A New Integration Method for MEMS Based GNSS/INS Multi-sensor Systems

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BIOGRAPHY

Junchuan Zhou obtained his Ph.D. in Navigation from the International Postgraduate Programme (IPP) Multi-Sensorics at the Center for Sensor Systems (ZESS) in the University of Siegen in 2013, Germany. He is the Institute of Navigation (ION) GNSS 2011 student paper award winner. He joined Trimble Terrasat in 2011.

Johannes Traugott is working with Trimble Terrasat where he is responsible for R&D concerning multi-sensor fusion and notably GNSS-INS integration. Before joining Trimble in 2010, he was working with the Institute of Flight System Dynamics at Technische Universität München (TUM) focusing on navigation and flight trajectory reconstruction. Johannes received a Ph.D. in aerospace engineering from TUM in 2011 and a M.Sc. in mechanical engineering from TUM in 2004.

Bruno Scherzinger is the Chief Technology Officer at Applanix Corporation, a company wholly owned by Trimble Navigation, where he is responsible for advanced navigation technology development and the core navigation technology behind the Applanix product line of Position and Orientation Systems. He has more than 30 years' experience in GNSS-INS integrated navigation systems technology, and has been a member of ION for 20 years and a member of the IEEE for 40 years. He holds 15 patents and has numerous publications in the field of geomatics and navigation.

Christian Miranda received his M.Sc. in tele-communication engineering and aeronautic in 2010 from UPC (Universitat Politècnica de Catalunya) in Barcelona, Spain. From 2010 to 2013, he worked on several R&D projects with emphasis on precise positioning and sensor fusion algorithms at the Institute of Geomatics, Spain. He joined Trimble Terrasat in 2013 and he is currently a GNSS software engineer at the sensor fusion group.

Adrian Kipka received a Ph.D. in Satellite Geodesy from the Technical University of Darmstadt (TUD) in 2006. He is working as Engineering Manager being responsible for GNSS post-processing and GNSS-INS integration at Trimble Terrasat. Prior to joining Trimble he was working in the German Air Traffic Control (DFS) as Software Engineer. He joined Trimble Terrasat in 2005.

ABSTRACT

Trimble has developed its new multi-sensor GNSS-INS integrated system which is called BD935-INS. It employs the new Quasi-tightly-coupled (QTC) integration architecture [1-3] and Trimble's centimeter-accuracy GNSS positioning technology to produce an accurate, robust and low-cost single-board integrated product for small and medium sized unmanned aerial vehicles (UAV), ground based and marine platforms. The new system has the salient characteristics of a tightly-coupled integration with a much simplified design. It features INS seeding of the GNSS RTK engine to increase the availability and accuracy of RTK output in challenging GNSS signal environments. In addition an observable subspace constraint (OSC) is applied in the INS-GNSS position measurement to block the uncorrected *a priori* INS errors for entering the integration Kalman filter (KF). The new system has been extensively tested. Field test results from land-based mapping vehicle missions in urban areas verify the benefits of QTC integration architecture. For UAV missions, it satisfies the high accuracy demands for position and orientation as well.

INTRODUCTION

Achieving highly accurate and robust navigation performance in mobile mapping and autonomous vehicle applications has been restricted to the usage of high-end inertial measurement units (IMU) for a long time. Over the last few years, micro-electro-mechanical sensor (MEMS) based technology has evolved to the point where it can be used for navigation in a GNSS aided-inertial architecture. Utilizing MEMS sensors has become very interesting for a wider range of applications because of the lower price, reduced size requirements and much lower power consumption. The new product BD935-INS was developed with Applanix' extensive experience in IMU algorithm development on low-cost MEMS-IMU platforms merged with Trimble's cm-accuracy GNSS positioning technology. Other than GNSS and INS, the new system is configurable to include additional aiding sensors such as magnetometers, distance measurement instrument (DMI: not supported in the first release) for deriving robust and accurate position and orientation solutions with high demands on the reliability even in GNSS hostile environments like urban canyons.

The kernel of the new product is based on the new QTC integration architecture [1-3]. In this architecture, the GNSS engine is able to produce highly accurate RTK position fixes even when the number of satellites drops below 4, and with much reduced complexity compared with a tightly-coupled integration implementation. The new product is able to satisfy the high accuracy demands for positioning as well as orientation of UAV's for guidance, control, precision landing and mapping. On a land vehicle in urban environments, it is able to show highly robust positioning by taking advantage of a multi-sensor integration system. This paper demonstrates the performance of the new product with various field tests made from land-based mapping vehicles and UAV under different signal environments.

In the remainder of the paper, the new Trimble DB935-INS product is introduced and profiled. The traditional integration architectures and the new QTC integration scheme are presented and compared. Land-based mapping vehicle tests in different GNSS signal environment are made to demonstrate the benefits of QTC integration scheme. Numerical results from a UAV mission are analyzed. A conclusion is given at the end of the paper.

TRIMBLE BD935-INS PRODUCT

The new multi-sensor GNSS-INS integration product is designed for applications requiring continuous centimeter level position accuracy and high demands on orientation as well in a compact package for precise guidance and control applications. The idea is to introduce a product with high accuracy and reliability positioned between commercial grade inertial navigation devices and higher end mapping solutions. For application that do not require centimeter positioning accuracy, the system is able to produce an integrated solution using un-differenced (autonomous) or differential GNSS (DGNSS) positioning fixes from a single point positioning module for robust navigation in challenging environments such as urban canyons. Based on the applications, two versions of the product have been produced with different performance levels. The Trimble BD935-INS produces cm level position and orientation in real-time to better than 0.1 degrees for roll, pitch (1 sigma) and 0.5 degrees for heading (1 sigma). The second version branded the Applanix APX-15 is further calibrated to produce real-time orientation accurate to 0.04 degrees roll, pitch, and 0.18 degrees heading (RMS), and post-processed orientation accurate to 0.025 degrees roll, pitch and 0.08 degrees heading (RMS).

