Baltimore County, Maryland, NAVD 88 GPS-derived Orthometric Height Project

William E. Henning, Edward E. Carlson, and David B. Zilkoski

ABSTRACT. During the past decade, global positioning system (GPS) survey data have been used to establish precise relative positioning in a three-dimensional system. GPS survey methods can and have been used to replace classical horizontal control terrestrial survey methods. However, it was only during the last few years that these techniques have been applied to classical leveling (vertical control) applications. GPS-derived orthometric heights were computed for 18 monuments of the Baltimore County, Maryland, geodetic control network following the NGS guidelines. Comparisons were made between six second-order leveling-derived NAVD 88 stations and GPS-derived orthometric heights computed using adjusted ellipsoid heights and a high-resolution geoid model. The precision of the GPS-derived ellipsoid heights was better than 2 cm and the GPS-derived orthometric heights agreed with published NAVD 88 values to within 2 cm.

Introduction

Since early 1983, the National Geodetic Survey (NGS) has performed control survey projects in the United States using the global positioning system (GPS). Analysis of GPS survey data has shown that GPS can be used to establish precise relative positions in a three-dimensional Earth-centered coordinate system. GPS carrier phase measurements are used to determine vector baselines in space where the components of the baseline are expressed in terms of Cartesian coordinate differences (Remondi 1984). These vector baselines can be converted to latitude, longitude, and ellipsoid height differences relative to a defined reference ellipsoid. As a result of analyses performed at the National Geodetic Survey (NGS) in computing ellipsoid heights, NGS, working with users, developed Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm). Following NGS guidelines for estimating GPS-derived ellipsoid heights, properly connecting to benchmarks with North American Vertical Datum of 1988 (NAVD 88) heights, and using the latest National high-resolution geoid model, GEOID96, can result in GPS-derived orthometric heights that meet a wide range of engineering requirements for vertical control.

Orthometric height differences (dH) can be obtained from the ellipsoid height differences (dh) by subtracting the geoid height differences (dN):

$$dH = dh - dN \tag{1}$$

While this is an approximate equation, the error is always small and can be considered insignificant.

During the past decade, results from projects have clearly shown that GPS survey methods can replace classical horizontal control terrestrial survey methods. However, until about 3 years ago, there was a problem in obtaining sufficiently accurate geoid height differences to convert GPS-derived ellipsoid height differences to accurate GPS-derived orthometric height differences (Zilkoski and Hothem 1989; Hajela 1990; Milbert 1991). Interest in obtaining accurate GPS-derived orthometric heights has increased during the last several years (Parks and Milbert 1995; Kuang et al. 1996; Satalich 1996; Zilkoski and D'Onofrio 1996).

Can the accuracies achieved for these orthometric height differences provide a viable alternative to classical geodetic leveling techniques? The answer is yes. With the completion of the general adjustment of the North American Vertical Datum of 1988 (NAVD 88) (Zilkoski et al. 1992), computation of an accurate national high-resolution geoid model (GEOID93, and, subsequently, GEOID96) (Smith and Milbert 1997), and the development of NGS Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm) (Zilkoski et al. 1997), GPS-derived orthometric heights can provide

William Henning is Survey Supervisor and Geodetic Project Manager, Baltimore County Bureau of Engineering, 111 W. Chesapeake Avenue, Towson, MD 21204. Phone: (410) 887-3540. **Edward Carlson** and **David Zilkoski** work as geodesists at the National Geodetic Survey, 1315 East-West Highway, Silver Spring, MD 20910.

Surveying and Land Information Systems, Vol. 58, No. 2, 1998, pp. 97-113

a viable alternative to classical geodetic leveling techniques for many applications.

Heights and Height Differences

Orthometric heights (*H*) are referenced to an equipotential reference surface, e.g., the geoid. The orthometric height of a point on the Earth's surface is the distance from the geoidal reference surface to the point, measured along the plumb line normal to the geoid. Ellipsoid heights (*h*) are referenced to a reference ellipsoid. The ellipsoid height of a point is the distance from the reference ellipsoid to the point, measured along the line which is normal to the ellipsoid for application purposes. The difference between an ellipsoid height and an orthometric height is defined as the geoid height (*N*).

Several error sources that affect the accuracy of orthometric, ellipsoid, and geoid height values are generally common to nearby points. Because these error sources are common, the uncertainty of height differences between nearby points is significantly smaller than the uncertainty of the absolute heights of each point.

Adhering to the NGS guidelines, ellipsoid height differences (*dh*) over short baselines (i.e., less than 10 km) can now be determined from GPS phase measurements with 2-sigma uncertainties that are typically +/- 2 cm. This is now possible because of the availability of a greater number of satellites, more accurate satellite orbits, full-wavelength dual-frequency carrier phase data, improved antenna designs, and improved data processing techniques.

Geoid height differences in the United States can be determined from gravity data and Stokes' integral method, with uncertainties that are typically less than 1 cm for distances of as much as 20 km and less than 2-3 cm for distances from 20 to 50 km. The small values for the differential geoid height uncertainties have been demonstrated in tests in several regions of the United States. Larger uncertainties can be expected in other areas, depending on the density of the gravity network and uncertainties in the determination of observed and interpolated gravity anomalies.

When high-accuracy field procedures are used, orthometric height differences can be computed from measurements of precise geodetic leveling with an uncertainty of less than 1 cm over a 50-kilometer distance. Less accurate results are achieved when third-order leveling methods are employed. Depending on the accuracy requirements, GPS surveys and high-resolution geoid models can be employed as alternatives to classical leveling methods. In the past, the primary limiting factor was the accuracy of estimating geoid height differences. With the computation of the latest national high-resolution geoid model, GEOID96, the limiting factors are estimating accurate GPS-derived ellipsoid heights and ensuring that the project's NAVD 88 orthometric height values are valid.

Project Area and Goals

Baltimore County is an extremely diverse municipality—geographically, demographically, and in its land use. Wrapping around the city of Baltimore, it rises from the tidelands of the Chesapeake Bay on the east and rolls through the valleys and hills of central Maryland until it reaches the hills of Pennsylvania's southern border on the Mason-Dixon line at an elevation of 966 feet (294.5 m) at its highest point. It lies east of the Appalachian Mountains which, along with the Bay to the east, helps to moderate the climate. The summers tend to be hot and humid, while the winters average about 22 inches of snow, with a freeze period from late October to mid-April. Total annual precipitation averages 42 inches. Area estimates of the county vary somewhat because of the extensive shoreline on its east. A state source lists the county as having 610 square miles, with 173 miles of Chesapeake Bay shoreline. The urban and suburban areas are in a band encircling Baltimore City and cover roughly two-thirds of the county, with the remaining northern third being primarily agricultural.

The county is constructing a new geodetic control system across this diverse area as part of the implementation of a new, high-quality geographic information system (GIS). Two-thirds of the county have been monumented at a typical spacing of 6 km and flown. State-of-the-art photogrammetric techniques employing GPS-controlled aerial triangulation techniques have been used under the local guidance of Mr. Yogendra Singh, consultant, with the data reduction and quality checking performed by the INPHO Group, West Germany, under Dr. Frederick Ackermann. The techniques employed have been described in a paper by Singh and Ackermann (1995).

The work to date has involved two phases in two consecutive years. In constructing the new geodetic control system, the county was separated into three phases. Figure 1 depicts the boundaries of the phases. Phase 1 photogrammetry (125 square miles) and a skeleton geodetic control network for horizontal control were completed in 1995, with McCrone, Inc., a local engineering and surveying firm, performing all GPS work and classical leveling observations for vertical control. Phase 2 photogrammetry

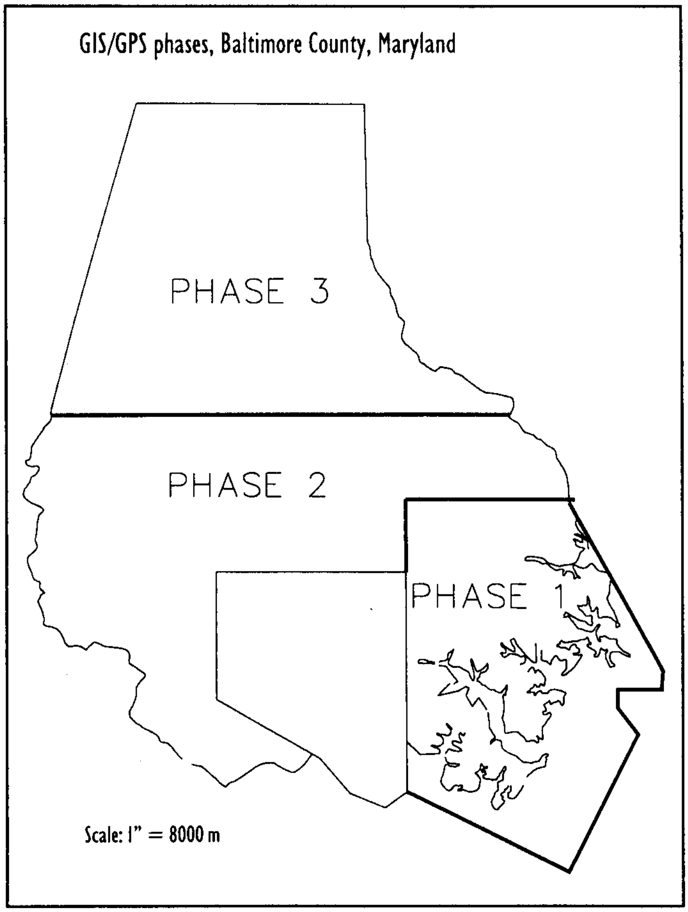

Figure 1. The boundaries of the Baltimore County, Maryland, and GIS/GPS phases.

