ROBUST INERTIAL POST-PROCESSING AIDED BY TRIMBLE PROPOINT GNSS TECHNOLOGY FOR URBAN HD MAPPING AND AUTONOMOUS NAVIGATION

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Abstract – **GNSS along with MEMS inertial sensors have been the most cost-effective and productive solution to provide seamless georeferencing information for HD Mapping and Autonomous Navigation for decades. In dense urban environments, however, obtaining robust and precise GNSS-aided MEMS inertial navigation solutions becomes quite challenging due to more GNSS measurement degradations and outages and hence larger inertial error drifts. This paper presents a new post-processed realization of the Trimble© ProPoint™ GNSS technology integrated into the Trimble© Applanix POSPac™ 9 aided-inertial software for robust and precise urban HD mapping and autonomous navigation. The new POSPac not only supports all the latest GNSS satellites, signals and frequency bands but also properly handles the multipath errors and outliers and effectively fuses GNSS data into a robust and accurate aided-inertial position and orientation solution. Real-world results from over 72 hours of dense urban area data show the new POSPac achieved over 100% position accuracy improvement for RTK-aided MEMS inertial systems.**

I. INTRODUCTION

High-Definition (HD) Mapping and Autonomous Navigation require robust and precise geographic position and orientation of the moving platforms to geo-code each pixel or point collected by an imaging sensor [1]. Global Navigation Satellite Systems (GNSS) along with inertial sensors have been used to provide seamless georeferencing for mobile mapping and navigation for decades [2][3][4]. GNSS measurements are used not only to provide precise positions but also to control the errors of the navigation solution computed by integrating acceleration and angular rate measurements made by an Inertial Measurement Unit (IMU) into position, velocity and orientation.

In dense urban environments, obtaining robust and precise GNSS-aided inertial navigation solutions becomes quite challenging especially when the cost-effective Micro Electro Mechanical System (MEMS) IMUs are used. This is because GNSS measurements are subject to multipaths, signal diffraction and blockages which might result in large error drifts or jumps in the integrated navigation solutions. Although with the advent of modern GNSS technologies more GNSS satellites and signals are now available in the sky to increase the GNSS observables redundancy, many GNSS observables will still be deteriorated in dense urban environments due to multipaths and signal diffraction. These deteriorated GNSS observables and multiple outliers in the measurements are usually difficult to model and identify in a GNSS Real-Time Kinematic (RTK) positioning engine. Therefore advanced GNSS signal filtering and quality assurance technologies along with optimal sensor fusion methods are very important for obtaining precise and reliable GNSS measurements and maintaining robust GNSS-aided inertial navigation solutions in dense urban environments.

This paper presents a new post-processed realization of the Trimble's latest ProPoint GNSS technology integrated into the Trimble's Applanix POSPac™ 9 aided-inertial software to deliver robust and accurate navigation solutions for urban HD mapping and autonomous navigation. This paper is structured as follows. Section II introduces the generic GNSS RTK positioning algorithm and discusses the performance metrics in GNSS challenging environments. Section III presents the Trimble© ProPoint™ GNSS RTK technology and describes its design and performance advantages for applications in GNSS challenging environments. In Section V, the post-processed ProPoint RTK aided-inertial processing technology is presented and examples of the performance improvement in dense urban areas is demonstrated. Finally, real-world results using data collected in dense urban environments are provided for accuracy assessments in section VI.

II. GNSS RTK POSITIONING

GNSS positioning is based on the line-of-sight signals from the satellites in space to measure the ranges from known satellite positions to unknown positions on land, at sea, in air and space [5]. With the signal wavelength of centimeter level, carrier phase measurements are used to estimate satellite-to-receiver range with high accuracy and hence to provide precise GNSS positioning. However, the quality of carrier phase measurements is affected by a variety of biases and errors during signal propagation. Equation (1) describes the measurement model of carrier phase, $\phi^k(j)$, from the *k*th satellite at epoch *j* [6].

