A New Level of Accuracy for Differential GPS Mapping Applications using EVEREST™ Multipath Rejection Technology

Trimble's Everest multipath rejection technology provides a new high-accuracy solution for code-based GPS mapping applications. By rejecting multipath signals before computing positions, the new GPS Pathfinder Pro XR with Everest provides up to 50% higher accuracy than previous Pathfinder mapping systems. These new systems deliver a horizontal RMS error of 35 centimeters, and a vertical RMS error of 55 centimeters on a second-by-second basis while static. Dynamic tests show even better results, with horizontal RMS errors as low as 15 centimeters and vertical RMS errors as low as 30 centimeters. Mapping area and line features with high accuracy can now be accomplished with errors consistently below 1% of the area size or line length for most features.

INTRODUCTION

Digital mapping has come of age with the union of Global Positioning System (GPS) and Geographic Information System (GIS) technologies. Creating accurate digital map databases from real world data has long been the dream of city planners, utility companies, foresters, farmers, and anyone whose daily work requires the use of up-to-date maps. With Trimble's new Everest technology, the dream becomes a reality by bringing a new level of accuracy to GPS mapping data.

Trimble Navigation Limited pioneered digital data collection for mapping with the GPS Pathfinder mapping product series. Using primarily code-based GPS signals, the Pathfinder products provide fast, flexible, efficient, and easy-to-use mapping solutions that meet the needs of all mapping projects. The advantages of Trimble's code-based GPS over carrier-phase systems include much faster processing times, flexible data collection techniques that don't require continuous satellite tracking, and instantaneous high accuracy results on a point-by-point basis.

Field mapping requires working in a variety of difficult conditions from forests or swamps to the urban canyons of city streets. For GPS mapping, these difficult field conditions mean reflected satellite signals. The main problem is that satellite signals are reflected from nearby objects such as buildings, trees, cars, fences, water surfaces, etc. These reflections, referred to as multipath signals, cause all GPS receivers difficulty in determining positions accurately. It's the same difficulty you have when trying to view the picture on your TV when there is a ghost (multipath) signal present. Or, when you try to listen to what someone is saying in a room with a strong echo; it's hard to determine what they're saying because you hear both the direct sound of their voice and the echo.

Multipath signals have limited the performance of code-based differential GPS mapping receivers to meter-level accuracy. To address the needs of today's demanding mapping projects and the ever-increasing requirements for higher accuracy, multipath signals must be removed before the GPS receiver calculates positions or stores code measurements for later differential correction. Trimble's new Everest technology does that, it removes multipath signals before code measurements are stored or used to calculate position. Using techniques patented by Trimble, Everest multipath rejection technology enhances mapping accuracy in any difficult field mapping environment.

Everest is now included in the GPS Pathfinder Pro XR and the GPS Pathfinder Community Base Station (CBS). These mapping products bring a new level of accuracy to the fast, efficient and easy-to-use code-based mapping techniques that Trimble's customers enjoy. In this paper, we show how these products can increase mapping accuracy by 50%, to levels previously associated only with carrier-phase processing and field techniques. In the discussions that follow, we are referring to code-based differentially corrected positions such as those produced by Trimble's Pathfinder Office differential correction software.

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WHAT IS ACCURACY?

Accuracy is a term that broadly describes the level of uncertainty, or error, associated with experimental measurements. Our measurements have high accuracy when errors are small, and low accuracy when errors are large. For GPS, measured positions can be compared with true geographic coordinates to assess the level of error. Since the creation of new map databases requires GPS mapping of previously unknown feature locations, accuracy can be hard to assess. The best way to assess accuracy during a field mapping project is to include several previously located features and to compare your results with the published geographic coordinates for those features. If no comparison is possible, then you must rely on a combination of your own experience, product specifications, and product performance reports like this one. If we do have knowledge of the true geographic coordinates of the features mapped, we can describe the accuracy of those features in the following ways.

For point features, there are usually many GPS positions collected and averaged, the error is the distance between the average position and the true geographic position of the point being measured. Because GPS errors are time dependent, averaging for longer periods reduces the error of the resulting average position. This time dependence also means the standard deviation of the set of positions that make up the average does not represent the error of the average position. Accuracy for point features is described by a Root Mean Square (RMS) horizontal and vertical error.