Additional aiding sensors are supported. A DMI can be easily plugged in and are configurable through the receiver web interface to aid the GNSS-INS for further improving the integration performance (not supported in the first release). Sophisticated integration algorithm estimates the sensor misalignment errors, sensor bias errors, scale factor errors and installation parameter errors, e.g., lever-arm, etc., providing robust and accurate navigation solution for meeting high accuracy demands for positioning as well as orientation. The size of a BD935-INS module is shown in Figure 1.

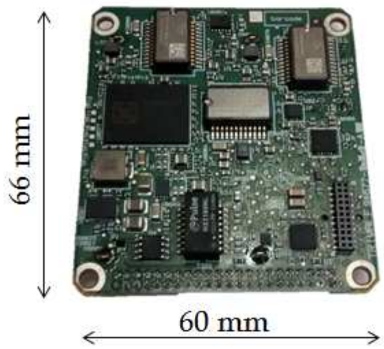


Figure 1. Trimble BD935-INS module

GNSS-INS INTEGRATION

GNSS receivers offer long-term stable absolute positioning information with its performance depending on signal environments. In an INS, angular rate and specific force measurements from the IMU are processed to yield position, velocity and attitude solutions. Such systems can act autonomously and provide measurements at a higher data rate. However, similar to other dead reckoning sensor systems, in an INS, the IMU sensor errors, such as sensor bias, scale factor error and noise will cause an accumulation in navigation solution errors over time. For example, the tilt errors caused by the integration of gyroscope errors blur the distinction between the acceleration measured by the vehicles motion and that due to the misresolved gravity, which yields inaccurate navigation solutions. An integrated GNSS-INS system combines the advantages of both sides and provides accurate and uninterrupted navigation results. The primary methods to fuse the INS and GNSS data are the loosely-coupled and tightly-coupled integrations.

Loosely-coupled integration

The loosely-coupled integration has a decentralized estimation architecture, which uses the output of the navigation solutions from a GNSS receiver and an INS. The INS and GNSS position and velocity estimates are compared, the resulting differences forming the measurement input to the integration Kalman filter. The filter yields the estimates of INS navigation errors with inertial sensor errors. The main advantages are:

- Observation model is simple which requires less computational burden in the integration KF.
- Encapsulation of GNSS processing algorithms into the GNSS navigation engine yields redundant GNSS navigation solutions

Main disadvantages are:

- With fewer than 4 satellites, the GNSS cannot compute a solution, in which case the integration KF

receives no aiding information and the INS state errors become unregulated.
- It is difficult for GNSS engine to provide realistic position and velocity covariance estimates in harsh environment, yielding unreliable integrated solution.

Tightly-coupled integration

In a tightly-coupled integration, a centralized KF is used, and the pseudorange and carrier phase measurements are employed. They are compared with the predicted quantities from the inertial system. The differences form the measurement input to the integration KF for estimating the INS navigation errors and sensor errors. The main advantages are:
- With less than 4 satellites in view, the remaining satellite measurements can still be used in the algorithm, which promotes the robustness of the navigation system.
- All systematic errors and noise sources of the distributed sensors are modeled in the same filter, which ensures that all error correlations are accounted for.

The main disadvantage is:
- There is no redundant GNSS solution output available. IMU data malfunctions, e.g., data gaps, saturation, may cause the system to become unstable and stop outputting solutions.

Quasi-tightly-coupled integration

QTC integration is by definition an enhanced loosely-coupled integration that exhibits the salient characteristic of a tightly-coupled system. It is achieved via two key mechanisms, which are the INS position seeding of GNSS RTK engine and observable subspace constraint (OSC) on INS position aiding.

INS position seeding

QTC integration uses the predicted antenna position computed from the current INS as the *a priori* position to the GNSS navigation engine. The GNSS engine computes a position fix using available observables that is statistically independent of the *a priori* position. The computed position-time space can be divided into observable and unobservable subspaces. The observable subspace corresponds to the space spanned by the range measurement models for the available satellites. With less than 4 satellites in view, a rank deficient measurement model defines an unobservable position-time subspace in which a GNSS navigation engine can't produce a fully constrained position-time solution. It contains uncorrected INS errors. Sending a GNSS solution with uncorrected INS errors to the integration KF causes an un-modeled error correlation. The uncorrected INS errors in the GNSS solution must be cancelled out. Otherwise the integrated KF estimated state becomes biased, and this is the reason for having the observable subspace constraint.

Observable subspace constraint (OSC)

A rank deficient range measurement model implies the GNSS position solution with INS seeding containing unobservable errors that can't be modeled in the integration KF. A singular value decomposition (SVD) of the rank deficient range measurement model matrix is used to characterize its kernel which is the unobservable subspace. The OSC matrix is computed from the SVD for the purpose of blocking the unobservable *a priori* inertial errors in the position measurement. The OSC constrains the INS-GNSS position measurement construction to the observable position-time subspace and thereby avoids erroneous modeling of the unconstrained INS position error in the integration KF. The detailed derivation of the OSC from SVD on the range observation model can be found in [1].

Main advantages of QTC integration are:
- It turns a GNSS navigation engine into a GNSS-INS configuration with little modifications to the engine.
- It provides GNSS navigation engine output in case an INS solution is not available or interrupted.
- It provides GNSS aiding to an aided INS when less than 4 satellites in view.
- It provides rapid RTK recovery after the recovery of 4 or more satellites.

The high level GNSS-INS QTC integration architecture is illustrated in Figure 2.

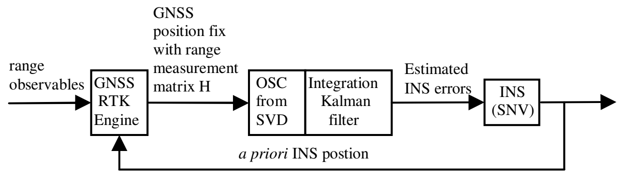


Figure 2. QTC GNSS-INS Architecture

It shows that the *a priori* INS position solution is looped back to the GNSS navigation engine as part of the INS position seeding functionality. The OSC occurs in the integration KF for cancelling the correlated uncorrected INS errors in GNSS position fix.