$$\phi^k(j) = r^k(j) + c\left(dT(j) - dt^k(j)\right) + I^k(j) + T^k(j) + \lambda N^k + \varepsilon^k(j) \quad (1)$$

where $r^k(j)$ is the true range, $dT(j)$ is the receiver clock offset, $dt^k(j)$ is the satellite clock error, $I^k(j)$ is the ionosphere delay, $T^k(j)$ is the troposphere delay, N^k is the carrier phase integer ambiguity, λ is the carrier phase wavelength, $\varepsilon^k(j)$ is the phase multipath and noise. The propagation errors that are similar between nearby receivers including satellite clock error, ionosphere delay and troposphere delay can be removed by between-receivers carrier phase differencing, denoted as Δ, as shown in Equation (2).

$$\Delta\phi^k(j) = \Delta r^k(j) + c\Delta dT(j) + \lambda\Delta N^k + \Delta\varepsilon^k(j) \quad (2)$$

where $\Delta\phi^k(j)$ is the between-receivers single-differenced carrier phase measurement, $\Delta r^k(j)$ is the single-differenced true range, $\Delta dT(j)$ is the single-differenced receiver clock offset, ΔN^k is the single-differenced carrier phase integer ambiguity, and $\Delta\varepsilon^k(j)$ is the single-differenced phase multipath and noise. Provided the integer nature of carrier phase ambiguities and redundant carrier phase measurements from different satellites, carrier phase ambiguities can be resolved by using integer least-squares estimation such as LAMBDA method [7]. After the integer ambiguities are determined, the precise ranges between satellites and receiver can be obtained and the receiver clock offset and receiver coordinates can be calculated by solving the Equation (3) via linearizing it about an approximate user position and solving iteratively using least squares or Kalman filtering algorithms.

$$\hat{r}^k = \sqrt{\left(x^k - X\right)^2 + \left(y^k - Y\right)^2 + \left(z^k - Z\right)^2} + dT \quad k = 1, 2, \ldots, K \quad (3)$$

where K is the total number of satellites used, $\hat{r}^k$ is the precise range estimate of satellite k, $\left(x^k, y^k, z^k\right)$ are the known coordinates of satellite k, dT is the receiver clock bias and (X, Y, Z) are the user coordinates to be determined.

The quality of the precise GNSS RTK position estimates depends basically upon two factors [6]:

1. The number of satellites being tracked and their spatial distribution characterized by the satellite geometry strength.
2. The quality of the range information from carrier phase measurements.

For short baseline single base RTK positioning, most of the carrier phase measurement biases can be removed by between-receiver single differencing because of the strong correlations of the errors in nearby geographic locations. In this case the multipaths and noises become the remaining dominant errors especially in GNSS harsh environments. Therefore, the key to obtaining precise solutions in such applications is to have the capability of processing more satellites and signals and effectively mitigating multipath errors in the GNSS RTK engine.

III. TRIMBLE PROPOINT TECHNOLOGY

Trimble© ProPoint™ GNSS technology along with Trimble© Maxwell™ 7 receivers support all modernized satellites and new signals transmitted on all frequencies which include:

- GPS: L1 C/A, L1C, L2E, L2C, L5
- GLONASS: L1 C/A, L1P, L2P, L2 C/A, L3 CDMA
- Galileo: E1, E5A, E5B, E5AltBOC, E6
- BeiDou: B1C, B1i, B2i, B2A, B2B, B3i
- QZSS: L1 C/A, L1S, L2C, L5, LEX
- IRNSS: S1 C/A, L5
- SBAS: L1 C/A, L5
- MSS: Trimble RTX, OmniSTAR

Trimble© ProPoint™ GNSS technology is capable of using all available signal inputs to deliver more accurate RTK solutions, provided a base receiver is tracking for the same signals. The increased number of GNSS observables and signals used in the RTK engine will improve the measurement availability and redundancy to better mitigate the impacts of multipaths, signal diffractions and blockages in GNSS challenging environments.

Trimble© ProPoint™ was also designed with an optimal data signal filtering approach by combining all of the measurements together into a single filter and estimating the carrier integer ambiguities. This approach provides the most flexible use of all available GNSS signals. The ProPoint engine can use any or all of the frequencies and signals, including individually in harsh tracking environments, to generate the optimal solutions. Empowered with the new robust estimation techniques, the ProPoint engine identifies any measurement that does not match a stochastic model and then will either reject or correct the measurement or adjust the stochastic model assigned to the measurement. In dense urban environments where the GNSS measurements might contain multiple deteriorated data and outliers, Trimble© ProPoint™ is able to provide precise and reliable position estimation.