For line features, the distance between the measured line and the true path is the error. The measured line may have a different length than the true path, and there may also be a path-perpendicular error that offsets the measured line from the true path. Path-perpendicular errors can be summarized by an RMS path-perpendicular error of all the points that make up the line feature. Length errors can be described in magnitude or as a percent of the total length of the true path.

For area features, the difference in size between the measured area and true area determines the error. Area size errors can be described by their magnitude or as a percent of the total true area. Since instantaneous GPS errors are relatively constant from point to point, the larger area that you measure, the smaller the percent-of-total-area error.

A WORD ABOUT RMS

When a Root Mean Square, or RMS, error is used to describe uncertainty, it implies that a repeated experiment has been performed. When an accuracy experiment has been repeated many times, each individual experiment has an associated error value. Because the error determined from each experiment is a little different, all the experiments together define a distribution of error. One way of summarizing the distribution of error from these repeated experiments is to use the RMS error. The RMS error is a single number that summarizes the entire error distribution.

If position errors are random, equally distributed in the east and north directions, and include no systematic errors, 63% of the positions have horizontal error less than or equal to the RMS horizontal error. If the RMS is multiplied by two, called the 2D RMS, 98% of the positions have horizontal error less than or equal to this value. If the errors are not equally distributed in the east and north directions, the percentages can vary. The percentages also vary when there are non-random systematic errors present. For GPS positions, the RMS usually varies from 63-67% and the 2D RMS from 95-98%, though it is possible to have other values as well.

These percentage values are often referred to as confidence levels. Thus, to have 63-67% confidence, you use the RMS to summarize your results. To have 95-98% confidence, you use the 2D RMS. In order to have a higher confidence level, you must accept a larger uncertainty (error).

In the following sections, we summarize the results of accuracy experiments performed by Trimble in and near Sunnyvale, California, in early 1997. These results illustrate the new level of accuracy provided by Trimble's patented Everest multipath rejection technology for mapping. For all tests, we used a GPS Pathfinder Pro XR with Everest for both the base station and the rover. At the base station we used Trimble's L1-Geodetic antenna (the standard groundplane antenna provided with the CBS). These experiments were conducted in relatively good GPS observing conditions.

In a final section, we compare the performance of using a different base station receiver, the GPS Pathfinder Pro XL. The Pro XL receiver uses older technology and was the standard for Trimble's Pathfinder Community Base Station systems. The new Community Base Station now includes the Pro XR with Everest receiver and provides substantial gains in accuracy for all users of base station data.

STATIC POINT FEATURES

Point feature accuracy is primarily determined by the amount of time spent at the point, the occupation time. If only one position is used for a point feature, the accuracy for that single position can be described by the instantaneous accuracy of your GPS system. GPS receiver specifications are usually reported as an instantaneous RMS error. Each differentially corrected position from the system has an error that lies within an error distribution characterized by the specified RMS. This means you can expect that about 63-67% of your positions will have an error less than or equal to the specified RMS.

For point features, the GPS antenna remains stationary relative to any multipath-generating reflective objects nearby. In this situation, multipath can have a strong influence on accuracy. The following results are from a test of the instantaneous static position accuracy of the GPS Pathfinder Pro XR with Everest when differential corrections are provided by the new Pathfinder Community Base Station. These instantaneous RMS errors were obtained by examining position errors continuously for 4 days while logging data at a 5-second rate.

Pro XR with Everest (Base and Rover) Instantaneous Static Position Accuracy	
Horizontal RMS Error	**35 cm**
Vertical RMS Error	**55 cm**

Longer occupation times mean higher accuracy of the resulting average of multiple positions. By averaging instantaneous positions, a more accurate position can be created that best represents all of the position measurements made during the occupation. The same data used above can be averaged for different occupation times to find how accuracy depends on occupation time. For each occupation time, we compute the average position for all the occupations available in our 4-day data set. Then we compute the RMS error of all the average positions at each occupation time. By plotting a graph of the RMS error versus occupation time, Figure 1 shows the accuracy gains achieved by averaging. By averaging for 20 minutes, the RMS horizontal error is reduced by 46% to 19 cm and the RMS vertical error is reduced by 42% to 32 cm. Thus, there is a trade-off between accuracy and occupation time. To achieve higher point feature accuracy requires investing more time.

