Specifications for Urban GPS Surveys

M.R. Craymer, D.E. Wells, P. Vaníček, R.L. Devlin

ABSTRACT. *The Urban GPS Research Project was sponsored by the City of Edmonton to determine the suitability of GPS technology in an urban environment and to develop specifications and guidelines for performing such surveys. The conventional approach to specifications restricts contractors to detailed procedures and specific equipment. In the case of GPS, this may not fully exploit the present and future capabilities of GPS. We therefore minimize strict specifications and instead emphasize contractor qualification where potential contractors demonstrate their capability of performing satisfactory GPS surveys using their own procedures. To this end we have developed specifications and guidelines for the establishment and use of a validation network for GPS surveys. This paper summarizes our proposed specifications and in particular the concept of contractor qualification.*

Introduction

In 1987 the City of Edmonton (latitude N 53° 32' 02", longitude W 113° 30' 02", population 760,000, area 262 sq. miles) and the Land Information and Services Division of Alberta Forestry, Lands and Wildlife (LISD) jointly initiated a research project to examine the suitability of GPS in an urban environment, particularly the need for specifications and guidelines for achieving second-order accuracy.

This project consisted of three phases. In Phase I we developed initial specifications and guidelines for such surveys which were circulated for review (see Rapatz et al. 1987). In Phase II of the project these specifications and guidelines were used by three contractors to perform independent GPS surveys of a test network within the City of Edmonton during November and December 1987. Each Phase II contractor used different equipment, procedures and software.

The test network was also observed to first-order horizontal and second-order vertical Canadian standards using conventional techniques (i.e., directions, distances and levelling). These conventionally derived results served as the "standard of reference" for our analyses.

In Phase III of the project we evaluated the results from the Phase II surveys with the aim of refining the proposed specifications and guidelines (see Craymer et al. 1989a,b). We also gathered feedback on the specifications and are refining them based on this feedback and our analysis of the Phase II surveys (see Craymer et al., 1989c). The most significant change in our specifications is a greater emphasis on contractor qualification rather than the strict specification of procedures. To this end we have also developed guidelines for the establishment and use of a validation network for GPS surveys.

These specifications and guidelines are intended for surveys using the Global Positioning System (GPS). They were developed to provide the information and guidance necessary to achieve second–order relative positional accuracy for lines of less than a few tens of kilometres in length, in an urban environment.

The accuracies of GPS observations can be exceptionally good but depend upon two factors; geometrical strength of the satellite configuration

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M.R. Craymer, **D.E. Wells**, and **P. Vaníček** are affiliated with the University of New Brunswick, Department of Surveying Engineering, Box 4400, Fredericton, New Brunswick, Canada E3B 5A3. **R.L. Devlin** is affiliated with the City of Edmonton Public Works Department, Roadways Engineering Branch, Ninth Floor, Century Plaza, 9803 – 102A Avenue, Edmonton, Alberta, Canada T5J 3A3. This paper was presented at the ACSM/ASPS Fall Convention in Clevland, Ohio, September 17-22, 1989.

and observational errors, both systematic and random. It has been found that the effect of random errors associated with GPS observations is almost negligible while the systematic errors (biases) affect the results significantly. In general, these specifications and guidelines are directed at the detection and/or elimination of these systematic biases.

The question of heights and the accuracy of heights must also be treated differently from conventional surveying. Conventional methods provide orthometric heights (i.e, heights above the geoid) whereas GPS provides geodetic heights (i.e., heights above the ellipsoid). Consequently, integrating these two systems requires a precise knowledge of the difference between the geoid and ellipsoid (i.e., the height of the geoid above the ellipsoid, called geoidal height).

During the course of the evaluation of the Phase II surveys, we identified three problems with our originally proposed specifications (see Craymer et al. 1989b). First, the proposed specifications for design and field procedures were too rigid for the required accuracy level. The contractors generally had no problem meeting second-order accuracy even though they did not follow all of the proposed specifications. Second, such rigid specifications would not take advantage of future changes in GPS positioning capabilities. This is particularly true of the "stop-and-go" type of surveys being vigorously investigated today, the completion of the full satellite constellation over the next few years and the implementation of "selective availability".