Figure 1 shows an example of satellite numbers used in the (a) previous generation engine and (b) Trimble© ProPoint™ engine in a downtown Toronto dataset. It can be seen that the Trimble© ProPoint™ has used and processed more satellite observables than the previous generation engine to provide better GNSS measurement redundancy. Figure 2 shows an example of the RTK positioning solution in the core downtown Toronto areas from (a) previous generation engine (b) Trimble© ProPoint™ engine without the robust estimation techniques and (c) Trimble©

ProPoint™ engine with the robust estimation techniques. It can be seen that the ProPoint engine has provided a lot more RTK positioning solutions than the previous generation engine and with the robust estimation techniques Trimble© ProPoint™ engine has identified and removed outliers from the solutions and delivered highly available and reliable precise RTK solutions in dense urban environments.

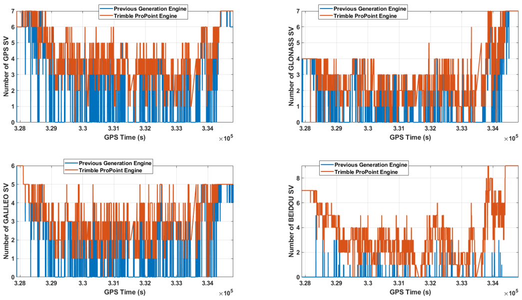
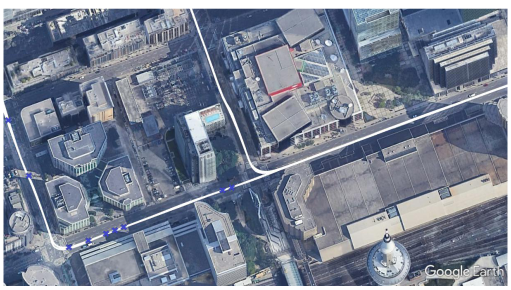
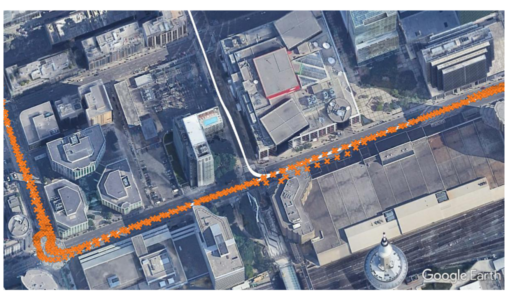


