

PRECISE POINT POSITIONING FOR MOBILE MAPPING

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ABSTRACT:

The method of precise point positioning (PPP) using un-differenced code and carrier phase observations in combination with measurement corrections is discussed. The implementation of PPP in mobile mapping is addressed. Two approaches are investigated. In the first, measurement corrections optimized for the work area, including atmospheric corrections, are wirelessly received from a local service provider operating a local real-time GPS reference network. In the second approach, only precise orbits and clock corrections received from an international service provider through the Internet are used. One major problem of relying on wireless corrections is the possibility of facing interruptions in reception of the measurement corrections, which would result in the deterioration of the PPP performance. A method is presented to solve this problem, in which the orbital, clock and wet tropospheric corrections stored during operation are lumped together, predicted in real time as a time series and used in the PPP mode when breaks of signal reception take place. To improve system reliability and to accelerate the process of phase ambiguity resolution, particularly when using global corrections, a dual-antenna system fixed on board the mobile mapping vehicle is utilized. The two antennae are also used to determine the orientation of the mapping sensors by determining the heading and pitch of the vehicle. An adaptive Kalman filtering approach is utilized in the system. The filter is used to adaptively reflect dynamics changes in vehicle trajectory through the use of a measurement residual sequence. Testing of the system showed that it has a good overall performance. It can achieve centimeter to decimeter positioning accuracy, and attitude determination accuracy at the arc-minute level.

1. INTRODUCTION

GPS positioning accuracy is affected by errors in measurements. These errors are traditionally reduced by double differencing of the rover measurements with observations from a base station of known coordinates, making centimeter accurate positioning possible. The shortcoming of this approach is the need to use synchronous measurements at the reference and the rover, and to allocate resources and time to occupy the base stations. In addition, a limited reference-to-rover distance is usually needed in order to significantly reduce measurement errors. Currently, there are both government and privately operated local real-time GPS reference networks that can transmit online the orbital, clock and atmospheric corrections. In addition, precise satellite orbits at centimeter-level accuracy and clock corrections at sub-nanosecond accuracy computed from continental and global networks can be received through the Internet. As a result, there is no longer a need to establish temporary 'own' reference stations. A positioning method known as precise point positioning (PPP) can be used, which is based on the processing of un-differenced observations from a single GPS receiver employing the measurement corrections. The PPP can serve well in mobile mapping. To achieve centimeter to decimeter positioning accuracy, carrier phase measurements need to be used. One problem is to accurately resolve the phase ambiguities, particularly when relying only on orbit and clock corrections. To successfully achieve good results, some methods are needed to aid GPS positioning, among which is the integration of GPS with an Inertial Measuring Unit as presented in Zhang and Gao, 2004. Other methods are still needed.

2. TREATMENT OF MEASUREMENT ERRORS IN PPP

The general code and phase observation equations of the GPS can be formulated in meter units as follows:

$$\rho_{(t)} = r_{(t, t-\tau)} + ds_{(t-\tau)} - cdT_{(t)} + cdt_{(t-\tau)} + d_{iono} + d_{tropo} + \varepsilon(\rho) \quad (1)$$

$$\phi_{(t)} = r_{(t, t-\tau)} + ds_{(t-\tau)} - cdT_{(t)} + cdt_{(t-\tau)} - d_{iono} + d_{tropo} + \lambda N + \varepsilon(\phi) \quad (2)$$

where $\rho_{(t)}$ and $\phi_{(t)}$ are the pseudo-range code and the phase measurements at the time of receiving the data (t), respectively. $(t-\tau)$ is the satellite time, where τ refers to the travel time from the satellite to the receiver. $r_{(t, t-\tau)}$ is the true geometric range, ds is the orbital error, c denotes the speed of light, dT and dt are the receiver and satellite clock errors, d_{iono} and d_{tropo} are the ionospheric and tropospheric delays respectively. λ denotes the carrier-phase wavelength, N is the integer phase ambiguity, and ε denotes the measurement noise, including the multipath and the antenna phase center variation. Treatment of the above errors in PPP is discussed in the following.

1. Orbital errors

For real-time applications, GPS users usually employ the broadcast ephemerides, which result in predicted orbits of low accuracy. The standard error for these orbits is about 2.7m (Springer and Hugentobler, 2001). To avoid using a differential approach, the user needs to utilize corrections to the broadcast orbits, which can be obtained at a few centimeters of accuracy, online from a local network operator, or after a short delay from organizations collecting data from global networks.

In post-mission processing, the user can obtain precise orbits (final after 1-2 weeks, or rapid after one day) from a global network such as the network used by the International GNSS Service (IGS), or from one of its seven analysis centers. The obtained orbit accuracy is usually within a few centimeters.

