Precise Point Positioning and Integrity Monitoring with GPS and GLONASS

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Terry Moore is a Professor of Satellite Navigation and Director of the NGI at the University of Nottingham. He holds a PhD degree in Space Geodesy from the University of Nottingham. He has over 20 years research experience in GNSS and is a consultant and adviser to many public and private organizations. Professor Moore is a Fellow of the RIN.

Chris Hill is a Principal Research Officer at the NGI. He has a PhD from the University of Nottingham on the subject of Satellite Laser Ranging, and has worked on a variety of GPS and GNSS research projects over the last 20 years. He is a Fellow of the RIN.

ABSTRACT

Precise Point Positioning (PPP) with GPS measurements has achieved a level of success. In order to benefit from the multiple available constellations, research has been undertaken to combine GLONASS and GPS measurements in PPP processing. In addition, integrity monitoring for PPP has been investigated with simulated multi-constellations signals. Previous work concluded that adding GLONSS measurements has little improvement in the accuracy for PPP. The main reasons identified were either the errors in GLONASS clock products or limited number of GLONASS satellites in view.
Due to the recent efforts in restoring full operation of GLONASS, there are 23 GLONASS satellites currently in operation. The Information Analytical Centre at Russian Federal Space Agency and the European Space Agency (ESA) provide precise satellite orbit and clock products both for GPS and GLONASS. These enable further research to be done in order to maximize the benefits to a user.

This paper has carried out research based on recent advances in PPP algorithms and GLONASS ephemeris products. The data pre-processing steps include applying satellite orbit and clock corrections, satellite antenna phase offset correction, receiver antenna phase offset correction, differential code bias corrections for GPS, Troposphere delay corrections and the Shapiro delay correction. The Ionosphere-free observation combination is used.

The positioning algorithm is based on an extended Kalman filter. In order to make the positioning robust, the GPS and GLONASS states are updated separately. The integrity monitoring algorithm is also embedded to detect and exclude potential failures.

The datasets from two locations, one in Europe and one in Canada, were used to test the algorithm developed. The results show that adding GLONASS measurements and products to the GPS PPP can improve both the accuracy of positioning solution and convergence time. The protection levels are also lower in the combined solutions. These show the potential significant benefits for users in difficult environments such as urban areas.

INTRODUCTION

The traditional way to provide highly accurate (centimeter level) positioning is to use the conventional Real Time Kinematic (RTK) method. It is based on cancelling and mitigating errors which are common and highly correlated, respectively, for two GNSS receiver by differencing measurements. Using conventional RTK requires at least one GNSS receiver in a known location. Therefore, using conventional RTK is problematic in places where there is no reference network infrastructure.

The principle of the Precise Point Positioning (PPP) method is to model and correct error sources instead of differencing measurements as in the case of conventional RTK. PPP can provide centimeter level accuracy which is sufficient to the most of applications. However, the primary problem with PPP is long solution convergence time. Depending on the processing model and data used, it can take up to 30 to 60 minutes to obtain smaller than 10cm position error (Bisnath and Gao, 2007). Long convergence time makes using PPP unsuitable for a wide range of applications.

Typical PPP models use the ionosphere-free combination with GPS C1/P1 and P2 code-phase and GPS L1 and L2 carrier-phase measurements. An example, of this kind of model is presented in (Héroux and Kouba, 2001).

Precise satellite orbit and clock corrections provided for example by the International GNSS Service (IGS) (IGS, 2009) are used by traditional PPP models. In addition to this, a minimum of models for the satellite and receiver antenna phase center error, site displacement effects and satellite antenna phase wind-up corrections are used with traditional PPP (Héroux and Kouba, 2001).

GPS is used exclusively in many traditional PPP approaches, for example in the Jet Propulsion Laboratory (JPL) Automatic Precise Positioning Service (APPS) (Laboratory, 2011) or in Novatel GrafNav prior the version 8.40(Novatel, 2011). However, using GLONASS has become more interesting recently, due to the restoration to a full constellation of GLONASS satellites. At the time of writing, there are 23 GLONASS satellites in the operational phase(Centre, 2011).