Stop-and-go, also called "kinematic" or "semi-kinematic", GPS surveying is a technique where the user's receiver(s) are moved from point to point while continuously tracking the satellites. Such techniques require only a few minutes of observations at the initial setup and only a few seconds at each other point for accurate position determination.

One of the greatest problems with the proposed specifications, however, was their looseness for the reporting of results. This made our evaluation of the contractors' results very difficult and time-consuming. Clearly more emphasis on the specifications for survey reporting was be required to allow the contracting agency to adequately verify the submitted results.

As a result of these short-comings, the approach we now advocate is one of validation rather than strict specification. We are now de-emphasizing rigid design and field specifications and instead are emphasizing strict specifications for the reporting of results and validation of accuracy.

To support the validation concept we also recommend that potential contractors be required to qualify for GPS surveys by demonstrating their ability to perform such surveys to a specific accuracy level on a test network. This would involve a test of the contractor's equipment, field procedures and software. By analysing the contractor's results, the contracting agency should determine whether contractors are able to meet the required accuracy standard. Before being allowed to bid on any GPS survey, the contractor would have to pass such a qualification test. In the event of a change in a contractor's equipment, procedures or software, they may be required to re-qualify.

A serious impediment to the proper validation of GPS results concerns the lack of realistic covariance matrices for the adjustment results. Without such information, most of the statistical tests become meaningless and may indeed lead to incorrect conclusions. To the best of our knowledge, there is no commercially available GPS software that can provide realistic covariance matrices. Although the relative information in the covariance matrices seems to be reliable, the Phase II results indicate a scale problem with most of the covariance matrices.

Although we are now de-emphasizing strict specifications for design and field procedures, we are not advocating that they be done away with completely. Instead we recommend including these as guidelines to be updated as new technology becomes available to the surveying community. These specifications are intended to provide the contractor with a reference for completing a satisfactory GPS survey, and to give the contracting agency the tools necessary to evaluate the contractor's results.

Throughout this document we consider specifications and guidelines only for conducting

GPS surveys to second-order standards. We deliberately avoid the much larger question of integrating GPS with existing conventional control. Without realistic covariance information for both the GPS and existing control, there is no proper method of accomplishing this. To determine which of a number of methods is, in some sense, the best would require further research. Although the transformation of existing control (including full covariance matrix) to NAD83 would help, the greatest problem at the present time is the generation of reliable and compatible GPS covariance matrices.

Although each recommendation has been carefully assessed, some points have not been explicitly tested. Because GPS is a new technology, these specifications are only preliminary in nature. It is expected that further refinement of this document will take place as technological advances and experience in urban GPS surveying increase.

Recently the Canada Centre for Surveying (CCS) and the Province of Alberta have adopted most of the proposals presented here in their own specifications for GPS surveys; in particular the contractor qualification concept (see Duval and Beck 1990). Many so-called "basenets" have also been established around Canada by CCS and, in Alberta, GPS surveying companies are already performing validation surveys to qualify for bidding on provincial GPS contracts.

Specifications

GPS surveying is a new and complex process which is subject to many possible biases and potential errors. Using GPS effectively requires innovation, expertise and experience on the part of the contractor. The purpose of these specifications is to enforce some basic procedures for such surveys that minimize the occurrence or effect of these biases and errors on the final results.

Specifications in this section will fall into three classes; requirements, recommendations and suggestions. Each of these are identified by the following words: shall or must — Either of these words denotes a condition that must be met by the contractor; should — This word denotes a recommendation to be taken under consideration and which, in our view, is necessary to achieve the required accuracy; may — This word connotes a suggestion which is left to the discretion of the contractor.

