Where in the world are my field plots? Using GPS effectively in environmental field studies

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Global positioning system (GPS) technology is rapidly replacing tape, compass, and traditional surveying instruments as the preferred tool for estimating the positions of environmental research sites. One important problem, however, is that it can be difficult to estimate the uncertainty of GPS-derived positions. Sources of error include various satellite- and site-related factors, such as forest canopy and topographic obstructions. In a case study from the Hubbard Brook Experimental Forest in New Hampshire, hand-held, mapping-grade GPS receivers generally estimated positions with 1–5 m precision in open, unobstructed settings, and 20–30 m precision under forest canopy. Surveying-grade receivers achieved precisions of 10 cm or less, even in challenging terrain. Users can maximize the quality of their GPS measurements by "mission planning" to take advantage of high-quality satellite conditions. Repeated measurements and simultaneous data collection at multiple points can be used to assess accuracy and precision.

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The global positioning system (GPS) is a powerful satellite-based tool for determining the location of points on and above the Earth's surface. Accuracy, ease of use, and low cost have made GPS technology an essential element in many environmental field studies, where it is used for mapping, surveying plots, and navigation. GPS receivers range in size, cost, and precision, from small, hand-held, recreational-grade units costing as little as $100, to larger surveying-grade units costing $20 000 or more. Recreational-grade receivers can provide position estimates with uncertainties of 10–100 m, mapping-grade receivers have uncertainties of 1–10 m, and surveying-grade equipment is capable of pinpointing a position to within 1 cm or less.

The uncertainty of GPS measurements varies due to the number and positions of the GPS satellites, obstacles that prevent or affect reception of satellite signals, atmospheric conditions, and other sources of error. Some of these factors are predictable (and manageable), such as satellite availability. Others, such as human error, can be minimized by using effective practices. Difficulties linked to a particular site are generally unavoidable. Our objective in this paper is to help environmental field scientists maximize the precision of their GPS measurements by (1) providing an overview of how GPS works; (2) discussing major sources of error in GPS; (3) offering guidance on obtaining the best possible results; and (4) presenting representative results of GPS measurements under ideal and challenging field conditions.

In a nutshell:

- The global positioning system (GPS) is a convenient tool for determining the geographic positions of research sites
- The precision of GPS measurements varies from less than one centimeter to several hundred meters, depending on the grade of receiver, method of measurement, satellite conditions, tree canopy, and other factors
- Researchers can maximize the quality of their GPS measurements using readily available planning tools
- Choosing an instrument capable of delivering the desired precision is crucial to a successful GPS mission

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The global positioning system

The Navigation System with Timing and Ranging (NAVSTAR), operated by the US Department of Defense, is the most established GPS. Russia is in the process of deploying satellites for its GLONASS GPS, and Europe is adding to its GPS constellation over the next few years. Most commercially available GPS receivers receive NAVSTAR transmissions, although some are capable of receiving both NAVSTAR and GLONASS signals.

The NAVSTAR GPS can be viewed as having three separate components. The *space segment* includes 24 operational satellites together with five spares, already in orbit, that can be placed in service as needed. Four satellites orbit the Earth in each of six paths, taking 12 hours to circle the globe at an altitude of approximately 20 200 km. This configuration ensures that at least four satellites are "visible" at any point on the Earth at all times. The *ground control segment* consists of a master control station in Colorado Springs and five tracking stations (Colorado Springs, Ascension Island, Diego Garcia, Kwajelein, and Hawaii). Based on observations from the tracking stations, precise updates of the satellite orbits are transmitted to the satellites. Finally, the *user segment* consists of the equipment necessary to receive and understand GPS signals. At a minimum, this involves a GPS antenna, receiver, and software to process the signals and display the results. Hand-held recreational- and mapping-grade GPS units contain these components in a single device.

How GPS works

The basic GPS measurement is the *range*, which is the distance from the satellite to the antenna. The signal transmitted by NAVSTAR GPS satellites includes two *pseudorandom noise* (PRN) codes, time data, and data on the status of the satellite. The PRN codes are random sequences of zeroes and ones. The *coarse acquisition code* is a short code, transmitted at a rate of about 1 million digits per second, repeated every millisecond. Recreational-grade and inexpensive mapping-grade receivers typically acquire only this signal. The precision code is transmitted at a rate of about 10 million digits per second and is repeated once a week. The *precision code* is more difficult to use, but allows extremely precise measurements. Surveying-grade GPS receivers and some mapping-grade receivers are capable of receiving both codes. The coarse acquisition and precision codes are both transmitted on several frequencies, two of which are available to civilian users. Single-frequency receivers access only one of these frequencies, while dual-frequency receivers access both. Dual frequency technology is currently limited to high-end, surveying-grade receivers.