(250 square miles) was accomplished in March 1996. Phase 2 GPS-leveling, which is described in this report, was performed in the fall of 1996. Phase 3 is currently under way (as of publication of this report).

The project was a combined field effort of Baltimore County survey personnel and McCrone personnel. During phase 1, all vertical control was established using classical leveling techniques. In conjunction with the new countywide GIS, a cooperative effort has developed between NGS and Baltimore County to obtain GPS-derived orthometric heights across a band of newly constructed monuments in the phase 2 area. The objective of the project was to obtain less than 2-centimeter ellipsoid height uncertainty and 2 cm or better GPS-derived orthometric height accuracy. The county's goal was to employ GPS leveling techniques to replace classical leveling techniques in phase 3. The 2-centimeter accuracy would be adequate for project site work and more than adequate for photogrammetric purposes.

Project Scope

Figure 2 shows the project area in relation to the entire county. The 18 monuments of the project span approximately 40 km in an "L-shaped" band to the north and west of Baltimore City. Of the 18 monuments, two are part of the Maryland State High Accuracy Reference Network (HARN) and are B-order, two are existing second-order benchmarks (vertical control), and four are second-order benchmarks which were leveled during phase 2 (see Table 1). All second-order leveling followed Federal Geodetic Control Committee (FGCC) specifications (FGCC 1984). The NGS guidelines for the 2-centimeter standard of GPS-derived ellipsoid heights were followed throughout the project for equipment, observation methodology, and processing (Zilkoski et al. 1997).

Monument Construction, Personnel, Equipment, and Procedures

Monumentation was performed by two three-person crews using two county vehicles. Each crew consisted of two Baltimore County surveyors and one McCrone GPS field person, which ensured the proper placement of the monuments in the proximity of the flight lines.

Monuments were poured in place using concrete mix and formed at the top 15 inches of the concrete with a 10-inch diameter cardboard sonotube. Holes were dug to a 3-foot depth, going beyond the typical 18-inch freeze line for this region. Two reinforcing rods were installed vertically to enable recovery with a metal detector, and a pre-stamped brass disk was installed in the middle of the surface of the concrete. Physical ties and "to reach" descriptions were recorded. It was agreed that not only did the two three-person crews work efficiently, but that invaluable experience was also gained from the interaction.

GPS data were collected by two Baltimore County surveyors and two surveyors from McCrone using four Ashtech dual-frequency Z-12 receivers with 6 MB RAM, Ashtech Geodetic III antennas (model number 700718.B), and SECO 2-meter fixed height poles. Fixed height poles are required for the 2 cm standard by the NGS guidelines. Standard Ashtech 12 volt batteries were used in a two-batteries-per-receiver setup to ensure an uninterrupted power supply. Ashtech 10-meter antenna cables and standard power cables were used. Cellular phones were used for communication. Following the

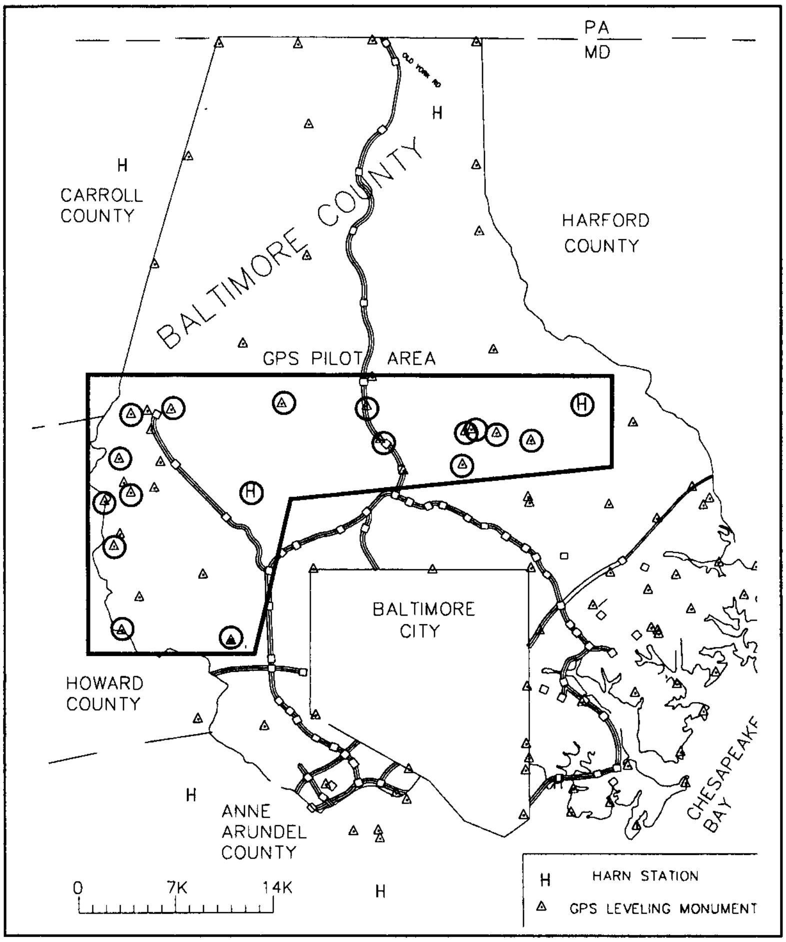

Figure 2. Project area in relationship to Baltimore County.

NGS guidelines, meteorological readings were taken. Sling psychrometers graduated in 1°F were used to obtain wet and dry bulb temperatures and relative humidity by a sliding scale, while pressure readings were obtained using a barometer graduated in millibars of mercury. All equipment performed flawlessly. Daily sessions were downloaded to an office PC using Ashtech's Prism software, and immediately backed up on an I Omega Ditto drive.

GPS Occupations

Observations at the 18 monuments followed a schedule prepared by NGS (Table 2). These sessions were taken over the course of six days, with each baseline being observed at least twice. Observing each baseline at least twice is required by the NGS guidelines. The epoch interval was set to 15 seconds and the elevation mask was set to 15 degrees. As a first step, the guidelines call for establishing at least three primary base stations that are connected to three high-accuracy control stations. The first 3 days (DOY[1] 263-Sept. 19, 264-Sept. 20, and 268-Sept. 24, 1996) were 5-hour GPS sessions on four monuments: two B-order HARN stations, one station (GIS-43) previously occupied during phase 1, and one new monument, GIS-92. Meteorological data were taken at the start of each session, midway through, and at the end of each session. See Figure 3a for the network design. Monuments GIS-43 and GIS-92 were leveled using second-order leveling specifications (FGCC 1984) in phase 2.

NGS guidelines require that the project be connected to at least three high-accuracy stations, to ensure that the local network is accurately tied to the statewide network. There are two HARN stations located within the project's boundaries. The next closest HARN stations were so far away from the

Station Name	Vertical Control NAVD 88 Height (m)	Horizontal Control NAD83 (1991)	
		Latitude	Longitude
GIS 43[a]	84.777	-	-
GIS 91[a]	167.910	-	-
GIS 92[a]	187.751	-	-
GIS 107[a]	145.228	-	-
HYDE[b]	-	39-28-53.41339N	6-29-05.76845W
LINE[c]	130.143	-	-
MELSAGE[b,c]	161.989	39-25-35.54491N	76-46-03.21432W

[a] New bench mark leveled to in project.

[b] HARN station.

[c] Existing benchmark.

Table 1. Geodetic control of the project.

---

[1] DOY = day-of-year; DOY 263 means "Julian [calendar] day 263."

