A PRACTICAL EVALUATION OF THE GPS RAPID STATIC METHOD

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The rapid static method is still an attractive method of surveying with GPS. It combines high accuracy and short observation periods, being useful in applications when redundancy of observations is desired, such as in legal surveys. This paper describes an experiment and its corresponding data analysis aimed at evaluating the GPS rapid static method in a production environment. The evaluation demonstrates the envelope for the method: occupation times, range, reliability and accuracy. For this purpose a rapid static survey was carried out over geodetic markers used as "ground truth". In the experiment, baselines of various lengths were used, from 3.8 km to 75 km. Data were collected using dual-frequency receivers. The data processing generated both single and dual-frequency solutions for three different lengths of sessions: 5, 10 and 15 minutes. The results were analysed in terms of accuracy and repeatability. The analysis suggests that L1-only solutions are reliable only for very short baselines. The same analysis of results indicates that the dual frequency solution is reliable for baselines of up to 15 km. There is practically no difference among solutions from the three sessions.

La méthode statique rapide avec le GPS est encore une technique de levés attrayante. Elle allie une haute précision et de courtes périodes d'observation; elle est utile dans les applications où la redondance des observations est souhaitée, notamment dans les levés officiels. Cet article décrit une expérience et l'analyse connexe des données, aux fins de l'évaluation de la méthode statique rapide avec le GPS dans un contexte de production. L'évaluation est consacrée à l'enveloppe de la méthode : temps d'occupation, portée, fiabilité et précision. À cette fin, un levé statique rapide a été réalisé sur des repères géodésiques servant de « vérité-sol ». Pour cette expérience, des bases géodésiques de diverses longueurs ont été utilisées – de 3,8 km à 75 km. Les données ont été collectées à l'aide de récepteurs bifréquences. Le traitement des données a produit des solutions monofréquence et bifréquence au cours de trois séances de durées différentes : 5, 10 et 15 minutes. Les résultats ont été analysés pour leur précision et pour leur répétabilité. L'analyse suggère que les solutions exclusivement L-1 ne sont fiables que pour les bases géodésiques très courtes. La même analyse des résultats indique que la solution bifréquence est fiable pour les bases géodésiques atteignant jusqu'à 15 km. Il n'y a pratiquement pas de différence entre les solutions des trois séances.

Introduction

The rapid static method is among the most attractive techniques for surveying with GPS. It is an alternative method to conventional surveying terrestrial techniques. Within the surveying methods using GPS, the rapid static method can be placed between the traditional static and the real-time kinematic (RTK). The traditional static method is based on a long occupation time offering the highest accuracy and the most reliable results. RTK is the fastest survey method based on single-epoch occupation (at the limit), but it is restricted to short baselines. Between them is the rapid static method, offering better accuracy and reliability than RTK and faster surveying than the traditional long occupation static method. The rapid static method also allows for the positioning of points with an accuracy comparable to that of the GPS traditional static method, for shorter baselines, in a much shorter period of time (less than 15 minutes, being the reason for the adjective "rapid"). The last characteristic is a consequence of the development of fast ambiguity resolution techniques.

The rapid static method has been widely used in support of many activities. Just a few found elsewhere in the literature will be mentioned here. *Wu and Lin* [1995] tried to get the best from the method for height determination. *Shepherd et al.* [1998] report on the application of the method in ground deformation monitoring. *Coe et al.* [2000] applied rapid static surveys in a restricted but mountainous area in Colorado, using dual-frequency receivers, for landslide movement monitoring. These papers tend to agree on formal errors less than or equal to 1 cm in the horizontal and 1.5 cm in the vertical, over baselines no longer than 15 km. These errors correspond to relative errors in the order of several millimetres plus 1 ppm. By "formal error" we mean here the standard deviation as estimated during data processing.

It is interesting to review typical values that are commonly quoted among various GPS receiver vendors (*http://www.ashtech.com, http://www.aoa-gps.com, http://www.leica-geosystems.com, http://www.trimble.com).* Generally speaking, for a dual-frequency receiver, relative errors vary between (0.5 cm plus 0.5 ppm) and (1 cm plus 1 ppm) for the horizontal component, and between (0.5 cm plus 1 ppm) and (2 cm plus 1 ppm) for the vertical component. For single-frequency receivers, the errors range between (0.5 cm and 1 cm plus 2 ppm) for the horizontal component. Even though the word "accuracy" is used some times, it may be thought that these relative errors refer to formal error (precision).