The range can be determined in two ways. First, the travel time of the signal can be calculated from the known time of transmission and the measured time of reception. This is used to estimate the *pseudorange*. The range is computed by adjusting the pseudorange for a number of biases and errors in the orbit and operation of the transmitting satellite. Alternatively, the range can be estimated by measuring the difference in the phase of the GPS signal between satellite and receiver. Using this *phase delay* can produce more accurate approximations of the range, but there is a fundamental problem: the signal that passes from the satellite to the receiver includes an unknowable whole number of code strings plus the partial code that is used to determine the phase delay. This whole number, referred to as the "phase ambiguity", must be resolved to estimate the range. Single-frequency receivers do this statistically, whereas dual-frequency receivers can use the two signals and the clock-based pseudorange to estimate the ambiguity precisely (Hofmann-Wellenhof *et al.* 2001).

With a range, *r*, computed from one satellite, the position of the antenna could be anywhere on a sphere of radius r centered on the satellite transmitter. With ranges from two satellites, the position is restricted to the circle forming the intersection of the two spheres. The spheres around three satellites intersect at two points, one of which is easily disregarded because it is not near the surface of the Earth. Thus, it should be possible to determine a position with only three satellites. Because the receiver clock is not precisely synchronous with the satellite clocks, the calculated ranges will contain clock error. A fourth satellite provides the data needed to calculate the clock error common to all range measurements. Additional satellites are redundant, but allow for the statistical refinement of the estimated position.

Sources of error in GPS

There are numerous sources of error in any GPS measurement; fortunately, many are small and techniques exist to offset others. Satellite clock errors and discrepancies in satellite positions (ephemeris errors) are monitored by the control segment and are corrected before they become problematic. Similarly, errors associated with receiver noise and performance tend to be minor. There are three principal sources of error that GPS users should understand: atmospheric refraction of GPS signals, multipathing, and poor satellite geometry.

Like all waves, GPS signals are affected by the medium through which they travel. Gases, especially water vapor, slow the GPS signal in the troposphere, resulting in an overestimation of the range. In the ionosphere, part of the signal is advanced by interaction with charged gases, while another part is delayed. Together, these errors are in the 1–5 m range (Misra and Enge 2001). Dual-frequency receivers nearly eliminate ionospheric effects by comparing the propagation of the signal at two frequencies (Leick 2003). Atmospheric effects are minimized when a satellite is directly above the antenna and increase as the *inclination angle* decreases. As a rule of thumb, satellites lower than 10°–15° above the horizon should not be used for positioning because of atmospheric refraction.

Because GPS satellites can be anywhere in the sky, GPS antennas must be omnidirectional. Therefore, in addition to receiving a signal directly from a satellite, the antenna also receives reflections of the signal from other surfaces, including the ground, water bodies, buildings, and cliff faces. This phenomenon, known as multipathing, is also caused by leaves and tree trunks in forests. The reflected signals are delayed and are weaker than the direct signal, causing statistical confusion as the receiver analyzes the GPS data. The magnitude of multipathing errors can be in the region of 1–5 m (Misra and Enge 2001). An obvious strategy to avoid multipathing is to move the antenna away from large surfaces or above the forest canopy. Unfortunately, this is not always practical, though there are ways to assess the precision of surveys influenced by multipath errors (see the Case Study section).

Even under ideal atmospheric and multipathing conditions, the results of GPS measurements may be compromised by poor satellite geometry. If two satellites are in approximately the same location relative to the antenna, they provide essentially the same information. The influence of satellite geometry is quantified using various *dilution of precision* (DOP) indices. Positional DOP (PDOP) expresses uncertainty in overall position, whereas uncertainty in horizontal and vertical position are indexed by