Session Date	Starting Time	Duration	Session Code	Occupied Stations			
SEPT 19 (DOY 263)	08:00am	5 HRS	1A	GIS 43	MELSAGE	HYDE	GIS 92
SEPT 20 (DOY 264)	08:00am	5 HRS	2A	GIS 43	MELSAGE	HYDE	GIS 92
SEPT 24 (DOY 268)	08:00am	5 HRS	3A	GIS 43	MELSAGE	HYDE	GIS 92
SEPT 25 (DOY 269)	08:00am	45 mins	4A	GIS 91	GIS 84	GIS 94	GIS 92
	09:30am	45 mins	4B	GIS 91	SAUTER RESET	GIS 90	GIS 43
	11:00am	45 mins	4C	GIS 97	SAUTER RESET	MELSAGE	GIS 92
	01:00pm	45 mins	4D	GIS 97	GIS 82	MELSAGE	GIS 92
	02:30pm	45 mins	4E	LINE	GIS 82	MELSAGE	GIS 81
SEPT 26 (DOY 270)	09:00am	45 mins	5A	LINE	GIS 98	GIS 78	GIS 80
	10:30am	45 mins	5B	GIS 79	GIS 107	HYDE	GIS 80
	12:00am	45 mins	5C	GIS 91	GIS 84	GIS 94	GIS 92
	01:30pm	45 mins	5D	GIS 91	SAUTER RESET	GIS 90	GIS 43
	03:00pm	45 mins	5E	GIS 97	SAUTER RESET	MELSAGE	GIS 92
SEPT 27 (DOY 271)	09:00am	45 mins	6A	GIS 97	GIS 82	MELSAGE	GIS 92
	10:30am	45 mins	6B	LINE	GIS 82	MELSAGE	GIS 81
	12:00am	45 mins	6C	LINE	GIS 98	GIS 78	GIS 80
	01:30am	45 mins	6D	GIS 79	GIS 107	HYDE	GIS 80

Table 2. Project occupation schedule.

project that two new HARN-type stations (B-order accuracy standards) were established inside the project's boundary. This was permitted only because of the project's small areal extent.

The two new HARN-type stations, GIS-43 and GIS-92, were occupied for three 5-hour sessions over three different days and tied to two Maryland HARN stations—MELSAGE and HYDE—to meet FGCC B-order standards. The two existing Maryland HARN stations and the three days of GPS observations were used to establish the required number of control base stations for the project. The two new HARN-type stations are being made consistent with Maryland's HARN and loaded into the NGS integrated data base. In addition, because of the small areal extent of the project and short distances between control stations (less than 40 km apart) the four control stations were also considered to be primary base stations. Thus the four stations served as both control and primary stations for the project[2], as required in the NGS guidelines (Table 3). These four monuments are on the project's perimeter.

The next step of a GPS-derived orthometric height project is to establish GPS-derived ellipsoid heights at secondary base stations and other local stations. Secondary base stations are required when primary base stations are greater than 40 km apart. Once again because of the small areal extent of the project and short distances between the primary base stations, i.e., less than 40 km apart, there was not a requirement for secondary base stations. To establish heights at the local project stations, each station was observed simultaneously with at least two of its nearest adjacent neighbors, and each baseline was observed twice with the second occupation obtained on a different day using significantly different satellite geometry (see Table 2).

The five sessions of DOY 269 (Sept. 25, 1996) and the first two sessions of DOY 270 (Sept. 26, 1996) comprise one set of geometry. The last three sessions of DOY 270 (Sept. 26, 1996) and the four sessions of DOY 271 (Sept. 27, 1996) are the repeat baselines using different satellite geometry on different days. (See Figure 3b for the network design.)

---

[2] It should be noted that there is not a requirement that control stations and primary base stations must be different stations. The only requirement is that each control station is within 75 km of a primary base station, and each primary base station should be within 40 km of another primary base station. Because station MELSAGE is located near the center of the project and because of the small areal extent of the project, the control stations and primary base stations were chosen to be the same stations.

These 45-minute sessions had meteorological data taken during the midpoint of the session only. Log book entries were made for each receiver at each session, consisting of station names, times, weather conditions, meteorological data, operator's name, antenna heights, etc. A disk rubbing was also taken for each session.

GPS Data Processing

Processing of the field data was accomplished with different software packages, and the results were compared. Baltimore County personnel processed the data using Ashtech's Prism v. 2.01, which inputs the downloaded raw binary files ("B" files), navigation message or ephemeris files ("E" files), and the site information files ("S" files). It then forms a common navigation file and undifferenced or "U" files. Processing was accomplished using L1 data only, for solutions of baselines less than 5 km. For solutions of baselines greater than 5 km, Ashtech's linear

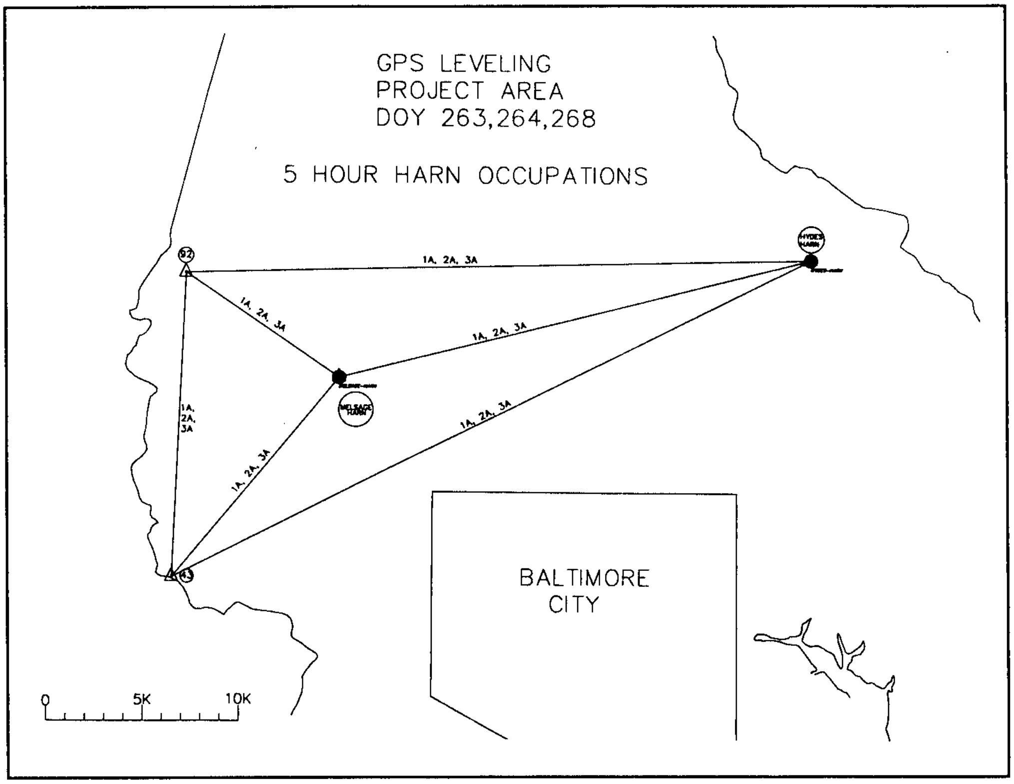

Figure 3a. Network design of primary base stations.

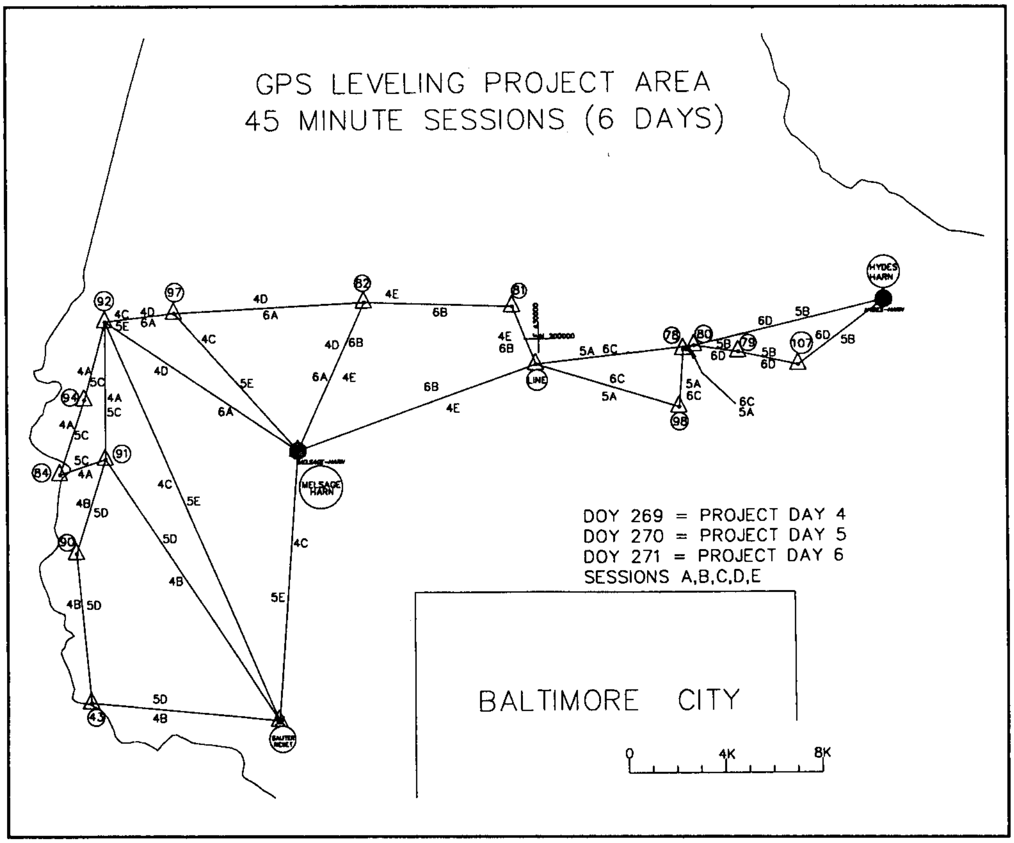

Figure 3b. Network design of secondary base and local network stations.

