Chapter 10
Post-Processing Differential GPS Observational Data

10-1. General

GPS baseline solutions are usually generated through an iterative process. From approximate values of the positions occupied and observation data, theoretical values for the observation period are developed. Observed values are compared to computed values, and an improved set of positions occupied is obtained using least-squares minimization procedures and equations modeling potential error sources. Observed baseline data are also evaluated over a loop or network of baselines to ascertain the reliability of the individual baselines. A generalized flow of the processes used in reducing GPS baselines is outlined below. This chapter will cover the steps outlined in this process.

- Create New Project File Area
- Download/Import Baseline Data from Receivers or Survey Data Collectors
- Download Precise Ephemeris Data if Required
- Make Changes and Edits to Raw Baseline Data
- Process all Baselines
- Review, Inspect, and Evaluate Adequacy of Baseline Reduction Results
- Make Changes and Rejects
- Reprocess Baselines and Reevaluate Results
- Note/Designate Independent and Trivial Baselines
- [Review Loop Closures and Adjust Baseline Network--Chapter 11]

a. The ability to determine positions using GPS is dependent on the effectiveness of the user to determine the range or distance of the satellite from the receiver located on the earth. There are two general techniques currently operational to determine this range: differential code pseudoranging and differential carrier phase measurement. This chapter will discuss general post-processing issues for differential carrier phase reductions that provide centimeter-level accuracy suitable for controlling project monuments. Post-processed differential code phase reductions, with accuracies ranging from 0.2 to 5 meters, are only briefly covered since these techniques are not intended for precise control surveys.

b. Baseline processing time is dependent on the required accuracy, processing software, computer hardware speeds, data quality, and amount of data collected. The user must take special care when processing baselines with observations from different GPS receiver manufacturers. It is important to ensure that observables being used for the formulation of the baseline are of a common format (i.e. RINEX).

10-2. General Differential Reduction Techniques

Differential reduction techniques basically involve the analysis of the Doppler frequency shifts that occur between the moving satellites and ground-based receivers, one of which may be in motion (e.g., RTK rover). Integration of the Doppler frequency offsets, along with interferometric processing and differencing techniques, provides for a resultant baseline vector between the two ground-based points, or velocity measurements on a moving receiver. Differencing and interferometric analysis techniques may be performed on both carrier frequencies (L1 & L2), the frequency difference (wide-laning), and on the code-phase observations. "Floating" and "Fixed" baseline solutions are computed from these interferometric differencing techniques. A variety of algorithms and methods are used to perform the reductions. Although these processes are relatively simple for static GPS observations, they become complicated when real-time (on-the-fly) integer ambiguity resolution is required. A variety of GPS data reduction software can be obtained from government agencies or commercial vendors. The detailed theory and derivations of these reductions are beyond the scope of this manual. The material presented in the following sections should be considered as only an overview. Examples of baseline reduction software will be limited to those software packages commonly used by Corps commands. Full discussions on carrier phase reductions can be found in the references listed in Appendix A. Kaplan 1996 (Chapter 8--Differential GPS) is recommended along with Leick 1995, and Remondi 1985.

10-3. Carrier Phase Observables

The carrier "beat" phase observable is the phase of the signal remaining after the internal oscillated frequency generated in the receiver is differenced from the incoming carrier signal of the satellite. The carrier phase observable can be calculated from the incoming signal or from observations recorded during a GPS survey. By differencing the signal over a period or epoch of time, one can count the number of wavelengths that cycle through the receiver during any given specific duration of time. The unknown number of cycles between the satellite and receiver antenna is known as the "integer cycle ambiguity." There is one integer ambiguity value per each satellite/receiver pair as long as the receiver maintains continuous phase lock during the observation period. The value found by measuring the number of cycles going through a receiver during a specific time, when given the definition of the transmitted signal in terms of cycles per second, can be used to develop a time measurement for transmission of the signal. Once again, the time of transmission of the signal can be multiplied by the speed of light to yield an approximation of the range between the satellite and receiver. The biases for carrier phase measurement are the same as for pseudoranges, although a higher accuracy can be obtained using the carrier phase. A more exact range between the satellite and receiver can be formulated when the biases are taken into account during derivation of the approximate range between the satellite and receiver.

10-4. Baseline Solution by Linear Combination

The accuracy achievable by pseudoranging and carrier phase measurement in both absolute and relative positioning surveys can be improved through processing that incorporates differencing of the mathematical models of the observables. Processing by differencing takes advantage of correlation of error (e.g., GPS signal, satellite ephemeris, receiver clock, and atmospheric propagation errors) between receivers, satellites, and epochs, or combinations thereof, in order to improve GPS processing. Through differencing, the effects of the errors that are common to the observations being processed are eliminated or at least greatly reduced. Basically, there are three broad processing techniques that incorporate differencing: single differencing, double differencing, and triple differencing. Differenced solutions generally proceed in the following order: differencing between receivers takes place first, between satellites second, and between epochs third (Figure 10-1).

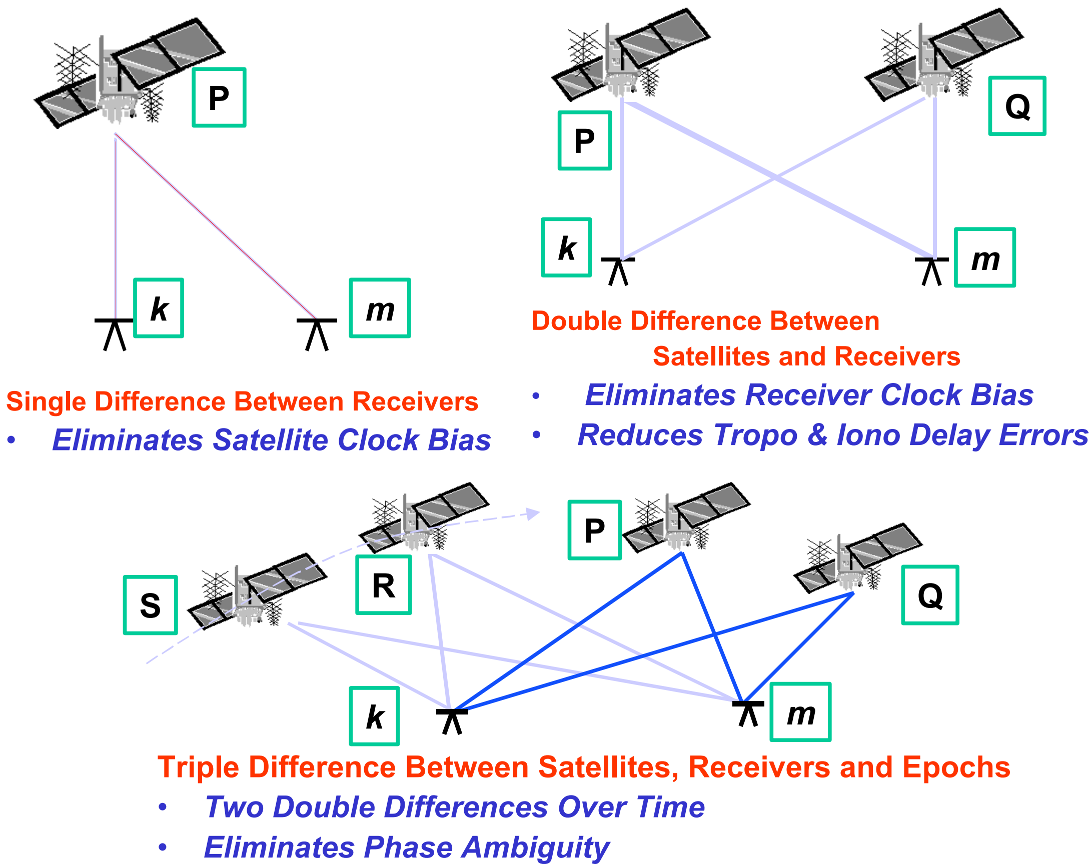

Figure 10-1. Carrier phase differencing techniques

a. Single differencing. There are three general single differencing processing techniques: between receivers, between satellites, and between epochs.

(1) Between receivers. Single differencing the mathematical models for a pseudorange (P- or C/A-code) or carrier phase observable measurements between receivers will eliminate or greatly reduce satellite clock errors and a large amount of satellite orbit and atmospheric delays. This is illustrated in upper left portion of Figure 10-1 where single differences are computed between the two receivers (*k* and *m*) and the satellite "P."

(2) Between satellites. Single differencing the mathematical models for pseudorange code or carrier phase observable measurements between satellites eliminates receiver clock errors. Single differencing between satellites can be done at each individual receiver during observations as a precursor to double differencing and in order to eliminate receiver clock errors.

(3) Between epochs. Single differencing the mathematical models between epochs takes advantage of the Doppler shift or apparent change in the frequency of the satellite signal by the relative motion of the transmitter and receiver. Single differencing between epochs is generally done in an effort to eliminate cycle ambiguities. There are three forms of single differencing techniques between epochs: Intermittently Integrated Doppler (IID), Consecutive Doppler Counts (CDC), and Continuously Integrated Doppler (CID). IID uses a technique whereby Doppler count is recorded for a small portion of

the observation period, the Doppler count is reset to zero, and then at a later time the Doppler count is restarted during the observation period. CDC uses a technique whereby Doppler count is recorded for a small portion of the observation period, reset to zero, and then restarted immediately and continued throughout the observation period.

b. Double differencing. Double differencing is actually a differencing of two single differences (as detailed above). There are two general double differencing processing techniques: receiver-time and receiver-satellite. Double difference processing techniques eliminate clock errors.

(1) Receiver-time double differencing. This technique uses a change from one epoch to the next, in the between-receiver single differences for the same satellite. Using this technique eliminates satellite-dependent integer cycle ambiguities and simplifies editing of cycle slips.