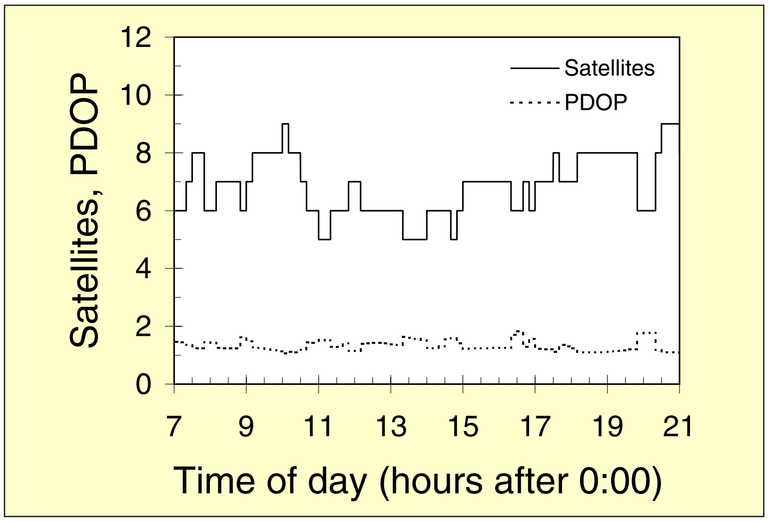

Figure 1. *Number of satellites and positional dilution of precision (PDOP) for August 2, 2002, at the Hubbard Brook Experimental Forest, NH. Only satellites positioned at greater than 15° above the horizon are included. PDOP values of less than 2 are desirable.*

HDOP and VDOP, respectively. DOP values generally range from 1–10 and can be viewed as multiples of the minimum uncertainty (Hofmann-Wellenhof *et al.* 2001). For example, a measurement made with an HDOP of 3.0 has an uncertainty in horizontal position that is approximately three times that of the receiver capability.

■ Mission planning – getting the most out of your GPS measurements

Because the orbits of the satellites in the GPS constellation are known and predictable, their number and geometry can be computed for any time in the future. Mission planning is the process of scheduling GPS observations at times when the number and geometry of satellites are ideal. Planning software is available at no cost from major GPS manufacturers (eg Trimble Navigation and Leica Geosystems).

Figure 1 shows the number of satellites and PDOP values for 7 am to 9 pm on August 2, 2002, at the Hubbard Brook Experimental Forest, NH. The 8:10–10:30 am and 5:00–7:40 pm periods offered the best GPS opportunities, with seven or more satellites available at almost all times and PDOP values of always less than two. Mission planning also allows the scientist to focus on other research activities during time periods when satellite availability is poor.

■ Modes of GPS measurement

The uncertainty of a single GPS measurement can be 10 m or more. This may be acceptable for general navigation or for mapping large land areas, but for applications requiring greater precision, *differential* GPS techniques can be used to improve measurement quality.

In differential GPS, simultaneous measurements are made at the point of interest and a point of known position. Ideally, this "control point" should be within a few km of the point being measured. Because the two points are very close to each other, relative to their distances from the satellites, the errors affecting the GPS signals at the two points are very similar. The difference between the known and computed positions of the control point (ie the measurement error) can therefore be applied to the computed position of the unknown point to improve accuracy. The GPS measurements at the two points are used to compute the length and direction of the baseline that connects them. These values are then used to compute the difference in latitude and longitude between the points and, subsequently, the position of the unknown point. The receiver positioned over the control point is called the "base", and the receiver at the unknown point is the "rover" (Figure 2). If multiple rovers are available, it is possible to measure simultaneously all the baselines connecting the observation points. This saves time and provides

Figure 2. *A rover antenna set up for differential GPS. The GPS antenna is the white disk at the top of the black pole; the receiver (yellow) is mounted halfway up the pole, facing the reader. The hand-held controller/data-logger (also yellow), used to set the data acquisition conditions and to download data after collection is complete, is mounted above the receiver.*