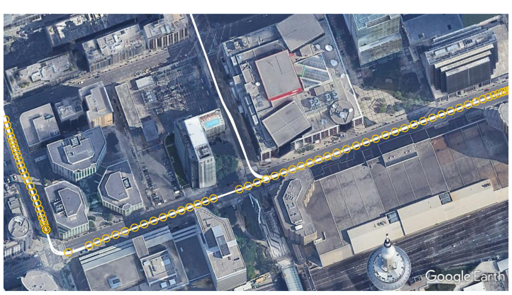
Figure 1: Number of Satellites Used



(a) Previous Generation Solution



(b) Trimble© ProPoint™ Solution without Robust Estimator



(c) Trimble© ProPoint™ Solution with Robust Estimator

Figure 2: GNSS RTK Solutions in Dense Urban Areas

IV. POST-PROCESSED PROPOINT RTK AIDED-INERTIAL PROCESSING

The latest Trimble's Applanix POSPac™ 9 aided-inertial software has tightly integrated Trimble© ProPoint™ GNSS engine into its new Trimble© Applanix IN-Fusion+™ technology to deliver robust and accurate navigation solutions for urban HD mapping and autonomous navigation. Figure 3 illustrates the architecture of Trimble© Applanix IN-Fusion+™ technology comprising an "aided-inertial" navigation system or Aided INS with aiding sensor components and Trimble© ProPoint™ engine. The IMU generates incremental velocities and angles resolved in the IMU sensor coordinate frame. The inertial navigator receives the inertial data from the IMU and computes the current IMU position, velocity and orientation. The error estimator, which is typically a Kalman filter, receives measurements from the aiding sensors such as GNSS receivers and a precise odometer here called a distance measurement indicator (DMI) and precise GNSS corrections from the Trimble© ProPoint™ engine. Incorporating sophisticated inertial and aiding sensor error models, the Kalman filter properly estimates the INS and aiding sensor errors. The error controller receives the estimated errors, computes the navigation corrections and applies these to the inertial navigator integration processes, thereby regulating the inertial navigator errors in a closed-loop error control loop to continuously maintain the inertial navigator errors at small magnitudes.

The Trimble© Applanix IN-Fusion+™ technology is also an optimal method of "blending" or "fusing" the information of all measurement systems into a robust and accurate position and orientation solution. It automatically adapts the measurement model according to its quality. With the Trimble© ProPoint™ GNSS technology providing more precise and reliable GNSS RTK measurements, Applanix IN-Fusion+™ technology achieves extremely robust high-rate Aided-INS position output under all types of signal environments.

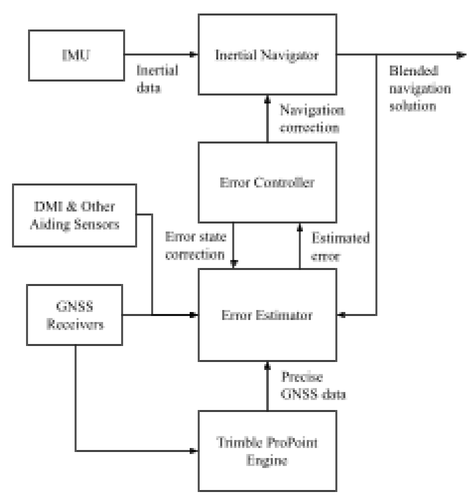


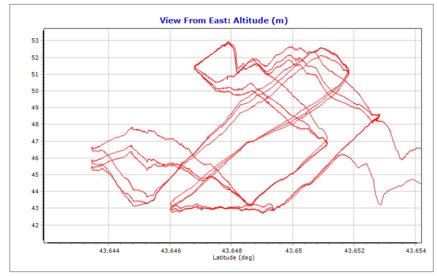
Figure 3: Trimble© Applanix IN-Fusion+™ Architecture

Figure 4 shows an example of the post-processed smoothed best estimated (SBET) solutions generated from (a) IN-Fusion Single Base technology using the previous generation engine and (b) IN-Fusion+ Single Base technology integrated with Trimble© ProPoint™ engine. The data were collected in the core downtown Toronto areas using Trimble© Applanix LVX product equipped with a cost-effective MEMS IMU. The test trajectories were repeated for three loops for map-based performance assessment purposes. It can be seen in Figure 4 on the left-side images that the IN-Fusion+ Single Base SBET trajectories are all within the vehicle lanes during a turn whereas one loop of the IN-Fusion Single Base SBET trajectories is shifted and on the edge of the curb. On the right-side images all the IN-Fusion+ Single Base SBET trajectories are overlapping on the same vehicle lane correctly whereas one loop of the IN-Fusion Single Base SBET trajectories does not overlap and is off by one vehicle lane. Figure 5 shows the altitude-vs-latitude SBET trajectories generated from (a) IN-Fusion Single Base technology and (b) IN-Fusion+ Single Base technology. It can be seen that the IN-Fusion+ Single Base solutions have much better trajectory overlapping than the IN-Fusion Single Base solutions. As the test was repeated on the same trajectory for three loops, the better overlapping the altitude-vs-latitude trajectories the more accurate the SBET solutions. Thanks to the Trimble© ProPoint™ GNSS technology providing more accurate and reliable GNSS RTK measurements to aid the inertial navigator, the IN-Fusion+ technology has delivered more accurate and robust navigation solutions than the previous generation technology in GNSS harsh environments as shown in these preliminary test results.