Some work has already been done related to combined GPS and GLONASS positioning by using the ionosphere-free model. According to (Tolman et al., 2010) or (Li et al., 2009), using GLONASS with GPS is beneficial, when there are only a few(less than five) GPS satellites available. However, worse quality of GLONASS orbit and clock products can even decrease performance in some cases(Tolman et al., 2010). According to (Cai, 2009), using GLONASS with GPS can improve the accuracy of coordinate components by 40% (East), 28%(North) and 24%(Up) and convergence time of coordinate components by 21%(East), 24%(North) and 19%(Up) in static cases. These results were observed based on test data from seven different IGS stations.

According to the previous work, it is difficult to conclude if using GLONASS with GPS is beneficial compared to using GPS alone. This is due to differences in error corrections and models used in different papers. In addition to this, GLONASS satellite orbit and clock corrections may have been improved since these papers have been published.

Only float carrier phase ambiguities are estimated by traditional PPP models. However, at present there are fixed ambiguity PPP models such as the Fractional Cycle Bias(FCB) estimation model (Geng et al., 2010) or the de-coupled clock model (Collins, 2008). Fixing carrier-phase ambiguities can improve accuracy after the fixing has been done. However, using only GPS has been discussed in these papers.

Fixing carrier-phase ambiguities is more difficult in the case of GLONASS PPP, because GLONASS signals use Frequency Division Multiple Access (FDMA) instead of Code Division Multiple Access (CDMA) which is used with GPS. There are satellite/frequency/receiver type...
specific inter-frequency biases in GLONASS code-phase and carrier-phase measurements. These GLONASS code-phase biases may even be different for the same type of GNSS receivers. GLONASS ambiguity fixing in the case of PPP was presented in (Reussner and Wanninger, 2011). However, they didn’t manage to fix GLONASS integer ambiguities in the case of PPP without using Global Ionospheric Maps (GIM), because a geometry dependent method was needed to solve wide-lane ambiguities. It was not possible to calibrate GLONASS differential code biases with sufficiently accuracy. Therefore, it was impossible to use the geometry-free Melbourne-Wubben combination to fix wide-lane ambiguities.

In this paper, only float carrier-phase ambiguities are estimated, by using the ionosphere-free measurement combination, because fixing GLONASS ambiguities is not possible without using Global Ionospheric Maps (GIM).

Integrity of PPP means that a user can be warned within a given period of time (time-to-alert), if a position error exceeds the alert limit. This detection must be made with given probabilities of false alarm and missed detection. The Imperial College Carrier phase-based Receiver Autonomous Integrity Monitoring (ICRAIM) presented in (Feng et al., 2009) or in (Feng et al., 2010) with some modifications is used in this paper.

USED GNSS OBSERVATIONS

The format of GNSS observation equations used in this paper is explained in this section. Equation 1 presents GNSS P code measurements (in meters), Equation 2 presents GNSS C/A code measurements (in meters) and Equation 3 presents GNSS carrier-phase measurements (in meters).

\[
P_{F}^{i} = e^{i} + c\delta_{r} - c\delta^{i} + \frac{i^{i}}{f_{F}} + \frac{s^{i}}{f_{F}} + T^{i} + M_{PF}^{i} + Q_{PP}^{i} + \text{bias}_{PF}^{i} - \text{bias}_{F}^{i},
\]

Equation 1

\[
C_{F}^{i} = e^{i} + c\delta_{r} - c\delta^{i} + \frac{i^{i}}{f_{F}} + \frac{s^{i}}{f_{F}} + T^{i} + M_{CF}^{i} + Q_{CP}^{i} + \text{bias}_{ CF}^{i} - \text{bias}_{C}^{i},
\]

Equation 2

\[
L_{F}^{i} = e^{i} + c\delta_{r} - c\delta^{i} - \frac{i^{i}}{f_{F}} - \frac{s^{i}}{f_{F}} + T^{i} + m_{PF}^{i} + q_{K}^{i} + \lambda_{F}(N_{K}^{i} + B_{F}^{i} - B_{F}^{i})
\]