II- Clock Errors

GPS satellite clocks are somehow unstable and difficult to be modeled. For post mission processing, the IGS computed final or rapid clock corrections have an accuracy of 0.1 ns, which gives a satellite-to-receiver range of approximately 3 cm. For real time processing, the accuracy of the predicted satellite clock corrections from IGS is within 5 ns. Better clock corrections can be obtained after a short delay from other service providers, e.g. Natural Resources of Canada (NRCan) and Jet Propulsion Laboratory (JPL) with an accuracy of 0.5-1 ns.

III- Atmospheric errors

Atmospheric errors comprise the ionospheric and tropospheric delays. The biggest effect of the ionosphere on the GPS signal is the group delay and carrier phase advance, which depends on the electron density of the ionosphere along the signal path. The ionosphere can be considered the dominant source of error in GPS positioning. Thus, most current GPS ionospheric studies mainly focus on ionospheric modeling to improve accuracy when estimating the ionospheric correction, in addition to ionospheric distribution and irregularity, including the relationship with solar and geomagnetic activities (Gao, S. et al., 2004). For users of single frequency receivers, the common options for reducing the ionospheric error, if detailed values from a local network are not available, are either to use the Klobuchar ionospheric model or the ionosphere maps. The former broadcasts via navigation messages and can only compensate for approximately 50% of the ionosphere range error. The latter is available from a network solution, local or global. An example of the latter is the Global Ionosphere Maps (GIMs) that are available from the Center for Orbit Determination in Europe (CODE) in the form of three types of maps, namely Predicted (COPG), Rapid (CORG) and Final (CODG) GIM [CODE, 2003]. Currently, 2-dimensional maps are available, in which TEC values are given at the geographical grids of 5° in longitude and 2.5° in latitude. The mapped values need to be interpolated at the user location.

Since the ionosphere is dispersive and frequency dependent, PPP users can employ a combination of dual frequency observations to eliminate the first-order ionospheric error, which accounts for more than 99% of that error. To minimize the impact of noise from code measurements, a code-phase combination in the form of their average can be used for the two frequencies (Shen, 2002). This significantly helps in convergence of the PPP solution, particularly while solving for the ambiguities. In addition, a traditional phase combination can be used. This approach was implemented in this study when testing the use of corrections from global networks, as will be discussed later. The model equations can be given as:

$$\rho_{Li(t)}^{IF} = \frac{P(Li) + \phi(Li)}{2} = r_{(t, t-\tau)} + ds_{(t-\tau)} - cdT_{(t)} + cdt_{(t-\tau)} + d_{tropo} + 0.5 \lambda_i N_i + 0.5 (\varepsilon(\rho(Li)) + \phi(Li)) \quad (3)$$

$$\phi_{(t)}^{IF} = \frac{f_1^2 \cdot \phi_1 - f_2^2 \cdot \phi_2}{f_1^2 - f_2^2} = r_{(t, t-\tau)} + ds_{(t-\tau)} - cdT_{(t)} + cdt_{(t-\tau)} + d_{tropo} + \frac{c \cdot f_1 \cdot N_1 - c \cdot f_2 \cdot N_2}{f_1^2 - f_2^2} + \varepsilon(\phi^{IF}) \quad (4)$$

where IF denotes the ionospheric free operator, f_1 and f_2 are the frequencies of the carrier waves L_1 and L_2 , respectively. i is the frequency operator, where $i=1$ for L_1 and $i=2$ for L_2 . The ionosphere has the same value for the code and phase measurements but with the opposite sign. Thus, their sum eliminates the ionosphere error in Eq.(3). Besides the traditional float estimation of the ambiguities from Eq. (4), the use of Eq. (3) helps in estimating a near-fixed solution if the value of the remaining errors is small enough.

In GPS positioning, the total tropospheric range delay resulting from propagation of the satellite signals through the neutral atmosphere is expressed as the sum of the hydrostatic and wet components. Range delays resulting from the hydrostatic (dry) component of the troposphere, which is the major part of tropospheric error, can be computed with an accuracy of a few millimeters using empirical models (e.g. Saastamionen model). Barometric and meteorological data (surface temperature and pressure), together with the height above mean sea level and the user latitude, are also used. One way to avoid using real measurements is to linearly interpolate the temperature and pressure mean values from a pre-made latitudinal profile and apply a seasonal variation model. In addition, a good mapping function is required to project the troposphere zenith delay into the user-satellite slant distance. In this study, the Niel mapping function was utilized. It is an empirical function that depends on latitude and time (see Leick, 2004).