(2) Receiver-satellite double differencing. There are two different techniques that can be used to compute a receiver-satellite double difference. One technique involves using two between-receiver single differences, as shown in the upper right of Figure 10-1. This technique also uses a pair of receivers, recording different satellite observations during a survey session and then differencing the observations between two satellites. The second technique involves using two between-satellite single differences. This technique also uses a pair of satellites, but different receivers, and then differences the satellite observations between the two receivers.

c. Triple differencing. There is only one triple differencing processing technique: receiver-satellite-time (epoch). All errors eliminated during single- and double-differencing processing are also eliminated during triple differencing. When used in conjunction with carrier beat phase measurements, triple differencing eliminates initial cycle ambiguity. During triple differencing, the data is also automatically edited by the software to delete any data that cannot be solved, so that the unresolved data are ignored during the triple difference solution. This feature is advantageous to the user because of the reduction in the editing of data required; however, degradation of the solution may occur if too much of the data is eliminated during triple differencing.

d. Differencing equations. The expressions for single differences between receivers and satellites can be formed from the general carrier phase observable given back in Chapter 5 as Equation 5-2 (Kaplan 1996), which is repeated below. Refer also to Figure 10-1.

$$\mathrm{f}_{\mathrm{k}}^{\mathrm{P}}(\mathrm{t}) = f_k^{\,P}(t) - f^{\,P}(t) + N_k^P + S_k + ¦\, t_P + ¦\, t_k - b_{\mathrm{iono}} + d_{\mathrm{tropo}} \qquad \text{(Eq 10-1)}$$

where

$\mathrm{f}_{\mathrm{k}}^{\mathrm{P}}(\mathrm{t})$ = length of propagation path between satellite "P" and receiver "k" ... in cycles
$f_k^{\,P}(t)$ = received phase of satellite "P" at receiver "k" at time "t"
$f^{\,P}(t)$ = transmitted phase of satellite "P"
N_k^P = integer ambiguity
S_k = measurement noise (multipath, GPS receiver, etc.)
¦ = carrier frequency (Hz)
t_P = satellite clock bias
t_k = receiver clock bias
b_{iono} = ionospheric advance (cycles)
d_{tropo} = tropospheric delay (cycles)

For a second receiver "m" another equation can be written for the propagation path between satellite "P" and the second receiver "m":

$$\mathrm{f}_{\mathrm{m}}^{\mathrm{P}}(\mathrm{t}) = f_m^{\,P}(t) - f^{\,P}(t) + N_m^{\,P} + S_m + \text{¦}\, t_P + \text{¦}\, t_m - b_{\mathrm{iono}} + d_{\mathrm{tropo}} \qquad \text{(Eq 10-2)}$$

Differencing the propagation path lengths between the two receivers "k" and "m" to the satellite "P" (Equations 10-1 and 10-2) results in a "single difference between receivers."

$$\mathbf{SD}_{\mathrm{km}}^{\mathrm{P}} = f_{km}^{\,P} + N_{km}^{\,P} + S^{P}_{km} + \text{¦}\, t_{km} \qquad \text{(Eq 10-3)}$$

When a second satellite "Q" is added, a "single difference between receivers" can be formed for the second satellite "Q":

$$\mathbf{SD}_{\mathrm{km}}^{\mathrm{Q}} = f_{km}^{\,Q} + N_{km}^{\,Q} + S^{Q}_{km} + \text{¦}\, t_{km} \qquad \text{(Eq 10-4)}$$

The "single difference" equations 10-3 and 10-4 can be differenced between themselves, thus creating a "double difference" involving two separate receivers (*k* and *m*) and two separate satellites (*P* and *Q*).

$$\mathbf{DD}_{\mathrm{km}}^{\mathrm{PQ}} = f_{km}^{\,PQ} + N_{km}^{\,PQ} + S^{PQ}_{km} \qquad \text{(Eq 10-5)}$$

It is seen in the above "double difference" equation that most of the original unknown terms have been eliminated by these differencing techniques, with only the integer ambiguity (*N*) and noise (*S*) remaining to be determined. Additional "double difference" equations can be written for the two receivers between other combinations of epochs of satellites in view, and these multiple double difference equations can be again differenced (i.e. Triple Differenced) to remove the integer ambiguity term $N_{km}^{\,PQ}$.

$$\mathbf{TD}_{\mathrm{km}}^{\mathrm{PQ}} = \mathbf{DD}_{\mathrm{km}}^{\mathrm{PQ}}(t+1) - \mathbf{DD}_{\mathrm{km}}^{\mathrm{PQ}}(t) \qquad \text{(Eq 10-6)}$$

where t and $t+1$ are successive epochs.

The results of the Triple Difference baseline solution can then be input back into the Double Difference equations in order to resolve, or "fix," the integers in the Double Difference solution. Fixing the integers in a Double Difference solution constrains the integer ambiguity *N* to a whole number of cycles, and is the preferred baseline solution--see Leick 1995.

10-5. Baseline Solution by Cycle Ambiguity Recovery

The resultant solution (baseline vector) produced when differenced carrier phase observations resolve the cycle ambiguity is called a "fixed" solution. The exact cycle ambiguity does not need to be known to produce a solution; if a range of cycle ambiguities is known, then a "float" solution can be formulated from the range of cycle ambiguities. A floating baseline solution is a least-squares fit that may be accurate to only a few integer wavelengths. It is always desirable to formulate a fixed solution. However, when the cycle ambiguities cannot be resolved, which sometimes occurs when a baseline distance is greater than 75 km in length, a float solution may actually be the best solution. Differences between floating and fixed solutions can be calculated over all the epochs observed. The fixed solution may be unable to determine the correct set of integers (i.e. "fix the integers") required for a solution.

10-6. Field/Office Baseline Processing

It is strongly recommended that baselines should be processed daily in the field. This allows the user to identify any problems that may exist. Once baselines are processed, the field surveyor should review each baseline output file. Certain computational items within the baseline output are common among software vendors, and may be used to evaluate the adequacy of the baseline observations in the field. Baseline outputs may include triple difference, float double difference, and fixed double difference distance vectors, variance and covariance statistics, and RMS accuracy estimates. The procedures used in baseline processing are software dependent; however, the output statistics and analysis of reliability are somewhat similar among different vendors. Discussion and examples in the following sections are largely taken from Trimble Geomatics Office software user guide manuals that are referenced in Appendix A.

Figure 10-2. Baseline processing (Huntsville, AL PROSPECT GPS Course--2002)

a. Baseline processing. Baseline processing software is now fairly automatic and user-friendly. Most software automatically performs all the interferometric differencing operations needed to solve for integer ambiguities, and displays the resultant baseline vectors along with adjustment and accuracy statistics that can be used to evaluate the results. The following procedures are taken from Trimble Navigation's "Weighted Ambiguity Vector Estimator" (WAVE) software (Trimble 2001d) and are believed to be representative of most packages. Trimble's WAVE baseline processor involves performing the following steps, in order:

1. Load raw GPS observation DAT files
2. Select the display options
3. Set the processing style & baseline flow sequence
4. Edit occupations (station names, antenna heights, etc.)
5. Import a coordinate seed (approximate point positions)
6. Choose baselines for processing (identify independent baselines)
7. Process the baselines
8. Review the results

Where multiple baselines are observed in a network, the software will process the baselines sequentially. Independent baselines should be identified during this phase. If a precise ephemeris is available, then it should be downloaded and input into the baseline reduction program. Complete details on performing each of these baseline processing steps is found in the *Trimble Geomatics Office--WAVE Baseline Processing Software User Guide* (Trimble 2001d).

b. Downloading GPS data. The first step in baseline processing is transferring the observation data from the GPS data collector device to a personal computer for processing and archiving. Various types of file formats may be involved, depending on the GPS receiver--e.g., Trimble Receiver *.DAT files, Trimble Survey Controller *.DC files, or RINEX ASCII files. Data adjustment software packages have standard downloading options for transferring GPS data files, or routines to convert proprietary GPS files to RINEX format. Trimble *.DAT files contain information on receiver type, antenna measurement method, antenna type, raw carrier phase observations, antenna height, satellite ephemeris, and station designation/name. RINEX files are also obtained for remote IGS tracking network stations or CORS base stations.

c. Preprocessing. Once observation data have been downloaded, preprocessing of data can be completed. Preprocessing procedures depend on the type of GPS data collected, e.g., static, RTK, Fast static, etc., and the type of initialization performed (static, known point, OTF, etc.). Preprocessing consists of smoothing/editing the data and ephemeris determination. Smoothing and editing are done to ensure data quantity and quality. Activities done during smoothing and editing include determination and elimination of cycle slips, editing gaps in information, and checking station names and antenna heights. In addition, elevation mask angles should be set during this phase along with options to select tropospheric and ionospheric models.

d. Ephemeris data. Retrieval of post-processed ephemerides may be required depending on the solution and type of survey being conducted. Code receivers do not require post-processed ephemerides since they automatically record the broadcast ephemerides during the survey. Most baseline reduction software provides an option to select either a broadcast or precise ephemeris.

e. Baseline solutions. Carrier phase baseline processing is fairly automatic on commercial software packages. Groups of baselines are processed in a defined or selected order. After an initial code solution is performed, a triple difference, then double-difference, solution is performed. If the integer ambiguities are successfully resolved, then a fixed solution can result. Solution types may include L1 Fixed, Ionospheric-Free Fixed, and Float. If all observed baselines are processed, any dependent baselines should be removed so they will not be used in subsequent network adjustments. Commercial baseline reduction software may have a variety of options that are automatically (or manually) set to determine the most "optimum" solution. Most software packages attempt to perform the most accurate fixed solution for short lines (e.g., less than 15 km for single-frequency and less than 30 km for dual-frequency receivers). The ability to derive an accurate fixed solution (i.e. 5 to 10 mm) will also depend on the length of time of noise-free data, good DOP, multipath, etc. For baselines longer than 30 to 50 km, if the fixed solution is not deemed to be reliable (based on various quality indicators discussed below), then the default float solution may be used. Although not as accurate as the fixed solution, if the session time is long enough (e.g., 1 to 2 hours) the float solution will be fairly accurate--e.g., 20 to 50 mm for lines less than 75 km. Most processing software provides numerous statistical and graphical displays of baseline solution results, allowing users to assess the reliability of a particular solution, and force an alternate solution if necessary--see Figure 10-3 for a typical example.

10-7. Resultant Baseline Output and Quality Criteria

Baseline post-processing software outputs vary with the software package. Baseline output data are used to evaluate the quality of the solution, and may be input into subsequent network adjustment criteria. Typically, the following types of information may be selected for text output or graphical screen display:

- number of processed baselines (in network)
- number of accepted and rejected baselines
- session time (date, time)
- data logging time (start, stop)
- station information: location (latitude, longitude, height), receiver serial number used, antenna serial number used, ID numbers, antenna height
- epoch intervals
- number of epochs
- meteorological data (pressure, temperature, humidity)
- ephemeris file used for the solution formulation
- listing of the filenames
- elevation mask
- minimum number of satellites used
- type of satellite selection (manual or automatic)
- triple difference solution
- double difference fixed solution
- double difference float solution
- L1 only solution
- Ionospheric-free solution (L1 & L2)
- baseline vector length in meters
- RMS of solution
- Post-fit RMS by satellite vs. baseline
- RMS--L1 phase
- RMS-L1 Doppler
- RMS--P-code
- Cycle slips
- reference variance
- ratio of solution variances of integer ambiguity
- phase ambiguities & drifts
- phase residual plots--L1 & C/A
- satellite availability and tracks during the survey for each station occupied
- DOP, PDOP, VDOP, HDOP
- solution files: Δx-Δy-Δz between stations, slope distance between stations, Δlatitude and Δlongitude between stations, horizontal distance between stations, and Δheight
- covariance matrix

For most Corps applications, only a few of the above parameters need be output in order to assess the results and quality of a baseline solution. These parameters can best be assessed from graphical summary plots, as shown in Figure 10-3 below. Some more sophisticated reduction software, such as Waypoint Consulting's "GrafNav" and the NGS's "PAGES," provide considerably more statistical information than most other baseline processing packages; however, this level of GPS accuracy assessment is usually not applicable to most Corps engineering and construction control survey work. These detailed statistics may have application in assessing the quality of airborne GPS (ABGPS) applications. For more information on these high-level baseline reduction methods, see NGS 2000 (*PAGE-NT User's Manual*) and Waypoint 2001 (*GrafNav/GrafNet, GrafNav Lite, GrafMov Operating Manual*).