This paper presents an experiment and its corresponding data analysis, which was designed to evaluate the accuracy of the rapid static method in a production environment. There are three interesting questions related to (a) increasing the distance between the reference station and the unknown points, (b) using only L1 observations as opposed to L1 and L2 observations, and (c) using observation sessions of various duration, namely, 5, 10 and 15 minutes long. The fast static survey was carried out over geodetic markers located on the Federal University of Paraná (UFPR) campus. A preliminary evaluation for a small sample was presented in *Santos et al.* [1998]. In this current paper a totally different evaluation is made, using the published coordinates of the geodetic markers as ground truth. The internal precision is also assessed by means of the short-term repeatability of the different solutions.

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Revisiting the Rapid Static Method

The rapid static method has been very well explained in the literature [e.g. *Kleusberg* 1990; *Seeber* 1993; *van Sickle* 1996]. The general idea behind this method is that a fixed reference receiver remains stationary on a base station of known coordinates. A rover receiver occupies the points of interest for a short period of time, typically between 5 and 15 minutes. This operational characteristic has an advantage over the static method per se, but comes with a restriction in terms of baseline length, which should not be longer than 10 kilometres.

The length of the session may be a function of the number of satellites in view since the method requires a great number of observations for a faster ambiguity resolution. Therefore pre-planning may be necessary even today with the full constellation. This certainly will change with the inclusion of a new GPS signal [*Hatch et al.* 2000]

The fast static method became feasible due to the development of computational algorithms allowing a fast ambiguity resolution, generally known as "on-the-fly" [*Abidin* 1992]. These techniques can be divided into three large groups, namely, the "extrawide laning" [*Wübenna* 1989], the ambiguity mapping function [*Counselman and Gouverich* 1981], and the least squares [*Hatch* 1990]. The "extrawide laning" method is based on creating artificial observations by linearly combining the respective observations at both L1 and L2 frequencies, being the so-called wide-lane and narrow-lane the two artificial observations mostly used. These artificial observations possess advantageous characteristics for a fast ambiguity resolution, such as a larger wavelength for the wide-lane. The ambiguity mapping function and the method based on least squares use a search technique relying on statistical criteria. In the former, a statistical test is performed on a function formed by a combination of observations, on either L1 or L1 and L2, between receivers and satellites. In the latter, a statistical test is operated on the *a posteriori* variance factor resulting from the adjustment of observations [*Vanícek and Krakiwisky* 1986]. Either the mapping function or the *a posteriori* variance factor corresponds to the correct ambiguity in a statistical sense. More effort has been made in order to increase the efficiency of those methods, such as the least squares LAMBDA method [*Teunissen et al.* 1997]. The fast ambiguity resolution for long baselines is very difficult mostly due to ionospheric effects and is still a matter under investigation [*Kim and Langley* 2000].

There is a reliability issue related to ambiguity resolution, which relates to how well the resolution actually occurs and the capability of the data processing software to identify it. There are four possible scenarios: (a) the ambiguities are correctly resolved and the software indicates such; (b) the ambiguities are resolved, perhaps correctly perhaps not, and the software indicates they are correctly resolved; (c) the ambiguities are resolved, perhaps correctly perhaps not, and the software indicates that there is a possibility the resolutions are wrong; and, (d) the software gives up trying to resolve the ambiguities (and settles for a float solution, for example), but informs the user what is happening. The reliability problem is case (b).

Experiment Description

An experiment was devised to assess the performance of the fast static method in a practical situation aimed at matching as best as possible a generic production environment. The idea was to carry out a rapid static survey on some geodetic markers, and to compare the computed coordinates with their published values. The geodetic markers used were the three ground monuments located within the test area of UFPR's Space Geodesy Lab. They are known as points RM01, RM02 and RM03. They are reference stations of the GPS permanent station PARA that belongs to the Brazilian GPS Continuous Monitoring Network (RBMC). As such, their coordinates are known with millimetre accuracy, all related to the South American Geocentric Reference System (SIRGAS) [*IBGE* 1997].

The control points used as reference stations belong to a GPS network maintained by the Electricity Company of the State of Paraná (COPEL), also connected to SIRGAS at the millimetre level. It was decided to use some of the points of the COPEL network, not only because of the quality of their coordinates, but also because of their increasing distance with respect to the test area, spanning from 3.8 km up to 72 km. This meant that the baseline would be of various lengths. Table 1 shows the station names, code, altitude and distance to the test area. All stations, including the ones at the test area, are located at the *Serra do Mar* plateau having nearly the same height. The exception is for station CRLI which is located close to sea-level.

