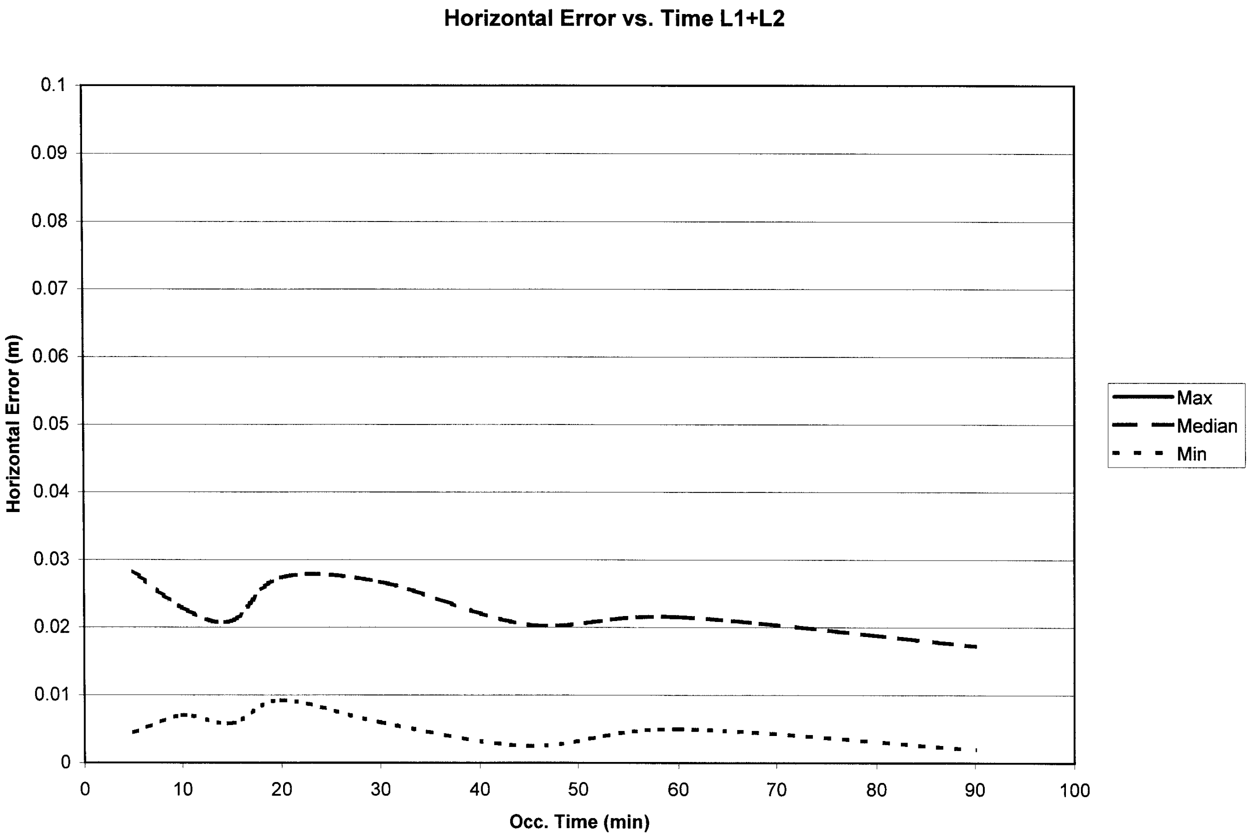


Figure 14A. Horizontal Error vs. Observation Time for OHP Base Alone - Alternate Scale

IX.U.