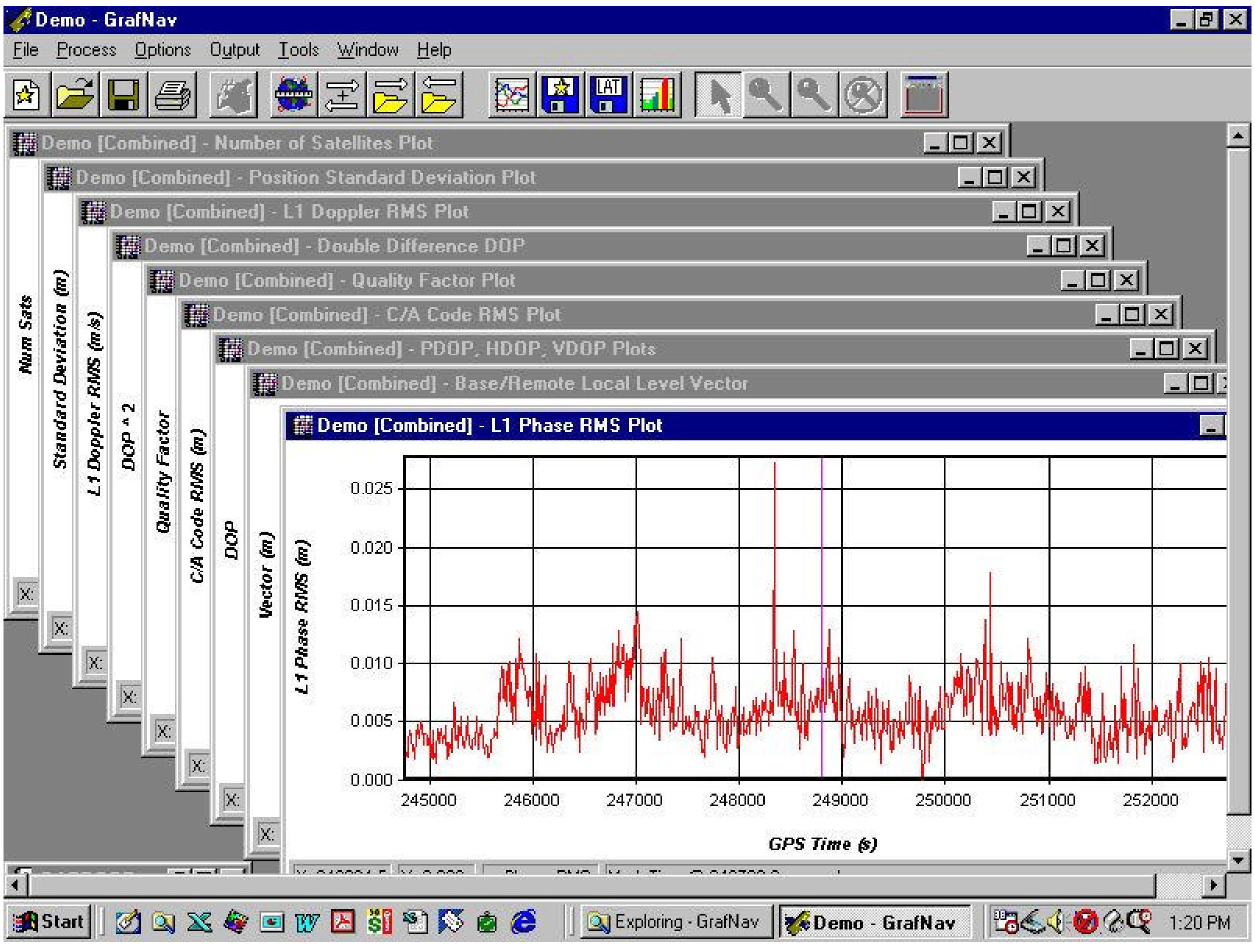

Figure 10-3. GrafNet baseline reduction output plots--some of the 28 selectable assessment options that may be plotted (Waypoint Consulting, Inc.)

a. Variance Ratio--floating and fixed solutions. A fixed solution indicates that the integer ambiguities have been successfully resolved. A floating solution may not have accurately resolved the integers; however, this may still be the best solution for that particular baseline observation. Trimble's WAVE solution computes the variances of each integer ambiguity solution and compares the solution with the lowest variance with the next higher variance solutions. This comparison "ratio" of the solutions should exceed 1.5 in order to accept the lowest variance as the fixed solution. If a variance ratio is less than 1.5 the processor defaults to the floating solution since there is no statistical basis for assuming a fixed solution has merit.

b. Reference variance. The reference variance indicates how well the computed errors in the solution compare with the estimated (*a priori*) errors for a typical baseline. A value of 1.0 indicates a good solution. Variances over 1.0 indicate the observed data were worse than the norm. Baselines with high reference variances and low variance ratios need to be checked for problems.

c. RMS. The RMS is a quality factor that helps the user determine which vector solution (triple, float, or fixed) to use in an adjustment. The RMS is dependent on the baseline length and the length of time the baseline was observed. RMS is a measurement (in units of cycles or meters) of the quality of the observation data collected during a point in time. RMS is dependent on line length, observation strength, ionosphere, troposphere, and multipath. In general, the longer the line and the more signal interference by other electronic gear, ionosphere, troposphere, and multipath, the higher the RMS will be. A good RMS factor (one that is low, e.g., between 0.01 and 0.2 cycles or less than 15 mm) may not always indicate good results, but is one indication to be taken into account. RMS can generally be used to judge the quality of the data used in the post-processing and the quality of the post-processed baseline vector.

d. Repeatability. Redundant lines should agree to the level of accuracy that GPS is capable of measuring to. For example, if GPS can measure a 10 km baseline to 1 cm + 1 ppm, the expected ratio of misclosure would be

$$(0.01 \text{ m} + 0.01\text{m}) / 10{,}000 \quad = \quad 1{:}500{,}000 \ \text{(1 part in 500,000)}$$

Repeated baselines should be near the corresponding ratio: (1 cm + 1 ppm) / baseline. Table 10-1 shows an example computation of the agreement between two redundant GPS baselines.

Table 10-1. Sample Computation of GPS Baseline Repeatability

Baseline Observation Date	X	Y	Z	Distance
Day 203	5000.214	4000.000	7680.500	9999.611
Day 205	5000.215	4000.005	7680.491	9999.607
Difference	0.001	0.005	0.009	

Ratio = $(0.001^2 + 0.005^2 + 0.009^2)^{½}$ / 9999.6 = 0.010 / 9999.6 = 1:967,000 [acceptable]

Table 10-2 below provides additional guidelines for determining the baseline quality if the fixed versus float solution is not readily assessed or available in the baseline processing software (i.e. Trimble variance ratio technique). If the fixed solution meets the criteria in this table, the fixed vector should be used in the adjustment. In some cases the vector passes the RMS test but after adjustment the vector does not fit into the network. If this occurs, the surveyor should try using the float vector in the adjustments or check to make sure stations were occupied correctly.

Table 10-2. Fixed Solution Acceptance Criteria

Distance Between Receivers (km)	RMS Criteria Formulation d = distance between receivers	Formulated RMS Range (cycles)	Formulated RMS Range (meters)
0 - 10	≤ (0.02+(0.004*d))	0.02 - 0.06	0.004 - 0.012
10 - 20	≤ (0.03+(0.003*d))	0.06 - 0.09	0.012 - 0.018
20 - 30	≤ (0.04+(0.0025*d))	0.09 - 0.115	0.018 - 0.023
30 - 40	≤ (0.04+(0.0025*d))	0.115 - 0.14	0.023 - 0.027
40 - 60	≤ (0.08+(0.0015*d))	0.14 - 0.17	0.027 - 0.032
60 - 100	≤ 0.17	0.17	0.032
> 100	≤ 0.20	0.20	0.04

Note:
1. These are only general post-processing criteria that may be superseded by GPS receiver/software manufacturer guidelines; consult those guidelines when appropriate.
2. For lines longer than 20 km, dual-frequency GPS receivers are recommended to meet these criteria.

e. Residual plots. Residual plots depict the data quality of the individual satellite signals. Typically the L1 phase residual error is plotted for all the satellites in view, or for as many that will fit on a computer screen. The plot is developed relative to the satellite chosen for double differencing. Variations about the x-axis are an indicator of noise for a particular satellite. If the satellite is used for double differencing, then no residual error will be shown for that period. Residual plots typically vary around ± 5 mm from the mean. Residual deviations exceeding ± 15 mm are suspect--see Table 10-3. A sample residual plot from a baseline solution is shown in Figure 10-4.