Three Ashtech Z-12 receivers were used in the experiment. Two of them, the ones that belong to the UFPR, were used for the rapid static survey of the geodetic markers RM01, RM02 and RM03. The third one, which belongs to COPEL, was used to occupy the reference stations belonging to the COPEL network. The survey took place in July 1997, over two consecutive days. Stations UBRB and CRLI were occupied on the first day; the others on the second day. Each geodetic marker was occupied for a period of 15 minutes, with a 5 seconds sampling rate. In this overall scheme, there are always three solutions (for the three geodetic markers) associated with each one of the reference stations.

Table 1: COPEL network points used as reference stations, and their height and distance to the test area.

NAME	CODE	HEIGHT (m)	DISTANCE (km)
Uberaba	UBRB	911.196	3.8
Atuba	CRCN	928.808	6.9
Pilarzinho	SPIL	985.699	9.5
KM03	KM03	952.840	11.1
Campo Comprido	SCCO	976.293	14.1
Bateias	SBAT	969.818	30.4
Paranaguá	CRLI	18.226	72.8

The points RM01, RM02 and RM03, and the COPEL points were tied to SIRGAS at an epoch previous to that of the rapid static survey. In order to make the analysis temporally consistent, the coordinates were made compatible with the epoch of the rapid static survey by applying the NNR-NUVEL1A plate motion model [*DeMets et al.* 1994]. The use of this model is recommended by the IERS [*McCarthy* 1996]. For the Brazilian shield, the NNR-NUVEL1A model shows good agreement with recent solutions based on space geodetic techniques such as the APKIM8.0 [*Drewes* 1993], and also with the recent results of a study carried out at the Federal University of Paraná by *Costa* [1999]. A difference of 2.5 cm exists between the two epochs and would have been translated into the results if not taken into account.

Data Analysis

The whole dataset was processed using Ashtech's Prism software. The idea behind using commercial rather than scientific software was to simulate a production environment. For the same reason, broadcast ephemerides were used in the data processing.

The data collected at the geodetic markers (in the test area) were divided into 5, 10 and 15-minute segments in such a way as to have different solutions computed from different sessions for each one of the geodetic markers. In addition, the data were processed using only L1 observations or L1 and L2 observations. These two types of solutions are hereafter referred to as L1-only solutions and L1/L2 solutions.

The resulting set of coordinates was first analysed externally, by comparing their respective published coordinates, and then internally, by means of short-term repeatability. The whole data analysis, which follows, was aimed at answering the three questions raised in the Introduction. Another interesting feature is the correlation between observation type, baseline length, duration of the observation session and ambiguity resolution, which becomes evident in the following analysis.

The first and fundamental aspect to note is how and whether the ambiguities were solved by the software. The only L1-only solution in which all the ambiguities were resolved is the one for the shortest baseline (3.8 km in length) with a 15-minute session. In all other L1-only solutions, no ambiguity was successfully solved. As far as the L1/L2 solution is concerned, all solutions related to the longest baselines (reference stations SBAT and CRLI) did not have any ambiguity solved. For the shortest baselines (up to 14.1 km), all ambiguities were solved, for all sessions (5, 10 and 15 minutes long). The exception is for two of the solutions related to reference station SPIL (baseline length: 9.5 km), for the 5 and 10-minute observation sessions, in which no ambiguity was solved. The reason for this could not be detected. As far as the reliability issue related to ambiguity resolution is concerned, the data analysis indicate that we are in cases (a) and (d): the software used was capable of correctly indicating whether ambiguities were solved or not.

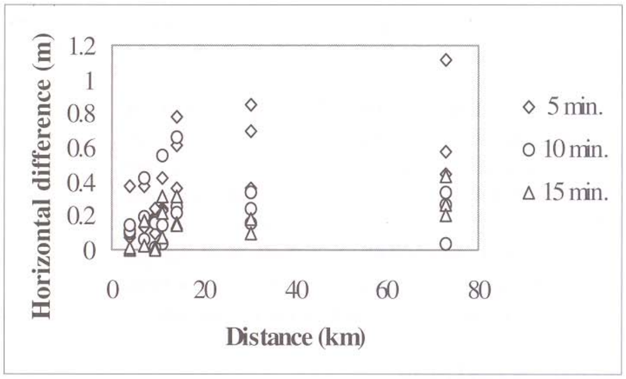

Figure 1: Horizontal difference based on the L1-only solution.