FIELD EXPERIMENT

Simulation tests of a QTC integration can be found in [1]. In this paper, the performance of BD935-INS is characterized using field tests with land-based mapping vehicle and UAV with rotors. The reference trajectory for the land vehicle tests was obtained from an Applanix POSLV system with an Applanix DMI and a dual antenna GNSS heading system. The Applanix DMI is also connected to one of the BD935-INS board for having the DMI aided navigation performance. The data collected from POSLV is post-processed using Applanix POSPac software to obtain a smoothed best estimate of trajectory (SBET) as reference. For UAV tests, the field collected data is directly post-processed in POSPac software to obtain the SBET solution to compare.

Van test in Munich

The van dataset from Munich area was collected with sensors setup shown in Figure 3. Two antennas were mounted on the roof of the van. The left antenna was used as the primary antenna for GNSS-INS integration. The right antenna was for POSLV dual antenna heading system. The Applanix DMI was onboard with inertial sensors rigidly mounted on the rear of the van. The DMI was connected to both the POSLV and one BD935-INS receiver that computed a DMI aided navigation solution.

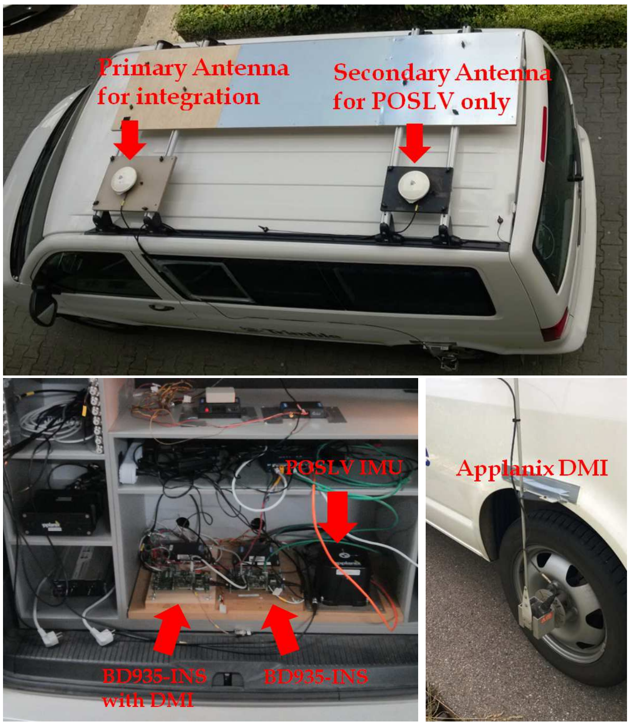


Figure 3. Sensors Setup in the Van

The test trajectory is shown in Figure 4, which is a round trip from the Trimble Terrasat office in Höhenkirchen (east-south corner) to Munich downtown (north).

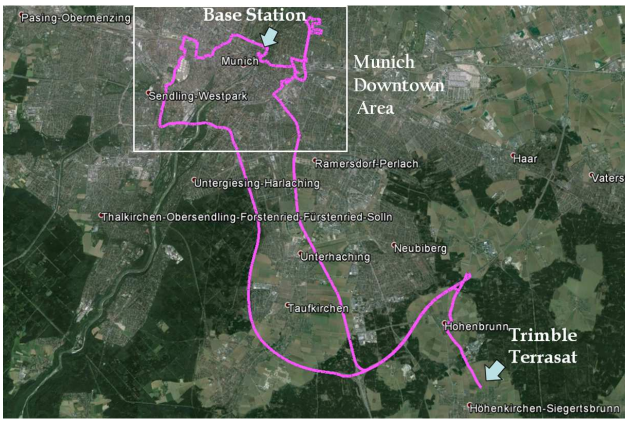


Figure 4. Munich test trajectory (plotted in Google Earth)

The distance from the Trimble office to downtown is about 15 km. The GNSS base station was located in the downtown area as shown in the plot. The van test lasted about 2.5 hours including open sky (highway) and urban areas. In downtown area, it contains a lot of tunnels and canopy areas. Examples can be seen in Figure 5.

a) Canopy

b) Tunnel

Figure 5. GNSS harsh environments in Munich downtown

This van test is used to demonstrate the performance of BD935-INS with focus on the benefits of QTC integration under benign and normal urban signal environments. The comparison is first made with available RTK outputs from the different configurations. In Table 1, the percentages of RTK output from GNSS only, QTC integration and QTC with DMI integration are compared.

Table 1. Comparison of RTK solution availability

	GNSS	QTC	QTC + DMI
RTK fixed	82.9%	90.84%	90.92%
RTK float	5.65%	3.25%	3.18%
Total RTK output	88.55%	94.09%	94.10%

It is worth mentioning that 2.79% of the trajectory is GNSS outage areas (i.e., tunnels). With QTC INS seeding, the percentages of RTK output is increased from 88.55% from GNSS only to 94.09%, in which the number of RTK fixed is increased by 7.94% with reduction on the RTK float by 2.4%. This shows that not only the availability but also the precision of RTK output is improved. With an additional aiding sensor, i.e., Applanix DMI, the GNSS RTK engine is further improved. That is, the aiding sensor improves the estimation of inertial navigation and sensor errors, which consequently improves the GNSS RTK output due to a better *a priori* inertial seeding solution.

The improved availability of the RTK solution occurs mainly in Munich downtown areas, as shown in Figure 6, where the RTK output from GNSS only (red) and QTC integration (blue) are depicted.