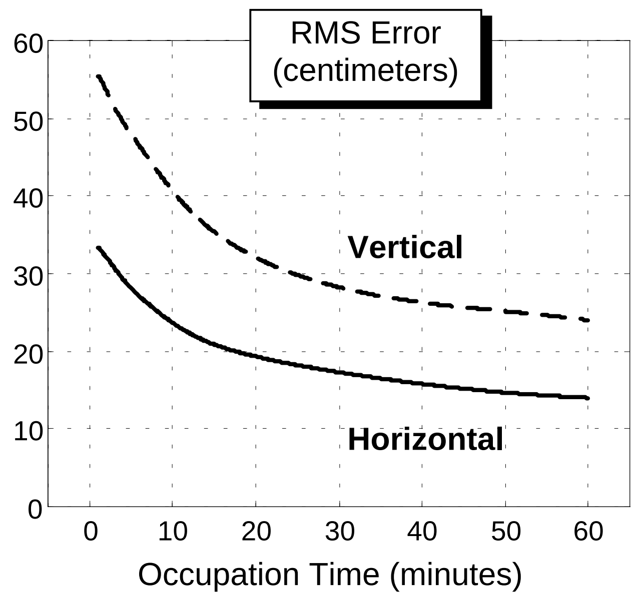

Figure 1. RMS error versus occupation time for static point features. Dashed line, vertical RMS error; solid line, horizontal RMS error. Accuracy of average positions improves rapidly during the first 20 minutes, and slowly after.

DYNAMIC LINE AND AREA FEATURES

Line feature accuracy is primarily determined by the proportion of the instantaneous error perpendicular to the path being traveled. Similarly, area feature accuracy is primarily determined by the proportion of the instantaneous error perpendicular to the perimeter of the area being mapped. Since the instantaneous errors are distributed in all directions, the path-perpendicular error is generally smaller than the instantaneous position error. Some errors lie along the direction of travel and contribute little to line-length, line-position, and area error.

While collecting line and area features, the GPS antenna is moving relative to nearby multipath-generating reflective objects. In dynamic situations multipath signals are less troublesome, and this can result in better accuracy than when the antenna is static.

In a test of dynamic accuracy performed near Sunnyvale, California, 15 circuits around a football-field track were walked during an approximately hour-long session (see the appendix). Positions were logged every second and "true" positions were provided by a survey-grade GPS receiver using the same antenna. The resulting differentially corrected positions between a base station Pro XR with Everest and the rover Pro XR with Everest were compared with the survey-grade carrier-phase baseline solutions to determine the accuracy of the mapping system. The following results summarize the average of the instantaneous RMS error for the 15 repeated circuits.

Pro XR with Everest (Base and Rover) Average Dynamic Position Accuracy	
Horizontal RMS Error	**28 cm**
Vertical RMS Error	**43 cm**

For comparison the instantaneous static RMS values are 35 cm horizontal, and 55 cm vertical. Better dynamic accuracy is a result of the relative motion between the antenna and the multipath-generating reflecting objects nearby. Multipath is less troublesome in dynamic conditions.

This test also provided 15 repeated measurements of a 0.4 km-long line and a 9,715 square meter (2.4 acre) area. The following results summarize the average feature accuracy of the 15 dynamic line and area features that were mapped.

Pro XR with Everest (Base and Rover) Average Dynamic Feature Accuracy	
Path-perpendicular RMS	**21 cm**
Path-parallel RMS	**18 cm**
Path-length Error	**20 cm**
Area-size Error	**24 m^2**
Percent Length Error	**0.05%**
Percent Area Error	**0.24%**

These impressive results show that line and area features can be mapped with high accuracy using Trimble's GPS Pathfinder Pro XR mapping systems with Everest.

PRO XL VS. PRO XR-EVEREST BASE

As an example of how Trimble's Everest technology improves accuracy by rejecting multipath signals, we compared the difference in performance when using older base station technology. In a test that uses one GPS Pathfinder Pro XR with Everest rover receiver, and two different base stations, a Pro XL and a Pro XR with Everest, a dramatic improvement in accuracy is observed.