Equation 3

The used indices are:

- \(i\) is the satellite index.
- \(F\) is the index of the GNSS frequency. For GPS satellites, indices are (\(F = 1\) (GPS L1), \(F = 2\) (GPS L2), \(F = 5\) (GPS L5)). For GLONASS satellites indices are (\(F = 1\) (GLONASS L1), \(F = 2\) (GLONASS L2). For Galileo satellites indices are (\(F = 1\) (GALILEO E1), \(F = 5\) (GALILEO E5), \(F = 6\) (GALILEO E6).

\(f_{F}\) is the GNSS frequency in hertz.

\(e^{i}\) is the geometric distance from the receiver to the satellite.

\(c\delta_{r}\) is the receiver clock error.

\(c\delta^{i}\) is the satellite clock error.

\(i^{i}\) is the first-order ionospheric error term.

\(s^{i}\) is the second-order ionospheric error term.

\(T^{i}\) is the tropospheric error term.

\(M_{PF}^{i}\) is the multipath error for P-code measurements on the frequency F.

\(M_{CF}^{i}\) is the multipath error for C-code measurements on the frequency F.

\(Q_{PP}^{i}\) is the noise for the P-code measurements on the frequency F.

\(Q_{CP}^{i}\) is the noise for the C-code measurements on the frequency F.

\(m_{PF}^{i}\) is the multipath error for carrier-phase measurements on the frequency F.

\(q_{K}^{i}\) is the noise for the carrier-phase measurements on the frequency F.

\(N_{K}^{i}\) is the carrier-phase ambiguity term on the frequency F.

\(B_{F}^{i}\) is a satellite side fractional cycle bias(FCB) on the frequency F. The FCB is also referred to as un-calibrated phase delay (UPD).

\(B_{F}^{i}\) is the receiver side fractional cycle bias(FCB) on the frequency F.

\(\lambda_{F}\) is the wavelength on the frequency F.

\(\text{bias}_{PF}^{i}\) is the satellite code bias for P code measurements on the frequency F.

\(\text{bias}_{PF}^{i}\) is the satellite code bias for C code measurements on the frequency F.

\(\text{bias}_{PF}^{i}\) is the receiver code bias for P code measurements on the frequency F.

\(\text{bias}_{PF}^{i}\) is the receiver code bias for C code measurements on the frequency F.

PPP ERROR CORRECTIONS WITH GPS AND GLONASS

The iNsight project (www.insight-gnss.org) POINT software was used to process data. GPS C1/P1, GPS C2/P2, GLONAS C1 and GLONASS C2/P2 code-phase measurements and GPS L1, GPS L2, GLONASS L1 and GLONASS L2 carrier-phase measurements were used.

The first-order ionospheric error \((\frac{\delta}{\rho})\) can be corrected by using the ionosphere-free measurement combination, because the first-order ionospheric error is dependent on the (GNSS) frequency. The measurement combination according to Equation 4 was used for code-phase measurements and the measurement combination according to Equation 5 was used for carrier-phase measurements in meters (Dach et al., 2007).
Both GPS P and C code measurements were used for processing. Therefore, C1/P1 and C2/P2 Differential Code Biases (DCB) need to be corrected. Corrections provided by The Center for Orbit Determination in Europe (CODE) were used (Schaer and Dach, 2010).

Precise final satellite orbit and clock corrections provided by the European Space Agency (ESA) were used (ESA, 2011). These products are suitable both GPS and GLONASS.

Receiver and satellite antenna offsets were corrected by using corrections, in the ANTEX format (Service, 2010), provided by the IGS.