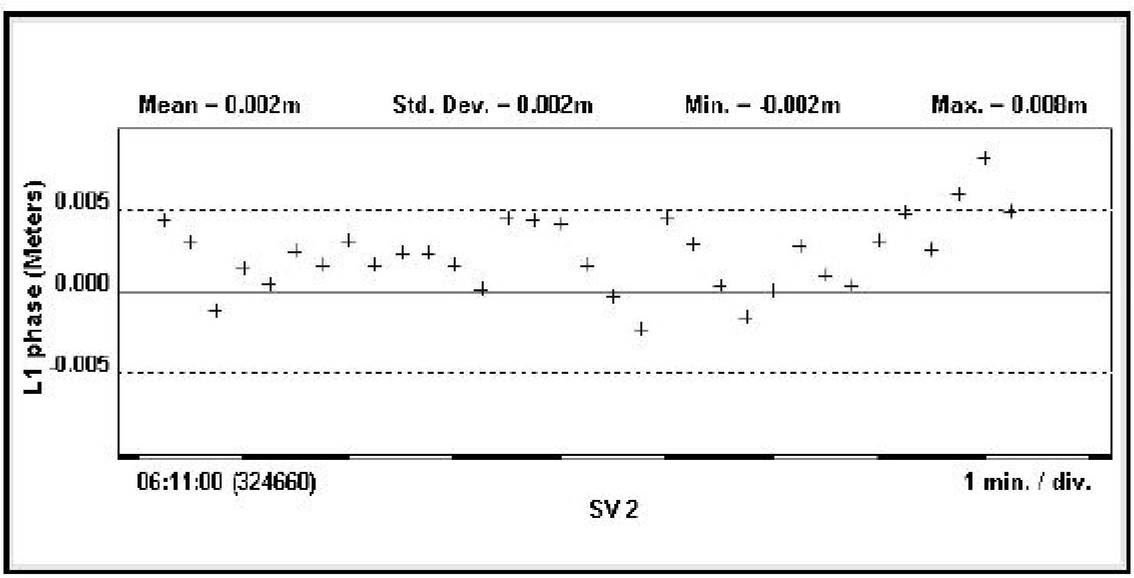

Figure 10-4. Sample residual plot (Trimble Navigation LTD WAVE baseline processing software)

f. Resolving poor baseline data. When baseline statistical data (e.g., reference variance and ratios, RMS, residual plots, etc.) does not meet the various quality checks outlined above, then a number of options are available. These include removing some or all baselines in a session (if possible), changing the elevation mask, removing one or more satellites from the solution, or, if necessary, reobserving the baseline. Eliminating multipath problems is not as easy. It may show up on the residual plot as a sinusoidal wave over time. Multipath is best minimized by good site selection, choke ring antennas, and long session times.

g. Baseline acceptance criteria (Trimble). Trimble Geomatics Office software has three levels of acceptance to assist in evaluating the quality of a processed baseline. These acceptance levels are "Pass" (passes all criteria), "Flag" (one or more quality indicators are marginal but within acceptable tolerances), and "Fail" (one or more quality indicators do not meet acceptable criteria). The "quality indicators" used are: RMS, Reference Variance, and Variance Ratio. The quality indicator Pass/Flag/Fail levels may be modified from the default levels recommended by Trimble.

h. Table 10-3 below summarizes the quality control criteria discussed above that should be used in assessing the adequacy of a baseline reduction.

Table 10-3. Summary of Baseline Processing Quality Control Criteria

Parameter	Allowable Limit
Solution:	
L1 Fixed	preferred for baselines < 10 km
Iono-free fixed	baselines 10 km to 75 km
Iono-free float	acceptable for baselines > 75 km
Reference Variance:	
Nominal value	1.0 to 10.0
Maximum NTE (L1 only)	10.0 (reject if > 20.0)
Maximum NTE (L1 & L2 iono free)	5.0 (reject if > 10.0)
RMS:	
< 5 km baseline	10 mm
< 20 km baseline	15 mm
20-50 km baseline	30 mm
NTE (with precise ephemeris)	50 mm
Variance Ratio for Integer solution	> 1.5 (fixed solution) < 1.5 (float solution) > 1.5 but < 3.0 (flag warning/suspect)
Satellite Residual Plot Deviation NTE	± 15 mm
Repeat baseline agreement	per FGCS standards

10-8. Examples of Baseline Reduction Software Output

The following pages contain example outputs from two processed baselines--one being a medium-length (26 km) ionospheric-free fixed solution and the second being a long (107 km) float solution. These baselines were observed using Ashtech receivers and were processed using Trimble WAVE Version 2.35 software. Explanatory annotations have been added to the first solution, and are similar on the 107 km solution.

IONOSPHERIC FREE FIXED DOUBLE DIFFERENCE BASELINE SOLUTION
MEDIUM LENGTH 26 KM BASELINE LENGTH (San Juan, PR--Puerto Nuevo Flood Control Project--Jacksonville District)
(Trimble Navigation LTD--WAVE 2.35)

Project Name:	[PUERTO NUEVO FLOOD CONTROL]		02097base
Processed:			Thursday, July 11, 2002 12:59
			WAVE 2.35
Solution Output File (SSF):			00038752.SSF

From Station:			COMERIO
Data file:			____1732.RNX
Antenna Height (meters):			2.122 True Vertical
Position Quality:			Point Positioning
WGS 84 Position:	18° 14' 08.746057" N	X	2444052.950
	66° 12' 52.306905" W	Y	-5545217.951
	150.797	Z	1983232.476

FROM Station
RINEX file
Antenna hgt to L1 phase ctr
Lat
Lon
ellip hgt

To Station:			DRYDOCK
Data file:			DRYD1732.RNX
Antenna Height (meters):			1.683 True Vertical
WGS 84 Position:	18° 26' 47.880251" N	X	2452927.215
	66° 05' 28.532019" W	Y	-5533065.770
	-41.244	Z	2005326.605

TO Station
RINEX file
Antenna hgt to L1 phase ctr
Lat
Lon
ellip hgt

Observed 5 hr 45 min @ 15-sec intervals

Start Time:	6/22/02 12:05:30.00 GPS	(1171 561930.00)	
Stop Time:	6/22/02 17:51:15.00 GPS	(1171 582675.00)	
Occupation Time	Meas. Interval (seconds):	05:45:45.00	15.00

Solution Type:	**Iono free fixed double difference**
Solution Acceptability:	Passed ratio test

Solution Type
Passed Variance Ratio Test

Ephemeris:	Broadcast
Met Data:	Standard

Broadcast ephemeris used

Slope distance and standard error

Baseline Slope Distance **Std. Dev.** (meters): **26731.603** **±0.000921**

	Forward	Backward
Normal Section Azimuth:	29° 09' 11.458111"	209° 11' 31.087237"
Vertical Angle:	-0° 31' 55.911654"	0° 17' 27.744089"

Forward & back azimuths & vertical angles

Baseline Components (meters):	dx	8874.265	dy	12152.181	dz	22094.129
Standard Deviations (meters):		±0.003151		±0.006977		±0.002847
	dn	23344.248	de	13021.638	du	-248.296
		±0.000927		±0.000838		±0.008072
	dh	-192.041		±0.008073		

Geocentric (x-y-z) and N-E-Up coordinates and standard errors

Covariance Matrix

$$\begin{vmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{YX} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{ZX} & \sigma_{ZY} & \sigma_Z^2 \end{vmatrix}$$

Aposteriori Covariance Matrix:

9.931756E-006		
-2.104302E-005	4.868030E-005	
8.247290E-006	-1.865503E-005	8.107185E-006

Covariance Matrix: variances & correlations in x-y-z coords

Variance Ratio / Cutoff:	**17.2**	1.5
Reference Variance:	**4.845**	

Variance Ratio >>> than 3.0 ... good
Reference Variance < 5.0 ... OK

IONOSPHERIC FREE FIXED DOUBLE DIFFERENCE BASELINE SOLUTION
MEDIUM LENGTH 26 KM BASELINE LENGTH (Continued)

```
Observable        Count/Rejected      RMS:       Iono free phase
                    6904/10           0.024
```

RMS = 24 mm ... < 30 mm ...OK

```
Processor Controls:

[General]
Process start time:             6/22/02 00:02:00 GPS          (1171 518520)
Process stop time:              6/23/02 00:01:30 GPS          (1172 90)
Elevation mask:                                       15 degrees
Maximum iterations:                                   10
Maximum fixable cycle slip:                           600 seconds
Ephemeris:                                            Broadcast
Residuals:                                            Disabled
Antenna phase correction:                             Enabled

[Observables]
L1 phase                                              Enabled
L2 phase                                              Enabled
Squared L2 phase                                      Enabled
L2 P code                                             Enabled
L1 C/A code                                           Enabled
L2 code (encrypted)                                   Enabled

[Static Network]
Baseline generation:                                  All baselines
Min baseline observation time                         120 seconds

[Quality]
Observation editing:                Edit multiplier                 3.5
Ratio test:                         Cutoff                          1.5
Reference variance test:            Disabled

[Tropo Correction]
Model:                                                Hopfield
Estimated zenith delay interval:                      2 hours
Use observed mets:                                    Enabled

[Iono Correction]                Ambiguity Pass                 Final Pass
Correction:                      Iono free                      Iono free
Applied to:                      Static, Kinematic              Static, Kinematic
Application threshold:           10 kilometers                  5 kilometers

[Final Solution]
Final solution type:             L1 Fixed

[Satellites]
Disabled:
```

IONO FREE FLOAT DOUBLE DIFFERENCE BASELINE SOLUTION
LONG 107 KM BASELINE LENGTH (San Juan, PR--Puerto Nuevo Flood Control Project-Jacksonville District)
(Trimble Navigation LTD--WAVE 2.35)

```
Project Name:                                   02097base
Processed:                                      Thursday, July 11, 2002  12:20
                                                WAVE 2.35
Solution Output File (SSF):                     00038632.SSF

From Station:                                   PUR 3
Data file:                                      PUR3177L.RNX
Antenna Height (meters):                        0.000  True Vertical
Position Quality:                               Point Positioning

WGS 84 Position:      18° 27' 46.670415" N                        X      2358177.597
                      67° 04' 01.076161" W                        Y     -5573621.134
                      90.397                                      Z      2007082.890

To Station:                                     PN 007
Data file:                                      00071771.RNX
Antenna Height (meters):                        2.143  True Vertical

WGS 84 Position:      18° 24' 00.838038" N                        X      2456974.099
                      66° 03' 22.369643" W                        Y     -5533057.526
                      -30.064                                     Z      2000457.530

Start Time:           6/26/02 15:06:40.00 GPS        (1172 313600.00)
Stop Time:            6/26/02 19:01:30.00 GPS        (1172 327690.00)
Occupation Time      Meas. Interval (seconds):        03:54:50.00           30.00

Solution Type:                              Iono free float double difference
Solution Acceptability:                     Acceptable

Ephemeris:                                 Broadcast
Met Data:                                  Standard
Baseline Slope Distance      Std. Dev. (meters):    107004.909      0.005491

                          Forward                        Backward
Normal Section Azimuth:   93° 33' 38.001101"             273° 52' 48.487830"
Vertical Angle:           -0° 32' 41.904306"              -0° 24' 57.517184"

Baseline Components (meters): dx    98796.502    dy   40563.608     dz        -6625.360
Standard Deviations (meters):       0.008147          0.011887                0.005161
                              dn    -6645.072    de  106793.528     du        -1017.770
                                    0.001934          0.005522                0.014145
                              dh     -120.461         0.014166

Aposteriori Covariance Matrix:   6.636701E-005
                                -6.583171E-005     1.413108E-004
                                 2.961492E-005    -5.613399E-005       2.663405E-005

Reference Variance:                                  5.359

Observable      Count/Rejected      RMS:     Iono free phase    2391/0     0.026

Ambiguity Summary (cycles):            SV      Ambiguity                    Error
Iono free                              04      -39932607.484                ± 0.251
                                       04      -41411233.741                ± 0.284
                                       05      -19296720.802                ± 0.357
                                       06      -31002785.279                ± 0.187
```