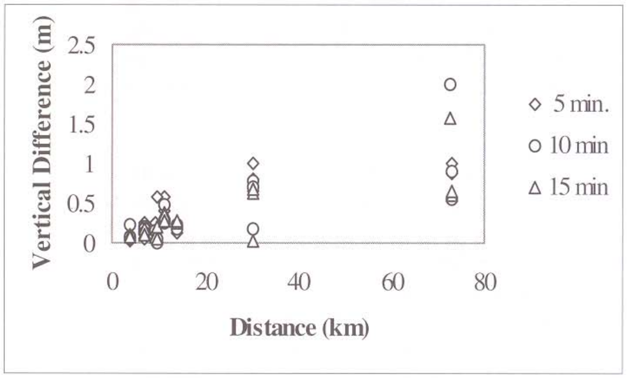

Figure 2: Vertical difference based on the L1-only solution

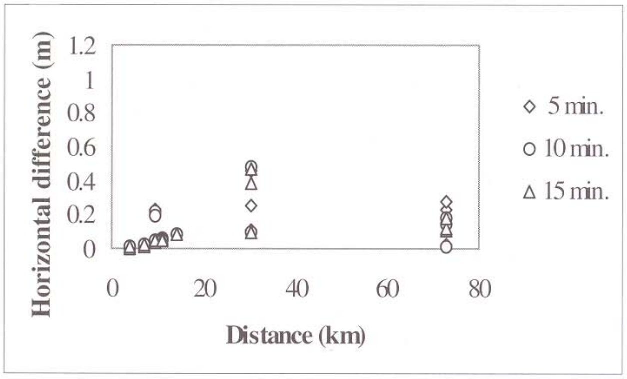

Figure 3: Horizontal difference based on the L1/L2 solution.

The first analysis was made to verify how close the estimated solutions of markers RM01, RM02, and RM03 were with respect to their corresponding published values, regarded as "ground truth". The differences in latitude, longitude and height were all expressed in length units. After that, the difference in the horizontal component was computed.

Figures 1 and 2 show the horizontal and vertical differences, plotted against distance from a reference station, for the L1-only solution. The three observation sessions are indicated. Each session contains a difference for the markers RM01, RM02, and RM03. Large and widely spread differences can be seen in the L1-only solution because the ambiguities could not be properly solved. The only exception is for the 3.8-km baseline, for the 15-minute session, in which the horizontal difference is below 5 cm. These plots stress the importance of ambiguity resolution. The results indicate that L1-only solutions can only handle ambiguities successfully for baselines shorter than the ones used in the experiment.

Figure 3 shows the horizontal difference, plotted against distance from a reference station, for the L1/L2 solution. Larger differences occur for the longest baselines when no ambiguity was solved. All 10 and 15-minute sessions for the L1/L2 solutions for baselines up to 11.1 km are below or at the 5-cm level (with the exception of two solutions for station SPIL), as can be better seen in Figure 4. The relative accuracy, involving only the solutions in which ambiguities were solved (L1/L2 solutions with baselines up to 14 km, except two of the solutions for station SPIL), was adjusted from Figure 4 and is equal to 5 ppm. Figure 4 also indicates that there is practically no difference between the results coming from a 5-minute, a 10-minute or a 15-minute session, if the ambiguities are resolved.

As for the vertical differences for the L1/L2 solution, they are shown in Figure 5. The differences between the three sessions for the baselines up to 14 km are better seen in Figure 6, being all below 0.25 m. The average relative accuracy for the vertical component, involving only the L1/L2 solutions in which ambiguity was solved, was adjusted from Figure 6 and is equal to 13 ppm.

The comparison between Figures 1 and 3, and Figures 2 and 5, clearly indicate the effect of using L1-only or L1/L2 solutions. The L1-only solution is widely spread and with larger differences as opposed to the L1/L2 solution. The incapacity of the L1-only solutions for solving the ambiguity is evident, with a solitary exception for the solution with a shorter baseline and longest session. The remaining analysis involves only the L1/L2 solutions because ambiguities were resolved in most of them.

The differences shown in Figures 1 to 6 are a little larger than typical values (e.g. those mentioned in the Introduction), which seem to be mostly related to internal precision. With this in mind, it was decided to look into the internal precision as well, using the short-term repeatability as an analysis tool. The short-term repeatability is an indicator on the scatter about the mean of the solutions.