Survey Design

In an urban situation where GPS will be used, it is recommended that a widely spaced, higher–order GPS control network be established first by the contracting agency to provide a framework for homogeneous densification. These points will act as "foot hold" or base points and should be chosen such that they are accessible and stable. This higher-order control network may be a provincial or federal first-order or higher network, or may be any other network of an order consistent with first-order standards.

At least three existing higher-order control points must be included in any proposed GPS survey. Whenever possible these should be three three-dimensional control points. Otherwise two sets of three points (three two-dimensional horizontal points and three vertical control points) must be used. These control points should be chosen to be roughly equidistant on the periphery of the network so that they enclose as much of the proposed network as possible.

Each new point to be established by the proposed GPS survey must be occupied at least two separate times to enable proper checking of blunders (e.g., incorrect point, setup errors, incorrect antenna heights). A separate occupation is one where the antenna has been taken down and set up again and the receiver restarted.

Each point must be connected by simultaneous occupations (i.e., baselines) to at least two other points in the network. Because it is generally easier to resolve the integer phase ambiguities over shorter baselines, adjacent points should be connected wherever possible. In addition, at least two long (network-wide) baselines, oriented roughly perpendicular to each other, should be included for improved scale and orientation.

At least two receivers must be used for relative positioning, although three or more may be used for more efficient operation and increased station reoccupation and baseline repeatability.

A preanalysis should be performed to determine the minimum occupation time required to achieve the required standard of accuracy. In addition, the most appropriate satellites to observe at each site should also be selected for receivers unable to track all of the "visible" satellites. The preanalysis should be specific for carrier phase relative positioning.

Field Survey Procedures

As stated earlier, it is not our intention to advise enforcement of some more or less arbitrary set of specifications for field procedures since different approaches are capable of achieving the required accuracy. Nevertheless the contractor must use the same field survey procedures as were used during contractor qualification.

In order to meet second-order accuracies, the carrier beat phase must be observed together with a time tag for each observation. Pseudo-range observations are not precise enough for control surveys and must not be used.

A detailed field log must be kept during observations taken at each station. At the very least the following information must be recorded:

1. Date of observations
2. Station identification (name and number)
3. Session identification
4. Serial numbers of receiver, antenna, and data logger
5. Receiver operator
6. Antenna height and offset from monument, if any (to 1 mm)
7. Station diagram illustrating location and deployment of equipment
8. Obstruction diagram showing any obstructions above 15° elevation
9. Starting and ending time (UTC) of observations
10. Satellites observed (including time of changes)
11. Weather (cloud state, temperature to 0.1°C, pressure to 0.1 mbar and relative humidity to 1 percent)
12. Any problems

Although the precision suggested above for the antenna height and weather measurements are not absolute requirements, it is strongly recommended that these be adhered to.

Data Processing

To enforce consistency in the processing of GPS data, all processing must be performed in the coordinate system defined by the GPS satellite ephemerides (i.e., WGS84/NAD83). The contractor must use the same data processing procedures and software used during the qualification stage. Results must also be presented to the contracting agency in this system. The contracting agency shall be responsible for converting these results to other coordinates systems and/or integrating them with existing networks.

A final network solution must be provided together with all single baseline solutions. The network solution must be performed using a minimally constrained (one point fixed) network adjustment. The contractor must use the NAD83 coordinates provided by the contracting agency for the fixed point.

Only one point is fixed, rather than all available "known" points, for two reasons. First, this provides a minimally constrained adjustment which allows us to examine only the GPS results without any influence from the existing control. Any problems with this solution are due only to the GPS and not the existing control network. The second, most important and practical reason is that the covariance matrices for the GPS solution and existing control are too unreliable to be used as weight constraints in the GPS solution.