Pro XR with Everest (Rover) Instantaneous Static Position Accuracy		
	Pro XL CBS	**Pro XR-Everest CBS**
Horizontal RMS Error	**52 cm**	**35 cm**
Vertical RMS Error	**107 cm**	**55 cm**

This comparison shows that multipath is a significant factor affecting position accuracy. With Trimble's Everest multipath rejection technology in the base station receiver, performance is improved by 33% in the horizontal and by 49% in the vertical. When compared with older Trimble technologies which used Pro XL receivers as both the base and rover receivers, the new Pro XR mapping systems provide 50% better horizontal and vertical accuracy.

If you use a Pro XL CBS, you must average positions for at least 40 minutes to achieve the instantaneous accuracy provided by the newer Pro XR with Everest CBS. Figure 2 compares the horizontal RMS error for averaging for both base station receivers.

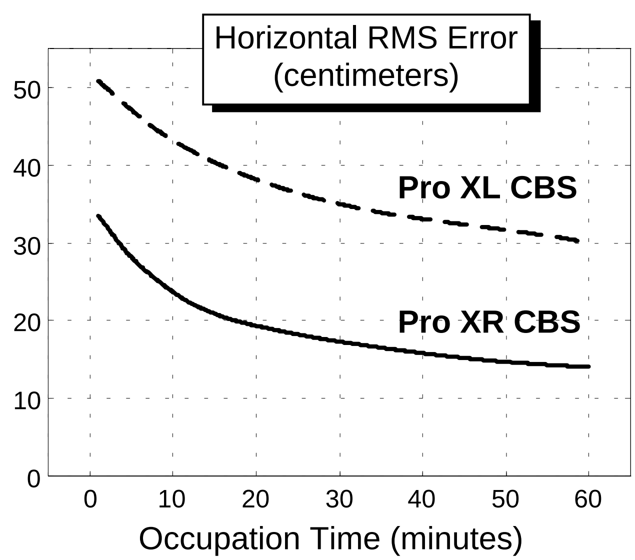

Figure 2. Horizontal RMS error versus occupation time for static point features. Dashed line, using Pro XL CBS; solid line, using Pro XR with Everest CBS. The Pro XR with Everest CBS provides a significant accuracy advantage.

FACTORS AFFECTING ACCURACY

Many factors affect the level of accuracy that you can achieve in a given mapping project. The following is a list of most of the important factors affecting mapping accuracy that you can control:

- Rover GPS receiver type
- Base station GPS receiver type
- Base station coordinate accuracy
- Base station antenna type
- Satellite geometry (PDOP)
- Synchronized logging rates
- Distance between the rover and the base

There are also some factors that you can not control, but affect the accuracy of your results:

- Multipath signals
- Signal obstructions
- Jamming signals
- Ionospheric conditions

In the following paragraphs, the factors you can control are explained in more detail.

The higher quality GPS receiver that you use for your rover, the higher accuracy you can expect. If you use a low quality receiver for either your base or rover your accuracy suffers. Higher quality GPS receivers are built with better electronics and the latest technologies, such as Everest, that allow the GPS signals to be captured with less noise.

Accurate mapping results depend critically on the coordinates of the base station receiver. Any error in the base station receiver coordinates will add to rover position error. Additionally, the base station coordinates must be expressed in the WGS84 datum (NAD83 can be used if the coordinate differences at the base station site are only a few centimeters). Use base stations whose coordinates have been derived from adjusted high-accuracy first-order surveys. It is best if base station coordinates are known with only a couple of centimeters uncertainty.

Using a groundplane antenna at the base station reduces some of the multipath and improves mapping accuracy for all rovers that use that base station. While using a groundplane antenna for rovers would increase accuracy, the physical size of an effective groundplane would be too inconvenient in most rover applications.

Satellite geometry also affects position quality, you should collect positions using the recommended PDOP for your receiver type. Many receivers provide a PDOP mask setting that allows you to control the logging of positions based on a threshold PDOP value. Positions will be logged only when the PDOP is below the threshold.