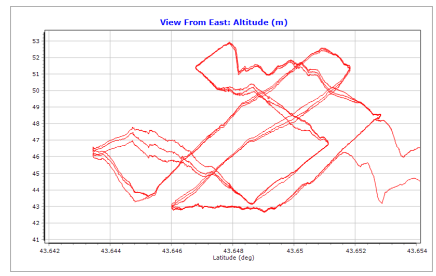
(a) IN-Fusion Single Base Solution

(b) IN-Fusion+ Single Base Solution

Figure 4: Horizontal SBET Trajectories in Dense Urban Areas



(a) IN-Fusion Single Base Solution



(b) IN-Fusion+ Single Base Solution

Figure 5: Altitude vs Latitude SBET Trajectories in Dense Urban Areas

V. URBAN NAVIGATION ACCURACY ASSESSMENT

This section presents the positioning accuracy and performance assessments of Trimble's Applanix POSPac™ aided-inertial software for urban HD mapping and autonomous navigation applications. The Applanix IN-Fusion™ and IN-Fusion+™ Single Base positioning solutions were assessed against the reference trajectories for 38 downtown Toronto datasets (equivalent to 72 hours of data). The test trajectories loop through the core downtown Toronto areas multiple times as shown in Figure 6. With plenty of skyscrapers and various height buildings from low-rise, multi-story to high rise, downtown Toronto provides extremely challenging and variously degraded GNSS signal reception conditions and hence serves as a great environment for evaluating the aided inertial positioning performance for urban HD mapping and autonomous navigation applications. A base station located within 10 km from the test trajectories was used to collect the base GNSS data for short-baseline RTK processing. The reference trajectories were generated using the post-processed GNSS RTK-aided inertial positioning solution with the use of the highly accurate navigation grade IMUs.

Figure 7 shows the POSPac SBET position errors when processing a downtown dataset collected by Trimble© Applanix LVX product with MEMS IMU using IN-Fusion Single Base and IN-Fusion+ Single Base technologies, respectively. It can be seen that the IN-Fusion+ technology has significantly reduced position error drifts and continuously maintained the SBET position accuracy of a cost-effective Trimble© Applanix LVX product throughout the GNSS challenging environments whereas the previous generation

IN-Fusion Single Base solutions suffer larger position error drifts in core downtown Toronto areas.

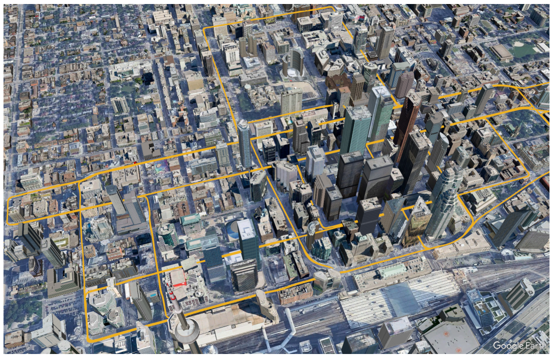


Figure 6: Test Trajectories in Downtown Toronto

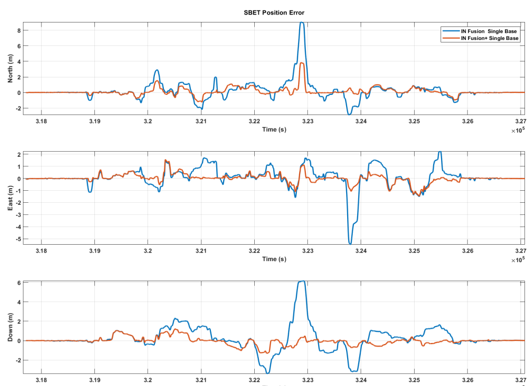


Figure 7: SBET Position Errors for One Dataset

Figure 8 and Figure 9 show the POSPac SBET 3-dimensional (3D) position error cumulative distribution function (CDF) using IN-Fusion Single Base and IN-Fusion+ Single Base technologies when processing all the downtown Toronto datasets collected by Trimble© Applanix LVX and AP+ 30 products, respectively. Both products use cost-effective MEMS IMU with next generation survey-grade GNSS receivers. The product specifications of Trimble© Applanix LVX and AP+ 30 are available at [8] and [9]. The CDF completely describes the distribution of the SBET position errors. For example, the CDF of the SBET position error at x gives the probability y that the SBET position error is less than or equal to that number x. Therefore the higher the probability y or the closer to the top-left corner the CDF, the better the SBET position accuracy. As shown in Figure 8 and Figure 9, the IN-Fusion+ Single Base technology has provided more accurate and robust SBET position solutions than the previous generation IN-Fusion Single Base technology in dense urban environments.