IONO FREE FLOAT DOUBLE DIFFERENCE BASELINE SOLUTION
LONG 107 KM BASELINE LENGTH (Continued)

```
                                       09      -34051430.580               ± 0.109
                                       10             25.791               ± 0.105
                                       10      -31703542.767               ± 0.157
                                       15      -20292127.579               ± 0.224
                                       17      -28200241.402               ± 0.178
                                       18      -27143528.717               ± 0.333
                                       23      -25788558.784               ± 0.112
                                       24       -9579372.631               ± 0.139
                                       26        -297437.123               ± 0.069
Processor Controls:
[General]
Process start time:                   6/26/02 11:02:00 GPS          (1172 298920)
Process stop time:                    6/26/02 20:59:10 GPS          (1172 334750)
Elevation mask:                       15 degrees
Maximum iterations:                   10
Maximum fixable cycle slip:           600 seconds
Ephemeris:                            Broadcast
Residuals:                            Disabled
Antenna phase correction:             Enabled
[Observables]
L1 phase                              Enabled
L2 phase                              Enabled
Squared L2 phase                      Enabled
L2 P code                             Enabled
L1 C/A code                           Enabled
L2 code (encrypted)                   Enabled
[Static Network]
Baseline generation:                  All baselines
Min baseline observation time         120 seconds
[Quality]
Observation editing:                  Edit multiplier                3.5
Ratio test:                           Cutoff                         1.5
Reference variance test:              Disabled
[Tropo Correction]
Model:                                Hopfield
Estimated zenith delay interval:      2 hours
Use observed mets:                    Enabled
[Iono Correction]                     Ambiguity Pass                Final Pass
Correction:                           Iono free                     Iono free
Applied to:                           Static, Kinematic             Static,
Kinematic
Application threshold:                10 kilometers                 5 kilometers
[Final Solution]
Final solution type:                  L1 Fixed
[Satellites]
Disabled:
```

10-9. Baseline Reduction Summaries

The following list is a typical report of baseline reductions performed over a network. For each baseline, the report lists the solution type, slope distance, reference variance, and ratio (for fixed solutions). Such a report is of value in assessing the overall quality of baselines in a network prior to performing rigorous adjustments. Most of the baselines less than 5 km have fixed solutions. Iono free fixed solutions were obtained in baselines up to and exceeding 100 km, most likely because observation times typically exceeded 6 hours over these lines and the integers were reliably fixed, albeit with smaller ratios. Lines not fixed had float solutions.

Sample Baseline Reduction Project Summary Report (Trimble Navigation LTD)
Puerto Nuevo, San Juan Puerto Rico--July 2002 (RLDA Inc.--Jacksonville District)

Station (From)	(To)	Solution Type	Slope Dist (m)	Ratio	Reference Variance	Entered Ant Hgt (From)	(To)
A 1001	MESAS	Iono free fixed	20841.965	6.6	3.814	1.674	1.559
A 1001	SJH 44	L1 fixed	4426.843	13.3	11.994	2.125	1.714
COMERIO	A 1001	Iono free float	28604.039		3.059	2.122	2.125
COMERIO	DRYDOCK	Iono free fixed	26731.603	17.2	4.845	2.122	1.683
COMERIO	MESAS	Iono free fixed	17436.970	20.4	3.522	2.122	1.504
COMERIO	MP 1	Iono free fixed	26466.871	15.9	3.535	2.122	1.651
COMERIO	SJH 44	Iono free fixed	26791.206	8.0	3.748	2.122	1.714
DRYDOCK	A 1001	L1 fixed	2099.928	3.5	23.933	1.683	2.125
DRYDOCK	SJH 44	L1 fixed	2986.722	4.1	19.858	1.683	1.714
MESAS	A 1001	Iono free fixed	20841.967	1.5	3.761	1.504	2.125
MESAS	DRYDOCK	Iono free fixed	19984.666	16.6	5.558	1.504	1.683
MESAS	SJH 44	Iono free fixed	21973.981	9.3	2.783	1.504	1.714
MP 1	A 1001	L1 fixed	2160.311	4.0	21.693	1.651	2.125
MP 1	PN 007	Iono free fixed	5114.381	19.0	4.801	1.775	2.143
MP 1	PN 030	L1 fixed	4609.931	8.5	27.470	1.775	1.656
MP 1	PUR 3	Iono free fixed	104015.014	2.3	9.541	2.125	0.000
MP 1	RRS 1	L1 fixed	3154.302	50.0	23.107	1.775	0.000
MP 3	TATI	L1 fixed	2605.904	15.4	37.889	1.717	0.000
PN 007	A 1001	Iono free fixed	6568.337	4.3	3.786	2.143	1.674
PN 030	MESAS	Iono free fixed	14465.715	11.5	5.609	1.715	1.559
PN 030	MP 3	L1 fixed	4721.907	30.6	44.769	1.656	1.717
PN 030	PN 007	L1 fixed	2845.129	21.9	34.393	1.656	2.143
PN 030	RRS 1	Iono free fixed	6624.379	14.0	3.073	1.656	0.000
PUR 3	A 1001	Iono free float	104825.284		2.262	0.000	1.674
PUR 3	A 1001	Iono free float	104825.202		2.859	0.000	2.125
PUR 3	COMERIO	Iono free fixed	93542.150	4.3	13.202	0.000	2.122
PUR 3	DRYDOCK	Iono free fixed	103078.898	2.4	19.846	0.000	1.683
PUR 3	MESAS	Iono free fixed	109219.386	3.3	15.726	0.000	1.504
PUR 3	MP 1	Iono free fixed	104015.205	5.4	22.988	0.000	1.651
PUR 3	MP 3	Iono free fixed	105251.631	4.0	10.456	0.000	1.717
PUR 3	PN 007	Iono free float	107004.909		5.359	0.000	2.143
PUR 3	PN 030	Iono free fixed	104207.465	22.5	6.769	0.000	1.715
PUR 3	RRS 1	Iono free fixed	106835.866	7.8	5.010	0.000	0.000
PUR 3	SJH 44	Iono free fixed	100402.386	3.8	10.331	0.000	1.621
PUR 3	SJH 44	Iono free float	100402.461		2.740	0.000	1.714
PUR 3	SJH 44	Iono free fixed	100402.341	3.7	8.679	0.000	1.666
PUR 3	SJHL11RM	Iono free float	101479.646		3.355	0.000	2.125
PUR 3	TATI	Iono free fixed	104537.036	3.8	8.956	0.000	0.000
RRS 1	PN 007	Iono free fixed	5639.477	9.6	4.974	0.000	2.143
SJH 44	A 1001	L1 fixed	4426.901	4.8	12.273	1.621	1.674
SJH 44	MESAS	Iono free fixed	21973.970	8.4	5.657	1.621	1.559
SJH 44	MP 1	L1 fixed	4201.519	2.9	21.210	1.611	2.125

Sample Baseline Reduction Project Summary Report (Trimble Navigation LTD)--Continued
Puerto Nuevo, San Juan Puerto Rico--July 2002 (RLDA Inc.--Jacksonville District)

Station (From)	(To)	Solution Type	Slope Dist (m)	Ratio	Reference Variance	Entered Ant Hgt (From)	(To)
SJH 44	MP 1	L1 fixed	4201.586	38.9	25.690	1.666	1.775
SJH 44	MP 3	Iono free fixed	5319.058	27.9	5.499	1.666	1.717
SJH 44	PN 007	Iono free fixed	9092.812	1.7	5.592	1.621	2.143
SJH 44	PN 030	Iono free fixed	7680.376	20.4	6.122	1.666	1.656
SJH 44	PUR 3	Iono free fixed	100402.358	8.0	6.727	1.611	0.000
SJH 44	RRS 1	Iono free fixed	6481.387	61.2	4.617	1.666	0.000
SJH 44	SJHL11RM	L1 fixed	3556.239	2.1	11.339	1.621	2.125
SJH 44	TATI	Iono free fixed	6204.031	8.0	5.361	1.666	0.000
SJHL11RM	A 1001	L1 fixed	4682.576	10.0	7.149	2.125	1.674
SJHL11RM	MESAS	Iono free float	18419.372		5.138	2.125	1.559
SJHL11RM	PN 007	Iono free fixed	6188.465	1.8	4.479	2.125	2.143
SJHL11RM	PN 030	L1 fixed	4247.108	1.6	31.691	2.125	1.715
TATI	PN 007	L1 fixed	2943.738	15.0	29.619	0.000	2.143
TATI	RRS 1	L1 fixed	4586.193	17.5	36.664	0.000	0.000

**** End of Report *****

Other useful baseline reduction summaries include satellite tracking summaries depicting signal losses, cycle slips, or residual plots for each satellite observed. These plots may be used to decide whether poor satellites should be removed from the reduction. In addition, graphical summary plots are much easier to review than pages of statistical text. A unique type of graphical baseline quality plot is shown in the following figure from Waypoint Consulting, Inc. In this plot, a quality number (from one to six) is computed using seven different baseline reduction statistics. A "good" quality value of "1" would represent a fixed integer solution, while values of 5-6 indicate worse DGPS accuracies. Each epoch is plotted with a certain color depending on its quality number, which allows for a quick visual inspection. Waypoint GrafNAV baseline reduction software contains options for 26 different types of graphical plots for use in assessing baseline quality. These include plots such as DOPs, L1 phase RMS, C/A-code RMS, forward/reverse separation, quality number, standard deviation, L1 Doppler RMS, ambiguity drift (i.e. solution stability), forward/reverse weighting, and satellite elevation and loss of lock plots for each satellite being tracked. Other commercial baseline reduction software provides options for similar graphical assessment features.

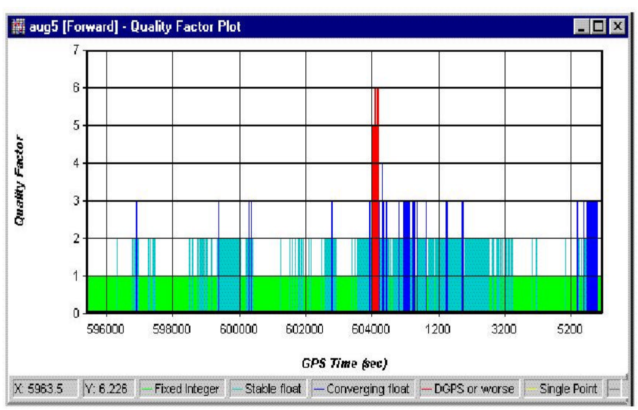

Figure 10-5. Typical quality factor plot for a baseline (Waypoint Consulting, Inc. GrafNAV)

10-10. Baseline Reduction in Mapping Grade GPS Receivers

Small hand-held, mapping grade GPS receivers are easy and efficient to operate, with minimal training. They are capable of achieving decimeter-level accuracy when paired and post-processed with a nearby CORS base station receiver. The software for performing the baseline reduction and position computation is fairly simple to operate. The following listing is an example of GPS positions logged by a hand-held Trimble GeoExplorer on points that potentially impact maintenance dredging limits. The resultant accuracy of the points is about 2 feet (95% RMS), which is more than adequate for defining dredging limits. The baseline reduction was performed using a nearby CORS reference station in Miami, FL.