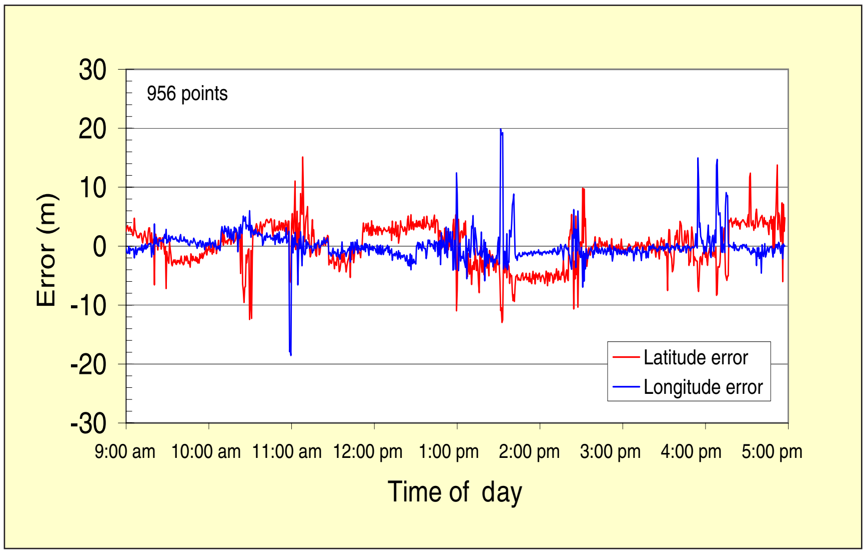

Figure 3. *Variations in GPS-estimated latitude and longitude in an open-field site in West Thornton, NH, near the Hubbard Brook Experimental Forest. "Error" is the difference between individual position measurements and the mean for the experiment. Data were collected at 30-second intervals.*

a means of assessing the precision of the GPS measurements.

Differential GPS is normally conducted by a technique known as "post processing". All surveying-grade receivers, and some hand-held receivers, can log raw GPS data. In a post-processing survey, raw data are collected at the control and unknown points for times ranging from a few minutes to a few hours. A computer program is then used to process the data and produce the estimated position of the unknown points. Post-processing software is typically provided by the instrument manufacturer.

If only one receiver is used, differential GPS can be performed by using a *continuously operating reference station* (CORS) as the control point. CORS sites are maintained by government and private organizations and provide GPS data free of charge. The data are posted on the National Geodetic Survey (NGS) website (www.ngs.noaa.gov). As of August 2004, there were 688 CORS stations listed on the web page, covering all 50 states, most US territories, and some foreign countries. The NGS website has a free, web-based interactive program called OPUS that will process GPS data using the three nearest CORS sites as controls.

At the high end of surveying-grade GPS is *real-time differential GPS*. This technique uses a radio modem that continuously transmits the GPS data from the base. The rover receiver processes the data immediately and produces the estimated position. The obvious advantage of real-time methods is that the user receives the results instantly, which is particularly valuable when navigating to a point of known position.

Recreational-grade and some mapping-grade receivers cannot be used for differential GPS. However, the accuracy of recreational-grade receivers can be improved when they are enabled to receive correction data from the *wide area augmentation system* (WAAS). The WAAS is a GPS-based navigation network that receives signals from GPS satellites at approximately 25 ground reference stations. Data from these stations are transmitted to geosynchronous satellites and broadcast to WAAS-enabled receivers. Position accuracies of 7 m or less can be obtained in unobstructed conditions.

■ Case study

To illustrate the quality of GPS measurements that can be obtained in environmental field studies, we present results from the Hubbard Brook Experimental Forest, NH. We examined the performance of both a high-quality, hand-held, mapping-grade receiver and surveying-grade equipment with mission planning in optimal (unobstructed) and challenging (under-canopy) conditions.

Mapping-grade measurements

The hand-held receiver used was the Rockwell Collins +96 Federal Precision Lightweight GPS Receiver (PLGR), developed for use by US Government agencies. The PLGR is a mapping-grade, non-differential instrument. On August 2, 2002, Genova and Barton (2004) deployed PLGR units at two nearby locations at the Pleasant View Farm facility at Hubbard Brook. One receiver was placed at an unobstructed site and the other was partially obstructed by forest canopy. The receivers were set on the ground and recorded the GPS position at 30-second intervals for 6 to 8 hours. The results of typical

Table 1. Measured and published coordinates of New Hampshire Department of Transportation disk (survey marker) #259-0500 at Lincoln, NH

	Northing (m)	Easting (m)
Measured coordinates	172 381.458	298 204.799
Published coordinates	172 381.445	298 204.808
Difference	0.013	0.009
Straight-line difference	0.016 m	
Distance from control point	30 704.951 m	
Precision	0.51 ppm	

Northing and easting values are grid coordinates in the north–south and east–west directions, respectively, based on an appropriate map projection. The values in this table refer to the New Hampshire State Plane Coordinate System, based on the 1983 North American Datum (NAD83).

tests are shown in Figures 3 and 4. The errors plotted in the figures represent the differences between each recorded GPS position and the corresponding mean value for the test.