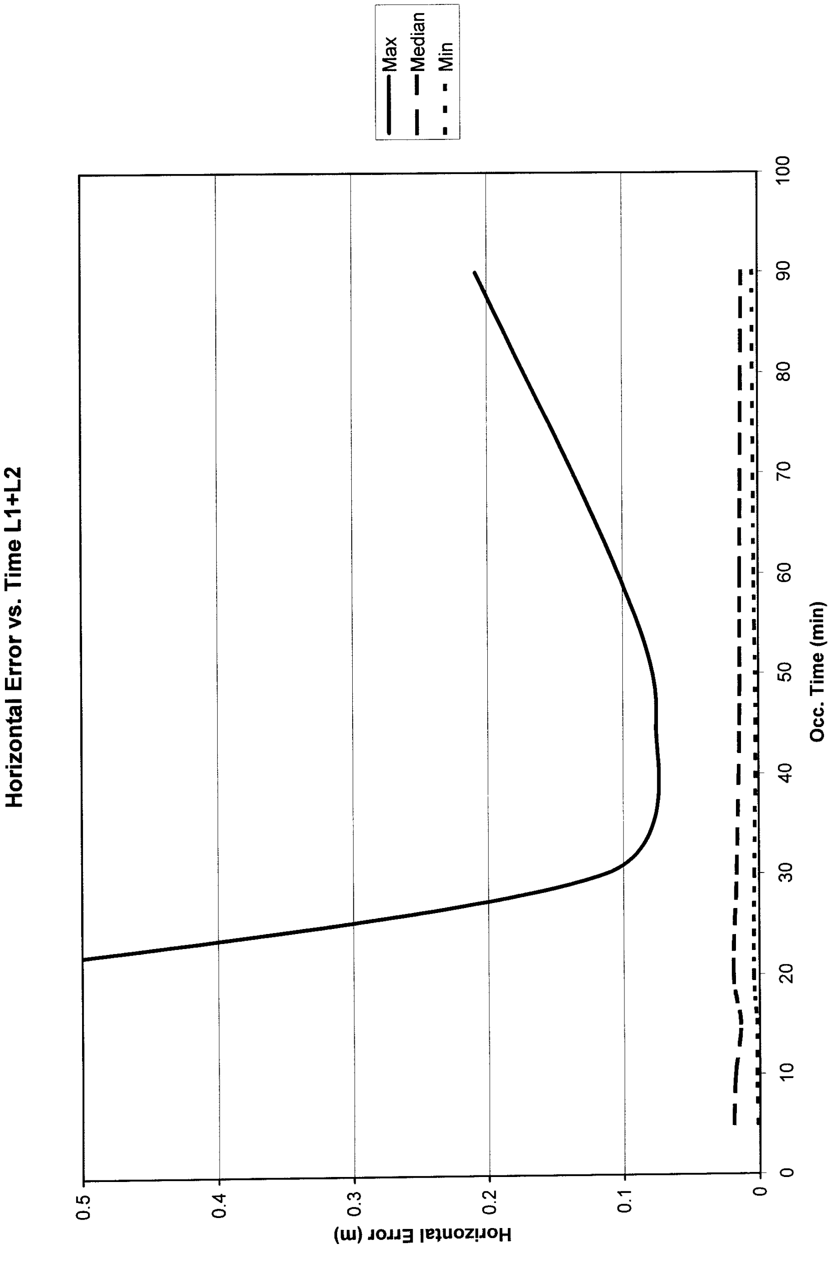


Figure 15. Horizontal Error vs. Observation Time for Two Base Stations (OHP and UCON)

IX.V.