The EGNOS troposphere model and mapping function (Penna et al., 2001) were used for modeling and correcting the tropospheric error. The tropospheric error correction for a satellite is calculated according to Equation 6, where \( d_{\text{trop}} \) is the EGNOS hydrostatic troposphere mapping function, \( d_h \) and \( d_w \) are the hydrostatic tropospheric and wet delay calculated by the EGNOS troposphere model, \( m(\varepsilon)_{azl} \) is the troposphere gradient mapping function, \( G_N \) is the troposphere gradient to the North, \( G_E \) is the troposphere gradient to the East, \( \varepsilon \) is the elevation of satellite and \( \phi \) is the azimuth of the satellite.

The Chen troposphere gradient mapping function (Zhang and Gao, 2006) was used according to Equation 7. Troposphere gradients \( G_N \) and \( G_E \) were estimated as Kalman filter states.

In addition to these error corrections, satellite phase wind-up (Kouba, 2009), site-displacement effects (Kouba, 2009) and the Shapiro delay (Parkinson et al., 1996) error corrections were applied.

**PPP DATA PROCESSING**

An extended Kalman filter as presented in (Feng et al., 2009) was used for data processing. Estimated Kalman filter states \( x_k \), where \( k \) is the epoch index, are explained in Table 1. The process noise standard deviation for the position states was set low (0.000001), because the positioning scenarios were static.

The Kalman filter prediction step for the state vector is presented by Equation 8, where \( x_k^{(-)} \) is the predicted state vector, \( \Phi \) is the state transition matrix and \( x_{k-1}^{(+)} \) is the state vector from the previous epoch. The Kalman filter prediction step for the state variance matrix is presented by Equation 9, where \( P_{k-1}^{(-)} \) is the variance matrix from the previous epoch, \( P_k^{(-)} \) is the predicted variance matrix and \( Q_k \) is the process noise variance matrix. Equation 10 is used to calculate the residual vector \( r_k \) against the predicted state vector, Equation 11 is to calculate the Kalman gain \( K_k \), Equation 12 is to calculate the weight matrix \( W_k \), Equation 13 is to update the state vector \( x_k^{(+)} \) and Equation 14 is to update the state variance matrix \( P_k^{(+)} \). Both ways to update the Kalman filter should provide similar performance in theory and practice.
<table>
<thead>
<tr>
<th>State</th>
<th>Initial value</th>
<th>Initial standard deviation</th>
<th>Process noise standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>Based on the least square solution.</td>
<td>100000m (The East component)</td>
<td>0.000001 m/\sqrt{s} (The East component)</td>
</tr>
<tr>
<td>Longitude</td>
<td>Based on the least square solution.</td>
<td>100000m (The North component)</td>
<td>0.000001 m/\sqrt{s} (The North component)</td>
</tr>
<tr>
<td>Altitude</td>
<td>Based on the least square solution.</td>
<td>10000m</td>
<td>0.000001 m/\sqrt{s}</td>
</tr>
<tr>
<td>Receiver clock error (GPS)</td>
<td>Based on the least square solution.</td>
<td>1000m</td>
<td>100 m/\sqrt{s}</td>
</tr>
<tr>
<td>Receiver clock error (GLONASS)</td>
<td>Based on the least square solution.</td>
<td>1000m</td>
<td>100 m/\sqrt{s}</td>
</tr>
<tr>
<td>Troposphere wet delay</td>
<td>Based on the EGNOS troposphere model.</td>
<td>0.1m</td>
<td>10^{-6} m/\sqrt{s}</td>
</tr>
<tr>
<td>Troposphere gradient $G_N$</td>
<td>0</td>
<td>0.001m</td>
<td>3.1667 m * 10^{-6} m/\sqrt{s}</td>
</tr>
<tr>
<td>Troposphere gradient $G_E$</td>
<td>0</td>
<td>0.001m</td>
<td>3.1667 m * 10^{-6} m/\sqrt{s}</td>
</tr>
<tr>
<td>Carrier-phase ambiguities</td>
<td>Based on the estimated range</td>
<td>1000cycles</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1 Estimated Kalman filter states.