Station Name	Control Station[1]	Primary Base Station	Secondary Base[2] Station	Local Station
GIS 43	**[3]	**		**
GIS 78				**
GIS 79				**
GIS 80				**
GIS 81				**
GIS 82				**
GIS 84				**
GIS 90				**
GIS 91				**
GIS 92	**[3]	**		**
GIS 94				**
GIS 97				**
GIS 98				**
GIS 107				**
HYDE	**	**		**
LINE				**
MELSAGE	**	**		
SAUTER RESET				**

[1] Primary base stations and control stations are the same because of the small areal extent of the project.

[2] Not required in this project because primary base stations are all less than 30 km apart.

[3] Control station established as part of the project.

Table 3. List of project stations by type.

combination method was used which yields ionosphere free, integer fixed, double difference solutions. The NGS guidelines call for the use of precise ephemerides; these were easily downloaded from the NGS Web site. For comparison purposes, NGS processed the data using Trimble's GPSurvey software following the same criteria as Baltimore County's Ashtech processing. In addition, NGS processing program OMNI was used to process the longer-duration sessions of DOY 263, 264, and 268.

There were some observing sessions that contained noisy data, particularly for DOY 269, sessions C, D, and E. This is most likely the result of the PDOP (and VDOP) climbing to higher levels due to obstructions during these sessions. In the interest of completing the project in a timely manner, and in support of evaluating the NGS guidelines to ensure different satellite geometry on different days, some sessions were used that suffered from relatively poor satellite geometry. This was expected, so in order to compensate for bad VDOP during some sessions, 45 minutes of data were collected at all stations instead of the minimum of 30 minutes required by the guidelines. These additional data were required to obtain sufficiently accurate vertical results. There is always a trade-off between observing longer sessions, e.g., 1 hour instead of 30 minutes, versus reobserving when baselines do not meet the tolerance criteria.

Several vectors, primarily for the shorter baselines between 5 km and 7 km, showed slightly better processing results using the L1 solution, but this solution was not used unless the ionosphere free solution showed RMS residuals greater than 0.018 m, "up" residuals (*du*) were greater than 0.02 m, or integer ambiguities could not resolved. Of the 72 vectors over 5 km, 12 L1 solutions were felt to yield a better output. Observed meteorological data can be useful in indicating significant atmospheric variations between sites for each session, especially for long baselines, and also for noting changing conditions such as a weather front passing through; for shorter baselines, however, observed meteorological data can distort the solutions if they do not accurately reflect the atmospheric conditions at both ends of the baseline.

Tables 4a and 4b list some of the differences in GPS-derived *du* values between repeat baselines processed using observed data collected in the field and those processed using standard meteorological data values from a model.[3] From Table 4a it is obvious that for this project, the standard meteorological data produced more consistent results between repeat baselines. All of the large differences, i.e., greater than 10 cm, in Table 4a involved station GIS-92. The reported barometric pressures at stations GIS 92 and MELSAGE were consistently 5 to 10 millibars lower than those reported at stations HYDE and GIS-43. This result may indicate that the reported meteorological data do not accurately reflect the atmospheric conditions at both ends of the baseline. It should be noted that the option to solve for tropospheric scale parameters was not available and

---

[3] It should be noted that the local "up" component (*du*) value of a baseline is not equal to the difference in ellipsoid height (dh) between the two stations for that baseline. Some GPS adjustment softwares compute the height component of the baseline in the local horizon system, i.e., *du* values. The guidelines require that differences in ellipsoid height values between repeat baselines meet a tolerance criterion, i.e., 2 cm. However, for baseline lengths less than 100 km, when the misclosure between repeat baselines is small (i.e., less than 5 cm), the difference in *du* values between repeat baselines and the difference in *dh* values for the same two baselines are, for all practical purposes, equal. That is, *d(du)* minus *d(dh)* is typically less than 1 mm.

From Station	To Station (Distance) (m)	Session Number	Observed Met. Data[1] (m) x_1 x_2	Difference (cm) (x_1-x_2)	Standard Met. Data[2] (m) y_1 y_2	Difference (cm) (y_1-y_2)	Difference (cm) (x_1-y_1), (x_2-y_2)
MELSAGE	GIS 92	1A	8.769	6.6	8.664	-0.4	10.5
	9,692	2A	8.703		8.668		3.5
		1A	8.769	**12.5**	8.664	**- 0.5**	10.5
		3A	8.644		8.669		- 0.5
		2A	8.703	5.9	8.668	- 0.1	3.5
		3A	8.644		8.669		- 0.5
MELSAGE	GIS 43	1A	- 94.766	- 4.2	- 94.725	1.5	- 4.1
	13,576	2A	- 94.724		- 94.740		1.6
MELSAGE	HYDE	1A	- 89.525	- 6.8	- 89.498	- 1.5	- 2.7
	25,079	2A	- 89.457		- 89.483		2.6
		1A	- 89.525	- 5.2	- 89.498	- 0.6	- 2.7
		3A	- 89.473		- 89.492		1.9
		2A	- 89.457	1.6	- 89.483	0.9	2.6
		3A	- 89.473		- 89.492		1.9
GIS 92	GIS 43	1A	-103.533	**- 11.0**	-103.389	**1.7**	- 14.4
	15,768	2A	-103.423		-103.406		- 1.7
GIS 43	HYDE	1A	5.249	- 0.7	5.230	- 1.8	1.9
	36,954	2A	5.256		5.248		0.8
GIS 92	HYDE	1A	- 98.297	**- 13.0**	- 98.164	**- 1.6**	- 13.3
	32,400	2A	- 98.167		- 98.148		- 1.9
		1A	- 98.297	**- 18.0**	- 98.164	- **0.2**	- 13.3
		3A	- 98.117		- 98.166		4.9
		2A	- 98.167	- 5.0	- 98.148	- 1.8	- 1.9
		3A	- 98.117		- 98.166		4.9

[1] Baselines were processed using observed meteorological data collected in the field.

[2] Baselines were processed using standard meteorological values based on a model.

Table 4a. Differences in GPS-derived height (*du*) values between repeat baselines using observed meteorological data and standard meteorological data for 5-hour sessions.

therefore they were not determined; solving for these scale parameters may reduce the differences between baselines due to reported meteorological data not accurately reflecting the atmospheric conditions at both ends of the baseline.

Two vectors (which exceeded NGS guidelines[4] tolerance limit of 2 cm) from DOY 269, session D (MELSAGE to GIS-82 and GIS-97 to GIS-82, session 4D), were rejected during the adjustment phase of the project (see Table 4b). MELSAGE to GIS-82 had four redundant baseline vectors. It was determined by analyzing repeat baselines and loop misclosures that the baseline observed during DOY 269, session D, was the potential outlier. This baseline was flagged as a statistical outlier, i.e., its normalized residual was greater than three times its expected value in a minimum-constraint least squares adjustment, and was rejected. GIS-97 to GIS-82 only had one repeat baseline, therefore, the repeat baseline analysis could not be used to indicate which baseline was the outlier. Loop misclosures and statistical results from a minimum-constraint adjustment both indicated that GIS-97 to GIS-82 on DOY 269, session D, was the outlier and was rejected. The baseline will be reobserved at a later date, however because stations GIS-82 and GIS-97 are directly connected to their two

---

[4] NGS guidelines have a requirement that all baselines must be repeated on different days and at a different time of the day. The misclosure between the two baselines must be less than a specified tolerance, i.e., 2 cm. These guidelines have been developed based on many years of analysis and, if adhered to, should produce the intended accuracy.