The wet part of the troposphere (approximately 10-20% of the total) is hard to model as it needs wet vapor measurements, which require special measuring equipment that is usually not available to normal users. Thus, in PPP, if detailed values of the wet tropospheric zenith delay are not available from a local network, this error can be considered as an additional unknown.

IV- Other Small Errors

Since positioning is carried out in PPP without differencing, some errors that can be ignored in the differential approach have to be taken into account. These errors are basically attributed to physical phenomena, and include:

- Relativity error, which is a function of the satellite motion and the Earth's gravity
 - Sagnac delay caused by the Earth's rotation during the transition time of the satellite signal
 - Phase wind up
 - Earth tide
 - Ocean tide loading
 - Atmosphere loading
 - The inter-frequency bias, resulting from using L_1 or L_2 alone.
- Some information about the definition and modeling of these errors are given in Abdel-Salam (2005).

The satellite antenna phase center offset is a special error resulting from the fact that the precise satellite positions supplied by most service providers (e.g. IGS) are referred to the satellite center of mass and not to the antenna phase center. The antenna offsets are provided in the satellite body fixed frame and thus need to be transformed to the satellite coordinates in the ITRF. For the sake of simplicity, it can be assumed that the satellite antenna offset in the body X-coordinate direction can be neglected (Le, 2004), noting that the X-offset is almost zero for block IIR and future satellites, and less than 30 centimeters for the satellites currently available in block II/IIA. The offset in the body Y-coordinate is practically zero for block II satellites. Thus, only the offset in the body Z coordinate direction, which points to the center of the Earth, can be taken into consideration.

3. SOURCES OF MEASUREMENT CORRECTIONS

In PPP, un-differenced observations from a single GPS receiver are used along with the measurement corrections. Thus, good estimation of the spatially correlated errors is the key to obtaining accurate positioning results. Currently, there are two basic methods to obtain the measurement corrections. In the first, measurement corrections are received from a local real-time GPS reference network through dedicated modems. In the second method, the reference network has a larger distribution, with a continental or global reach. The corrections are received via the Internet, online or in post-mission. The former method has the advantage of providing the local atmospheric corrections and the ability to provide corrections at high rates.

3.1 Corrections from Local Reference Networks

In this approach, a local network of GPS reference stations is used, whereby observations from multiple stations are gathered and processed in a common network adjustment at a central processing facility and measurement corrections are computed and sent to the rover through dedicated modems to correct its observations and to accurately determine its position. The information can be sent at a high rate (arbitrary, from 1 to 75 seconds). The sent data usually include corrections to orbital, clock, tropospheric, and ionospheric errors.

Many techniques can be employed in positioning with corrections from a local reference network, particularly in real time, among which are: the area correction parameters technique (FKP), the correction grid method, and the correction function method. The virtual reference station approach (VRS) is also commonly used. Some details of these methods can be found in Cannon et al. (2001), Wübbena and Willgalis (2001), Raquet and Lachapelle (2001), and Euler and Zebhauser (2003). These methods differ in the amount of data to be sent to the user, the processing strategy, amount of computations at the center station and by the user, and the type of communications between the network center and the rover receiver.

In March 2002, the Dubai Municipality started operating such a network system for Real-Time-Kinematic (RTK) positioning, known as DVRS, whereby users can receive the corrections online throughout the Emirate of Dubai, UAE. The corrections are also archived for post-processing purposes. The main software used in the processing of the DVRS data uses the FKP method to analyze the data and to estimate and represent the state of individual GPS errors in real time.

3.2 Corrections from Continental or Global Reference Networks

Measurement corrections from these types of networks are derived from the GPS data recorded at numerous global ground-based stations. For post-mission processing, the precise final or rapid satellite positions and clock corrections from the International GNSS Service (IGS) products are widely used, and can be obtained via the Internet.

For real-time processing, sub meter-level positioning accuracy can be obtained using the IGS ultra-rapid orbits and clocks. The predicted IGS data can give 3D estimates of satellite positions with an error in the 30 to 40-cm range (Soler and Snay 2004), and clock corrections accuracy at the level of nanoseconds (Kouba and Héroux, 2001). Unlike the local network corrections, which are sent at a high rate, the IGS orbits are provided at 15-minute intervals, four times a day. Thus,

interpolation is needed at the required positioning intervals. Interpolation of the satellite orbits is usually carried out using a polynomial or a trigonometric function (Schenewerk, 2003). The ultra rapid clocks are predicted one day ahead and issued twice a day.