**THE ICRAIM METHOD**

The integrity monitoring algorithm used in this paper is based on the ICRAIM method presented in (Feng et al., 2010).

\[
\begin{align*}
z &= \begin{bmatrix} p_{\text{iono,free}} \\ \Phi_{\text{iono,free}} \end{bmatrix} \\
R &= \begin{bmatrix} R_{p_{\text{iono,free}}} & 0 \\ 0 & R_{\Phi_{\text{iono,free}}} \end{bmatrix}
\end{align*}
\]

Equation 15

Equation 16

Different measurement types ($p_{\text{iono,free}}$ is ionosphere-free pseudorange and $\Phi_{\text{iono,free}}$ is ionosphere-free carrier-phase) are grouped in the Kalman filter according to Equation 15. The variance of the measurements is represented by Equation 16.

With the ICRAIM method, test statistics are calculated from different subsets of measurements. The reason is to detect and exclude better errors with different types of measurements. For example, carrier-phase only test statistics can be used to detect cycle slips. The total test statistic is calculated according to Equation 18, the test statistic for ionosphere-free pseudorange measurements is calculated according Equation 19 and the test statistic for ionosphere-free carrier phase measurements is calculated according to Equation 20. The measurement residual vector after the Kalman filter update is calculated according to Equation 17.

(Feng et al., 2009)

\[
re = z_k - H_k x_k^{(+)}
\]

Equation 17

\[
T = \sqrt{r^T W r}
\]

Equation 18

\[
T_p = \sqrt{r^T_{p_{\text{iono,free}}} P_{\text{iono,free}}^{-1} r_{p_{\text{iono,free}}}}
\]

Equation 19

\[
T_{\text{iono,free}} = \sqrt{r^T_{\text{iono,free}} R_{\text{iono,free}}^{-1} r_{\text{iono,free}}}
\]

Equation 20

As with the traditional RAIM, the test statistics obey the chi-square distribution. Therefore, error detection thresholds can be determined based on the probability of false alarm, the probability of missed detection, noise standard deviation and the degrees of freedom. The degrees of freedom used with the ICRAIM method are equal to the number of measurements. (Feng et al., 2009)

In the case of the ICRAIM method two separate horizontal and vertical protection levels are calculated. The $HPL_1$ can be calculated according to Equation 23, where horizontal position uncertainty is calculated according to Equation 21 and $k_H$ is a factor which reflects the probability of missed detections. The $VPL_1$ can be calculated according to Equation 24, where vertical position uncertainty is calculated according to Equation 22 and $k_V$ is a factor which reflects the probability of missed detections. (Feng et al., 2009)

\[
\sigma_H = \sqrt{P_{11} + P_{22}}
\]

Equation 21

\[
\sigma_V = \sqrt{P_{33}}
\]

Equation 22

\[
HPL_1 = k_H \sigma_H
\]

Equation 23

\[
VPL_1 = k_V \sigma_V
\]

Equation 24

HSLOPE according to Equation 26 and VSLOPE according Equation 27 provide information about the relationship between the test statistic and position error. S
is calculated according to Equation 26. Detecting position errors is most difficult in the case of failures of the satellite with the largest SLOPE value. Therefore, the horizontal protection level (Equation 29) and vertical protection level (Equation 30) are determined for the most pessimistic case, when the error happens with the satellite with the largest SLOPE value. The standard deviation (Equation 28) used is calculated based on satellite (i) with the largest slope value. \( P_{\text{bias}} \) value is calculated statistically based on defined probability of the false detection and the probability of the missed detection. (Feng et al., 2009)

\[
S = (I - HK)^T(I - HK)
\]

Equation 25

\[
HSLOPE(i) = \sqrt{\frac{K_{31}^2 + K_{21}^2}{S_{ii}}}
\]

Equation 26

\[
V SLOPE(i) = \frac{K_{31}}{\sqrt{S_{ii}}}
\]

Equation 27

\[
\sigma = \sqrt{\sum_{j=1}^{n} R_{i,j}}
\]

Equation 28

\[
HPL_2 = HSLOPE_{\text{MAX}} P_{Bias} \sigma
\]