From Station	To Station (Distance) (m)	Session Number	Observed Met. Data (m) x_1 x_2	Difference (cm) (x_1-x_2)	Standard Met. Data (m) y_1 y_2	Difference (cm) (y_1-y_2)	Difference (cm) (x_1-y_1), (x_2-y_2)
SAUTER RESET	GIS 43	4B	- 68.058		- 68.101		4.3
	7,882	5D	- 68.076	1.8	- 68.109	- 0.8	3.3
GIS 43	GIS 90	4B	63.809		63.897		- 8.8
	6,242	5D	63.879	7.0	63.908	- 1.1	- 2.9
GIS 90	GIS 91	4B	24.404		24.421		- 1.7
	4,062	5D	24.392	1.2	24.407	1.4	- 1.5
GIS 91	GIS 84	4A	- 42.298		- 42.331		3.3
	2,088	5C	- 42.286	- 1.2	- 42.325	- 0.6	3.9
GIS 84	GIS 94	4A	39.767		39.801		- 3.4
	3,483	5C	39.741	2.6	39.781	2.0	- 4.0
GIS 94	GIS 92	4A	17.595		17.614		- 1.9
	3,288	5C	17.574	2.1	17.591	2.3	- 1.7
GIS 92	GIS 91	4A	- 15.079		- 15.094		1.5
	5,703	5C	- 15.067	- 1.2	- 15.076	1.8	0.9
GIS 91	SUATER RESET	4B	- 20.205		- 20.217		1.2
	13,036	5D[1]	- 20.167	- 3.8	- 20.191	- 2.6	2.4
SUATER RESET	GIS GIS 92	4C	35.296		35.308		- 1.2
	18,029	5E	35.252	4.4	35.298	1.0	- 4.6
SUATER RESET	MELSAGE	4C[2]	26.646		26.655		- 0.9
	11,120	5E	26.605	4.1	26.618	3.7	- 1.3
GIS 92	GIS 97	**4C[3]**	17.867		17.878		- 1.1
	2,831	**5E[3]**	17.840	2.7	17.849	2.9	- 0.9
		4D	17.869		17.824		4.5
		6A	17.844	2.5	17.843	-1.9	0.1
		5E	17.840		17.849		
		6A	17.844	- 0.4	17.843	0.6	0.1
GIS 92	MELSAGE	**4D[3]**	- 8.687		8.704		1.7
	9,692	**6A[3]**	- 8.657	3.0	- 8.664	-4.0	0.7
		4C	- 8.651		- 8.660		0.9
		5E	- 8.649	0.2	- 8.671	1.1	2.2
MELSAGE	GIS 97	4D[4]	26.518		26.529		- 1.1
	7,821	6A	26.489	2.9	26.524	0.5	- 3.5
MELSAGE	GIS 82	4D[4]	33.542		33.510		
	6,722	6A	33.351	19.1	33.361	15.0	- 1.0
		4E	33.343		33.369	- 0.8	- 2.6
		6B	33.403	- 6.0	33.389	- 2.0	1.4

[1] SAUTER RESET is outside allowable tolerance for baseline misclosures and will be reobserved at a later date.

[2] Large residuals in adjustment, 2.1 cm, and baseline lenghts are greater than 10 km.

[3] Another set of baselines meets allowable misclosure.

[4] Rejected in adjustment because of large normalized residual (>3 sigma).

Table 4b. continued on next page......

Table 4b. continued ....

From Station	To Station (Distance) (m)	Session Number	Observed Met. Data (m) x_1 x_2	Difference (cm) (x_1-x_2)	Standard Met. Data (m) y_1 y_2	Difference (cm) (y_1-y_2)	Difference (cm) (x_1-y_1), (x_2-y_2)
GIS 97	GIS 82	**4D[4]**	7.048		7.017		3.1
	7,958	**6A**	6.855	19.3	6.855	16.2	0.0
GIS 82	GIS 81	4E	-101.434				
	6,186	6B	-101.513	7.9			
GIS 81	LINE	4E	34.841		34.846		- 0.5
	2,462	6B	34.822	1.9	34.822	2.4	0.0
MELSAGE	LINE	4E[5]	- 33.261		- 33.271		1.0
	10,497	6B	- 33.286	2.5	- 33.313	4.2	2.7
LINE	GIS 78	5A	- 56.742		- 56.771		2.9
	6,068	6C	- 56.733	- 0.9	- 56.782	1.1	4.9
LINE	GIS 98	5A	- 55.900		- 55.924		2.4
	6,135	6C	- 55.886	- 1.4	- 55.937	1.3	5.1
GIS 98	GIS 78	5A	- 0.847		- 0.845		- 0.2
	2,375	6C	- 0.842	- 0.5	- 0.842	- 0.3	0.0
GIS 78	GIS 80	5A	- 0.310		- 0.310		0.0
	366	6C	- 0.312	0.2	- 0.312	0.2	0.0
GIS 80	GIS 79	5B	- 6.530		- 6.536		0.6
	1,839	6D[6]	- 6.545	1.5	- 6.545	0.9	0.0
		341			- 6.547	1.1	
GIS 79	GIS 107	**5B**	62.854		62.894		- 4.0
	2,532	**6D[6]**	62.842	1.2	62.842	5.2	0.0
		341			62.903	- 0.9	
GIS 107	HYDE	**5B**					
	4,674	**6D[6]**	- 55.423		- 55.439		1.6
		341	- 55.401	2.2	- 55.400	- 3.9	0.1
					- 55.449	1.0	
		5B					
GIS 80	HYDE	6D[6]	0.909		0.924		- 1.5
	8,294	341	0.907	0.2	0.907	1.7	0.0
					0.914	1.0	

[5] Large residual, -4.0 cm, in adjustment and base line length greater than 10 km.

[6] Session reobserved on December 6, 1996 (DOY 341).

Table 4b. List of differences in GPS-derived height (*du*) values between repeat baselines using observed meteorological data and standard meteorological data for 45-minute sessions.

adjacent neighbors (see Figure 3b), it still fulfills the requirements of the guidelines and there is still one baseline that directly connects the two stations.

Repeat baselines relative to SAUTER RESET had some large misclosures which did not meet the NGS guideline tolerance limits for repeat baselines, i.e., 2 cm. Two baselines—GIS-91 to SUATER RESET, session 5D, and SUATER RESET to MELSAGE, session 4C—will be reobserved at a later date (see Table 4b). It should be noted that the repeat baselines with large misclosures are all greater than 10 km, which exceeds the maximum length requirement stated in the NGS guidelines. It was anticipated that this could present a problem, but this baseline was included in the project as part of the evaluation of the NGS guidelines.

validity. Station SAUTER RESET, however, is involved with two sets of baselines—SAUTER RESET tied to GIS-43 and SAUTER RESET to GIS-92—that meet the allowable tolerances for repeat baselines of the guidelines. The only real problem here is that the two baselines from SAUTER to MELSAGE are outside the guidelines' allowable 2-cm tolerance value for misclosure.

Baseline misclosures involving station GIS-107 for sessions 5B and 6D were also greater than the stated 2-cm allowable values (see footnote 4). It was decided to reobserve the baselines associated with GIS-107 because both sets of baselines that were processed using the standard meteorological data involving GIS-107 did not meet the allowable tolerance.

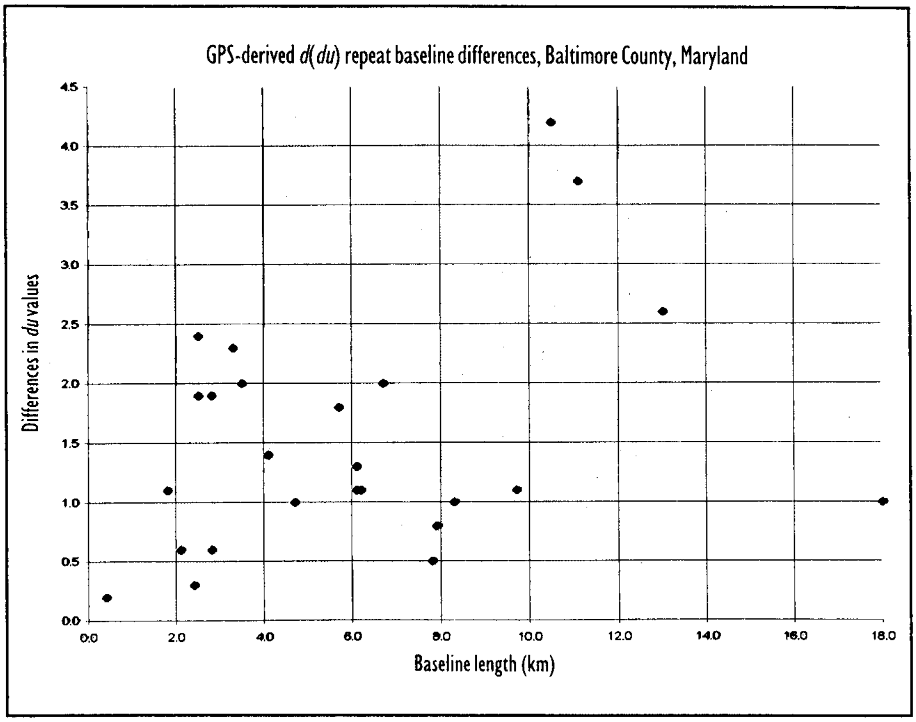

Figure 4a. Plot of the differences in GPS-derived *d*(*du*) values between repeat baselines in 45-minute sessions. (Differences computed using Prism and standard meteorological values.)

Figure 4a is a plot of the differences in *du* values [*d*(*du*)] (computed using Prism and standard meteorological values) between repeat baselines involved in the 45-minute sessions. Three out of four baselines which are greater than 10 km have misclosures that are greater than 2.5 cm.