Because most existing GPS data processing software cannot provide realistic covariance matrices for the estimated parameters (the formal covariance matrices provided by such software are generally overly optimistic), the contractor may scale the formal covariance matrix with the following restrictions. Only scale factors greater than one may be used in order to obtain a more realistic covariance matrix and the same scale factor employed for the contractor qualification must be used for all production surveys. The same scale factor must also be used for the entire covariance matrix so as to not destroy the relative information (i.e., correlations).

Second-Order Accuracy

Second-order accuracy is defined by the Surveys and Mapping Branch of Energy, Mines and Resources Canada by the maximum allowable size r_{2d} of the semi-major axis of the horizontal, relative error ellipse at the 95% confidence level, where

$$r_{2d} \text{ mm} = 50 \text{ ppm} \cdot d \text{ km} + 10.0 \text{ mm}$$

and d is the distance between any two stations. This accuracy standard refers to two–dimensional positions.

Given the three–dimensional nature of the Global Positioning System (GPS), it is necessary that the horizontal standard be related to a confidence ellipsoid at the 95% level. Because no such standard yet exists in Canada, we have derived it from the two-dimensional standard. Dividing by the horizontal 95% confidence level expansion factor (2.447) and re-scaling by the three-dimensional factor (2.795) gives r_{3d} for the maximum allowable semi-major axis of the 3-d relative error ellipsoid at the 95% confidence level:

$$r_{3d} \text{ mm} = 57 \text{ ppm} \cdot d \text{ km} + 11.4 \text{ mm} .$$

For the remainder of this paper, this will be referred to as the three–dimensional second–order standard.

Survey Reporting

The final report shall be the main source of information for judging the satisfactory completion of the contractor’s work. It shall be the responsibility of the contractor to supply sufficient information in the report to facilitate verification by the contracting agency. The following subheadings represent a list of general information to be presented. The contracting agency may specify further details such as data formats, etc.

Survey description. There shall be a short description of the survey location, the aim of the survey, and number of points positioned. This shall be accompanied by a sketch of the survey area, including all stations, existing and new.

Field procedures. There shall be a clear description of the survey procedures used in the field. This includes, but is not limited to the information entered into the field log and auxiliary information such as logistics, preanalysis and satellite selection results, personnel involved and difficulties encountered. The daily diary containing the field log specified above shall be presented along with all other material.

Office procedures. There shall be a clear description of the procedures used in the office. This includes, but is not limited to, computer software and hardware used to process observations, options used (if any), data editing performed, source of orbital data, parameters adjusted and held fixed, results of self-validation and any difficulties encountered. In particular, the version number and date of the software used must be reported. The contractor must also specifically report the percentage of data rejected for each station occupation, excluding observations rejected by the horizon mask angle. Special note shall be made of all initial carrier phase ambiguities, including their estimated real values and standard deviations. All parameters used for any coordinate transformations shall be presented and any scaling of the covariance matrix by the contractor must be described in detail.

Results. The adjusted three-dimensional coordinates of monuments to the nearest millimetre shall be presented in the coordinate system specified. The full, formal, covariance matrix of the adjusted parameters (including nuisance parameters) must be included. If the covariance matrix has been scaled, the scale factor used must also be presented. These results must be reported for all single baseline and network solutions. Statistical testing of the survey results from the network solution, including analysis of variance factors, semi-major axes of 2-d (horizontal) and 3-d 95% relative confidence regions between all possible pairs of points (which must be less than the allowable maximum specified above), residuals and residual outliers shall be provided. In addition the results of any self-validation checks must be reported, including but not limited to, comparisons of any repeated single baseline solutions and comparisons of single baseline and network solutions, all of which must meet the specifications above.

Archiving and standard file of survey results. All measurement data obtained shall be submitted on the original media along with the field notes. The survey results from the single baseline and network solutions shall also be submitted in the form of data files for validation by the contracting agency. The final archiving media and format specified by the contracting agency shall be used.