Equation 29

\[
VPL_2 = VSLOPE_{\text{MAX}} P_{Bias} \sigma
\]

Equation 30

\[
HPL = \max(HPL_1, HPL_2)
\]

Equation 31

\[
VPL = \max(VPL_1, VPL_2)
\]

Equation 32

Final protection levels are calculated as maximums according to Equation 31 and Equation 32. This is done to estimate levels according to the worst case. (Feng et al., 2009)

MODIFICATIONS TO ICRAIM

Issues appear with the protection level calculation, especially in static positioning cases when using ICRAIM algorithm. When the position estimate has converged to some value, Kalman gain values related to the position states are small. Therefore, it is not possible to use Kalman gain values to calculate realistic protection levels as by Equation 26 and Equation 27. Protection levels calculated in this way describe only what magnitude of position error can be caused by measurements from the current epoch, but these protection levels do not inform users regarding the total position error.

Protection levels can be calculated based on the variance of the position estimate as by Equation 23 and Equation 24. However, in this case the reliability of the protection level estimates is dependent on how realistically the Kalman filter P matrix estimates variance of the position states. In the case of PPP positioning, all error sources cannot be modeled or corrected totally. Therefore, for example errors in satellite clock and orbit corrections or with troposphere modeling can cause non-white noise type range bias to measurements. This needs to be taken account to calculate realistic protection levels.

A 5cm nominal range bias is applied based on the IGS published performance values (IGS, 2009) of final satellite orbit and clock corrections and estimated error in troposphere modeling. The effect of the range bias in the horizontal position domain can be calculated by Equation 33 and Equation 34 and the effect in the vertical level can be calculated by Equation 33 and Equation 35. The horizontal protection level can be calculated by Equation 36 and the vertical protection level can be calculated by Equation 37. This method of calculating protection levels is used in this paper.

\[
G = \left( \frac{u^T u}{r} \right)^{-1} H^T \ast \frac{1}{r}
\]

Equation 33

\[
ah = \sum_{i=1}^{n} (g_{1,i}^2 + g_{2,i}^2)
\]

Equation 34

\[
av = \sum_{i=1}^{n} |g_{3,i}|
\]

Equation 35

\[
HPL = k_H \sigma_H + \text{nominalBias} \ast ah
\]

Equation 36

\[
VPL = k_V \sigma_V + \text{nominalBias} \ast av
\]

Equation 37

TEST DATA AND RESULTS

Data from two IGS stations was used to test this method. The used IGS stations were UNB3 (in Canada) and ZIM2 (in Switzerland). Data was recorded on 25th February 2011 and 10th March 2011. Data recording was started at 1pm and the length of recorded data set was four hours.
Table 2 Convergence time analysis (the shortest time in red)

<table>
<thead>
<tr>
<th>Station</th>
<th>Day</th>
<th>Constellations</th>
<th>SW</th>
<th>3D (s)</th>
<th>Hor (s)</th>
<th>Ver (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNB3</td>
<td>25th Feb</td>
<td>GPS</td>
<td>P</td>
<td>906</td>
<td>668</td>
<td>899</td>
</tr>
<tr>
<td>UNB3</td>
<td>25th Feb</td>
<td>GPS, GLONASS</td>
<td>P</td>
<td>1125</td>
<td>405</td>
<td>1111</td>
</tr>
<tr>
<td>UNB3</td>
<td>25th Feb</td>
<td>GPS</td>
<td>G</td>
<td>814</td>
<td>505</td>
<td>673</td>
</tr>
<tr>
<td>UNB3</td>
<td>10th Mar</td>
<td>GPS</td>
<td>P</td>
<td>779</td>
<td>271</td>
<td>271</td>
</tr>
<tr>
<td>UNB3</td>
<td>10th Mar</td>
<td>GPS, GLONASS</td>
<td>P</td>
<td>723</td>
<td>273</td>
<td>721</td>
</tr>
<tr>
<td>UNB3</td>
<td>10th Mar</td>
<td>GPS</td>
<td>G</td>
<td>491</td>
<td>363</td>
<td>484</td>
</tr>
<tr>
<td>ZIM2</td>
<td>25th Feb</td>
<td>GPS</td>
<td>P</td>
<td>2563</td>
<td>2517</td>
<td>1047</td>
</tr>
<tr>
<td>ZIM2</td>
<td>25th Feb</td>
<td>GPS, GLONASS</td>
<td>P</td>
<td>340</td>
<td>221</td>
<td>317</td>
</tr>
<tr>
<td>ZIM2</td>
<td>25th Feb</td>
<td>GPS</td>
<td>G</td>
<td>2721</td>
<td>2633</td>
<td>517</td>
</tr>
</tbody>
</table>