A few organizations, such as the JPL and NRCAN, can provide near real-time data known as IGDG and GPS.C, respectively. These corrections can give much better positioning accuracy compared with the predicted IGS data. The corrections can be obtained over the Internet. The precise orbit and clock data from JPL is generated based on data from a network consisting of about 70 globally distributed reference stations. The estimated accuracy is about 20 cm for orbits and 0.5 ns for clocks (Gao and Chen, 2004). Data latency is about 4 seconds with 1 second intervals. The precise orbit and clock data from NRCAN is generated by data from a network consisting of about 20 globally distributed reference stations, with accuracy for orbits of about 10 cm and clocks of about 1 ns, respectively. The data latency for NRCAN's precise orbit and clock is at several hours and the update interval is 2 seconds.

The two methods of computing measurement corrections, using local or global networks, allow for positioning in post processing or in real time, but with different positioning accuracy levels. For instance, since local networks provide information about the local atmospheric errors, facilitating their removal, better accuracy is expected from this method in all cases. In addition, data are sent at a higher rate and with less delay compared with the global networks. Thus, the impact of the interpolation and prediction processes on the degradation of accuracy is minimized. Moreover, since the distance between the rover and the nearest network station in the local networks is generally less than 100 km, and the corrections are optimized for the work area, most of the spatially-correlated errors are significantly reduced. Thus, cm-level positioning accuracy can generally be obtained within a few seconds in post processing or in real time. On the other hand, when using corrections from a global network, accuracy at the sub-decimeter level can be achieved in post processing after a long convergence time of the filter results. However, positioning can be recovered, from its start, by rewinding the data, utilizing the estimated ambiguities. In real time, only decimeter-level positioning accuracy can be achieved until convergence is reached, which may take several minutes, after which, positioning at the sub-decimeter accuracy level can be reached.

4. MODELING

As mentioned earlier, when receiving measurement corrections from a local or global reference networks, the rover works in a PPP mode utilizing un-differenced observables. The observation equations of code-phase combination and phase combination after applying the precise orbits and clock corrections, and modeling out the dry component of the tropospheric error using an empirical model, take the following form:

$$\rho_{Li(t)}^{IF} = \frac{P(Li) + \phi(Li)}{2} = r_{(t,t-\tau)} - cdT_{(t)} + d_{wet} + 0.5 \lambda_i N_i + 0.5 (\varepsilon(\rho(Li) + \phi(Li))) \quad (5)$$

$$\phi_{(t)}^{IF} = \frac{f_1^2 \cdot \phi_1 - f_2^2 \cdot \phi_2}{f_1^2 - f_2^2} = r_{(t,t-\tau)} - cdT_{(t)} + d_{wet} + \frac{c \cdot f_1 \cdot N_1 - c \cdot f_2 \cdot N_2}{f_1^2 - f_2^2} + \varepsilon(\phi^F) \quad (6)$$

In PPP, processing of measurements is usually carried out by using Kalman filtering. The unknown vector includes the three position coordinate parameters, a receiver clock offset parameter, the wet tropospheric component, and the ambiguities. The state vector can be formulated as:

$$\bar{X}_u = [(x, y, z)_w, c dT_{(t)}, d_{wet}, (N)_{1...n}]^T \quad (7)$$

If an estimation of the wet tropospheric component can be obtained through a local reference network, the state vector becomes:

$$\bar{X}_u = [(x, y, z)_w, c dT_{(t)}, (N)_{1...n}]^T \quad (8)$$

In our approach, the user receiver clock bias and drift are modeled as a random-walk process. The receiver clock error can then be formulated as:

$$(c dT_{(t)})' = d_c(t) + w_f(t) \quad (9)$$

$$d_c'(t) = w_g(t) \quad (10)$$

where d_c is the clock drift, and w_f and w_g are zero-mean white Gaussian noise. The wet troposphere can be estimated using a random-walk process or a first order Gauss-Markov process. Multipath is treated as white noise. The signal received at low elevation angles are given less weight in the solution as they can be more affected by multipath, ionosphere errors, troposphere errors and antenna gain pattern. The observation weights are assumed to be inversely proportional to the sine of the satellite-user elevation angle.

The estimation of un-differenced ambiguities is carried out using an on-the-fly approach in the standalone mode. However, in PPP, a non-zero initial phase is experienced due to the unsynchronization of the satellite-transmitted and receiver-generated signals, which is usually cancelled out in the traditional double-differencing approach. As a result, the ambiguities in PPP are real numbers, including the ambiguities in Eq. (5). Thus, integer un-differenced ambiguities are first estimated as constants. Next, they are adjusted to their float numbers as the data accumulates and the filter converges to a stable condition.