For the receiver in the unobstructed location (Figure 3), errors in latitude and longitude were generally less than ± 5 m, with occasional deviations up to ± 20 m. Errors in latitude were not synchronous with those in longitude and were generally larger. The latitude error was ± 5 m or less for 86% of the measurements, and ± 10 m for 98% of the measurements. In contrast, the longitude error was ± 5 m or less for 96% of the measurements, and ± 10 m for 99% of the measurements. The large errors at approximately 11:00 am, 1:40 pm, and 2:40 pm (Figure 3) occurred at times when only five satellites were visible (Figure 1). In another experiment, Genova and Barton (2004) deployed two identical PLGR units side by side at the open site and observed that errors ± 5 m were not synchronous between the two instruments. This suggests that errors in this range are due to the technical limitations of these mapping-grade instruments.

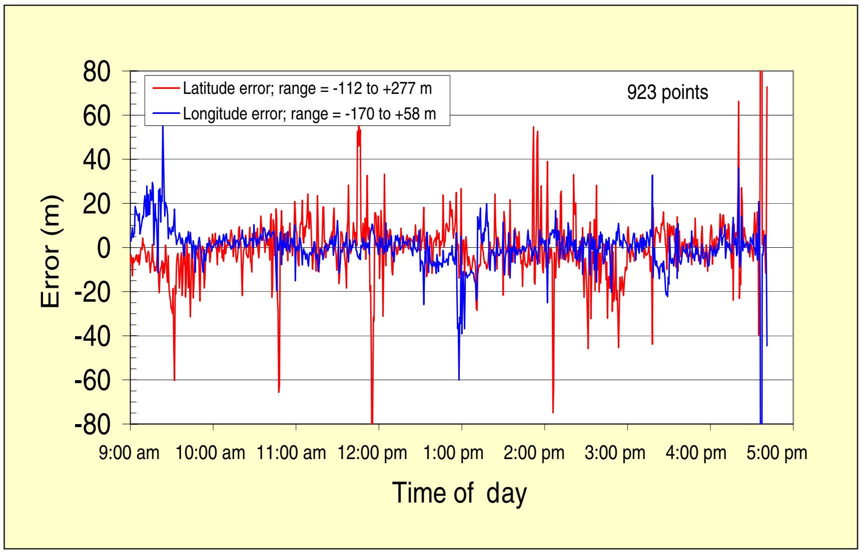

Figure 4. *Variations in GPS-estimated latitude and longitude under forest canopy in West Thornton, NH, near the Hubbard Brook Experimental Forest. "Error" is the difference between individual position measurements and the mean for the experiment. Data were collected at 30-second intervals.*

Figure 4 shows the errors in latitude and longitude for the receiver positioned under the forest canopy. The uncertainty in this experiment was considerably greater than in the open area. Deviations of individual observations from the mean were as great as 277 m. The latitude error was ± 5 m or less for 47% of the measurements, and ± 10 m for only 74% of the measurements. In longitude, the error was ± 5 m or less for 62% of the measurements, and ± 10 m for 85% of the measurements.

Because the experiments took place simultaneously, the differences between Figures 3 and 4 reflect the effect of canopy cover on the precision of the GPS measurements. The PLGR receivers are among the best of the non-differential, mapping-grade receivers. Our results suggest that precision levels of ± 5 m are obtainable at unobstructed sites, but precision under the forest canopy is about ± 20–30 m. For more precise measurements, differential methods would be required.

Table 2. Measured coordinates of the New Hampshire Department of Transportation survey marker located outside of the Forest Service office at the Hubbard Brook Experimental Forest, NH

Control station	Northing (m)	Easting (m)
Plymouth, NH	160 408.049	297 235.162
Lincoln, NH	160 408.029	297 235,163
Difference	0.020	0.001
Straight-line difference	0.020 m	
Average distance to control point	15 119.873 m	
Precision	1.32 ppm	

Northing and easting values refer to the New Hampshire State Plane Coordinate System, based on the 1983 North American Datum (NAD83).

Differential GPS with a surveying-grade system

We also examined the effectiveness of surveying-grade GPS equipment at Hubbard Brook. Trimble's System 5700 is a dual-frequency receiver best suited for differential GPS. We used one receiver as a base and up to five others as rovers. Our objective was to determine the positions of a control marker (NHDOT #459-0560) at the Hubbard Brook headquarters building (HBHQ) and six US Geological Survey elevation benchmarks within the Hubbard Brook forest (Figure 5). The marker at HBHQ lies in an open area, acting as a test for the equipment in an unobstructed setting. The USGS benchmarks lie under the forest canopy, providing a more challenging trial.