Figure 4b is a plot of the differences of *du* values [*d*(*du*)] between repeat baselines that are less than 10 km in length. Only two baselines have repeat baseline misclosures >2 cm and neither one of these misclosures is greater than 2.4 cm. This indicates that the NGS requirement to limit the length between baselines to no more than 10 km for short observing sessions appears to have

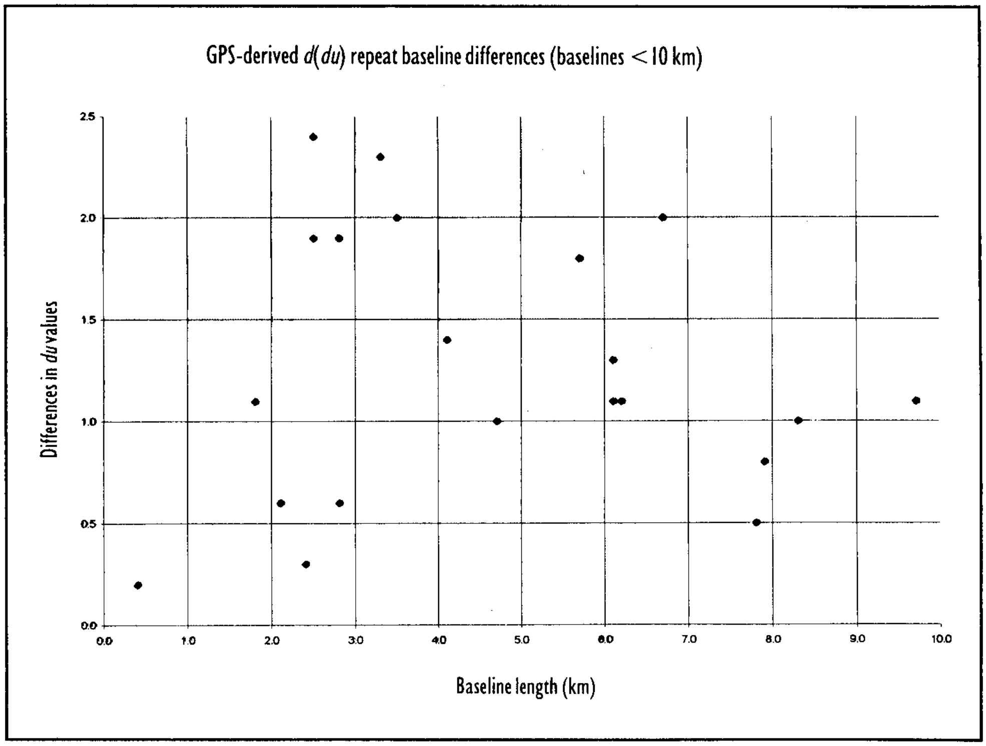

Figure 4b. Plot of the differences in GPS-derived *d*(*du*) values between repeat baselines less than 10 km in length and involved in the 45-minute sessions. (Differences computed using Prism and standard meteorological values.)

From Station (Session)	To Station (Distance)	Ashtech DX_1 DY_1 DZ_1	OMNI DX_2 DY_2 DZ_2	Differences (cm) $(DX_1 - DX_2)$ $(DY_1 - DY_2)$ $(DZ_1 - DZ_2)$	Computed (cm) DN DE DU
MELSAGE	GIS 0043	-7,006.423	-7006.427	0.3	1.3
(Day163A)	(13.5 km)	-8,356.331	-8356.311	-1.7	1.3
		-8,087.276	-8087.294	1.6	1.5
MELSAGE	GIS 0043	-7,006.424	-7006.419	-0.6	-1.5
(Day164A)		-8,356.317	-8356.333	1.6	0.5
		-8,087.271	-8087.274	0.3	-0.7
MELSAGE	GIS 0043	-7,006.424	-7006.422	-0.2	-0.3
(Day168A)		-8,356.331	-8356.333	0.2	-0.1
		-8,087.279	-8087.280	0.1	0.0
				------------------------	------------------------
				Average Difference	-0.2 0.6 0.3
MELSAGE	GIS 0092	-8,636.834	-8,636.838	0.3	1.1
(Day163A)	(9.6 km)	1,451.585	1451.600	-1.2	0.9
		4,152.333	4152.322	1.0	-0.6
MELSAGE	GIS 0092	-8636.837	-8636.839	0.1	0.6
(Day164A)		1451.580	1451.586	-0.6	0.5
		4152.334	4152.329	0.5	-0.4
MELSAGE	GIS 0092	-8636.835	-8636.836	0.1	1.2
(Day168A)		1451.580	1451.592	-1.2	0.7
		4152.336	4152.329	0.7	-0.4
				------------------------	------------------------
				Average Difference	1.0 0.7 -0.5
MELSAGE	HYDE	22758.558	22758.558	0.0	-0.3
(Day163A)	(25.1 km)	9443.996	9443.996	0.3	-0.2
		4674.012	4674.012	-0.2	0.2
MELSAGE	HYDE	22758.562	22758.562	0.0	0.1
(Day164A)		9443.975	9443.974	0.1	-0.7
		4674.010	4674.017	-0.7	0.2
MELSAGE	HYDE	22758.564	22758.561	0.3	0.3
(Day168A)		9443.985	9443.980	0.5	-0.4
		4674.006	4674.011	-0.5	0.6
				------------------------	------------------------
				Average Difference	0.0 -0.4 0.3

Table 4c. List of differences in X, Y, Z, and N, E, U values between the two GPS data processing programs (Prism and OMNI) used for the project.

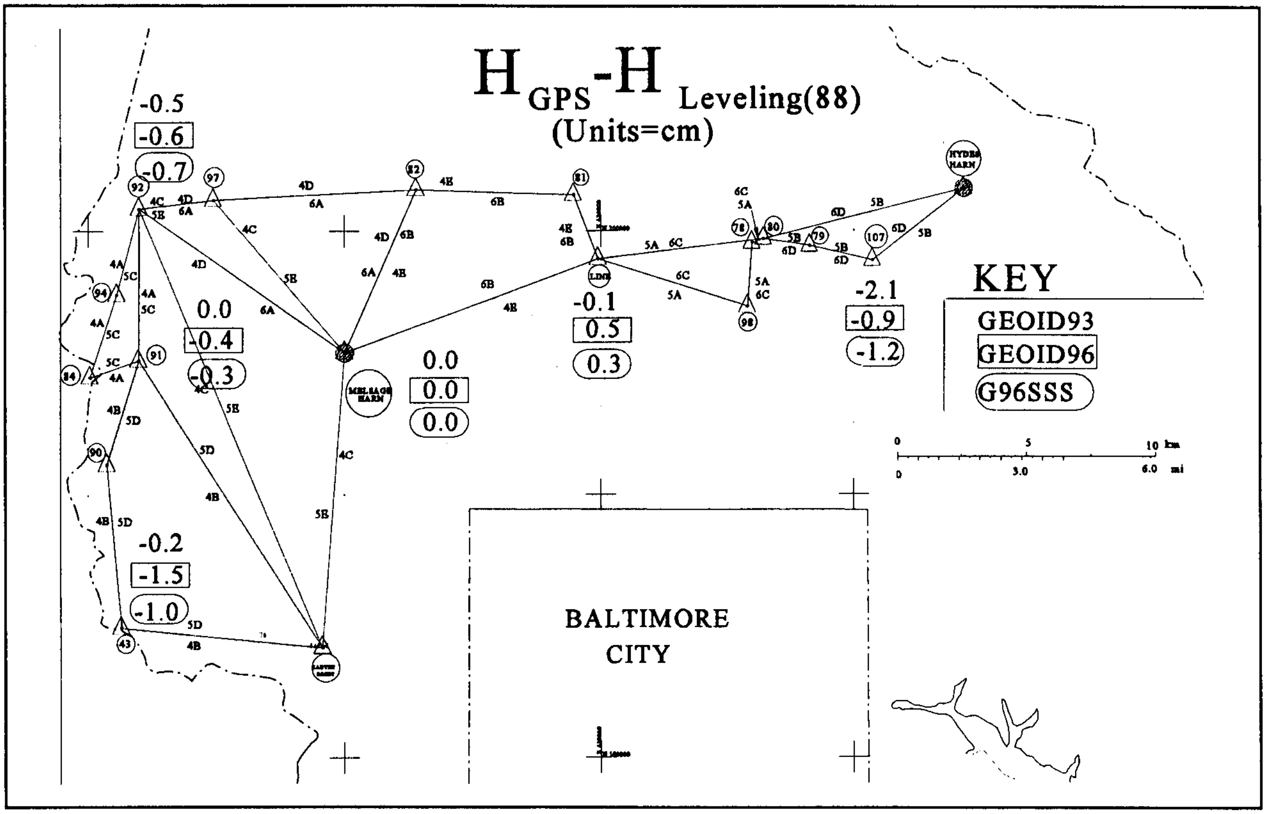

Figure 5. Differences between GPS-derived orthometric height values and leveling-derived orthometric height values using GEOID96, G96SSS, and GEOID93.