Table 1 compares the Applanix IN-Fusion™ Single Base with Applanix IN-Fusion+™ Single Base SBET position solution accuracy in dense urban environments for Trimble© Applanix LVX and AP+ 30 products, respectively. Comparing to the IN-Fusion Single Base solution, the one sigma 3D SBET position error of the IN-Fusion+ Single Base solution in dense urban environments has been reduced from 64.01 cm to 31.86 cm equivalent to 100.89% improvement for Trimble© Applanix LVX products and from 43.17 cm to 19.96 cm equivalent to 116.22% improvement for AP+ 30 products, both using cost effective solid-state MEMS inertial sensors. The net result is the more accurate and robust spatial knowledge solution with the cost effective approach for the highest level of productivity in urban HD mapping and autonomous navigation can be achieved by using Trimble© Applanix POSPac™ 9 software powered by Applanix IN-Fusion+™ technology.

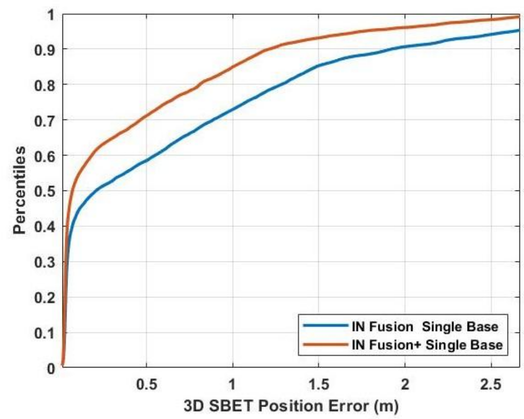


Figure 8: LVX SBET Position Errors CDF

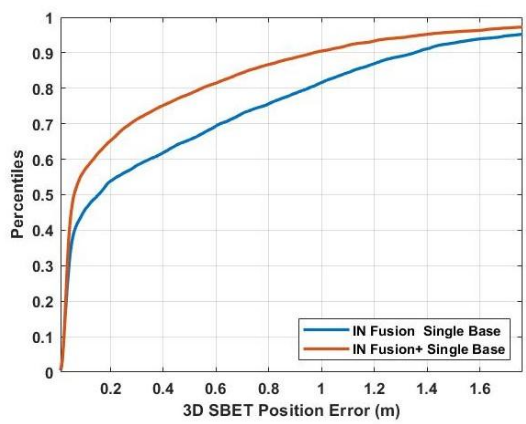


Figure 9: AP+ 30 SBET Position Errors CDF

Table 1: SBET Position Accuracy and Improvement

System	SBET 3D Position Error (1σ)		SBET Position Accuracy Improvement
	IN Fusion Single Base	IN Fusion+ Single Base	
LVX	64.01 cm	31.86 cm	100.89%
AP+ 30	43.17 cm	19.96 cm	116.22%

VI. CONCLUSIONS

Trimble© ProPoint™ GNSS technology is Trimble's latest precise GNSS processing engine that not only fully supports all modernized satellites and new signals but also effectively mitigates multipath errors and outliers in GNSS challenging environments. Trimble© Applanix POSPac™ 9 aided-inertial software has tightly integrated Trimble© ProPoint™ GNSS technology into Applanix IN-Fusion+™ engine to deliver robust and accurate land navigation solutions in all environments. Real-world results from over 72 hours of data collected in dense urban environments shows the significant POSPac SBET performance improvement when using the Applanix IN-Fusion+™ technology compared to the previous generation solutions. Seamless and robust spatial knowledge solutions with position accuracy of 20~30 cm can be achieved by using the aided MEMS inertial post-processing solutions generated by Applanix POSPac™ 9 software which offers the highest level of productivity with the most cost-effective approach in urban HD mapping and autonomous navigation.

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