To use reasonable stochastic information, an adaptive Kalman filtering approach is utilized. The filter is used to adaptively reflect dynamics changes in object trajectory through the use of a measurement residual sequence. In this approach, the residual sequence η_i was first computed as:

$$\eta_i = M_i - h(X_i) \quad (11)$$

Next, the adaptive formulation of the covariance matrices of the dynamics model and the measurement model (R and Q) in Kalman filtering can be given as follows (Mohammed and Schwarz, 1999):

$$C_\eta = \frac{1}{n} \sum_{j=j_0}^i \eta_j \eta_j^T \quad (12)$$

$$R_i = C_\eta + H_i P_i H_i^T \quad (13)$$

$$Q_i = K_i C_\eta K_i^T \quad (14)$$

where X_i is the state vector component, M_i is the measurement vector, h is their functional relationship. P denotes the covariance matrix of the filter states, H_i represents the linearized design matrix derived from the observation equation, K is the Kalman gain matrix, C_η denotes the covariance matrix of the residual sequence, and $j_0 = i - n + 1$ is the first epoch inside the estimation of a moving time window of the size (n), which can be taken as 20-30 epochs.

As discussed earlier, in PPP, when using corrections from a local GPS RTK reference network, a solution with correct ambiguities can be achieved within a few seconds. On the other hand, when using corrections from a global network, such as the IGS data or the IGDG and GPS.C corrections, which are received after a relatively longer delay and lack the atmospheric data, a longer time is needed for the convergence of the solution for the ambiguities and positions. However, this problem can be minimized in the mobile mapping application since processing can be performed in post mission. The data can first be utilized for estimation of the ambiguities. Next, the data is rewound and re-processed with the solved ambiguities, starting from their initial epoch, to determine the required positions.

5. PREDICTION OF MEASUREMENT CORRECTIONS FOR REAL-TIME APPLICATIONS

In real time PPP for mobile mapping, the corrections are received through wireless modems. One major problem when using wireless communication is the possibility of experiencing breaks in reception of the data. In post-mission processing, the problem can be alleviated by interpolation of the corrections using the standard methods. However, in real-time, other methods should be used and the success of PPP will depend on their performance.

To achieve accurate real-time positioning if breaks of measurement corrections take place, the following method was developed (El-Mowafy 2006 A, B):

- At the rover, during reception of the measurement corrections, a routine runs at a relatively long time interval to store and model, as a time series, the time change of the spatially correlated measurement corrections received (orbit, clock, and wet troposphere) for each satellite. In this process, the prediction coefficients for the corrections are determined. To reduce the computation load, the prediction parameters are estimated for each observed satellite in a sequential process.
- When reception of the measurement corrections is interrupted, the corrections are predicted for several minutes ahead utilizing the estimated prediction coefficients.
- The rover receiver then works autonomously in a precise point positioning mode using the un-differenced measurements, which are corrected by adding the predicted corrections.

In this approach, all spatially-correlated corrections can be lumped together into one term. The satellite clock error usually makes the largest contribution to the total error budget. Thus, the time-series prediction model used for predicting the combined error corrections is best selected as the model appropriate for prediction of the satellite clock corrections, as long as it gives good performance in prediction of the other measurement corrections. After a thorough investigation of possible time-series methods that can be used for the application at hand, the double exponential smoothing method is proposed for prediction of the combined measurement corrections. In this method, a level component (a constant) and a trend component are employed at each period. Two weights, or smoothing parameters, can be used to update the two components

(NIST/SEMATECH 2005). The smoothing equations can then be written as follows:

$$L_t = \alpha ds_t + (1 - \alpha)(L_{t-1} + T_{t-1}) \quad (15)$$

$$T_t = \gamma(L_t - L_{t-1}) + (1 - \gamma)T_{t-1} \quad (16)$$

$$\widehat{ds}_t = L_{t-1} + T_{t-1} \quad (17)$$

where L_t and T_t denote the level and the trend at time t . α and γ are their weights, which are estimated by exponential smoothing. \widehat{ds}_t is the fitted orbital correction, or one-step-ahead forecast, at time t . For the application in hand, equal weights can be assumed (e.g. 0.2), noting that large weights usually result in more smoothing of the fitted data.

The proposed method is based on the assumption that measurement error corrections change with time according to some pattern, which the method tries to model in real-time and use for prediction. The concept is valid as long as prediction is made for only a few minutes. In addition, it should be noted that modeling of the time series should avoid outliers in the data values as these can result in either a biased prediction or wrong modeling. Therefore, data included in the time series have to be checked against such outliers. An empirical check can be formulated as follows:

$$(y_k - y_{k-1}) < \zeta \quad (18)$$

where y_k is the error correction, estimated at time k , and ζ is a tolerance value which can be taken as 3σ of the average estimation accuracy of the correction. If such an outlier is detected, the corresponding error correction has to be removed from the estimation process of the parameters. However, since a time series analysis requires a continuous data sequence, the error correction value at the removed or missing epoch can be replaced by an interpolated value, or simply computed as a weighted moving average estimated within a short time window.