Contractor Qualification

A contractor must successfully complete a test of equipment, procedures and software to be used for GPS surveying before being qualified to perform GPS surveys for the contracting agency. The qualification network employed for such testing shall be one specified by the contracting agency (e.g., one established by the contracting agency itself or possibly those used by provincial/state or federal organizations). This end-to-end test consists of surveying the test network using exactly the same equipment, procedures, and software that will be used for the proposed GPS contractual survey. The specifications described above must be followed and the results of this survey must be presented to the contracting agency for evaluation.

Qualification networks have both public and private purposes. As a public facility such networks permit contractors and others to perform self-qualification surveys for testing refinements in procedures or new equipment. The private purpose, which is our primary concern here, permits contracting agencies to qualify potential contractors. In this case it may be desirable if the established coordinate values and their covariance matrix were maintained as confidential information by the contracting agency. On the other hand, this would prevent the beneficial public use of the network. It may also be very difficult to maintain the confidentiality of the coordinate values once several contractors have performed qualification surveys and have GPS positions available.

Establishing a Qualification Network

The qualification network should consist of a mixture of baselines of different lengths (200 m to 10 km), different orientations and different slopes and contain at least 10 points. The exact geometry of the network is not overly important and will be dictated by available points in the area.

All points of the network should be easily accessible and in locations free of electrical and mechanical disturbances. Network points should be monumented so that centring to an accuracy of ±1 mm can be done reliably. The satellite mask angle (elevation angle below which satellite visibility is blocked by an obstruction) should be no greater than 15° in all directions at each test network point. High flat-roof buildings (with no curved metal structures which could cause multipath problems) could be used to provide monuments with meaningfully different elevations. However, ends of short baselines should not be located on tall building roofs, since building sway may be larger than the required tolerances.

The qualification network should be tied into national horizontal and vertical geodetic control networks of at least second-order accuracy. NAD83 horizontal coordinates should be determined for all test network points (whether or not contractors' urban survey results are to be supplied in NAD83 or some other system), using either conventional survey techniques, or GPS. This ensures that the individual horizontal positions are known to about 1 m accuracy in an absolute sense (i.e., relative to the NAD83 coordinate system origin). Relative coordinates should be accurate to at least first-order standards. Orthometric heights of network points should be determined by levelling. In Canada, geoidal heights for the region of the network should be obtained from the Geodetic Survey Division of the Canada Centre for Surveying, Ottawa, Ontario. This ensures that the geodetic heights of the individual points are known to about 1 m accuracy. A realistic covariance matrix for all coordinates must also be produced.

Using a Qualification Network

The purpose of the qualification network is to provide a facility for potential contractors to demonstrate, and for contracting agencies to evaluate, the equipment, field procedures, and processing procedures of the potential contractor.

The specifications above must be followed by the potential contractor. The only difference between a production GPS densification survey and a qualification survey using the test network is that in the former case, only some of the network points are "known" whereas in the latter case, all network points are "known".

Evaluation of Results

The purpose of the validation is to determine whether the GPS survey results meet second-order standards. This is performed by evaluating both the internal accuracy and external compatibility of the results. The contracting agency shall be responsible for all "official" analyses although potential contractors may wish to perform these analyses as part of their own self-validation.

At the present time, a proper evaluation is hampered by the lack of realistic accuracy information (i.e., covariance matrices) for the results. The problem is primarily one of correct scaling of the covariance matrix of the results. This is somewhat alleviated by requiring the contractor to use the same scale factor for the formal covariance matrices that will be used in actual production GPS surveys.

The information specified earlier must be supplied to the contracting agency for evaluation. This includes estimates of the coordinates and their associated covariance matrix from the final network solution as well as estimated coordinate differences and their covariance matrices for all single baseline solutions.

The evaluation of internal accuracy is concerned with the assessment of both the strength of the network design and the influence of some of the errors and unmodelled biases which may affect GPS results. The internal accuracy can be evaluated using the covariance matrix of the results as well as comparisons between single baseline and network results.