On DOY 341 (Dec. 6, 1996) county survey personnel reobserved session DOY 271D (6D). Care was taken to use different satellite geometry than was used for the redundant session DOY 270B (5B). The difference between adjusted GPS-derived orthometric heights using DOY 270B with published NAVD 88 heights was less than the difference using DOY 217D baselines. The guidelines require that repeat baselines must be obtained on different days and using significantly different geometry. Therefore, the DOY 341 session was observed so the geometry was different from DOY 270, session 5B.[5] The results of the reobservation of session 6D on DOY 341 are listed in Table 4b. DOY 341 baseline values and session 5B meet the guidelines' allowable tolerance.

Different GPS processing programs can produce different results if different options are selected. To ensure that Baltimore processing and NGS processing techniques were the same, NGS processing program OMNI was used to process the longer-duration sessions of DOY 263, 264, and 268. Table 4c lists the differences in X, Y, Z and ΔN, ΔE, ΔU values between the two processing softwares (OMNI and Prism) with MELSAGE used as the reference station. OMNI was used in its multistation baseline processing mode with cross-correlation. Most of the differences are less than 1 cm and the mean differences are never greater than 1 cm. The larger differences, i.e., those greater than 1 cm, are currently under investigation. Minor differences in processing techniques can have significant influence when the results must agree to within 2 cm. What is important to note is that the two results do not appear to have any large biases and that only one ΔU value is greater than 1 cm.

The vector output files ("O" files from the Ashtech processing) and the output listing files ("L" files) were examined to be sure that the ambiguities were fixed to integers, the number of measurements used was greater than 95 percent, and the RMS error was within the guidelines' RMS tolerance value of 1.5. The vectors were then imported into the least squares network adjustment.

---

[5] The user must remember to account for the fact that the satellites' locations relative to a user's local position are shifted by four minutes each day due to the difference between sidereal time and universal time (UT). In other words, if a certain satellite geometry configuration exists at 9:00 UT today, this geometry configuration will be roughly the same at 8:56 UT the next day.

Station Name	Ashtech's FILLNET		Trimble's TRIMNET		Differences	
	Latitude Longitude (min, sec)	Ellipsoid Height (m)	Latitude Longitude (min, sec)	Ellipsoid Height (m)	Latitude Longitude (cm)	Ellipsoid Height (cm)
GIS 43	39 19 58.33909		39 19 58.33899		- 0.3	
	76 52 07.85773	52.664	76 52 07.85761	52.664	- 0.3	0.0
GIS 78	39 27 43.92722		39 27 43.92700		- 0.7	
	76 34 56.61630	48.139	76 34 56.61596	48.138	- 0.8	- 0.1
GIS 79	39 27 41.08610		39 27 41.08590		- 0.6	
	76 33 26.30956	44.981	76 33 26.30919	44.985	- 0.9	0.4
GIS 80	39 27 48.71311		39 27 48.71290		- 0.6	
	76 34 42.59485	48.530	76 34 42.59451	48.529	- 0.8	- 0.1
GIS 81	39 28 42.50876		39 28 42.50859		- 0.5	
	76 39 53.03382	64.983	76 39 53.03352	64.979	- 0.7	- 0.4
GIS 82	39 28 55.50921		39 28 55.50911		- 0.3	
	76 44 11.30854	167.134	76 44 11.30846	167.138	- 0.2	0.4
GIS 84	39 24 59.55827		39 24 59.55807		- 0.6	
	76 53 04.89748	97.789	76 53 04.89749	97.782	0.0	- 0.7
GIS 90	39 23 19.42542		39 23 19.42537		- 0.1	
	76 52 37.67901	113.974	76 52 37.67898	113.973	- 0.1	- 0.1
GIS 91	39 25 24.29969		39 25 24.29959		- 0.3	
	76 51 43.62836	135.831	76 51 43.62839	135.829	- 0.1	- 0.2
GIS 92	39 28 29.21742		39 28 29.21746		0.1	
	76 51 41.06524	155.658	76 51 41.06528	155.654	0.1	- 0.4
GIS 94	39 26 46.82601		39 26 46.82583		- 0.5	
	76 52 19.35405	136.776	76 52 19.35412	136.762	0.2	- 1.4
GIS 97	39 28 42.72849		39 28 42.72855		0.1	
	76 49 43.88724	168.584	76 49 43.88730	168.580	0.1	- 0.4
GIS 98	39 26 27.29037		39 26 27.29016		- 0.6	
	76 35 06.33717	46.494	76 35 06.33679	46.494	- 0.9	0.0
GIS 107	39 27 23.24104		39 27 23.24088		- 0.5	
	76 31 42.91377	122.555	76 31 42.91345	122.552	- 0.8	- 0.3
HYDE	39 28 53.41358		39 28 53.41340		- 0.6	
	76 29 05.76892	70.241	76 29 05.76841	70.230	- 1.2	- 1.1
LINE	39 27 30.02682		39 27 30.02661		- 0.6	
	76 39 09.82635	97.736	76 39 09.82618	97.733	- 0.4	- 0.3
MELSAGE	39 25 35.54491		39 25 35.54491		0.0	
	76 46 03.21432	129.785	76 46 03.21432	129.785	0.0	0.0
SAUTER	39 19 33.18858		39 19 33.18847		-0.3	
RESET	76 46 40.37799	108.675	76 46 40.37776	108.674	-0.6	-0.1

Table 5. Set of adjusted coordinates and their differences between Fillnet and Trimnet results.

Station Name	Ellipsoid Height (h) (m)	Geoid Height (GEOID96) (m)	GPS-derived Orthometric Height (H_{GPS96}) (m)	NAVD88 Orthometric Height (H_{88}) (m)	HGPS96 - H88 (cm)	HGPS - H88 Differences Relative to MELSAGE (cm)
GIS 43	52.664	-32.085	84.749	84.777	- 2.8	- 1.5
GIS 91	135.831	-32.062	167.893	167.91	- 1.7	- 0.4
GIS 92	155.658	-32.074	187.732	187.751	- 1.9	- 0.6
GIS 107	112.555	-32.651	145.206	145.228	- 2.2	- 0.9
LINE	97.736	-32.399	130.135	130.143	- 0.8	0.5
MELSAGE	129.785	-32.191	161.976	161.989	- 1.3	0.0

Table 6a. Differences between GPS-derived orthometric height values computed using GEOID96 and published NAVD 88 heights. (Vertical free adjustment results.)

Station Name	Ellipsoid Height (h) (m)	Geoid Height (G96SSS) (m)	GPS-derived Orthometric Height (H_{GPS96}) (m)	NAVD88 Orthometric Height (H_{88}) (m)	HGPS96 - H88 (cm)	HGPS - H88 Differences Relative to MELSAGE (cm)
GIS 43	52.664	-32.961	85.625	84.777	84.8	- 1.0
GIS 91	135.831	-32.934	168.765	167.910	85.5	- 0.3
GIS 92	155.658	-32.944	188.602	187.751	85.1	- 0.7
GIS 107	112.555	-33.519	146.074	145.228	84.6	- 1.2
LINE	97.736	-33.268	131.004	130.143	86.1	0.3
MELSAGE	129.785	-33.062	162.847	161.989	85.8	0.0

Table 6b. Differences between GPS-derived orthometric height values computed using G96SSS and published NAVD 88 heights. (Vertical free adjustment results.)

Station Name	Ellipsoid Height (h) (m)	Geoid Height (GEOID93) (m)	GPS-derived Orthometric Height (H_{GPS96}) (m)	NAVD88 Orthometric Height (H_{88}) (m)	HGPS96 - H88 (cm)	HGPS - H88 Differences Relative to MELSAGE (cm)
GIS 43	52.664	-32.421	85.085	84.777	30.8	- 0.2
GIS 91	135.831	-32.390	168.221	167.910	31.1	0.0
GIS 92	155.658	-32.398	188.056	187.751	30.5	- 0.5
GIS 107	112.555	-32.962	145.517	145.228	28.9	- 2.1
LINE	97.736	-32.716	130.452	130.143	30.9	- 0.1
MELSAGE	129.785	-32.514	162.299	161.989	31.0	0.0

Table 6c. Differences between GPS-derived orthometric height values computed using GEOID93 and published NAVD 88 heights. (Vertical free adjustment results.)

GPS Least Squares Adjustment

Baselines were incorporated into minimum constraint adjustments on a day-by-day basis for blunder checking. After all data were collected and processed, a combined 6-day set of baselines were incorporated into a minimum constraint adjustment where the latitude, longitude, and ellipsoid height value of MELSAGE were held fixed. MELSAGE was selected because it is near the middle of the project and is a published HARN station (Figure 5). All independent baselines were imported into the Ashtech Fillnet v. 3.00 least squares adjustment program accessible through the Prism software.