The short-term horizontal and vertical repeatability σ_s was computed by:

$$\sigma_s = \sqrt{\frac{\frac{n}{n-1}\sum_{i=1}^{n}\frac{(x_i-\bar{x})^2}{\sigma_i^2}}{\sum_{i=1}^{n}\frac{1}{\sigma_i^2}}}\ , \qquad (1)$$

where n is the number of solutions associated with a reference station (in this case, n equals 3: one solution for RM01, one solution for RM02, and one solution for RM03), x refers to the quantity under investigation (here either horizontal or vertical components), $\bar{x}$ is the average value of x, and σ is the estimated formal error for the component. Figure 7 shows the horizontal repeatability for the L1/L2 solution. The effect caused by the longer baselines can be seen: the solution, for baselines up to 11.1 km, has repeatability at the millimetre level. Figure 8 shows the vertical repeatability. The same comments made for the horizontal repeatability can be repeated. A horizontal and vertical formal relative error was derived from Figures 7 and 8. The resulting derivation is 0.5 ppm and 1 ppm, respectively.

It can be seen from equation (1) that the short-term repeatability is a function of the estimated formal error. The average formal error $\bar{\sigma}$ was computed by:

$$\bar{\sigma} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\sigma_{\phi_i}^2+\sigma_{\lambda_i}^2+\sigma_{h_i}^2}\ , \qquad (2)$$

where n is again the number of solutions associated with a reference station, and σ_ϕ, σ_λ and σ_h are the standard deviations for latitude, longitude and com-height, as given by the software. A value of $\bar{\sigma}$ was puted for the L1/L2 solutions. Figure 9 shows the average formal error for the L1/L2 solution, for sessions of 5, 10 and 15 minutes. The formal error seems to be correlated to baseline length, observation session and ambiguity resolution. It can be seen that the value of $\bar{\sigma}$ increases with longer baseline lengths and shorter observation sessions.

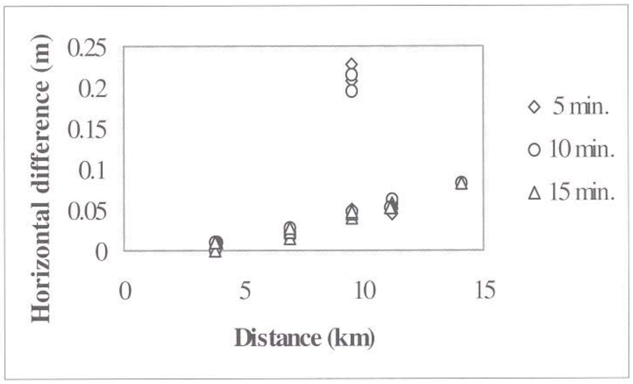

Figure 4: Horizontal difference based on the L1/L2 solution, only for baselines up to 14 km.

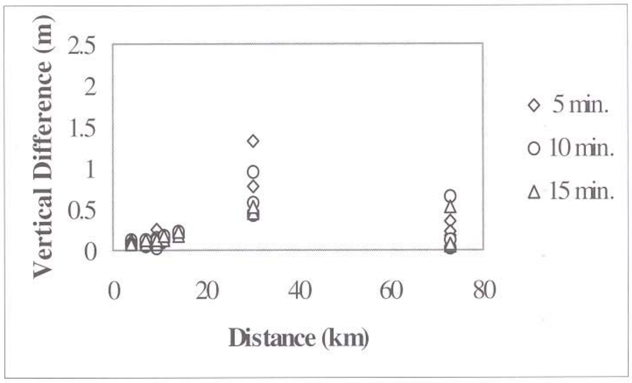

Figure 5: Vertical difference based on the L1/L2 solution.

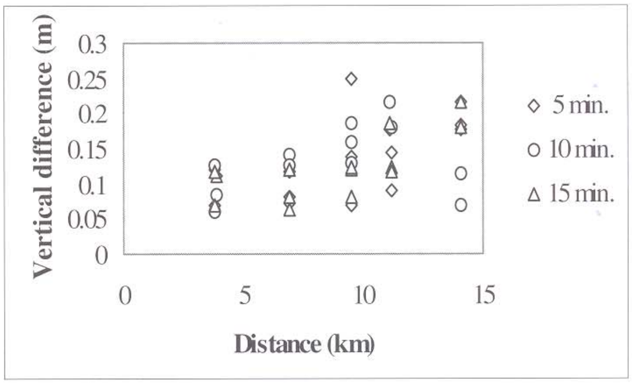

Figure 6: Vertical difference based on the L1/L2 solution, only for baselines up to 14 km.