To assess the internal accuracy of the final network solution, relative confidence regions must be determined from the network covariance matrix. Each of the semi-major axes of all possible 2-d (horizontal) and 3-d 95% relative confidence regions must meet second-order standards with respect to baseline length.

The external accuracy of the final GPS solution can be assessed by examining its compatibility with the "known" coordinates established by first-order standards. Coordinate discrepancies between the GPS solution and existing higher-order control can be analysed using various statistical tests and strain analyses. The more "known" control points that are included in the final network solution, the more reliable is the assessment of compatibility. There is therefore a trade off between cost efficiency (few "known" control points) and reliability of evaluation (more "known" control points).

The coordinates from the GPS network solution can be statistically tested for compatibility with the "known" control points using the Chi-square test

$$\Delta\mathbf{x}^T \, \mathbf{C}_{\Delta\mathbf{x}}{}^{-1} \, \Delta\mathbf{x} \le \xi_{\chi^2_{u,1-\alpha}} \qquad (1)$$

The $\Delta\mathbf{x}$ vector is composed of differences between corresponding coordinates of the "known" control points. The $\mathbf{C}_{\Delta\mathbf{x}}$ matrix is the sum of the two covariance matrices associated with the coordinates from the GPS solution and the "known" control. ξ is the abscissa of the Chi-squared distribution function for a significance level of α. u is the number of parameters being tested.

Five different compatibility tests can be performed by defining the $\Delta\mathbf{x}$ and $\mathbf{C}_{\Delta\mathbf{x}}$ in the previous expression in different ways:

1. $\Delta\mathbf{x}$ contains only the x (north) differences
2. $\Delta\mathbf{x}$ contains only the y (east) differences
3. $\Delta\mathbf{x}$ contains only the z (height) differences

4. $\Delta\mathbf{x}$ contains only the differences in both horizontal components (two-dimensional x and y)
5. $\Delta\mathbf{x}$ contains all coordinate differences (three-dimensional)

In each case, the appropriate $\mathbf{C}_{\Delta\mathbf{x}}$ is to be formed.

These subvector tests can also be performed in two ways: either "out of context" of the other parameters in the network (i.e., ignoring the presence of the other parameters) or "in the context" of all the parameters being tested simultaneously (see Vaníček and Krakiwsky 1986). The in-context test therefore is concerned with the probability that all separate coordinate Chi-square statistics are simultaneously less than some critical value. Thus, if we desire to test all coordinate components individually but in the context of the others, the significance level for each of the individual tests is just the significance level of the simultaneous test divided by the number of individual tests.

More specifically we can define the significance level α_k of a subvector as

$$\alpha_k = \frac{k}{N}\alpha \ , \qquad (2)$$

where k is the number of parameters in the subvector, N is the total number of station parameters and α is the significance level for the in-context test. For testing, say, only the x coordinates in a network of 12 stations at a simultaneous significance level of 0.05, we have 3 individual Chi-square tests each with an in-context significance level of 0.05(12/36)=0.017. For the in-context test of only the horizontal coordinates, we use a significance level of 0.05(24/36)=0.033.

A Helmert transformation of the GPS solution onto all the common points in the existing network which are included in the GPS solution can be performed using seven parameters (3 rotations, 3 translations and scale) to determine any systematic network-wide differences in scale and rotation and location between the GPS and existing network solutions. One purpose of this evaluation is to detect unmodelled biases in the GPS data, the effect of which is often network-wide distortions. Another purpose is to identify the causes of failure of the statistical compatibility tests which may be due to network-wide distortions in either the GPS network (due to unmodelled biases) or in the existing network solution (for any number of causes).

The Helmert transformation should first be applied without constraining any of the transformation parameters. The transformation should then be repeated, constraining the least significant parameter to zero, until only statistically significantly parameters remain at a confidence level of 95% (i.e., different from zero by more than the 95% confidence interval).