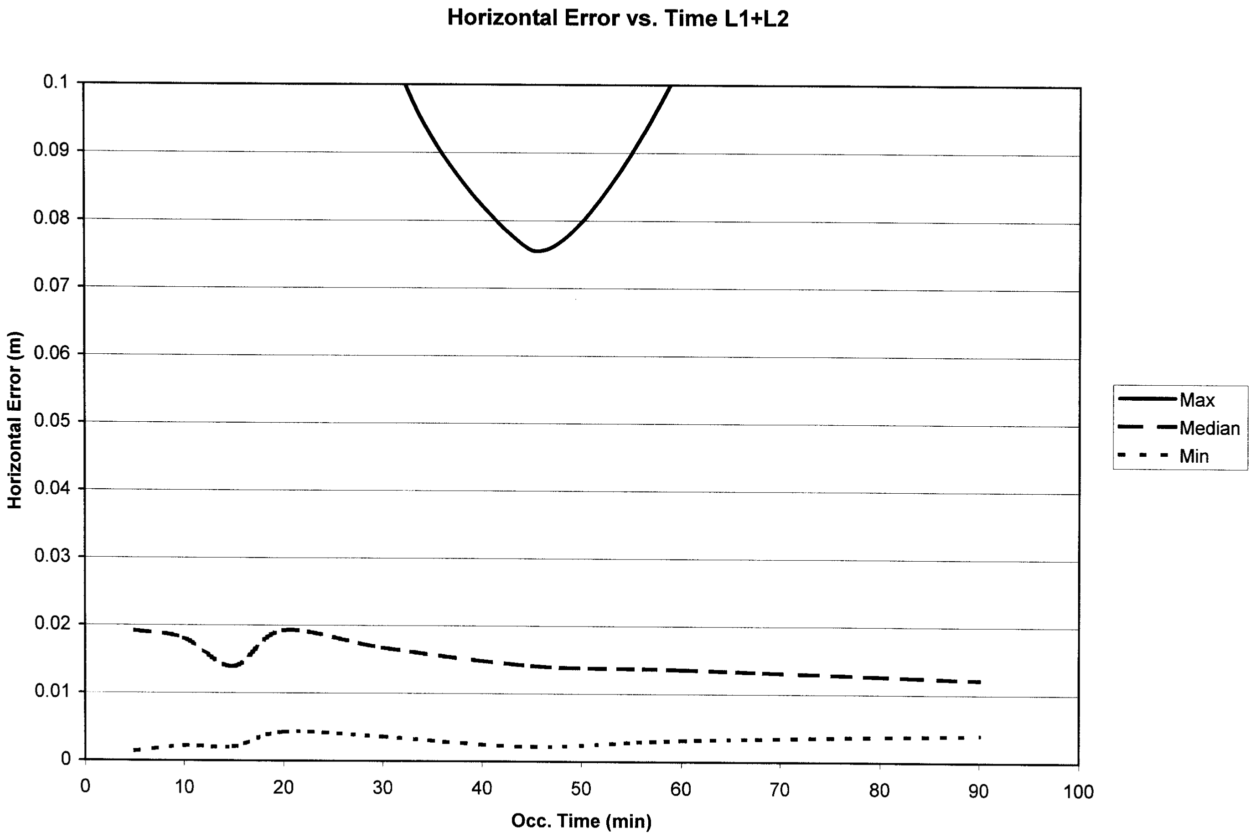


Figure 15A. Horizontal Error vs. Observation Time for Two Base Stations (OHP and UCON) - Alternate Scale

IX.W.