First, we used two NGS-published survey markers in the vicinity of Hubbard Brook to measure the GPS coordinates of a "known" point as if it were unknown. We deployed the base receiver over the Plymouth marker (NGS H-35), about 19 km to the south of Hubbard Brook, and a rover over the Lincoln marker (NHDOT #259-0500), about 12 km to the north. The estimated coordinates of the Lincoln benchmark were within 16 mm of the published coordinates (Table 1).

Next, we measured the coordinates of the HBHQ marker twice, using the Plymouth benchmark as the base, then with the base at Lincoln. These two measurements agreed to within 2 cm (Table 2), indicating that extremely precise measurements are obtainable in open areas using differential GPS. Our computed posi-

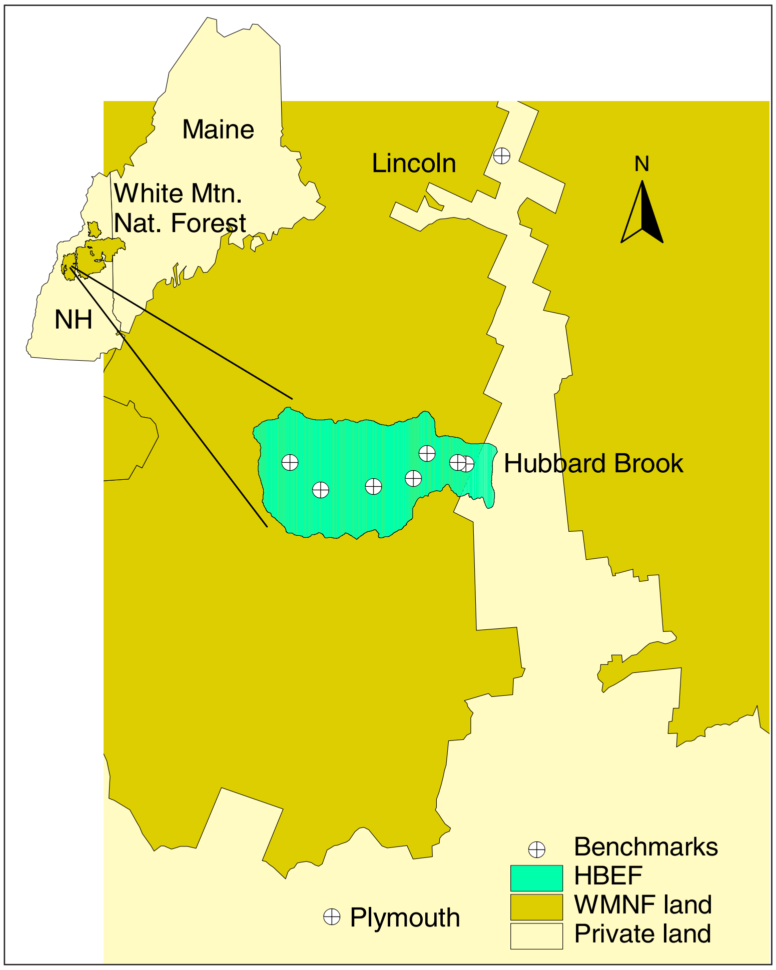

Figure 5. *Map of the Hubbard Brook Experimental Forest (HBEF) within the White Mountain National Forest (WMNF), NH, showing survey markers used in the case study.*

tion was also within 15 cm of the position provided by the New Hampshire Department of Transportation (Table 2), which was determined by differential GPS as well.

After establishing reliable coordinates for the HBHQ marker, we next determined coordinates for the USGS benchmarks in the forest. To assess measurement precision, multiple observations were collected at each benchmark, on different dates, using different control points. Some of the benchmarks were in particularly challenging locations. For example, BM1765 is on the abutment of a culvert, about 2 m below the adjacent road (Figure 6), so the GPS antenna was at ground level, under the canopy, in steep terrain. Nevertheless, three independent measurements differed by a maximum straight-line distance of only 18 mm (Table 3). Results for the other markers were equally good.

Multiple GPS observations allow the user to assess precision directly. For hand-held recreational-grade receivers, this may be the only estimate of precision the user can obtain. Multiple observations also allow the user to identify outlying measurements. For example, the measurement of BM918 made on May 16 was substantially different from the others (Table 3; note especially the "easting" value). This observation can be deleted and the coordinates estimated from the remaining values. Ideally, multiple observations are made on different days or from different control points or both.