Convergence time analysis (Table 2) was made by comparing the time taken to obtain smaller than 10cm position error compared to the known ITRF 2005 coordinates of the stations. GPS only, GPS and GLONASS processing strategies were tested. Both POINT (P) and Novatel GrafNav 8.30 (G) processing software were tested.

According to these results, using GLONASS with GPS provided shorter or equal horizontal convergence time compared to GPS only. However, vertical convergence time was longer in the both of UNB3 cases when GLONASS was used with GPS compared to using GPS only. This may be due to problems with troposphere or measurement standard deviation modeling in POINT. 3D convergence time was shorter when using both GPS GLONASS compared to using GPS only, except in the UNB3 (25th February) case.

Figures from the magnitude of the position error and protection levels in the case of using GPS only (POINT), GPS and GLONASS (POINT) and GPS only (GrafNav) are presented.

The results obtained by processing data from the UNB3 25th February 2011 scenario are presented by Figure 1 (horizontal level 1st forward Kalman), Figure 2 (vertical level 1st forward Kalman), Figure 3 (horizontal level 2nd forward Kalman) and Figure 4 (vertical level 2nd forward Kalman). In this scenario, using GLONASS with GPS did not give benefit in terms of smaller magnitude of the position error. However, estimated protection levels were smaller when using both GPS and GLONASS compared to using GPS only.
The results from the UNB3 10th March 2011 scenario are presented by Figure 5 (horizontal level 1st forward Kalman), Figure 6 (vertical level 1st forward Kalman), Figure 7 (horizontal level 2nd forward Kalman) and Figure 8 (vertical level 2nd forward Kalman). In this scenario, using GPS with GLONASS gave the smallest horizontal and vertical position error specially when performing the second forward Kalman filter processing. In addition to this, the estimated protection levels were smaller when using both GPS and GLONASS compared to using GPS only.

The results from the ZIM2 25th February 2011 scenario are presented by Figure 9 (horizontal level 1st forward Kalman), Figure 10 (vertical level 1st forward Kalman), Figure 11 (horizontal level 2nd forward Kalman), Figure 12 (vertical level 2nd forward Kalman). In this case, using
GLONASS with GPS gave much shorter convergence time (Figure 9 and Figure 10) compared to using GPS only. In this case, using GrafNav provided longer convergence time than using the POINT software. In the second forward Kalman filter solution, using both GPS and GLONASS provided the smallest horizontal position error. With the same solution, the smallest vertical error was provided by GrafNav when using GPS only. When using POINT software, the smallest vertical error was provided by using both GPS and GLONASS. A problem was identified with calculating vertical protection levels especially in the second forward Kalman filter solution, because the protection levels were smaller than position error.

The reason for this failure to overbound the vertical position errors by the vertical protection levels is most likely caused by a bias in the inaccurate troposphere estimation.

![Figure 9 ZIM2 25th February 2011, horizontal level (1st forward Kalman filter)](image)

![Figure 10 ZIM2 25th February 2011, vertical level (1st forward Kalman filter)](image)

**FAULT DETECTION AND EXCLUSION**

The UNB3 25th February data is used to test the modified ICRAIM for fault detection and exclusion. If a failure causes larger position errors than a protection level, this failure must be detected by ICRAIM.