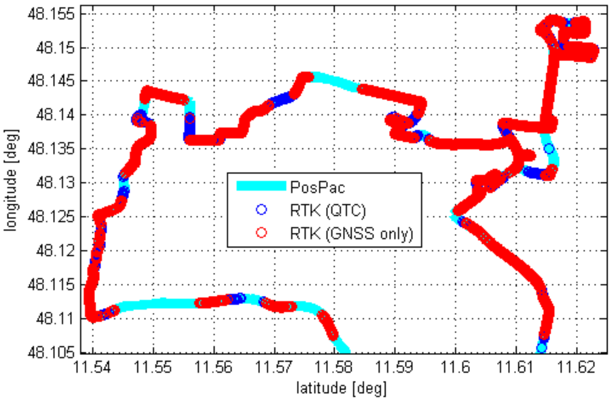
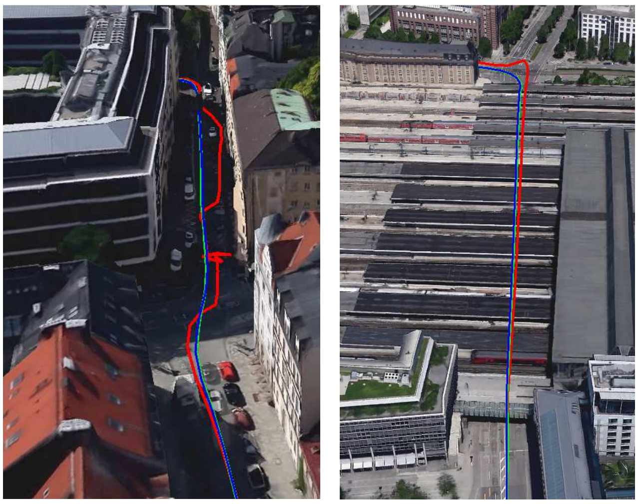


Figure 6. RTK availability comparison

Regarding the integrated solutions, a comparison is made with respect to a loosely-coupled integration. In benign signal environments, the INS seeding of RTK engine does not play an important role due to the large number of carrier phase observables (no need for INS seeding). In challenging areas with corrections from remaining carrier phase measurements, improved estimation of inertial navigation and sensor errors can be achieved. Better integration performance results in better dead-reckoning behavior due to accurate sensor errors estimation, better navigation performance in challenging area and faster recovery of the true path after harsh environments. Figure 7 shows such examples, where the red curve is a loosely-coupled solution and the green curve is the QTC integrated solution, which is overlaid with the POSPac post-processed reference trajectory (blue).



a) Urban canyon b) Tunnel

Figure 7. Loosely-coupled (red) and QTC (green) performance comparison in challenging signal environments (plotted in Google Earth)

Figure 7 subplot a) shows a typical urban canyon area. With INS seeding of RTK, the integrated solution is improved, because the remaining accurate carrier phase measurements are used in the solution when the number of SVs dropped to less than 4. In the loosely-coupled integration, the availability of RTK output is low. Using meter level DGNSS and autonomous solutions results in significantly degraded integration performance due to multipath effects. In subplot b), it can be seen that the dead-reckoning behavior from QTC integration is much better (overlaid with POSPac solution). Besides, when system exits the tunnel, a faster recovery effect can be observed. The error statistics of loosely-coupled and QTC integrated position and attitude estimates of the Munich van test are given in Table 2 and Table 3.

Table 2. Error statistics from loosely-coupled (containing downtown and long dead-reckoning areas)

Errors	50%	68%	90%	95%	99.7%
2D pos. [m]	0.070	0.116	0.746	1.783	15.553
3D pos. [m]	0.124	0.173	1.096	2.163	15.719
Roll [deg]	0.045	0.083	0.161	0.226	0.681
Pitch [deg]	0.069	0.123	0.226	0.411	1.533
Yaw [deg]	0.189	0.325	0.553	0.851	4.654

Table 3. Error statistics from QTC integration (containing downtown and long dead-reckoning areas)

Errors	50%	68%	90%	95%	99.7%
2D pos. [m]	0.052	0.081	0.213	0.495	11.307
3D pos. [m]	0.106	0.138	0.275	0.715	11.510
Roll [deg]	0.057	0.078	0.113	0.128	0.190
Pitch [deg]	0.031	0.044	0.077	0.101	0.272
Yaw [deg]	0.201	0.266	0.386	0.467	0.703

As shown in the tables, for the low percentile numbers (50% to 68%), the differences are small, because the INS seeding of RTK does not have much impact in benign areas. For the high percentile numbers, the difference is big. The benefit of QTC integration results comes from the fact that the RTK availability is improved, especially in urban area. With more RTK output, the usage of non-RTK solutions can be reduced, which improves the overall robustness and accuracy of the system. In the 2D and 3D position error 99.7 percentiles, the big errors are due to a very long tunnel in Munich which is over 1.5 kilometers in length. With a MEMS-based low-cost IMU, this kind of unconstrained drift is unavoidable with no additional aiding. A promising approach is to add aiding sensors with complimentary error characteristics. The error statistics for QTC integration with an Applanix DMI is given in Table 4.

Table 4. Error statistics of QTC + DMI integration (containing downtown and long dead-reckoning areas)

Errors	50%	68%	90%	95%	99.7%
2D pos. [m]	0.054	0.089	0.215	0.407	3.257
3D pos. [m]	0.106	0.142	0.282	0.572	3.704
Roll [deg]	0.057	0.075	0.112	0.130	0.196
Pitch [deg]	0.023	0.038	0.076	0.097	0.192
Yaw [deg]	0.171	0.257	0.379	0.450	0.627

With DMI aiding, the dead-reckoning performance is significantly improved. Although DMI is also a type of dead-reckoning sensor, it provides accurate position displacement in the along-track direction, which effectively suppresses the INS position drift in dead-reckoning area.

Van test in San Francisco downtown

For analyzing the performance in deep urban canyon areas, a van test was made in San Francisco downtown. The trajectory is a round trip from Trimble's Sunnyvale headquarter office parking lot to the San Francisco downtown area which are about 50 km apart, as shown in Figure 8. The GNSS base station was located near downtown area.