6. THE USE OF A DUAL-ANTENNA SYSTEM

In PPP for mobile mapping, the use of two independent antennae on board the moving vehicle offers supplementary information to help in the case of data loss from either antenna. In addition, the distance between the two antennae, measured beforehand, can be used to improve the reliability and accelerate the phase ambiguity resolution in post-mission processing or in real time, particularly when using the global corrections. In this case, several candidate ambiguity sets that are included in the search space can be eliminated if they do not satisfy, within some tolerance, a length constraint. This constraint is formulated such that the known length between the two antennae is compared with the computed length, derived from the GPS solution. However, the advantages come at the expense of resolving phase ambiguities for two antennae instead of one. The length constraint can be written as:

$$b_{1-2}^2 - \Delta X_{1-2}^2 + \Delta Y_{1-2}^2 + \Delta Z_{1-2}^2 = \delta \quad (19)$$

where b_{1-2} is the known baseline length between the antennae 1 & 2, and ΔX_{1-2} , ΔY_{1-2} , ΔZ_{1-2} are their baseline vector components, based on the tested candidate ambiguity sets. δ denotes the tolerance, which is based on the expected

positioning accuracy and can be taken as a few centimeters. The baseline length check can also be applied to verify the correctness of the computed positions in subsequent epochs after ambiguity estimation. The height difference between the two antennae can also be computed from the known distance between the antennae and using the attitude data. This difference can be compared to the computed height from the GPS to check for the consistency of the height differences.

The use of a dual-antenna system on board the mobile mapping vehicle also helps in estimating the attitude of the mapping camera by determining the vehicle heading and pitch (attitude) and linking them to the orientation of the cameras. These parameters can be directly estimated from the local-level antenna vector (ΔE , ΔN , ΔU) as follows:

$$\text{Heading} = \tan^{-1} \frac{\Delta E_{12}}{\Delta N_{12}} \quad (20)$$

$$\text{Pitch} = \tan^{-1} \frac{\Delta U_{12}}{\sqrt{(\Delta E_{12})^2 + (\Delta N_{12})^2}} \quad (21)$$

To determine accurate attitude, the antenna vector should be determined at the mm level of accuracy. To reach this accuracy, the vector has to be re-solved taking one of the antennae as the base, e.g. the rear one. The antenna spacing is limited to a few meters, and thus all spatially-correlated errors are practically eliminated in the differencing process.

In case of the need to re-initialize the carrier phase ambiguities, the knowledge of the heading of the rover object can help in speeding up the process by narrowing down the number of candidate ambiguity sets within the search space, as the solution derived from correct phase ambiguities has to satisfy the known heading values. These values may need to be predicted within a few seconds. However, the process can still be valid as the heading usually slowly changes with time.

7. FIELD TESTING

7.1 Comparing the PPP Accuracies Using Corrections from Local and Global Networks

To investigate the performance of the PPP approach using measurement corrections from local and global networks, a test was conducted in Dubai, UAE. A set of 13 points with distances ranging between 18.88m and 36.97m were established for this purpose. The layout of these points is illustrated in Figure 1. The coordinates of the test points were first determined using Leica SR530 receivers in a standard differential GPS method. The points were referenced to a known control station that was approximately 9.2 km away. The estimated coordinates are used as a reference for examining the accuracy of the PPP method when applied at the same points. Two approaches were used with the PPP. In the first approach, point coordinates were estimated in real-time kinematic mode using measurement corrections from the local real-time GPS reference network of Dubai (DVRS). Positions were estimated at a rate of 1 Hz. To evaluate repeatability of results, three independent surveys were carried out at different times of the day to allow for significant changes in satellite geometry and atmospheric conditions. During some periods, the reception of the measurement corrections was subjected to breaks. During these periods, the corrections were predicted as a time series as explained above.

In the second PPP approach, the collected code and phase data were re-processed in post mission using only corrections from the IGS rapid orbits and clock corrections obtained via the Internet. The measurement corrections of the local network were sent at five seconds intervals, while these of the IGS rapid orbits were generated at 15-minute intervals and the clock corrections at 5-minute intervals. Therefore, the satellite positions (orbits) and clock corrections were interpolated at the measuring epoch for both PPP modes.