Precision can also be estimated using the concept known to surveyors as "loop closure". Figure 7 shows the HBHQ control point and two of the USGS markers. By making simultaneous GPS observations at all three points, one can independently estimate the three baselines that connect them. For example, using only the data from HBHQ and BM1765, we could compute the length and direction of the line connecting them. Next, using only the data from BM1765 and BM1250, the second leg of the triangle is computed, and similarly for the third leg. Because these estimated baselines are independent, there is no guarantee that the three legs will actually form a properly closed triangle. The loop closure is the distance by which the triangle fails to close (Benton and Taetz 1991). This value, divided by the total distance around the loop, and expressed as parts per million (ppm), is a measure of the precision of the survey. A precision level of 10

Table 3. Results of repeated position measurements of US Geological Survey benchmarks at the Hubbard Brook Experimental Forest, NH

Benchmark	Control point	Date	Northing (m)	Easting (m)
USGS BM918	Plymouth	5/14	160 488.991	296 871.441
	HBHQ	5/15	160 489.212	296 871.402
	HBHQ	5/16	160 489.717	296 870.931
	HBHQ	5/20	160 489.203	296 871.394
	BM1765	5/20	160 489.314	296 871.451
USGS BM1250	Plymouth	5/14	160 784.657	295 746.432
	HBHQ	5/15	160 784.693	295 746.463
	HBHQ	5/16	160 784.679	295 746.464
USGS BM1439	HBHQ	5/20	159 776.124	295 172.189
	BM1765	5/20	159 776.139	295 172.096
USGS BM1511	HBHQ	5/15	159 448.102	293 723.953
	HBHQ	5/20	159 448.100	293 723.963
	BM1765	5/20	159 448.102	293 723.967
USGS BM1765	Lincoln	5/15	159 161.955	291 746.797
	HBHQ	5/15	159 161.960	291 746.798
	HBHQ	5/17	159 161.970	291 746.806
USGS BM1772	HBHQ	5/17	160 193.069	290 522.358
	HBHQ	5/20	160 193.080	290 522.362
	BM1765	5/20	160 193.083	290 522.378

Northing and easting values are New Hampshire State Plane coordinates, based on NAD83.

ppm, for example, represents 10 mm of error per kilometer traversed in the loop. The loop shown in Figure 7 had a closure of 15 and 16 mm on two different dates, yielding precision levels of 5.3 and 6.0 ppm.

When more than three receivers are deployed simultaneously, a web-like network of baselines is produced (Figure 8). Networks like this are extremely valuable, although they require considerable GPS resources. First, numerous triangular loops can be constructed within the network to assess precision. Second, individual baselines that have poor precision can be deleted without compromising the network. For example, if any of the three baselines in Figure 7 were discarded, there would be no loop left to assess precision. In contrast, three or four of the baselines in Figure 8 could be discarded, yet numerous loops would still be available.

Taken together, our loop closures and repeated measurements indicate that differential GPS using surveying-grade instruments can provide precise estimates of horizontal positions, even under the challenging conditions experienced in the White Mountains of New Hampshire.

Figure 6. *This location (BM1765 in Figure 5) offers a real challenge for GPS surveying. The marker is about 2 m below the adjacent road, under the forest canopy, in hilly terrain.*

■ Cutting butter with a scalpel

What is the best approach for using GPS in your study? Not surprisingly, the answer depends on how the data are to be used. Many environmental researchers use GPS to locate their plots on a site map. Unless the map scale is very small, a single measurement with a hand-held receiver is almost certainly sufficient. Using surveying-grade receivers would be, as a colleague once quipped, "like cutting butter with a scalpel". Similarly, to determine the distances and directions between widely spaced research plots – for geostatistical analysis, for example – mapping-grade receivers can produce good results if the plots are more than a few hundred meters apart. Repeat measurements at a subset of plots would allow the researcher to assess the uncertainty of the coordinates.