Figure 8. Trajectory of San Francisco test (plotted in Google Earth)

The sensor setup can be seen in Figure 9 with receivers mounted in the rear of the van.

Figure 9. Sensor setup for San Francisco van test

The San Francisco downtown area is considered as one of the most challenging signal environments in the United States and it is a big challenge for an integrated GNSS-INS system with a low-cost MEMS-IMU. This is a perfect scenario to prove the robustness of QTC integration and its potential benefits. The downtown area is depicted in Figure 10 which is full of skyscrapers and where the signal environment is extremely poor and highly reflective. During most of time, there is no RTK output from a GNSS only engine.

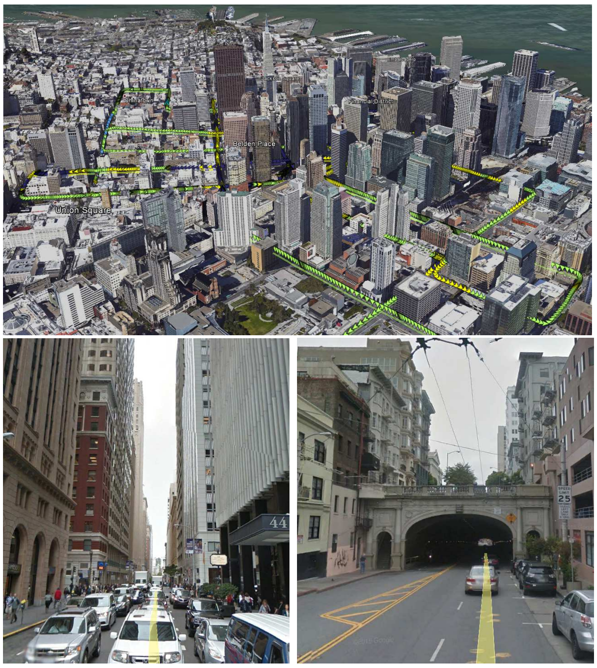


Figure 10. Urban canyon in San Francisco downtown

The focus of this dataset is in the downtown segment of the whole trajectory, as shown in Figure 11.

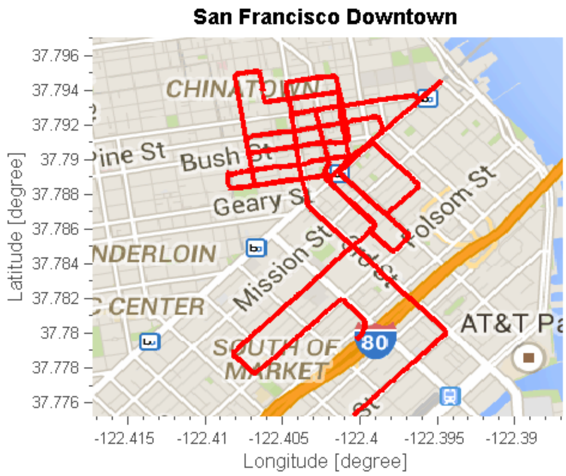


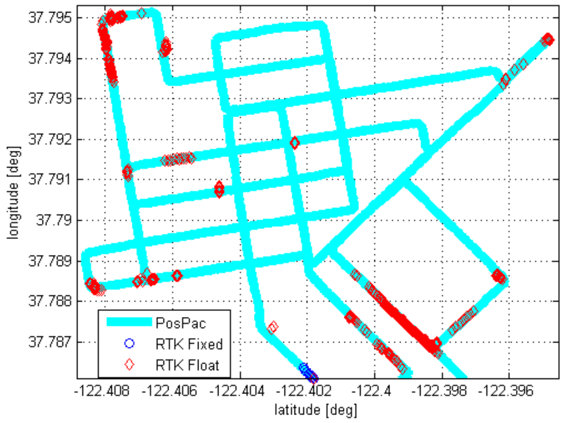
Figure 11. San Francisco downtown (plotted using google map)

A comparison of RTK availability from QTC integration and GNSS only is made and results are shown in Table 5. The percentages are computed based on the time when the van was in San Francisco downtown area (Figure 11).

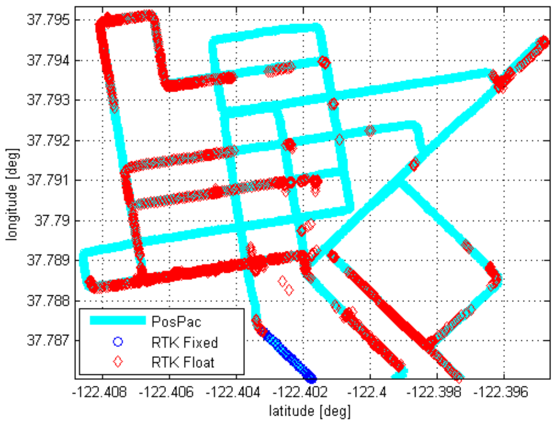
Table 5. Comparison of RTK solution availability

	GNSS	QTC	QTC + DMI
RTK fixed	1.36%	4.09%	4.71%
RTK float	21.86%	44.03%	44.98%
Total RTK output	23.22%	48.12%	49.69%

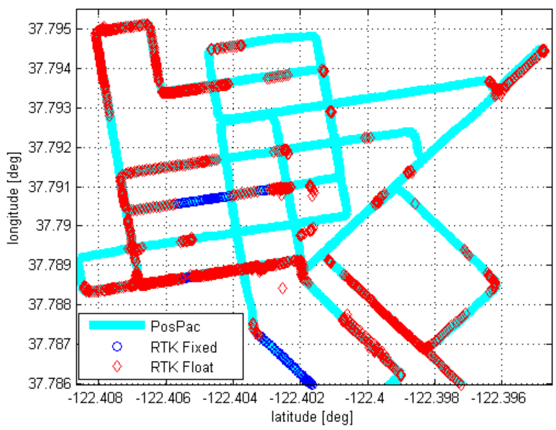
As shown in Table 5, with QTC integration the number of RTK outputs is doubled in the downtown area when comparing with the GNSS only case. With Applanix DMI aiding, both numbers of fixed and float solutions are further increased. The places with RTK output for GNSS only and QTC integration are shown in Figure 12. The non-RTK GNSS solution is also plotted for comparison purpose in the subplot d) of Figure 12. For the BD935-INS system, in case there is no RTK output, the non-RTK solution (autonomous or DGNSS) will be used in the integration.