LOCATIONS OF DOCKS AND BULKHEADS ALONG THE MIAMI RIVER
Sample results from post-processed differential carrier observations using nearest CORS station in Miami, FL.
GeoExplorer carrier phase differential data--5-sec update rate. All Float solutions

Point	Ref No.	Point Description	FL SP Coordinate X	FL SP Coordinate Y	Obs	95% Precision * Y	X	X-Y	Z
38-1	38	Concrete Bulkhead, in line with East edge of Building	920,742.89	522,331.98	720	0.6 ft	0.6 ft	0.8 ft	0.9 ft
38-2	38	Concrete Bulkhead, in line with West edge of Building	920,696.28	522,324.20	120	1.0 ft	1.0 ft	1.3 ft	1.6 ft
94-3	94	Northeast corner of concrete pier @ La Coloma Marina	918,350.11	525,035.11	723	0.5 ft	0.5 ft	0.7 ft	0.8 ft
94-4	94	Northwest corner of concrete pier @ La Coloma Marina	918,343.00	525,039.66	101	1.2 ft	1.2 ft	1.6 ft	2.7 ft
110-5	110	Point on corrugated steel bulkhead	917,156.88	525,821.07	676	0.9 ft	0.9 ft	1.1 ft	1.6 ft
116-6	116	Northeast corner of wooden pier @ Langer-Krell Marine Electronics	916,946.64	525,963.01	724	0.5 ft	0.5 ft	0.6 ft	0.7 ft
46-7	46	Northeast corner of wooden pier	919,868.69	522,728.61	794	0.5 ft	0.5 ft	0.7 ft	1.4 ft
46-8	46	Point on concrete bulkhead	919,736.36	522,881.29	200	1.8 ft	1.8 ft	2.3 ft	6.8 ft **
177-9	177	Southwest corner of finger pier @ Hurricane Cove Marina	910,470.96	528,929.65	724	0.6 ft	0.6 ft	0.8 ft	0.8 ft
177-10	177	Southwest corner of finger pier @ Hurricane Cove Marina	910,574.96	528,899.27	181	0.9 ft	0.9 ft	1.2 ft	2.7 ft
177-11	177	Southwest corner of finger pier @ Hurricane Cove Marina	910,692.35	528,851.62	168	1.2 ft	1.2 ft	1.5 ft	3.8 ft

* computed by Trimble Pathfinder Office software
** apparent multipath problem at this point

10-11. Field/Office Loop Closure Checks

Post-processing criteria are aimed at an evaluation of a single baseline. In order to verify the adequacy of a group of connected baselines, one must perform a loop closure computation on the formulated baselines. When GPS baseline traverses or loops are formed, their linear (internal) closure should be determined in the field. If job requirements are less than Third-Order (1:10,000 or 1:5,000), and the internal loop/traverse closures are very small, a formal (external) adjustment may not be warranted.

a. Loop closure software packages. The internal closure determines the consistency of the GPS measurements. Internal closures are applicable for loop traverses and GPS networks. It is required that one baseline in the loop be independent. An independent baseline is observed during a different session or different day. Today, most post-processing software packages come with a loop closure program, such as the example in Figure 10-6. These loop closure routines allow for a graphical selection of baselines in a network from which a loop closure is automatically computed in real-time. Refer to the individual manufacturer post-processing user manuals for a discussion on the particulars of the loop closure program included with the user hardware.

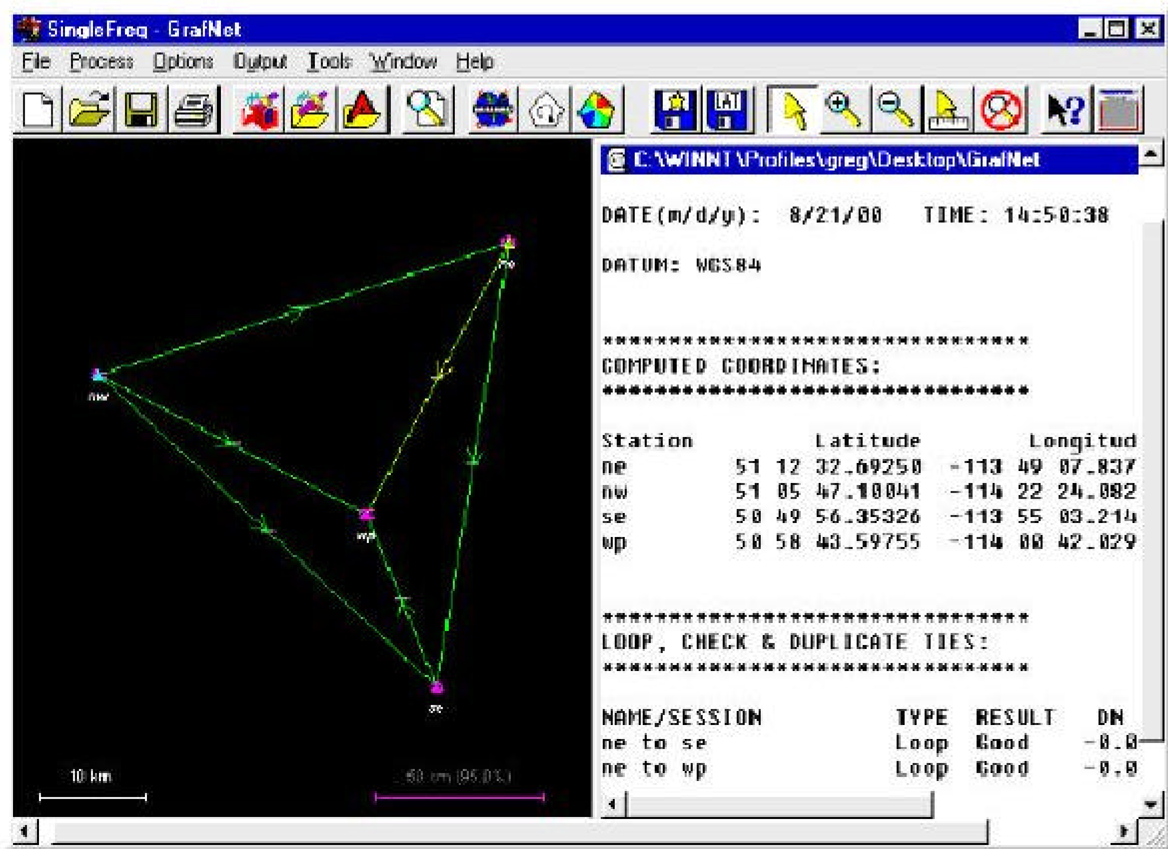

Figure 10-6. Loop closure diagram (Waypoint GrafNet)

b. General loop closure procedure. If the user post-processing software package does not contain a loop closure program, the user can perform a loop closure as shown below.

(1) List the Δx-Δy-Δz differences and length of the baseline being used in a table of the form shown in Table 10-4.

Table 10-4. Loop Closure Procedure

Baseline	Julian Day	Session	Δx	Δy	Δz	ΔDistance
Baseline #1	Day	#	Δx #1	Δy #1	Δz #1	Distance #1
Baseline #2	Day	#	Δx #2	Δy #2	Δz #2	Distance #2
Baseline #3	Day	#	Δx #3	Δy #3	Δz #3	Distance #3

(2) Sum up the Δx -Δy- Δz differences and distance components for all baselines used in the loop closure. For instance, for the baselines in Table 10-4, the summation would be ΣΔx, ΣΔy, ΣΔz, and ΣDistances or (Δx#1 + Δx#2 + Δx#3), (Δy#1 + Δy#2 + Δy#3), (Δz#1 + Δz#2 + Δz#3), and (ΔDistance#1 + ΔDistance#2 + ΔDistance#3), respectively.

(3) Once summation of the Δx, Δy, Δz, and ΔDistance components has been completed, the square of each of the summations should be added together and the square root of this sum then taken. This resultant value is the misclosure vector for the loop. This relationship can be expressed in the following manner:

$$m = [(\Sigma\Delta x^2) + (\Sigma\Delta y^2) + (\Sigma\Delta z^2)]^{1/2} \qquad \text{(Eq 10-7)}$$

where

m = misclosure for the loop
ΣΔx = sum of all Δx vectors for baselines used
ΣΔy = sum of all Δy vectors for baselines used
ΣΔz = sum of all Δz vectors for baselines used

(4) The loop misclosure ratio may be calculated as follows:

$$\text{Loop misclosure ratio} = m/L \qquad \text{(Eq 10-8)}$$

where
L = total loop distance (perimeter distance)

(5) The resultant value can be expressed in the following form:

1: Loop Misclosure Ratio

with all units for the expressions being in terms of the units used in the baseline formulations (e.g., m, ft, mm, etc.).

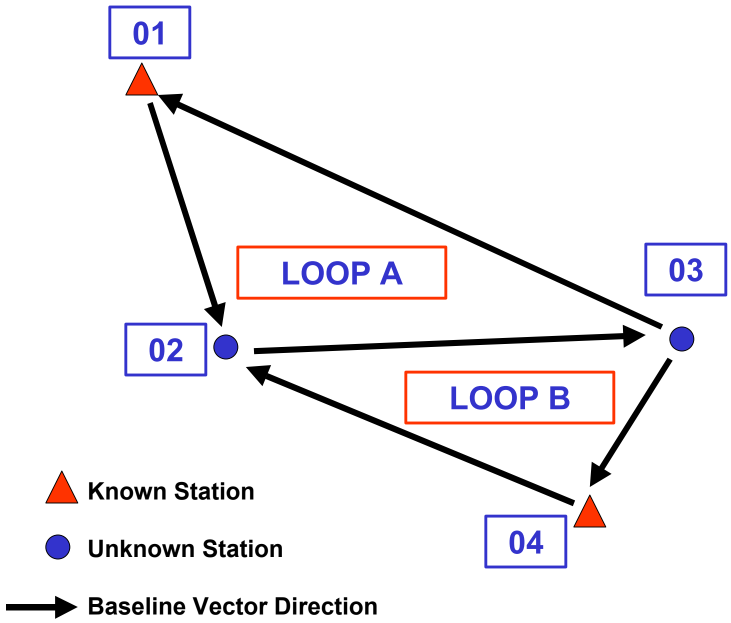

Figure 10-7. Internal loop closure scheme

c. Sample loop closure computation. Figure 10-7 shows two loops that consist of four stations. Stations 01 and 04 were known control stations. During Session A on day 065, three GPS receivers observed the baselines between Stations 01, 02, and 03 for approximately 1 hour. The receivers were then turned off and the receiver at Station 01 was moved to Station 04. The tripod heights at Stations 02 and 03 were adjusted. The baselines between Stations 02, 03, and 04 were then observed during Session B, day 065. This provided an independent baseline for both loops.