Differential GPS is the better option for applications requiring greater precision. For example, the computation of nutrient outputs from small watersheds, a focus of research at Hubbard Brook

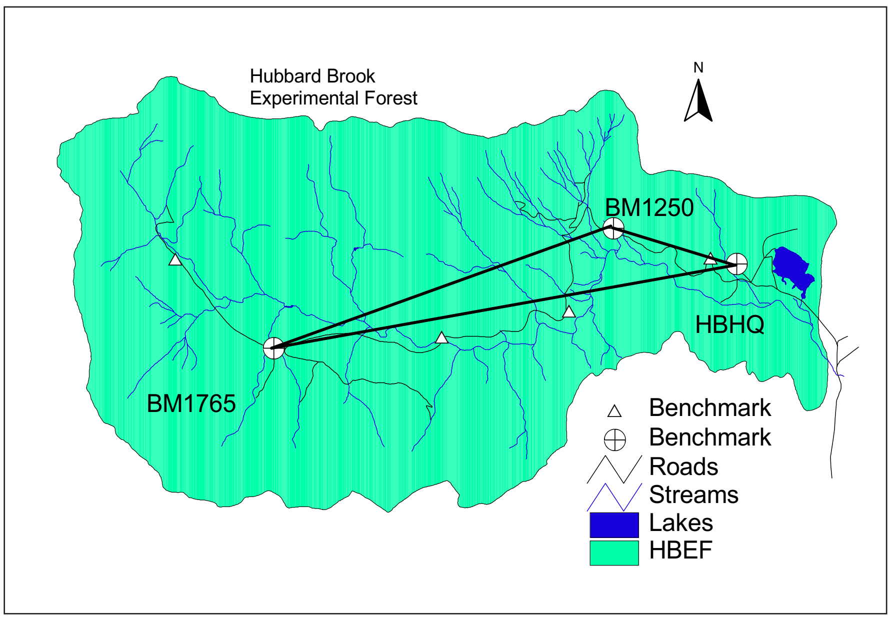

Figure 7. *A simple survey loop with three points. Simultaneous GPS measurements at the three points yield independent estimates of the baselines connecting the points. The precision of the survey can be estimated by computing the distance by which the loop fails to close.*

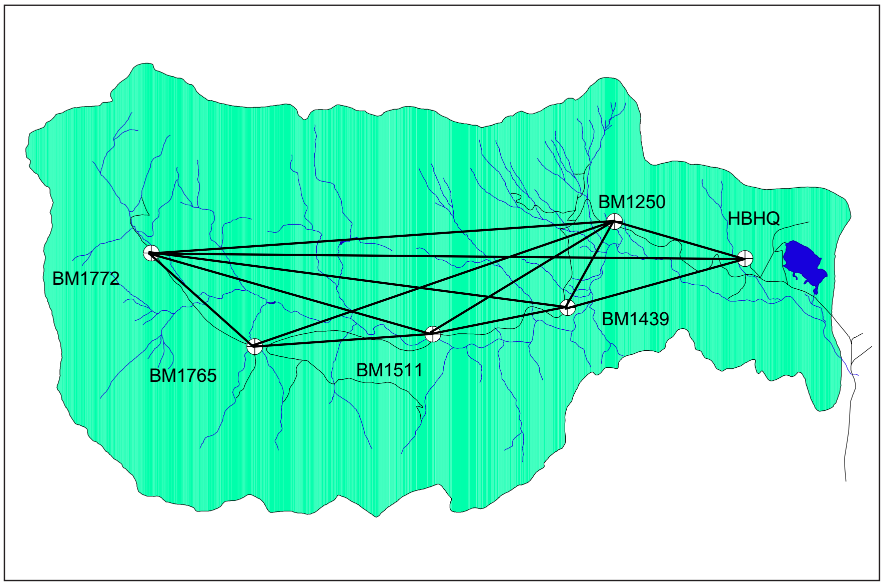

Figure 8. *With more than three receivers operating simultaneously, it is possible to construct a network of baselines. This network provides numerous loops that can be used to assess precision. Furthermore, any individual baseline can be omitted without compromising the survey.*

(Likens and Bormann 1995), requires accurate estimates of watershed area. The perimeter of Watershed 1 (WS-1) at Hubbard Brook is approximately 2200 m. Using a good quality, mapping-grade receiver can result in uncertainties of ± 10 m or more in the forest. Thus, the uncertainty in the watershed area could be ± 2.2 ha or more. This represents 19% of the 11.8 ha total area of WS-1, a major source of uncertainty for this type of research. High-precision differential GPS measurements could reduce this uncertainty by two or three orders of magnitude. Other applications that may benefit from differential GPS include geostatistical studies involving fine-scale grids, studies of bird nesting patterns, and studies involving irregularly shaped plots. Whatever the application, using the appropriate GPS tool is the key to obtaining satisfactory position data.

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