If there are enough common points, a strain analysis should also be performed in order to detect any local distortions between the GPS solution and "known" control points. Here local distortions are quantified in the form of strain ellipses and differential rotations. Depending on the vertical profile of the network, the strain may be two-dimensional (horizontal) or three-dimensional. This analysis may be performed using the technique described by Craymer et al. (1989d).

Although performing all of these analyses is not an easy task, computer software can automate the procedure. One such program is NETVAL (GRSL 1990). In addition to all of the above described analyses, it also provides pass/fail flags to help easily identify problems in the network.

Qualification of Contractors

A contractor shall be considered to have successfully qualified for performing GPS surveys if all of the following conditions are met:

1. All 95% relative confidence regions meet second-order, two- and three-dimensional accuracy standards

2. The final adjusted coordinates of all points agree with the "known" values to within second-order three-dimensional standards

3. The final adjusted coordinates are statistically equivalent to the “known” values at the 95% confidence level

So long as the equipment, procedures, and software remain unchanged, the contractor shall be considered to have qualified as a bidding agency for any future urban GPS survey. However, if the equipment, procedures, or software are modified or changed in any way, the contracting agency must be informed and, if requested, the qualification test repeated.

Recommendations

A number of improvements for the handling of GPS surveys should be investigated for future incorporation into these specifications and guidelines. These include:

1. Improved stochastic modelling (i.e., realistic covariance matrices) for GPS
2. Improved stochastic modelling (i.e., realistic covariance matrices) for existing control
3. Improved and consistent NAD27/NAD83 transformation procedures
4. Use of weighted constraints for existing control in the GPS network adjustment
5. Improved handling of geoidal heights

Each of these will be discussed separately below.

Improved Stochastic Modelling for GPS

The covariance matrix provided by most GPS processing software is not sensitive to biases which may exist from unmodelled effects of orbit errors and atmospheric effects. While it is possible to propagate the influence of these errors into the estimated covariance matrix, most software does not yet do this. The covariance matrices are therefore overly optimistic and do not realistically represent the errors associated with the GPS solutions. To the best of our knowledge, there is no commercially available GPS software that can provide realistic covariance matrices.

It has become standard practice in Transit, VLBI, and GPS positioning to multiply the formally estimated covariance matrices by a preconceived scale factor to account in part for these unmodelled influences. The most common value used to multiply standard deviations by is 3.0 (covariance matrix multiplied by 9.0). This value has been used in the past by the VLBI community (Herring, 1983), and is thought to be built into several GPS software packages. Unfortunately the software output does not always indicate whether the covariance matrix has been so scaled. As we have shown in Craymer et al. (1989b), the Phase II contractors' covariance matrices have apparently been scaled by different scale factors which were not reported in two of three cases.

The use of such preconceived scale factors represents a major hindrance for statistical testing since one can appropriately scale any covariance matrix so that it passes all statistical tests. Nevertheless the evaluation of the results, including the scaled covariance matrix, during contractor validation will ensure that the covariance matrices are scaled reasonably or at least pessimistically. The only restrictions are that the same scale factor must be used for all GPS surveys and for the entire covariance matrix.

The greatest problem with unrealistic covariance matrices concerns the integration of GPS with the existing conventional control. Without a knowledge of at least the relative weights of all the observations (including GPS), it becomes impossible to properly combine them. Although it may be possible to estimate a common scale factor for GPS using techniques such as minimum norm quadratic estimation (see Rao and Kleffe 1988), the formal covariance matrices from different GPS solutions should all be scaled consistently.

Improved Stochastic Modelling for Existing Control

The same problem with unrealistic covariance matrices also plagues the estimated accuracy of the existing network control. Until realistic covariance matrices for these points are known, it will not be possible to integrate properly the GPS solutions into the existing control short of performing a complete readjustment of all GPS and conventional observations (assuming realistic covariance matrices for GPS are available).

The conversion of the national framework and integration of other control to NAD83 will greatly facilitate this by making full covariance (and cross-covariance) matrices available for all control points. The NAD83 coordinate system is very similar to that used for GPS (see below), therefore eliminating the need for any coordinate transformation from GPS to the existing control network.