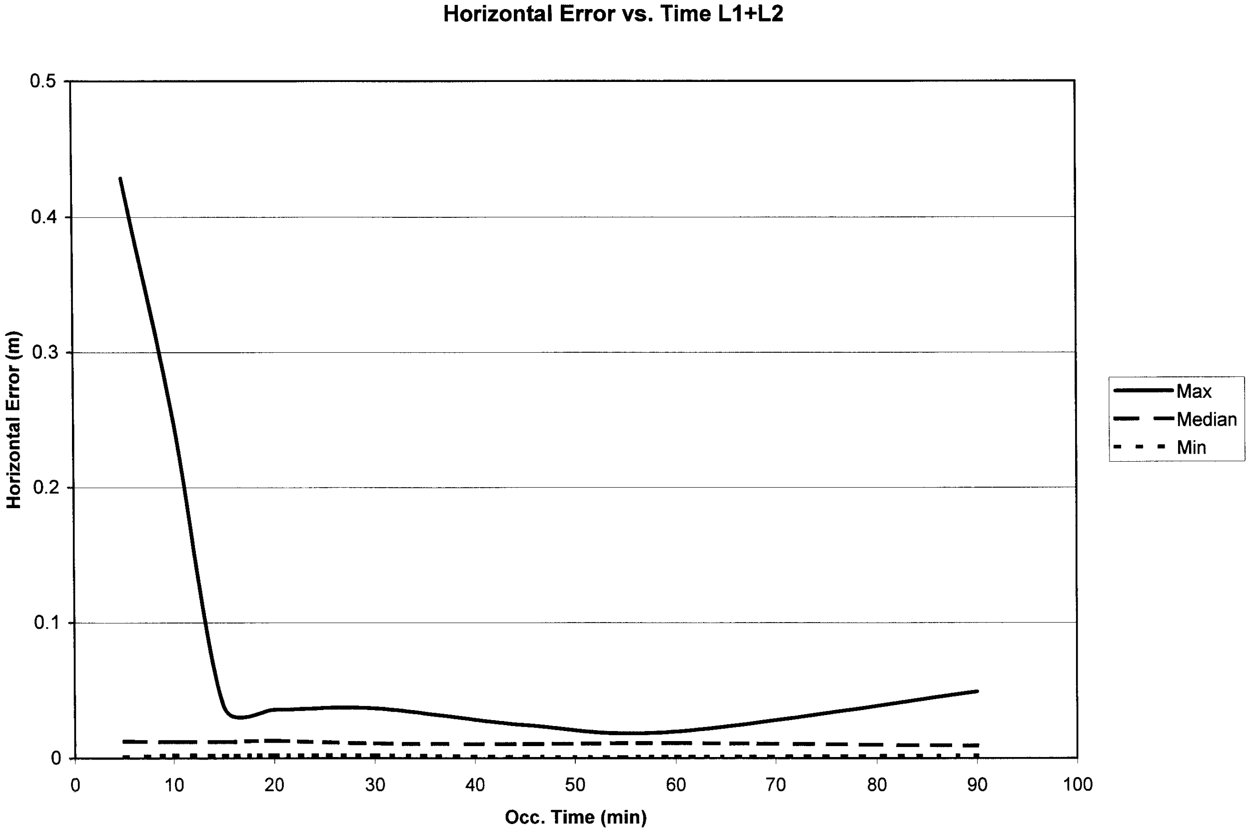


Figure 16. Horizontal Error vs. Observation Time for Three Base Stations (OHP, UCON and MNP1)