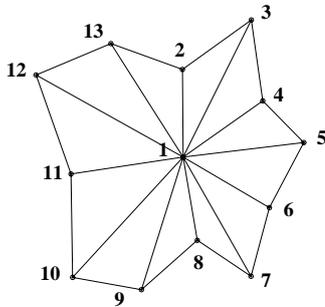


Figure 1. Layout of the test points

When examining PPP accuracy using corrections from the DVRS local network, differences between coordinates of test points estimated from this method and their coordinates from the reference differential approach were computed, and generally found to be of a few centimeters. The resultant 3D (spatial) differences ranged from 0.81cm to 3.61 cm. The estimated differences at each point for the three tests are illustrated in Figure 2. The statistics of average coordinate differences in E, N, h coordinates, which represent the PPP accuracy, are given in Table 1. To evaluate positioning errors due to prediction of the corrections if breaks in reception are experienced, the corrections were intentionally interrupted for two periods, for a length of five minutes each. Results were compared with the output positions if no breaks had taken place. Positioning errors due to prediction of the corrections were found to grow with time; however, the errors were limited to a few centimeters, with an average of 7.6 cm.

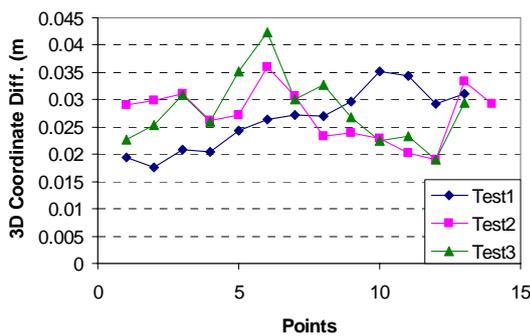


Figure 2. 3D accuracy using the local network corrections

| | E | N | h |
|----------------------------|-------|-------|--------|
| Average | 0.019 | 0.047 | -0.014 |
| Max. | 0.033 | 0.049 | 0.069 |
| σ | 0.024 | 0.052 | 0.049 |

Table 1. Statistics of PPP accuracy using the local network corrections (m)

The accuracy of the coordinates of the 13 test points estimated by applying the second tested PPP approach using only corrections from the IGS rapid orbits and clocks was evaluated by comparing their values with the reference coordinates estimated from the differential approach. The same collected code and phase data of the rover receiver used in the first mode were re-processed in post mission. As a result of working with no information on the atmospheric errors and with a longer information rate, which generated more prediction errors, carrier-phase ambiguity resolution and the filter took a longer time to converge to stable results. For the 13 test points, two to eleven minutes were needed to reach the stability condition. In addition, after convergence, the accuracy was slightly worse compared with the first case of using the local network corrections. Table 2 gives the statistics of PPP results using this method. Figure 3 shows the coordinate differences between the PPP coordinates and the reference coordinates of the differential approach for the first test, which is given as an example.

| | E | N | h |
|----------------------------|-------|-------|-------|
| Average (Absolute) | 0.028 | 0.046 | 0.036 |
| Max. | 0.051 | 0.063 | 0.071 |
| σ | 0.024 | 0.052 | 0.049 |

Table 2. Statistics of PPP accuracy using IGS corrections (m)

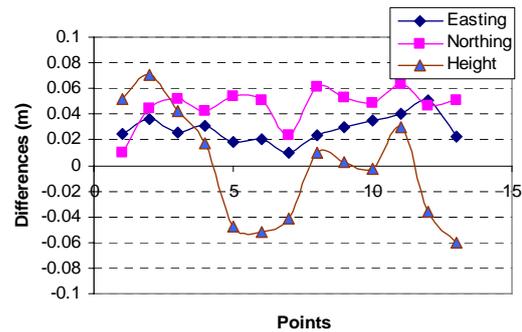


Figure 3. PPP accuracy with rapid products of the IGS corrections

7.2 Kinematic Testing on a Vehicle

To investigate the performance of the PPP approach for mobile mapping, another test was conducted in the city of Al Ain, UAE. Two antennae were mounted on the roof of a 4-wheel drive vehicle, and along its centerline. The antennae were 1.52 m apart, and were connected to Ashtech UZ-12 receivers. Figure 4 illustrates the antenna setup on the test vehicle. Since no local GPS reference network was available in this area, the PPP approach was carried out by collecting the phase and code data and post processing them in a kinematic mode using only corrections from the IGS rapid orbits and clocks. The data were collected at 1 Hz intervals. The work environment was urban in general, resulting in variable PDOP values, which ranged from 1.1 to 6.3. The same data were post processed in a standard differential GPS scheme with a nearby known control station to establish a reference for comparison with the PPP results. The vehicle collected data for approximately 37 minutes. The trajectory of the test is illustrated in Figure 5, where the Easting and Northing coordinates are given in the local Transverse Mercator projection system using the WGS84 datum.