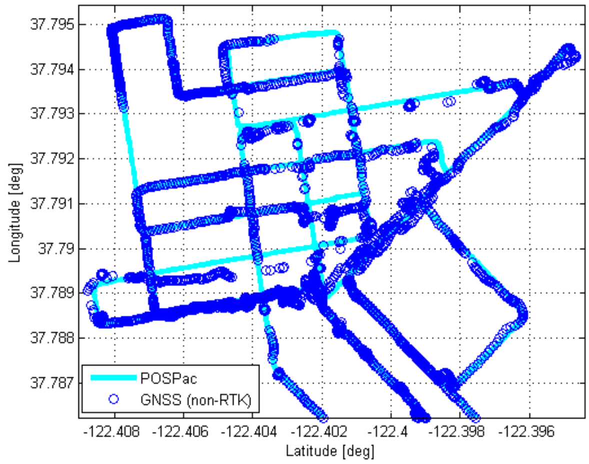
a) GNSS only (RTK solution)



b) QTC (RTK solution)



c) QTC + DMI (RTK solution)



d) GNSS only (Non-RTK solution)

Figure 12. Comparison of RTK availability in San Francisco downtown area

In subplot a) for the GNSS only case, there is very limited RTK output in the whole downtown area. It shows that a loosely-coupled GNSS-INS integration has to use the non-RTK (autonomous and DGNSS) solutions (subplot d)) for aiding. In such a highly reflective environment, it is difficult or not feasible for the GNSS engine to provide realistic covariance information for position and velocity estimates. As a consequence, it causes the integrated solution to be unreliable. This is a big challenge for loosely-coupled integration with low-cost inertial sensors.

In subplot b), with QTC INS seeding of RTK, the number of RTK output is significantly increased. In some areas, uninterrupted continuous RTK output is presented. Although at some epochs, very wrong INS aided RTK solutions are provided due to the very limited and poor GNSS observables. However, such jumping positioning errors can be easily detected and wiped off in the integration KF by using measurement innovations outlier rejection. It is unlike the non-RTK output, whose error gradually drifts over time and drives the INS to follow. In that case, the innovation contains no outliers and the measurement innovations outlier rejection does not work.

As shown in subplot c), with DMI aiding of GNSS-INS, not only the availability but also the accuracy is improved, as it causes more RTK solutions to be fixed.

In subplot d), the non-RTK solution errors are strongly correlated over time. The diameter of downtown area is about 1km. The non-RTK GNSS horizontal errors are sometime over 50 meters.

For having robust and reliable integration performance, it is logical to choose non-RTK output as little as possible. The QTC integration significantly increases RTK availability which makes the integration with low-cost inertial sensors feasible even in such extremely harsh GNSS area. A direct comparison of horizontal position errors from integrated solutions is given in Figure 13 with their error statistics shown in Table 6. It is worth mentioning that in this paper, we consider the POSPac output as ‘truth’ and the difference to POSPac output as errors. However, in downtown San Francisco, the RMS error of POSPac horizontal position estimates are also very high, as is shown in Figure 14.

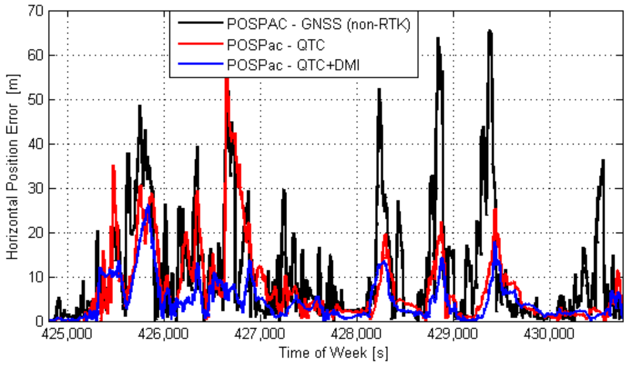


Figure 13. Horizontal position error in downtown area

Table 6. 2D position error comparison

Errors [m]	50%	68%	90%	95%	99.7%
GNSS (non-RTK)	4.28	9.82	30.45	37.92	64.81
QTC	4.05	7.73	18.95	25.71	50.65
QTC+DMI	2.96	4.99	10.88	13.00	24.78

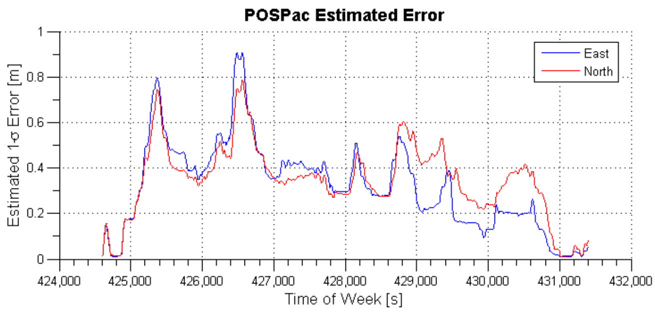


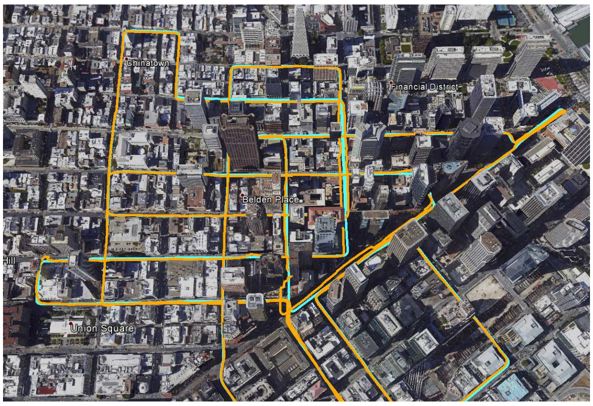
Figure 14. Horizontal position RMS error from POSPac

Figure 13 shows that the QTC integration outperforms the GNSS only solution. For the GNSS only (black curve), the spikes in the plot are actually the strongly time correlated errors due to the multipath, as the van spent more than 1.5 hours in the downtown areas. The GNSS only errors are the errors in the non-RTK output. In the QTC integration case, the RTK availability is significantly increased which results in the improved navigation performance. However the non-RTK solution is still frequently employed.