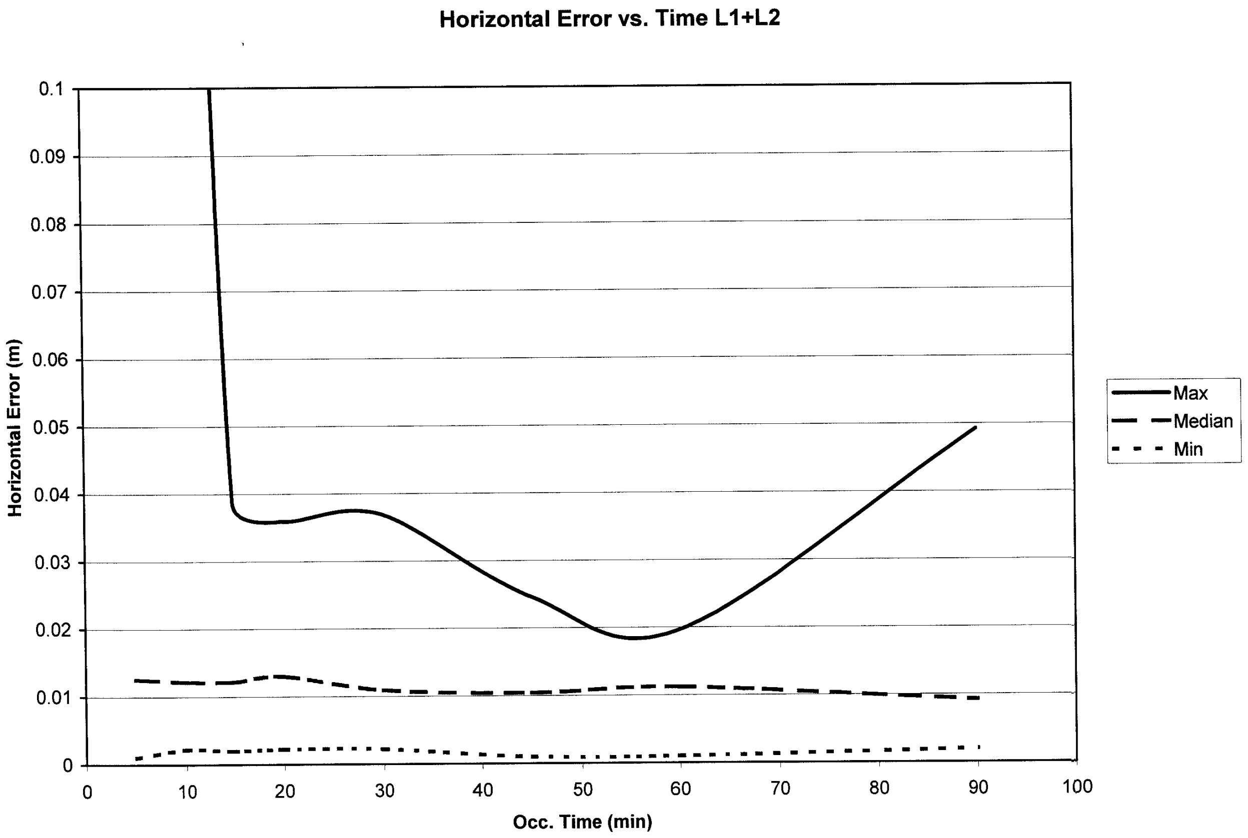


Figure 16A. Horizontal Error vs. Observation Time for Three Base Stations (OHP, UCON and MNP1) - Alternate Scale

IX.Y.

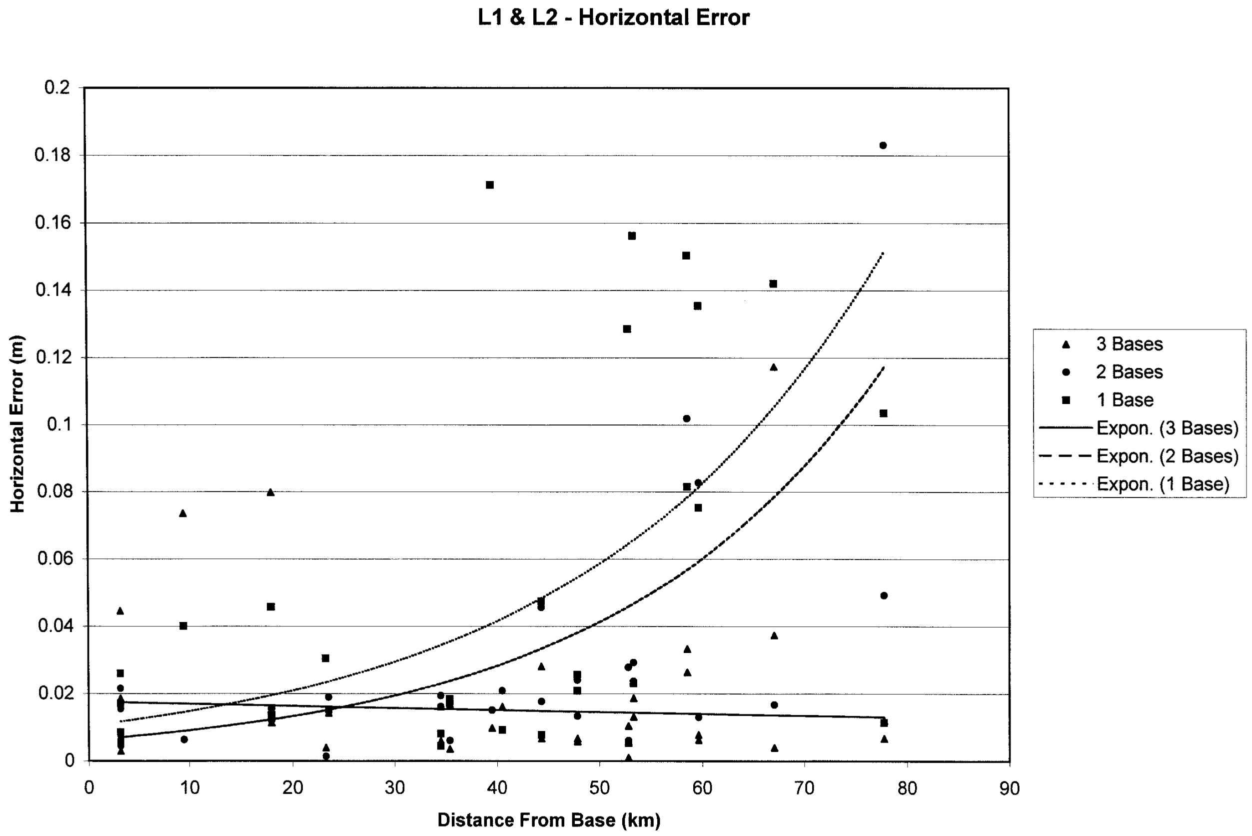


Figure 17. 5 Minute Observation Horizontal Error vs. Distance From OHP Base Station for Various Combinations of Base Stations

IX.Z.