Figure 4. The test vehicle

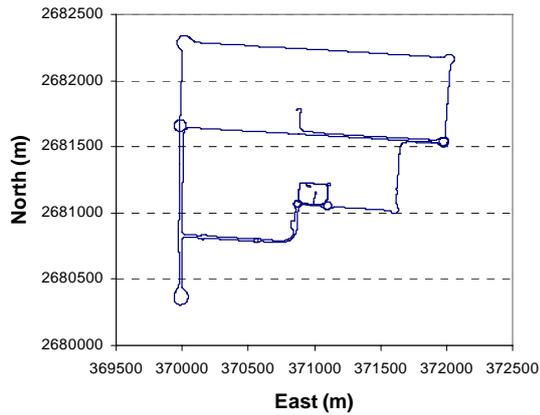


Figure 5. The test trajectory

Due to the fact that only orbit and clock corrections were used when processing the data in post mission, several minutes were needed for convergence of the filter solution. The data were next reworded and the estimated ambiguities were used from the start to compute improved positions. Real numbers were used to account for the non-zero initial phase errors. A similar process was repeated when initialization of the ambiguities was needed. Due to processing in a kinematic mode, a limited number of observations was available for positioning at each epoch. Accordingly, positioning accuracy was slightly degraded compared to the two previous cases. Table 3 gives the statistics of PPP results in this test. However, the accuracy was, in general, at the sub decimeter level. The maximum 3D positioning difference between the PPP processing and the differential GPS at any coordinate was 15.44 cm. On average, positioning errors ranged between 4 cm and 9 cm.

| | E | N | h |
|----------------------------|----------|----------|----------|
| Average (Absolute) | 0.063 | 0.048 | 0.086 |
| Max. | 0.104 | 0.083 | 0.123 |
| σ | 0.071 | 0.049 | 0.060 |

Table 3. Statistics of PPP accuracy in the kinematic test (m)

The use of two antennae on the rover has an advantage in increasing the integrity and reliability if one antenna experiences malfunction. An important gain comes in speeding up the carrier phase ambiguity resolution and increasing its

reliability. Testing showed that the ambiguity resolution for each antenna was approximately 20% faster than if being performed without the length constraint. Independent from the PPP solution, the data of the two antennae were re-processed in a differential mode, taking the rear antenna as the base to estimate the heading and pitch (attitude parameters) of the vehicle. This attitude can be linked to the mapping cameras on the roof of the vehicle to provide their orientation during surveying. The average accuracy of the heading and pitch obtained from the test are given in Table 4, which are estimated from statistics of processing. The achieved accuracy was at the arc-minute level. However, this accuracy is dependent on the quality and number of GPS observations as well as the distance between the two antennae. Thus, if a longer distance is employed using a different vehicle (e.g. a van), better accuracy of the attitude results can be achieved.

| | Average | σ |
|----------------|----------------|----------------------------|
| Heading | 4.51 | 2.67 |
| Pitch | 5.93 | 3.32 |

Table 4. Attitude accuracy (arc-minutes)

8. SUMMARY AND CONCLUSIONS

The precise point positioning (PPP) approach represents a flexible method for positioning in mobile mapping. Dedicated reference stations are no longer needed. The rover receiver in this mode operates with un-differenced measurements. To achieve good positioning accuracy, the final coordinates should be computed using carrier phase measurements and corrections to spatially-correlated errors. These corrections can be obtained from various sources, including a local real-time reference network through dedicated modems, or via the Internet from global networks. In the former approach, orbital, clock and atmospheric corrections can be received at a high rate. In the latter approach, only orbit and clock corrections can be obtained. Results showed that positioning accuracy at the sub decimeter level can be achieved with the PPP method. However, employment of corrections from a local real-time network gave better accuracy and a faster solution compared with using the IGS rapid orbit and clock products, even when the latter was carried out in post-mission. In the case of interruption of reception of the measurement corrections, all corrections of spatially-correlated errors can be lumped together into one term and predicted using the double exponential smoothing method. Positioning errors due to prediction of the corrections for a few minutes were limited to a few centimeters. In addition, faster and more reliable ambiguity resolution can be obtained if two antennae are used on the rover. The two antennae can be used to estimate the heading and pitch (attitude) of the vehicle. This attitude can be linked to the mapping cameras on the roof of the vehicle to provide their orientation during mapping. An accuracy of a few arc-minutes can be achieved for most types of mapping vehicles.

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