With DMI aiding, the overall performance is further improved. The error statistics from Table 6 shows that, the horizontal errors are reduced almost by half in all percentile statistics. With a better INS *a priori* solution, it not only improves the RTK engine performance, but also helps the measurement outlier detection in the integration KF to remove suspicious non-RTK outputs.

The horizontal position estimates of QTC integration with and without DMI are also depicted in Figure 15 with cyan curve representing the POSPac reference solution.

a) QTC (purple) vs. POSPac (cyan)



b) QTC with DMI (yellow) vs. POSPac (cyan)

Figure 15. QTC integration performance in San Francisco downtown area (plotted in Google Earth)

As shown in Figure 15, with DMI aiding, the integrated solution is overlaid with the reference solution much better than without DMI, and both approaches show promising ways on using low-cost MEMS-IMU in extremely harsh signal areas.

In the first release of the BD935-INS product, the DMI is not supported. However, in this paper, we have demonstrated the ways a DMI sensor can help the integration solution in a QTC integration architecture. It not only helps the dead-reckoning behavior in long tunnels (as shown in the Munich van test), but also improves the overall robustness and accuracy in deep urban canyon area.

UAV test (with rotors)

The performance of the BD935-INS in a UAV mission was examined using a hexacopter UAV in a test made by the Trimble Sunnyvale team. The size of the UAV is seen in Figure 16 with sensor setup shown in Figure 17. The GNSS antenna is mounted on the top of the UAV with receiver IMU board mounted beneath.

Figure 16. Hexacopter UAV test

Figure 17. Sensor setup

The flying trajectory is shown in Figure 18 where the arrow points to the take-off and landing location. The base station is about 15 km away.

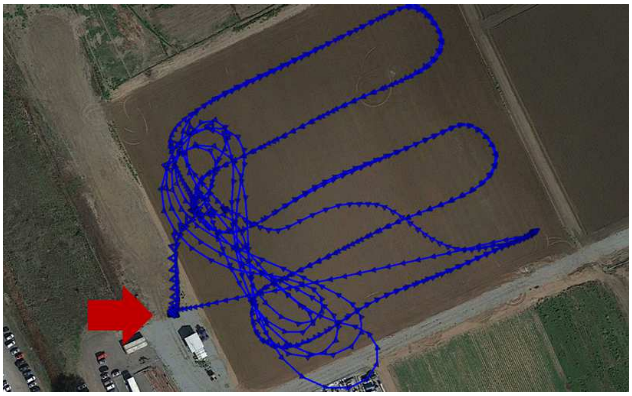
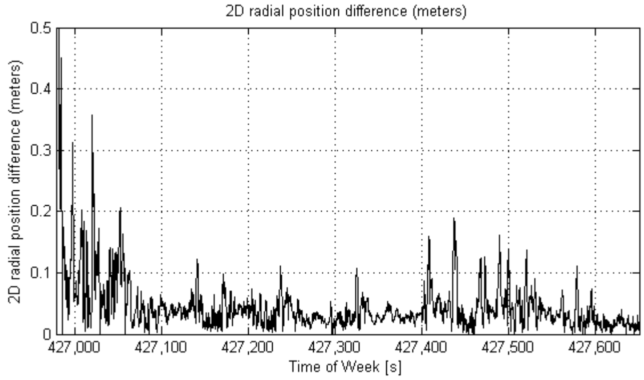
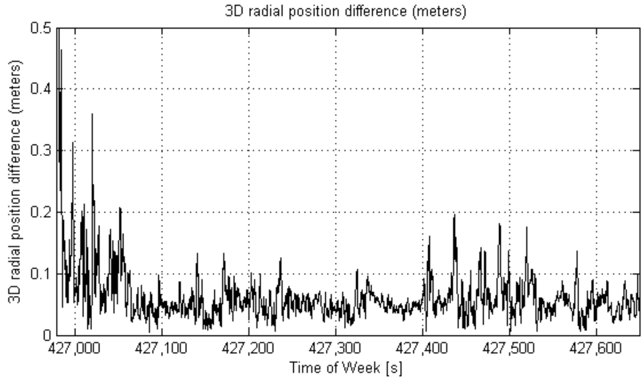


Figure 18. UAV flight trajectory

As shown in the figure, after the hexacopter has taken off, it executed a figure-8 maneuver to promote dynamic heading alignment before entering the survey lines. Unlike the van test, there are no aiding sensors onboard other than the GNSS receiver. This can make heading error estimation somewhat more difficult than on a road vehicle. The 2D and 3D position errors with respect to POSPac post-processed reference are shown in Figure 19 and the attitude estimation errors are given in Figure 20. The error statistics are given in Table 7.