Four types of different failures are tested: a step type of failure in a carrier-phase measurement, a step type of failure in a code-phase measurement, a ramp type of failure in a carrier-phase measurement and a ramp type of failure in a pseudorange measurement.

Test1: A step type error was generated by adding a one cycle bias to GPS satellite (id 2) L1 and L2 carrier phase measurements from the epoch 1000s to the epoch 2000s. This kind of error was detected at the epoch 1000s by the cycle slip detection method in POINT software, which is based on the method presented in (Liu, 2011). Therefore, this error had minimal effect to performance and the protection levels were not exceeded.
Test2: A step type error was generated by adding a 100m bias to the GPS satellite (id 2) C1 pseudorange measurement from epoch 1000s to epoch 2000s. This error was first detected at the epoch 1000s by the cycle slip detection check, because this kind of large change in pseudorange measurement caused wrong cycle slip detection. However, it is not a problem, because it caused excluding measurements from the GPS satellite 2 for four seconds and resetting the ionosphere-free ambiguity term. Thereafter, at the epoch 1004s this faulty code-phase measurement was detected by ICRAIM and excluded from the solution. Therefore, this faulty pseudorange measurement did not have any effect to position performance except the effect of one usable satellite less.

Test3: A ramp type of error was generated by adding 1cm bias each second to the GPS satellite (id 2) L1 carrier-phase measurement from the epoch 1000s to the epoch 2000s. This error was detected and excluded from the solution after 36 seconds from the first epoch when the error appeared. An effect of the error to horizontal error is presented by Figure 13 and to vertical error is presented by Figure 14. The magnitude of the error does not exceed protection level. In addition to this, the magnitude of the error was smaller when using both GPS and GLONASS compared to using GPS only.

Test4: A ramp type of error was generated by adding 1m bias each second to the GPS satellite (id 2) L1 pseudorange measurement from the epoch 1000s to the epoch 2000s. This error was detected after 81 seconds from the first epoch when it appeared. In this scenario, both horizontal (Figure 15) and vertical (Figure 16) position error were below the protection levels.
CONCLUSIONS
The tests presented in this paper were made using a small dataset consisting of data only from two IGS stations. Therefore, it is not possible to make conclusions that apply to all cases. As future work, a plan is to develop an automatic test system for the POINT software.

According to these results, using GLONASS with GPS can provide significant benefit in some scenarios such as the ZIM2 scenario. However, in some cases using GLONASS with GPS may decrease performance, but in general this is small. Therefore, according to this dataset, there are more benefits from using both GPS and GLONASS than negative aspects.

ICRAIM showed that is able detect and exclude failures in the tested cases. However, there are still problems with calculating realistic protection levels. This is probable due to biases which have not taken account by Kalman filter variance estimation (P matrix).

The standard deviation value employed was 4cm for carrier-phase measurements. This value is unrealistically large, but it provided more accurate results than smaller values. As future work, it would be beneficial to include a more accurate error model from measurements than using only constant standard deviation values.

In addition to this, obtaining more realistic bias estimates is need to calculate more accurate protection levels. Assuming a constant bias is not suitable for all cases, for example the vertical protection level was too small in the ZIM2 scenario.

As future work, integrity monitoring should also be tested in fixed ambiguity cases.

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REFERENCES
COLLINS, P. 2008. Isolating and Estimating Undifferenced GPS Integer Ambiguities. ION NTM. San Diego, CA


REUSSNER, N. & WANNINGER, L. 2011. GLONASS Inter-frequency Biases and Their Effects on RTK and PPP Carrier-phase Ambiguity Resolution. *ION GNSS* Portland, OR

SCHAEER, S. & DACH, R. Biases in GNSS Analysis IGS Workshop, 2010 Newcastle England


TOLMAN, B. W., KERKHOFF, A., RAINWATER, D., MUNTON, D. & BANKS, J. 2010. Absolute Precise Kinematic Positioning with GPS and GLONASS. *ION GNSS* Portland, OR.