Generally, it is best to use synchronized logging rates at base and rover receivers so that every position recorded at the rover has a corresponding set of measurements recorded at the base station at the same instant of time. If the logging rates differ, the processing software has to do some interpolation; for example, when the base station is using a 5-second logging rate and the rover is using a 1-second logging rate, interpolation does not introduce significant error into the corrected positions. Using a larger difference in logging rates reduces accuracy.

The distance between the base station and the rover receiver introduces a small additional error to corrected positions. For the GPS Pathfinder Pro XR system, the specification indicates that horizontal error increases with distance at the rate of one ppm (part-per-million). It's handy to remember that one ppm means that you add one millimeter of additional error per kilometer of distance between your base and rover.

While the following factors are generally out of your control, keeping up with the latest technologies can provide great advantages in these areas as well.

Multipath signals reduce accuracy and they are present in every mapping environment. Since you will have to map in areas of multipath signals, the best you can do is to apply the latest technology: Trimble's Everest multipath rejection technology.

Obstructions to the signals that cause partial blockage, such as trees or other overhead canopy, reduce signal strength and can degrade accuracy. Working in these especially difficult conditions requires that you perform careful tests to assess the level of accuracy that you can achieve.

Jamming occurs when non-GPS radio signals interfere with the reception of the GPS signals in the receiver. Very close to radio transmission towers, jamming signals can be troublesome. The Pathfinder Pro XR with Everest includes Trimble's best anti-jamming technologies to help reduce the effects of interfering signals.

The ionosphere is a layer in the earth's atmosphere that is electrically conductive. The path of any electric field, such as a GPS signal, that passes through the ionosphere is altered depending on the density of the ionosphere along the signal path. While models are used to approximate the ionospheric errors, the entire effect can not always be removed during processing. Changes in the density of the ionosphere are caused by many factors, but are primarily linked to the sunspot cycle. In periods of high sunspot activity, ionospheric density increases causing more disturbance to GPS signals and reducing position accuracy.

SUMMARY

Trimble's patented Everest multipath rejection technology provides a new level of accuracy to GPS mapping applications. Because multipath signals are rejected before the measurements are stored or used to compute positions, the most significant accuracy improvements are obtained using Everest at both the base and rover receivers. This new technology results in 50% better static accuracy than when using older Pro XL technology. In dynamic conditions where the GPS antenna is in motion relative to multipath generating sources, accuracy is even higher. As Trimble continues to incorporate the latest technologies into the Pathfinder mapping products, our customers continue to benefit from the efficiencies of code-based GPS mapping techniques. The fast, efficient, and easy-to-use mapping systems that Trimble's customers have come to enjoy now provide 50% better accuracy by incorporating Trimble's patented Everest multipath rejection technology.

APPENDIX

Our dynamic test was performed at a football-field track. The inner edge of the track was mapped with a GPS Pathfinder Pro XR with Everest mapping system. The base station, 11 kilometers away, was a CBS also equipped with a Pro XR with Everest receiver. The rover antenna was connected to two receivers, the Pro XR and a 4000 SSi survey-grade receiver. With this equipment, the inner edge of the track was traversed 15 times at walking speed. The survey system provided "true" positions every second with which we compared the differentially corrected Pro XR positions to determine their error. Our "true" positions, which were derived from survey-grade carrier-phase solutions, were deemed to have only two to three centimeters of horizontal error. Figure A1 shows the differentially corrected Pro XR with Everest positions from all 15 trips around the track.