Concluding Remarks

An experiment aimed at a practical evaluation of the GPS rapid static method was conducted. The objective was to duplicate a production environment using commercial software and broadcast orbits. An evaluation was made by comparing the

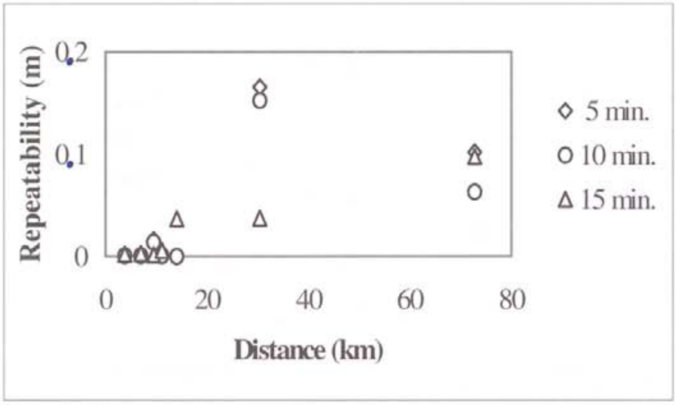

Figure 7: L1/L2 horizontal repeatability.

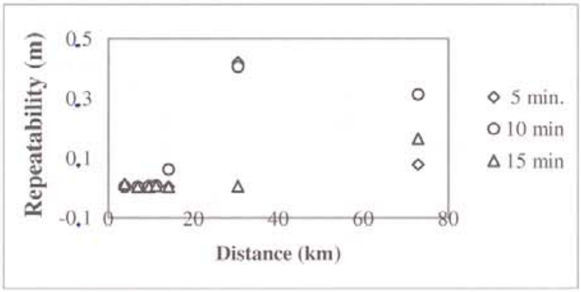

Figure 8: L1/L2 vertical repeatability.

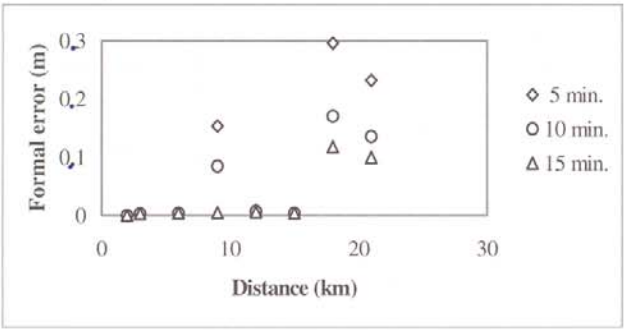

Figure 9: Average formal error for the L1/L2 solution.

estimated coordinates with their published values and by means of short-term repeatability.

Some of the results were expected, due to the evident correlation between observation type, baseline length, duration of the observation session and ambiguity. Ambiguities were more difficult to resolve for baselines longer than 15 km and also in cases when only L1 observations were used. The best results were obtained using the L1/L2 combination. In general, the shorter the baseline the better the results.

For a better evaluation of the L1-only solution, test baselines varying from 100 m to 5 km maximum should have been used. The results suggest that L1-only solutions are only reliable for very short baselines.

Relative errors were derived for only those solutions in which ambiguities were solved, since this is key to high accuracy positioning. The relative errors derived from the coordinate differences are higher than similar values quoted in the literature and by some GPS vendors. Nevertheless, they were derived in a controlled situation and may represent a more conservative situation. More samples would have enhanced the analysis. On the other hand, the formal relative errors derived from repeatability values are much smaller.

Ambiguity is the key to high-accuracy GPS positioning. Therefore, only the solutions based on solved ambiguities were effectively used in the analysis. The same applies for an actual production situation, when high-accuracy positioning is desired. From a production perspective, it is interesting to note that there is no practical difference between the solutions using 5 minutes, 10 minutes or 15 minutes worth of data, provided the ambiguities are solved.

The data treated in this paper were collected in 1997. The major difference between that time and today is not necessarily with the constellation (25 satellites in 1997; 27 satellites in 2000) but with the removal of SA. If an ambiguity technique implemented in software makes use of the C/A pseudorange, then it makes the ambiguity resolution a little faster.

The results demonstrate that the reliability problem, identified as case (b), does not occur with rapid static using the receivers and software in this experiment. The rapid static method is still useful today in spite of the popularity of RTK. Case (b) still plagues RTK, a situation that may change with the deployment of the new signal structure that is to be in effect in the next 10 to 15 years. Until then rapid static will remain a competitive method. There are many situations in which redundancy of observations, allied to short occupation periods, is important. For those situations, the rapid static method is an option.

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