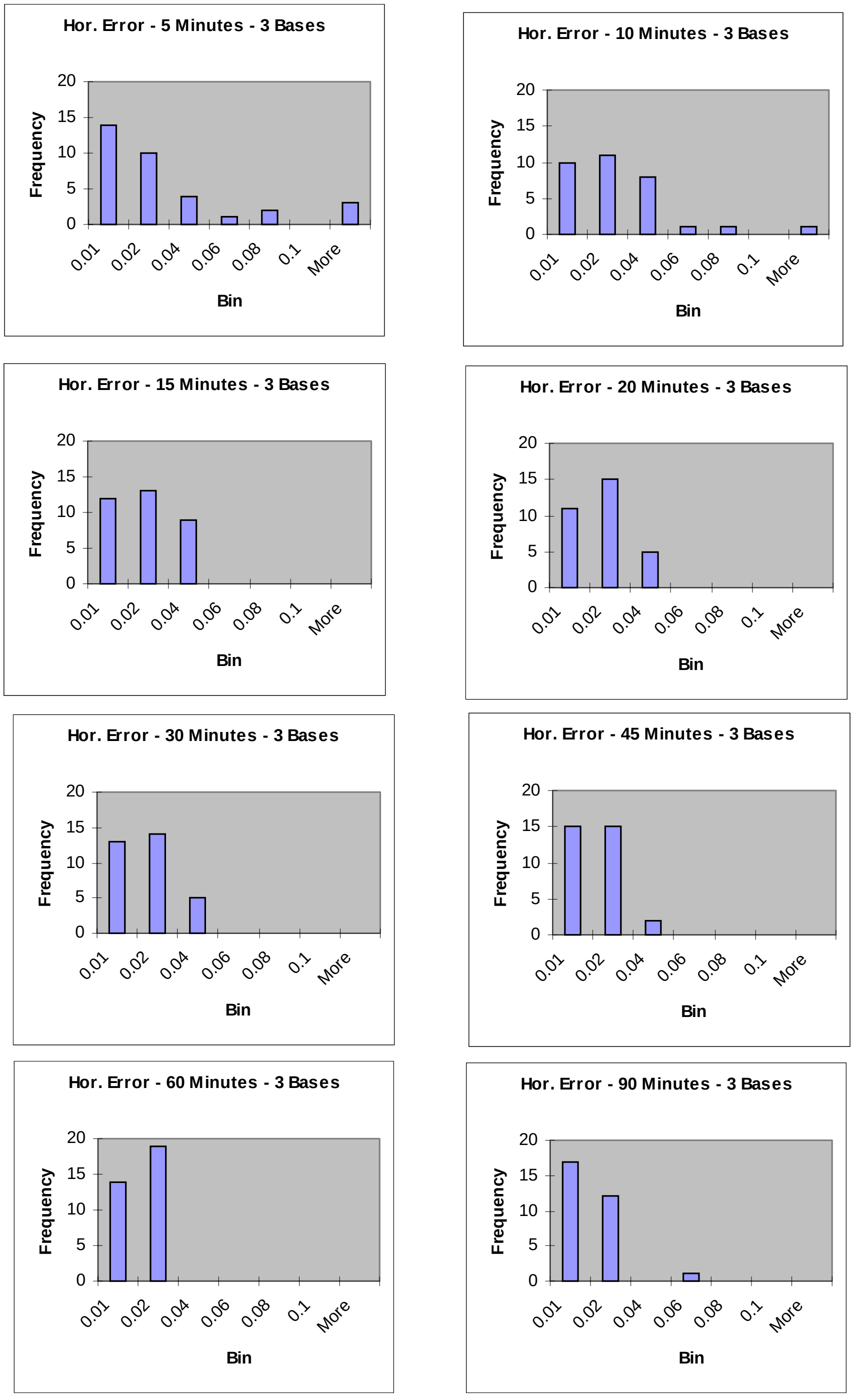


Figure 18. Distribution of Horizontal Error for Varying Occupation Times