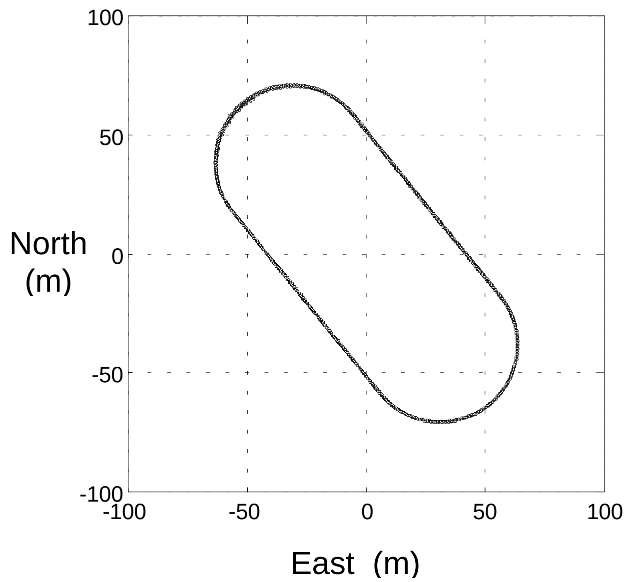

Figure A1. Pro XR with Everest differentially corrected positions (4,083) for 15 passes around inner edge of football-field track in a local east and north coordinate system. Position scatter at the northwest end of the track is due to signal obstruction by trees which caused satellite constellation switching and some 2D positions to be logged.

Each pass around the track was completed in about 4.5 minutes and contains about 270 positions. The PDOP mask and PDOP switch were set to 6, and the elevation mask to 15 degrees. With each pass around the track, a 0.4 km-long line and a 9,715 square-meter (2.4 acre) area are mapped. For each of the 15 passes, we calculated an RMS horizontal and vertical error, a line-length error, and an area error by comparing the mapping data to the survey data. The horizontal errors are best expressed in the coordinate system of the instantaneous direction of travel; those two coordinates are path-perpendicular and path-parallel. The path-perpendicular, path-parallel, and vertical RMS errors are shown in Figure A2.

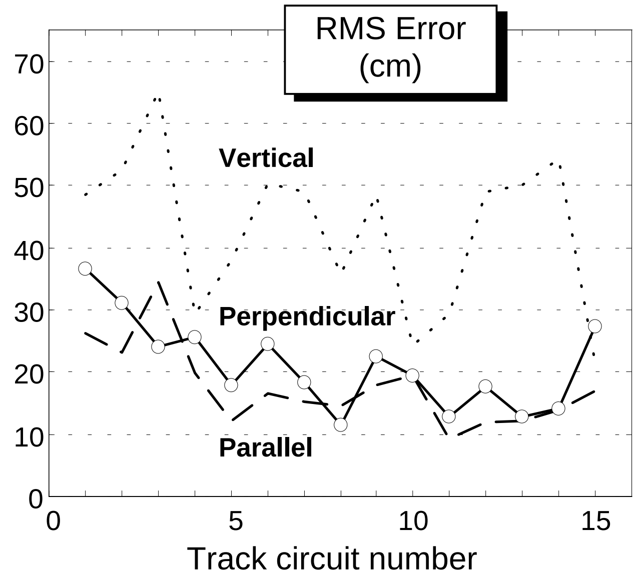

Figure A2. RMS error for the vertical, path-perpendicular and path-parallel components for each circuit around track. Dotted line, vertical; solid line with circles, path-perpendicular; dashed line, path-parallel.

The path-perpendicular errors have the most influence on line position, and line length and area size calculations. In this test, the path-perpendicular errors average 21 centimeters. Figure A3 shows the percent area error and the percent line-length error for each circuit.

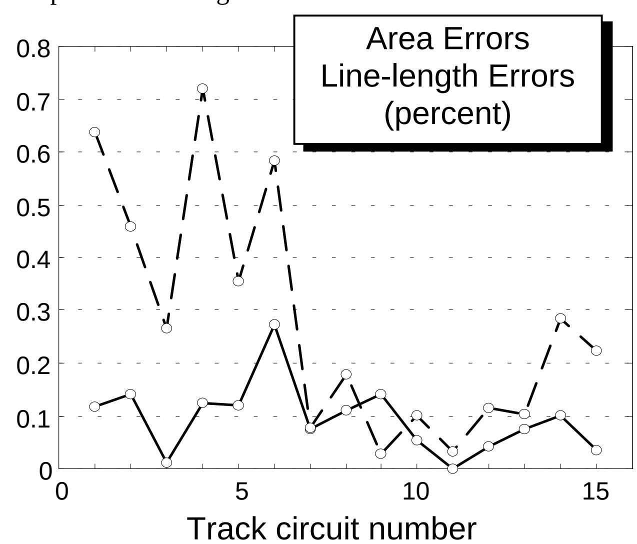

Figure A3. Percent area error and percent line-length error for each circuit around track. Dashed line, percent area error; solid line, percent line-length error.