(1) The closure for loop 01-02-03 is computed with the vectors 01-02 and 01-03, day 065, session A, and the vector 02-03, day 065, session B. The vector 02-03 from session B provides an independent baseline. The loop closure is determined by arbitrarily assigning coordinate values of zero to station 01 (X=0, Y=0, Z=0). The vector from 01-02 is added to the coordinates of Station 01. The vector from 02-03, session B, is added to the derived coordinates of Station 02. The vector from 03-01 is then added to the station coordinates of 02. Since the starting coordinates of Station 01 were arbitrarily chosen as zero, the misclosure is then the computed coordinates of Station 01 (dx, dy, dz). The vector data are listed in Table 10-5.

Table 10-5. Vector Data for Stations 01, 02, and 03

Baseline	Julian Day	Session	ΔX	ΔY	ΔZ	ΔDistance
01-02	065	A	-4077.865	-2877.121	-6919.829	8531.759
02-03	065	B	7855.762	-3129.673	688.280	8484.196
03-01	065	A	-3777.910	6006.820	6231.547	9443.869

(2) To determine the relative loop closure, the square root of the sum of the squares of the loop misclosures (mx, my, mz) is divided into the perimeter length of the loop:

$$\text{Loop misclosure ratio} = [\,1 / L\,] \cdot [\,(\Delta x^2) + (\Delta y^2) + (\Delta z^2)\,]^{½} \qquad \text{(Eq 10-9)}$$

Where the perimeter distance (L) = Distance 01-02 + Distance 02-03 + Distance 03-01, or:

$$L = 8531.759 + 8484.196 + 9443.869 = 26{,}459.82$$

And where distance 03-01 was computed from:

$$(-3777.912^2 + 6006.8202^2 + 6231.5472^2)^{1/2} = 9443.869$$

(Other distances are similarly computed)

Summing the misclosures in each coordinate:

$$\Delta x = -4077.865 + 7855.762 - 3777.910 = -0.0135$$
$$\Delta y = -2877.121 - 3129.673 + 6006.820 = +0.0264$$
$$\Delta z = -6919.829 + 688.280 + 6231.547 = -0.0021$$

then the loop misclosure is

$$(\Delta x^2 + \Delta y^2 + \Delta z^2)^{1/2} = 0.029$$

Loop Misclosure Ratio = 0.029/26,459.82 or (approximately) 1 part in 912,000 (1:912,000)

(3) This example is quite simplified; however, it illustrates the necessary mechanics in determining internal loop closures. The values Δx , Δy, and Δz are present in the baseline output files. The perimeter distance is computed by adding the distances between each point in the loop.

d. External closures. External closures are computed in a similar manner to internal loops. External closures provide information on how well the GPS measurements conform to the local coordinate system. Before the closure of each traverse is computed, the latitude, longitude, and ellipsoid height must be converted to geocentric coordinates (X,Y,Z). If the ellipsoid height is not known, geoid modeling software can be used with the orthometric height to get an approximate ellipsoid height. The external closure will aid the surveyor in determining the quality of the known control and how well the GPS measurements conform to the local network. If the control stations are not of equal precision, the external closures will usually reflect the lower-order station. If the internal closure meets the requirements of the job, but the external closure is poor, the surveyor should suspect that the known control is deficient and an additional known control point should be tied into the system.

10-12. On-Line Positioning User Service (OPUS)

OPUS is a free on-line baseline reduction and position adjustment service provided by the National Geodetic Survey. OPUS provides an X-Y-Z baseline reduction and position adjustment relative to three nearby national CORS reference stations. OPUS is ideal for establishing accurate horizontal control relative to the NGRS. It can also be used as a quality control check on previously established control points. OPUS input is performed "on-line" by entering at least two hours of static, dual-frequency GPS

RINEX data--see Figure 10-8. The resultant adjustment is returned in minutes via e-mail. Either the ultra-rapid or precise ephemeris is used for the solution.

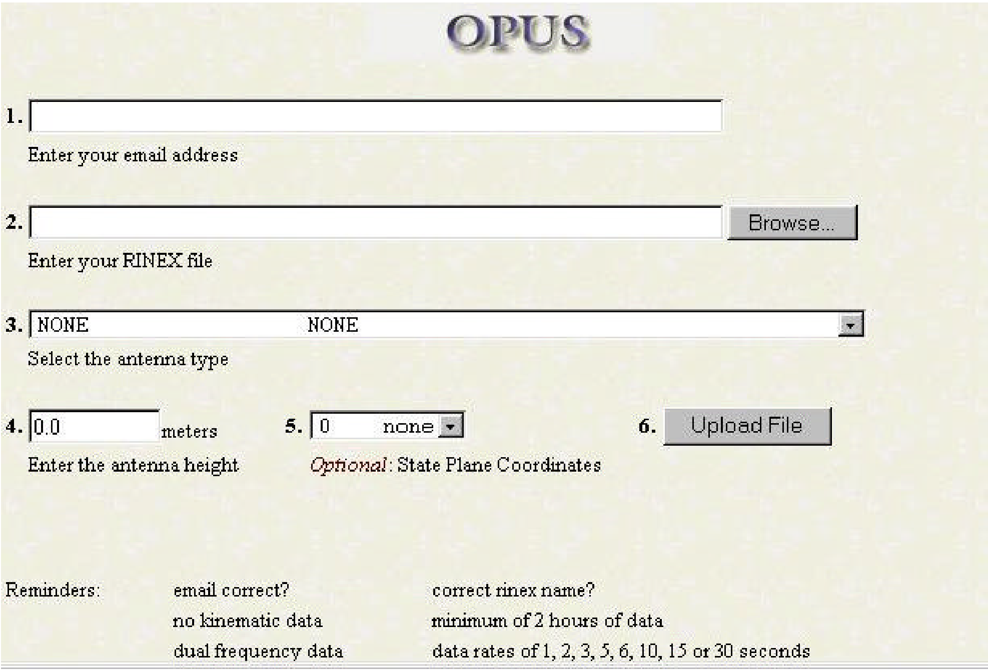

Figure 10-8. On-Line Positioning User Service (OPUS) Web input screen

a. On-line data input. OPUS is accessed at the following web page address: www.ngs.noaa.gov/OPUS. The various data on the screen in Figure 10-8 are entered, e.g., e-mail address, RINEX file path, antenna height, and local SPCS code. The antenna height in meters is the vertical (not slope) distance measured between the monument/benchmark and the antenna reference point (ARP). The ARP is almost always the center of the bottom-most, permanently attached, surface of the antenna. If 0.0000 meters is entered for the height, OPUS will return the position of the ARP. The type of antenna is selected from the drop down menu.

b. Solution. OPUS computes an average solution from the three baselines. NGS baseline reduction software is used for the solutions. Output positions are provided in both ITRF and NAD 83. An overall RMS (95%) confidence for the solution is provided, along with maximum coordinate spreads between the three CORS stations for both the ITRF and NAD 83 positions. An orthometric elevation on NAVD 88 is provided using the Geoid 99 model. The orthometric accuracy shown is a function of the spread between the three redundant baseline solutions.

c. Sample adjustment. The following example was performed to locate a permanently mounted GPS antenna that is used for real-time kinematic hydrographic surveys and dredging on the St. Marys River offshore entrance channel leading to the Kings Bay FBM Submarine Base. This antenna point was originally positioned in 1997 relative to local NGRS/HARN control. The NAVD 88 elevation was established in 1997 using conventional differential levels. Five hours of dual-frequency data were recorded in May 2002 and processed in OPUS against three distant CORS points in Charleston, SC, Cape

Canaveral, FL, and Savannah, GA. The solution was performed using both the Rapid Ephemeris and Precise Ephemeris.

OPUS Solution: Kings Bay FBM Submarine Base Entrance Channel
Fernandina Pier Bath House RTK GPS Antenna

FILE: 58421440.02o
2004 WARNING! The IGS precise orbit was not available at processing ***[Rapid orbit will be used]***
2004 time. The IGS rapid orbit was/will be used to process the data.
2004
1008 WARNING! Antenna offsets supplied by the user in the RINEX ***[permanent RTK antenna mounted on mast above Bath House]***
1008 header or via the web were zero. Coordinates returned will
1008 be for the antenna reference point (ARP). Please refer to
1008 the following web address for an example.
1008 http://www.ngs.noaa.gov/CORS/OPUS/Preprinfile.html

NGS OPUS SOLUTION REPORT (RAPID EPHEMERIS)

USER: francis.m.woodward\@saj02.usace.a	DATE: May 28, 2002	
RINEX FILE: 58421440.02o	TIME: 18:10:55 UTC	
SOFTWARE: page5 0203.19	START: 2002/05/24 13:05:00	
EPHEMERIS: igr11675.eph [rapid]	STOP: 2002/05/24 18:05:00	***[5 hours of observation]***
NAV FILE: brdc1440.02n	OBS USED: 8259 / 9034 : 91%	
ANT NAME: TRM22020.00+GP	# FIXED AMB: 63 / 71 : 89%	
ARP HEIGHT: 0.0	OVERALL RMS: 0.021(m)	***[overall solution RMS 95%]***

[Adjusted positions ... note that accuracy estimates are based on maximum spread between 3 solutions]

REF FRAME:	NAD83(CORS96)(EPOCH:2002.0000)	*[spread]*	ITRF00 (EPOCH:2002.3936)	*[spread]*
X:	818024.398(m)	0.014(m)	818023.781(m)	0.014(m)
Y:	-5427733.157(m)	0.055(m)	-5427731.620(m)	0.057(m)
Z:	3237328.073(m)	0.033(m)	3237327.879(m)	0.034(m)
LAT:	30 41 59.95964	0.003(m)	30 41 59.98095	0.003(m)
E LON:	278 34 14.36555	0.011(m)	278 34 14.35123	0.012(m)
W LON:	81 25 45.63445	0.011(m)	81 25 45.64877	0.012(m)
EL HGT:	-20.012(m)	0.065(m)	-21.497(m)	0.067(m)
ORTHO HGT	8.591(m)	0.069(m) [Geoid99 NAVD88]		

UTM:	Zone 17
NORTHING:	3396432.577(m)
EASTING:	458884.381(m)
SPC:	Zone 1001(GA)
NORTHING:	77823.887(m)
EASTING:	270630.929(m)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
AH6078	sav1 SAVANNAH 1 CORS ARP	N320818	W0814146	161511
AH2496	ccv3 CAPE CANAVERAL 3 CORS ARP	N282736	W0803242	262608
AF9630	cha2 CHARLESTON 2 CORS ARP	N324526	W0795035	273177

NEAREST NGS PUBLISHED CONTROL POINT

BC1755	FERNA RESET	N304207	W0812602	487

This position was computed without any knowledge by the National Geodetic Survey regarding the equipment or field operating procedures used.