IX.AA

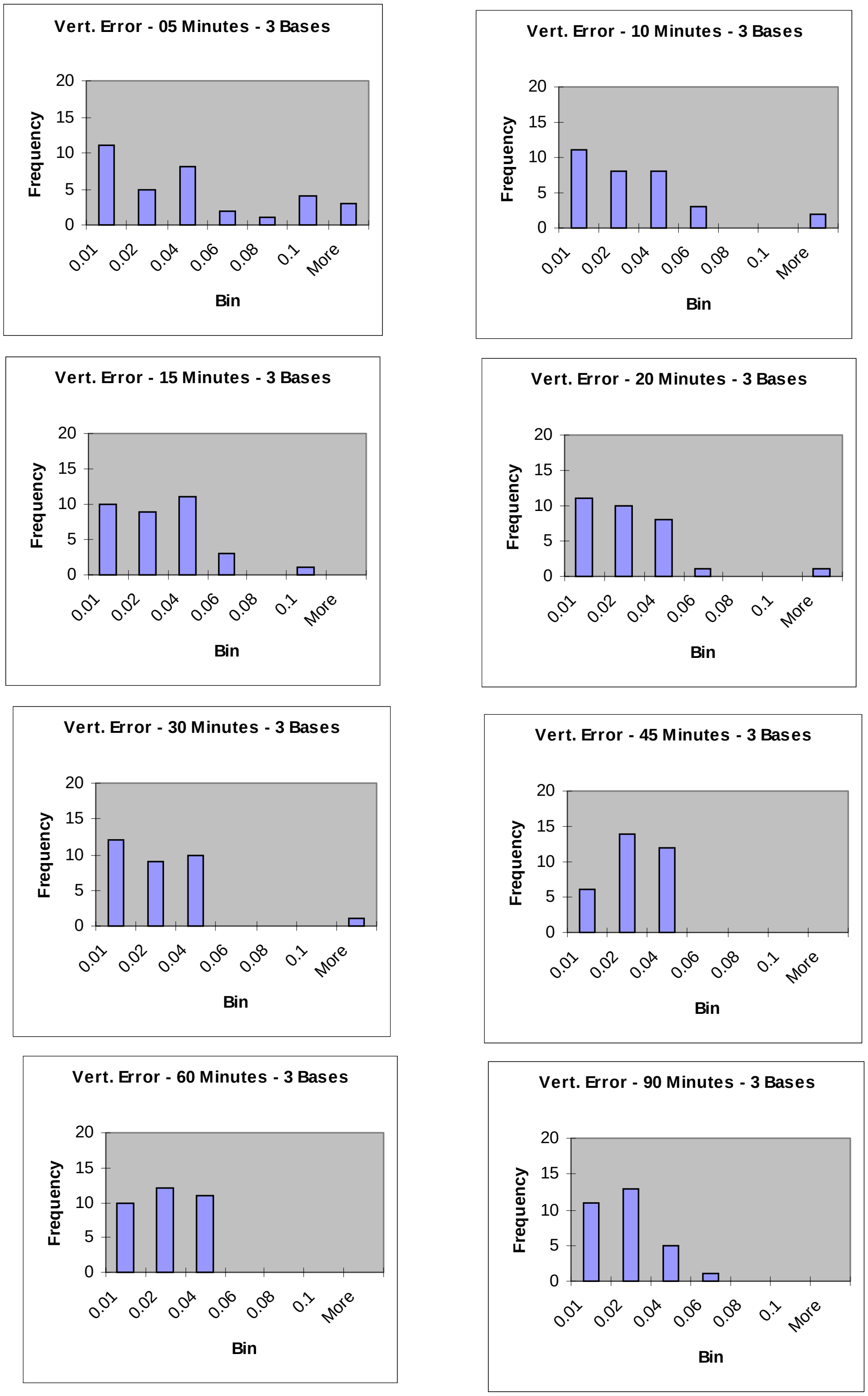


Figure 19. Distribution of Vertical Error for Varying Occupation Times