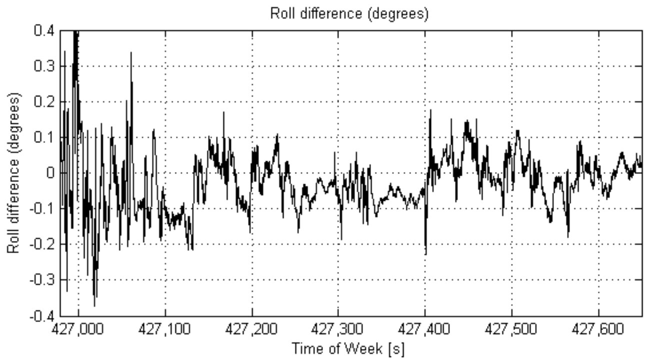


a) 2D position error

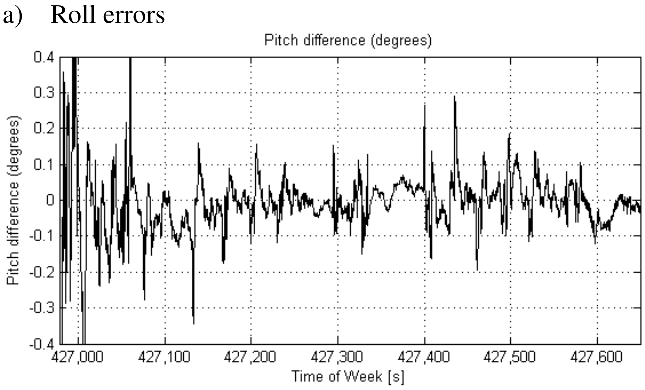


b) 3D position error

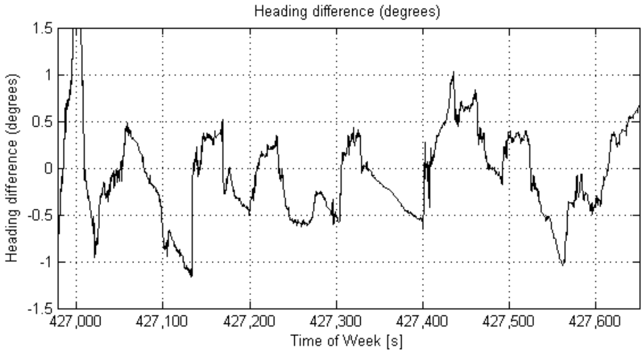
Figure 19. 2D and 3D radial position errors



a) Roll errors



b) Pitch errors



c) Yaw errors

Figure 20. Attitude estimation errors

Table 7. Error Statistics of QTC integration

Errors	50%	68%	90%	95%	99.7%
2D pos. [m]	0.033	0.045	0.092	0.123	2.170
3D pos. [m]	0.052	0.063	0.104	0.136	2.181
Roll [deg]	0.053	0.077	0.130	0.162	0.372
Pitch [deg]	0.035	0.057	0.116	0.165	1.018
Yaw [deg]	0.341	0.457	0.764	0.942	1.814

As shown in the table, the standard deviations for roll and pitch are below 0.1 degree. For the yaw, the standard deviation is below 0.5 degrees. For the UAV mission, when the vehicle turns or accelerates or decelerates, the tilt angles (roll and pitch) will change dramatically, as shown in Figure 21.

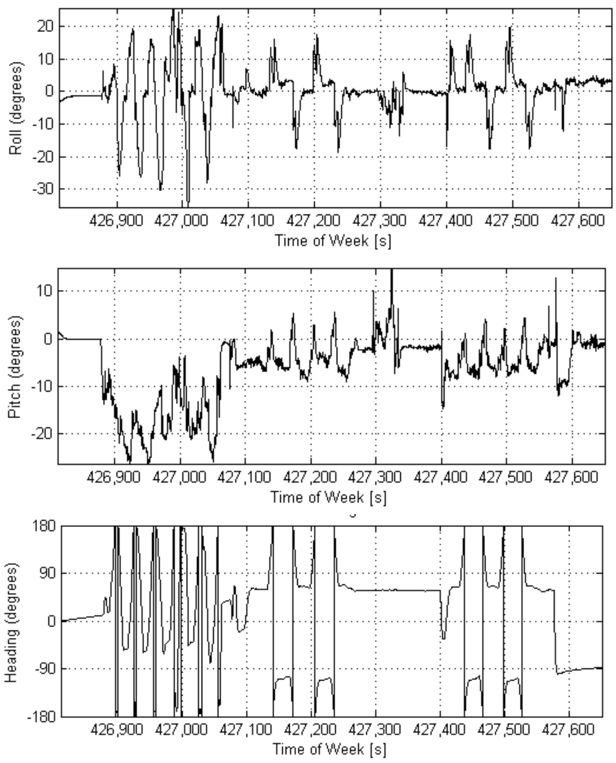


Figure 21. Attitude estimates of hexacopter

The 2D and 3D position errors standard deviations are at the centimeter level (about 5cm) due to the open sky environment. The high percentile (99.7%) errors are coming from the heading initialization period before the system entered the survey line.

CONCLUSIONS

A new GNSS-INS integrated system, the BD935-INS, was developed by Trimble using the QTC integration methodology. QTC integration comprises INS seeding of the GNSS solution and an observable subspace constraint in the construction of the INS-GNSS position measurement in the integration Kalman filter. It allows the GNSS engine to compute a partially constraint position with less than 4 satellites in view. It increases the availability of GNSS RTK solutions in areas with poor GNSS coverage. Although DMI aiding is not supported in the first release of the product, we have shown that it improves the *a priori* INS position in a QTC integration and consequently yields an improved RTK output. In the field experiments, the Munich van test shows the benefits of QTC integration in a relatively benign environment. The San Francisco downtown van test showed the performance of the system in an extremely harsh GNSS environment, which is a big challenge for the integration of GNSS with low-cost inertial sensors. QTC integration as an enhanced loosely-coupled GNSS-INS integration shows its strength in such areas by returning robust and reliable navigation solutions. In such downtown areas, the number of RTK solutions is more than doubled comparing with GNSS only, which is a significant achievement of QTC integration. In the high dynamic UAV test, the system meets the high accuracy demands of guidance and control and precision landing of a UAV by providing a cm-level position solution (1-sgima) and less than 0.1 degrees error (1-sgima) for roll and pitch and less than 0.5 degrees error (1-sigma) for heading.

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