OPUS Solution: Kings Bay FBM Submarine Base Entrance Channel (Continued)

RECOMPUTING WITH PRECISE EPHEMERIS:

SOFTWARE: page5 0203.19	START: 2002/05/24 13:05:00
EPHEMERIS: igs11675.eph [precise]	STOP: 2002/05/24 18:05:00
NAV FILE: brdc1440.02n	OBS USED: 8259 / 9034 : 91%
ANT NAME: TRM22020.00+GP	# FIXED AMB: 63 / 71 : 89%
ARP HEIGHT: 0.0	OVERALL RMS: 0.021(m)

REF FRAME:	NAD83(CORS96)(EPOCH:2002.0000)		ITRF00 (EPOCH:2002.3936)	
X:	818024.399(m)	0.013(m)	818023.781(m)	0.013(m)
Y:	-5427733.166(m)	0.060(m)	-5427731.630(m)	0.062(m)
Z:	3237328.081(m)	0.039(m)	3237327.888(m)	0.041(m)
LAT:	30 41 59.95972	0.004(m)	30 41 59.98104	0.005(m)
E LON:	278 34 14.36552	0.014(m)	278 34 14.35117	0.016(m)
W LON:	81 25 45.63448	0.014(m)	81 25 45.64883	0.016(m)
EL HGT:	-20.000(m)	0.070(m)	-21.484(m)	0.073(m)
ORTHO HGT:	8.603(m)	0.075(m) [Geoid99 NAVD88]		

SUMMARY OF SOLUTION RESULTS

	1997 POSITION	OPUS (RAPID)	Diff	OPUS (PRECISE)	Diff
Lat:	30-41-59.9588	30-41-59.95964	2 cm	30-41-59.95972	3 cm
Lon:	81-25-45.6344	81-25-45.63445	0 cm	81-25-45.63448	0 cm
Ellip Hgt:	-20.015 m	-20.012 m	3 mm	-20.000 m	15 mm

The above example illustrates the reliability of an OPUS solution in the horizontal plane. The position difference between the old 1997 position and the 2002 OPUS/CORS solution is at the few centimeter-level and is therefore insignificant for the purposes of the project control function. Although the ellipsoid elevation agreed to within a few millimeters, this OPUS solution should not be relied on given the large estimated variances between the baselines. This large variance illustrates that vertical control cannot be reliably extended over baselines of this length. It is also apparent in this example that the differences between the rapid ephemeris and precise ephemeris were not significant for this observation series. The following OPUS solution illustrates a case where two nearby CORS stations were used in the solution. Horizontal accuracies using the ultra-rapid orbit were at the centimeter level.

OPUS Solution using two nearby CORS stations--New Orleans District

Huber, Mark W MVN

From: opus@ngs.noaa.gov
Sent: Thursday, March 28, 2002 2:17 PM
To: Huber, Mark W
Subject: OPUS solution : lms60871.02o

```
 FILE: lms60871.02o

 2005   WARNING!  The IGS precise and IGS rapid orbits were not available
 2005   at processing time.  The IGS ultra-rapid orbit was/will be used to
 2005   process the data.
 2005
                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: mark.w.huber\@mvn02.usace.army.mi       DATE: March 28, 2002
RINEX FILE: lms60871.02o                            TIME: 20:16:31 UTC


  SOFTWARE: page5  0102.26                         START: 2002/03/28  15:10:00
 EPHEMERIS: igu11594.eph [ultra-rapid]              STOP: 2002/03/28  18:33:00
  NAV FILE: brdc0870.02n                        OBS USED:  3904 /  3998   :  98%
  ANT NAME: TRM22020.00+GP                     # FIXED AMB:    31 /    34   :  91%
ARP HEIGHT: 1.5895                             OVERALL RMS: 0.018(m)


 REF FRAME:        NAD83(CORS96)                        ITRF00 (EPOCH:2002.2375)

         X:       -13017.957(m)   0.006(m)           -13018.572(m)   0.002(m)
         Y:     -5531626.227(m)   0.015(m)         -5531624.732(m)   0.007(m)
         Z:      3164465.455(m)   0.011(m)          3164465.266(m)   0.007(m)

       LAT:   29 56 18.86623      0.003(m)       29 56 18.88512      0.008(m)
     E LON:  269 51 54.58370      0.006(m)      269 51 54.56066      0.002(m)
     W LON:   90  8  5.41630      0.006(m)       90  8  5.43934      0.002(m)
    EL HGT:          -19.076(m)   0.018(m)              -20.464(m)   0.008(m)
 ORTHO HGT:            7.041(m)   0.031(m) [Geoid99 NAVD88]

       UTM:          Zone  15
  NORTHING:      3315431.810(m)
   EASTING:        776566.549(m)

       SPC:      Zone  1702(LA)
  NORTHING:       160062.781(m)
   EASTING:      1115698.887(m)

                              BASE STATIONS USED
PID       DESIGNATION                       LATITUDE LONGITUDE   DISTANCE(m)
AF9544 eng1 ENGLISH TURN 1 CORS ARP          N295244 W0895630       19786
AF9574 ndbc STENNIS CORS ARP                 N302122 W0893636       68543
AF9559 mob1 MOBILE POINT 1 CORS ARP          N301339 W0880126      205980

                 NEAREST NGS PUBLISHED CONTROL POINT
AU0558      50+38.40 USE                     N295618 W0900805          29

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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10-13. Scripps Coordinate Update Tool (SCOUT)

SCOUT is another free differential GPS baseline processing service that operates similarly to OPUS. The major difference is that SCOUT uses nearby International GPS Service (IGS) stations, which are more densely spaced than CORS. A RINEX file is uploaded for adjustment using an ftp access point--see the SCOUT input box in Figure 10-9. A minimum observation time of one hour is recommended. SCOUT is operated by the Scripps Orbit and Permanent Array Center (SOPAC) at the Scripps Institution of Oceanography, University of California, San Diego, in La Jolla, California. SOPAC's primary scientific role is to support high precision geodetic and geophysical measurements using GPS satellites, particularly for the study of earthquake hazards, tectonic plate motion, plate boundary deformation, and meteorological processes. SOPAC investigators also conduct research on the implementation, operation and scientific applications of continuously monitoring GPS arrays and Synthetic Aperture Radar (SAR) interferometry. SOPAC is a major participant in projects for the International GPS Service for Geodynamics (IGS), the Southern California Integrated GPS Network (SCIGN), the University NAVSTAR Consortium (UNAVCO), NOAA's Forecast Systems Laboratory (FSL), and the California Spatial Reference Center (CSRC).

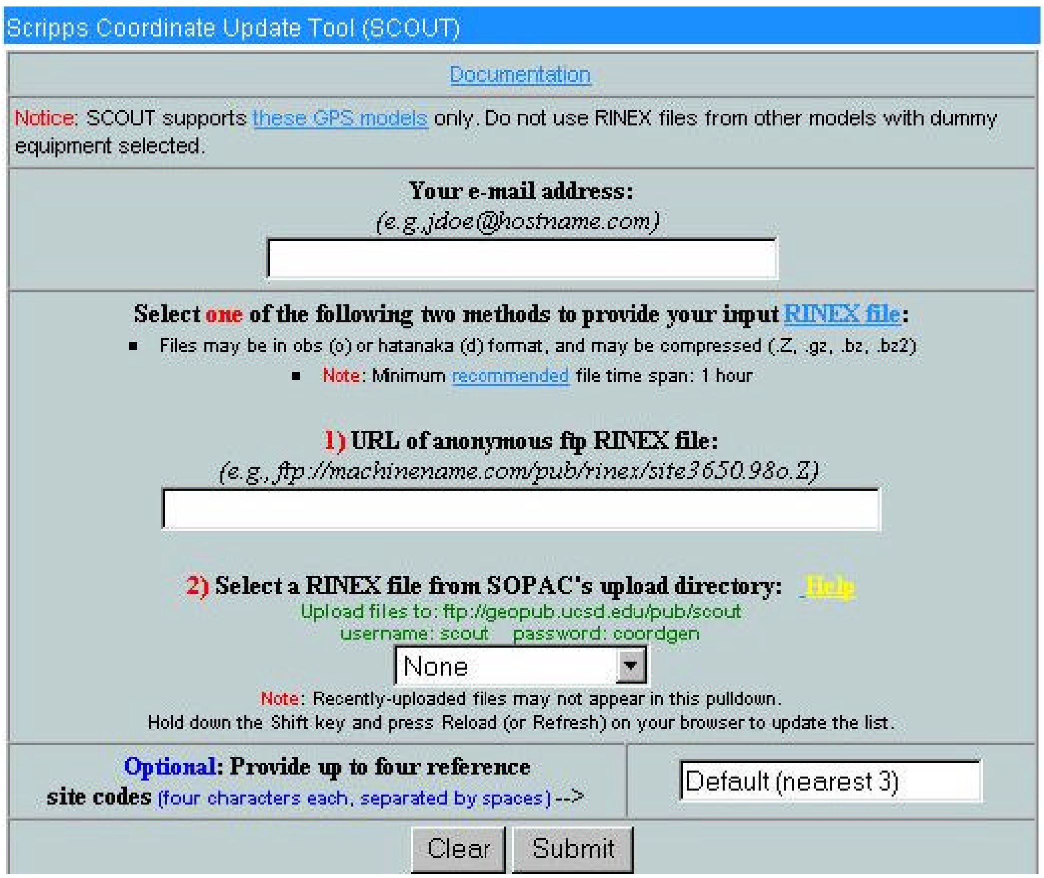

Figure 10-9. Scripps Coordinate Update Tool (SCOUT) Web input screen

10-14. Automated GIPSY Analyses (Jet Propulsion Laboratory)

GIPSY is a free point processing service which performs a single point solution. Its e-mail/fts interface is known as auto-GIPSY or "ag." It does a basic analysis of GPS data in a RINEX file. All the processing occurs on a computer at JPL using final orbital data. E-mail is used to inform "ag" about the location of user data. E-mail is then sent from "ag" to inform the user about the location of the results. Anonymous ftp is used by "ag" to retrieve the results. Users need to place their RINEX observation file--preferably compressed--in an area that is accessible by anonymous ftp. Its name should conform to the RINEX standard. Point solutions should be returned in a few minutes. JPL claims accuracies of a few mm in horizontal components and about a cm in the vertical for data from a stationary site with a geodetic-quality receiver. GIPSY does not make corrections for antenna heights.

10-15. Baseline Data Management and Archival

The raw data are defined as data recorded during the observation period. Raw data shall be stored on an appropriate medium (CD-ROM, portable hard drive, magnetic tape, etc.). The raw data and the hard copy of the baseline reduction (resultant baseline formulations) shall be stored at the discretion of each USACE Command. See also data archiving requirements covered in Chapter 11.