It is therefore strongly recommended that all agencies integrate their networks into NAD83 as soon as possible. It is also important that rigorous integration procedures be used in order to properly propagate the errors from the higher-order control into the integration network. Once accomplished, it will be a much simpler task to integrate GPS with the control network using the realistic covariance matrices of the existing control as weighted constraints in the GPS solutions. It will also greatly aid in statistically testing the compatibility of the GPS solutions with the existing control.

Improved and Consistent Transformation Procedures

Coordinates of existing control points are, and will continue to be for some time to come, given in the NAD27 (non-geocentric) coordinate system. On the other hand, GPS positions are most naturally computed in the geocentric Conventional Terrestrial (CT) coordinate system, in one of its several realizations (GRS80, NAD83, WGS84, etc.). This is because GPS satellite orbits are expressed in the CT-coordinate system. To use GPS relative positions together with existing control points in an effective way requires that the relationship between these two systems be accurately known, and uniformly understood. The Phase III results revealed that this uniform understanding is so far greatly lacking (Craymer et al. 1989b). This is a problem that is wider than the issue of urban GPS surveys, and one with which the surveying profession in Canada must come to grips.

In Canada, tables prepared for the publication *Surveying Offshore Canada Lands* over a decade ago have outlived their usefulness. These tables precede GPS, being based on Transit positioning, and attempt to model the local distortions in NAD27 networks by local values for the datum translation components. Orientation distortions are ignored. We propose that this publication be replaced by a three element approach:

1. A single set of standard values for three datum translation components and three misalignment angles between NAD27 and the CT system should be adopted for all of Canada. This would handle most of the coordinate differences (hundreds of metres).

2. The local distortions (tens of metres) would then be represented by four parameters: two translations (in the horizontal coordinates), one rotation (in azimuth), and a scale factor. Tables, algorithms, and/or software are required which would permit the surveyor to implement these transformations (including the local NAD27 network distortions and in both directions).

3. As far as merging GPS and conventional surveys is concerned, the residual differences between the coordinates (sub-metre) would be handled as follows: At least three, and preferably more, higher-order control points would be occupied during any GPS densification survey. Their NAD27 coordinates with their full covariance matrix should be taken into account as weighted constraints in the adjustment of the GPS observations. Some commercially available software allows weighted constraints to be used.

Integration with Existing Control

The GPS solutions should be integrated into the existing control by either performing a complete readjustment of all GPS and conventional observations or by using a weighted constrained adjustment. In the later approach the existing network control points should be weighted in the GPS solution using the inverse of their fully populated covariance matrices. As noted above, this approach will require realistic covariance matrices for the existing network control in the NAD83 coordinate system.

We therefore recommend that, until network control has been converted to NAD83 and realistic covariance matrices are available for the control points, minimally constrained GPS solutions should be performed and subsequently integrated by transforming to the existing control using a Helmert transformation or another procedure specified by the contracting agency. However, once this information is available, the weighted constraint approach should be used for all integration, whether GPS or conventional methods are used.

Relation Between Geodetic and Orthometric Heights

The relationship between heights above the ellipsoid and heights above the geoid is another issue requiring a uniform approach. This was dramatically demonstrated in Phase II of this project when each contractor handled the problem differently, none of them in a manner which was consistent with what was done for the LISD adjustment. This is also a problem that is wider than the issue of urban GPS surveys. Its solution, however, is more one of education.

The contractor must supply the kind of height specified by the contracting agency. In transforming geodetic heights to orthometric heights and vice versa, the contractor must use the geoidal heights and geoidal height differences specified by the contracting agency. In Canada, these are available upon request from the Geodetic Survey Division of the Canada Centre for Surveying or may be computed using software such as CndGeoid (GRSL, 1989) available from Geodetic Research Services Limited. Errors in geoidal heights and geoidal height differences should also be propagated into the solution.

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