Baltimore County personnel used Ashtech's Fillnet program to adjust the data and NGS personnel used Trimble's Trimnet program. The adjustments used the same data and similar weighting schemes. Comparison of the results of the two adjustments showed good agreement. Table 5 contains a set of adjusted values and their differences. A summary of the differences between the adjusted positions from the two programs shows: latitude: 0.0 to 0.6 cm, average = 0.4 cm; longitude: 0.0 to 0.4 cm, average = 0.2 cm; ellipsoid heights: -0.7 to 1.4 cm, average = 0.3 cm. A few of the larger differences are currently being investigated, but except for 1 difference, they were all less than 1 cm. There does, however, appear to be a small positive bias, i.e., 0.3 cm, between the two adjustment results.

Station Name	GPS-derived Orthometric height relative to MELSAGE from minimally constrained adjustment (m)	GPS-derived Orthometric height from final constrained adjustment (m)	Minimally constrained minus final constrained adjustment (cm)
GIS 43	84.762	84.777 C	- 1.5
GIS 78	80.697	80.694	0.3
GIS 79	77.587	77.589	- 0.2
GIS 80	81.094	81.094	0.0
GIS 81	97.356	97.357	- 0.1
GIS 82	199.366	199.372	- 0.6
GIS 84	129.844	129.851	- 0.7
GIS 90	146.039	146.046	- 0.7
GIS 91	167.906	167.910 C	- 0.4
GIS 92	187.745	187.751 C	- 0.6
GIS 94	168.846	168.851	- 0.5
GIS 97	200.692	200.703	- 1.1
GIS 98	79.076	79.076	0.0
GIS 107	145.219	145.228 C	- 0.9
HYDE	102.932	102.935	- 0.3
LINE	130.148	130.143 C	0.5
MELSAGE	161.989	161.989 C	0.0
SAUTER RESET	140.895	140.918	- 2.3

C = constrained in adjustment.

Table 7. The final set of GPS-derived orthometric heights.

By applying GEOID93, GEOID96, and the NGS scientific geoid (G96SSS) geoid heights to the adjusted ellipsoid heights from Prism's Fillnet results, GPS-derived orthometric heights were obtained and compared with existing NAVD 88 orthometric heights determined from differential geodetic leveling. With the high degree of confidence in the adjusted ellipsoid heights, the adjusted second-order differential levels, and the relative accuracy of the geoid models in this area, a high degree of confidence can be placed in the orthometric elevations obtained from the vertically constrained adjustment. The difference between the published NAVD 88 height and the GPS-derived orthometric height computed using the published ellipsoid height of MELSAGE and GEOID96 is -1.3 cm; it is 85.8 cm when using G96SSS, and 31.0 cm when using GEOID93 (Tables 6a, 6b, and 6c).

The difference of 87 cm between GEOID96 and G96SSS is due the to the fact that GEOID96 has been developed to support direct conversion between ellipsoid heights expressed in the NAD 83 (1986) reference frame and orthometric heights expressed in the NAVD 88 vertical datum (Smith and Milbert 1997). For more information about GEOID96 and G96SSS, please refer to Smith and Milbert (1997). The fact important to our discussion is the relative difference between the GPS-derived orthometric heights and the published NAVD 88 heights of stations in the project. The last column in Tables 6a, 6b, and 6c list the differences between the H_{gps} and H_{88} from the minimum constraint adjustment when station MELSAGE's coordinates were held fixed. The differences illustrated in Figure 5, imply that the typical uncertainty between a NAVD 88 leveled height value and the GPS-derived orthometric height value is less than 2 cm across the project, i.e., the relative difference between stations GIS-43 and GIS-107 is -0.6 cm [-1.5 - (-0.9)], while between stations GIS-43 and GIS-92 it is -0.9 cm [-1.5 - (-0.6)], and between stations GIS-92 and GIS-107 the relative difference is 0.3 cm [-0.6 - (-0.9)] for GEOID96 (see also Table 6a). These differences are all related to MELSAGE, the constraint used in the minimum constraint adjustment. The largest difference is between stations GIS-43 and LINE, but even this difference is only -2.0 cm [-1.5 - (0.5)].

Similar results were obtained using GEOID93 values. GEOID93 results did indicate better agreement in the western half of the project, but the overall difference between stations GIS-107 and GIS-43 was 1.9 cm, while the difference was only -0.6 cm when using GEOID96.

The final set of adjusted GPS-derived orthometric heights was obtained by constraining all valid NAVD 88 heights and using the GEOID96. The results of the baseline repeatability and the adjustment presented in this report indicate that the GPS-derived ellipsoid heights and NAVD 88 leveling-derived heights are all valid and can be constrained in a final adjustment. Table 7 contains the final set of GPS-derived orthometric heights, where all benchmarks height values and one set of horizontal control station values of MELSAGE were held fixed. The fourth column of Table 7 lists the differences between the final set of GPS-derived orthometric heights and the minimum constrained set of heights. The differences between neighboring stations should be small, i.e., 1 cm. If the relative differences in adjusted values between closely spaced stations are large, i.e., greater than 2 cm, then it is possible that a constrained height value has distorted the final set of adjusted heights. In other words, if they exceed 2 cm, it is possible that an incorrect or invalid station value was held fixed. Table 7 shows that all of the relative differences between neighboring stations in the Baltimore County GPS project are less than 1 cm. For instance, the relative difference between GIS 107 and HYDE is -0.6 cm [-0.9 cm - (-0.3 cm)] and the relative difference between GIS 107 and GIS 79 is -0.7 cm [-0.9 cm - (-0.2 cm)].

Conclusions

The following are a few items that users should consider when performing GPS-derived orthometric height studies. Vertical control is imperative at the project limits to prevent distortion of data when constraints are applied. Great care should be taken in planning occupation times, as the vertical component of GPS data shows a sensitivity to high PDOP and VDOP. Precise ephemerides should be used in processing GPS height data and, at present, default standard meteorological data should be used during baseline processing of short baselines unless the observed meteorological data accurately reflect the atmospheric conditions at both ends of the baseline. Field meteorological data should continue to be taken because they might prove helpful during data analyses.

The latest national high-resolution geoid model, GEOID96, will yield accurate orthometric elevations in relatively small areas, when GEOID96 geoid heights are applied to adjusted ellipsoid heights. Two-centimeter GPS-derived orthometric heights can be obtained when the NGS guidelines for establishing GPS-derived ellipsoid heights are adhered to, proper connections are made to NAVD 88 vertical control, and GEOID96 is employed.

REFERENCES

Federal Geodetic Control Committee. 1984. *Specifications for geodetic control networks*. National Geodetic Survey Information Center, Silver Spring.

Hajela, D. 1990. Obtaining centimeter precision heights by GPS observations over small areas. *GPS World* (January/February): 55-9.

Kuang, S., C. Fidis, and F. Thomas. 1996. Modeling of local geoid with GPS and leveling: A case study. *Surveying and Land Information Systems* 56(2): 75-88.

Milbert, D. G. 1991. Computing GPS-derived orthometric heights with the GEOID90 Geoid height model. *Proceedings of GIS/LIS'91 Annual Conference*, Bethesda.

Parks, W., and D. Milbert. 1995. A geoid height model for San Diego County, California, to test the effect of densifying gravity measurements on accuracy of GPS-derived orthometric heights. *Surveying and Land Information Systems* 55(1): 21-38.

Remondi, B. W. 1984: *Using the global positioning system (GPS) phase observable for relative geodesy: Modeling, processing, and results*. PhD. dissertation, Center for Space Research, University of Texas. National Geodetic Survey Information Center, NOAA, Silver Spring. 360 pp.

Satalich, J. 1996. Optimal selection of constraints in GPS-derived orthometric heights. *Surveying and Land Information Systems* 56(2): 103-8.

Singh, Y., and F. Ackermann. 1995. High accuracy GIS data base georeferenced on GPS aerial triangulation. In: *Proceedings of GIS/LIS '95 Annual Conference*, November, Nashville, Tennessee.

Smith, D. A., and D. G. Milbert. 1997. The GEOID96 high resolution geoid model for the United States. (In preparation for submission to Journal of Geodesy.)

Zilkoski, D., J. D. D'Onofrio, and S. Frakes. 1997. Guidelines for establishing GPS-derived ellipsoid heights (Standards: 2 cm and 5 cm), Version 4.3. NOAA Technical Memorandum NOS NGS-58 (In press). National Geodetic Survey Information Center, Silver Spring.

Zilkoski, D. B., and J. D. D'Onofrio. 1996. Geodetic phase of NOS' San Francisco Bay demonstration project. In: *Proceedings of GIS/LIS '96 Annual Conference*, Denver, Colorado, November 19-21. pp. 116-127.

Zilkoski, D., J. Richards, and G. Young. 1992. Results of the general adjustment of the North American Vertical Datum of 1988. *Surveying and Land Information Systems* 52(3): 133-49.

Zilkoski, D., and L. Hothem. 1989. GPS satellite surveys and vertical control. *Journal of Surveying Engineering* 115(2): 262-82. ■