AsteRx High-End GNSS Receiver coupled with MEMS-based IMU for Industrial Applications

Leen Vander Kuylen, Jianchen Gao, Frank Boon, *Septentrio*

BIOGRAPHY

Leen Vander Kuylen holds a Ms.Sc. in Aerospace Engineering from Delft University of technology. She is responsible for the design and implementation of integrated GNSS/IMU algorithms and GNSS-based attitude algorithms in the firmware of Septentrio's GNSS receivers. Her research interests include precise GNSS positioning algorithms.

Jianchen Gao holds a Ph.D. in Geomatics Engineering from the University of Calgary. He works on the design and implementation of GNSS/IMU algorithms at Septentrio. His research interests include GNSS, IMU and multi-sensor fusion for precise positioning and navigation applications.

Frank Boon holds a Ms.Sc. in Aerospace Engineering from Delft University of technology. He is head of the research group at Septentrio. His research interests include error modeling of GNSS measurements and optimization of positioning algorithms for highly dynamic applications. He previously worked on OTF ambiguity fixing methods and GNSS/IMU integration.

ABSTRACT

High-end GNSS receivers are deployed in rapidly increasing numbers in industrial applications such as agriculture and vehicle automation applications. Formerly regarded as high-end equipment, the receivers are now considered as off-the-shelf components in automated vehicle guidance systems where high reliability and accuracy are required. Despite the known characteristics of high-end GNSS receivers such as high-sensitivity, robustness and dual-frequency operation, these receivers have limitations for many industrial applications. In an ideal world, a reliable position and velocity solution would be continuously available at a high update rate. Reality however exposes the vulnerabilities of GNSS receivers in industrial applications: horizon obstructions and high vehicle vibrations continuously influence the signal quality and availability. Hence the reliability, accuracy and availability of the position-solution are directly proportional to the vehicle motion along and under the obstructions. In these circumstances, GNSS receivers can satisfy accuracy and reliability requirements only by sacrificing availability.

This problem is traditionally solved by integration of the GNSS receivers with high-end IMU systems. This solution, however, remains too expensive for many industrial applications. The maturation of MEMS-based IMU sensors gives the possibility to provide a cost-efficient solution that still fulfils the accuracy, reliability and availability requirements needed for most industrial applications.

In this paper, Septentrio presents the design and performance of a loosely-integrated GNSS/IMU receiver, based on its high-end AsteRx GNSS receiver and the MMQ50 MEMS-based IMU of Systron Donner. The main goal of this integrated system is to increase the availability of a reliable position solution in industrial applications without sacrificing accuracy. To demonstrate the performance of the system in an industrial environment, results of testing in an agriculture environment are presented.

INTRODUCTION

High-end GNSS receivers, such as the new AsteRx line of receivers, are typically selected for industrial applications where high availability and quality are the key requirements. GNSS signals, however, are limited in availability due to blockage and are vulnerable to deterioration in typical industrial environments. Periods of (partial) GNSS satellite masking can occur during operation near obstructions such as dense vegetation or crane structures. This results in frequently changing GNSS signal availability and quality, due to signal fading and reflection effects. Especially for satellites at low and even moderate elevations, the variation in signal strength and quality will cause continuous fluctuations in the thermal noise and error components of the code and phase measurements and significantly influence the position accuracy and reliability.

Fast re-acquisition methods, adaptive tracking loops and advanced multipath mitigation available in most GNSS receivers can mitigate these effects. However, increased usage of high-end receivers shows the limits of GNSS and GNSS receiver manufacturers have to make a trade-off between accuracy, reliability and availability.

Integrating GNSS receivers with other sensors, such as inertial sensors, can mitigate the GNSS errors further to provide a solution that fulfils the requirements needed for industrial applications. With the maturation of MEMS technology, aiding of high-end GNSS receivers coupled with MEMS-based IMU are becoming a cost-effective alternative for the high-end integrated GNSS/IMU systems that traditionally use tactical or navigation grade IMU systems.

This paper will describe the typical requirements of industrial applications, the chosen design and the performance of the prototype AsteRx/IMU in an agriculture application. Agriculture applications often use GNSS-based position and velocity information for automated vehicle guidance systems in order to increase the yield and quality of the crop. The performance discussion will focus on increasing the availability of a position solution by evaluating the position accuracy during periods of GNSS outage. As will be shown, the system performance depends on the accuracy of the estimated attitude.

GNSS IN INDUSTRIAL ENVIRONMENTS

Historically, applications for GNSS receivers are limited by satellite visibility. Consequently their usage in industrial applications is optimal in clear sky operation. Despite this, operators increasingly employ GNSS receivers in adverse conditions due to the experienced benefits and the decreasing costs of GNSS receivers, without relaxing their availability, reliability and accuracy requirements. Additionally an attitude solution is required, for example for automated vehicle guidance. GNSS antenna mounting is mostly an afterthought and is mostly determined by satellite visibility. Consequently, the GNSS antenna position may need to be transformed into the vehicle position required to allow optimal guidance, for which roll and pitch information is required.

As generally known, integrating GNSS receivers with inertial sensors provides a solution that may fulfill all these requirements. Traditionally navigation and tactical grade IMU systems are used for this purpose, which drastically increases the cost of the integrated system. With the maturation of MEMS, however, an integrated system that also fulfils the cost requirement has become available.

Usage of inertial sensors increases the availability of a position and velocity solution since the inertial measurements are provided and processed at high update rates (50Hz or higher). A high update rate is, for example, required for automated vehicle guidance since increasing the update rate increases the controllability of the vehicle.

The controllability also depends on the accuracy of the provided solution. Consequently, a reliable and accurate position is required continuously: when operating in a clear sky environment as well as during operation near obstructions. GNSS-based positioning only cannot fulfill this requirement. Changing satellite and signal availability, bad satellite geometry and multipath effects near obstructions result in errors and jumps in the provided position solution. Inertial measurements are insensitive to most GNSS errors. Consequently, the integrated system can mitigate these GNSS errors to provide a smoother and more accurate position solution. Insensitivity of inertial measurements to GNSS errors also allows additional integrity testing, when only a few satellites are available.

SCALABLE SOLUTION

The AsteRx receiver will be extended with Commercial-Off-The-Shelf (COTS) inertial sensors to service industrial applications, such as agriculture and harbour applications, at moderate cost. To keep the cost down, proper IMU selection is necessary. The selection is determined by the expected maximum period of GNSS outage that needs to be bridged and the accuracy that is required at the end of this period. An overview of IMU sensor classification according to their performance can be found in [1], [2] and [3]. In order to provide a cost-efficient solution adapted to the needs of a certain application, a scalable solution will be provided.

The IMU will interface with the receiver using a RS232 connection and provide the receiver with the specific forces and angular rates. The IMU mechanization and integration algorithms will run on the CPU of the receiver in parallel to the GNSS positioning engine and the DSP. As a prototype, the AsteRx receiver is integrated with the MMQ50 IMU of Systron Donner, containing three quartz rate sensors and three MEMS accelerometers. For a detailed description and the characteristics of the MMQ50, refer to [4] and [5].

INTEGRATION STRATEGY

As receiver manufacturer, low-level GNSS information is available for GNSS/IMU integration. This enables usage of the whole range of integration strategies from loosely- to deeply-coupled, which are described in [6]. For the prototype, a closed-loop, loosely-coupled integration strategy is chosen. The (dis)advantages of loosely-coupled integration over tightly-coupled integration are given in [7].

Figure 1 shows a block diagram of a closed-loop, loosely-coupled integration strategy. The algorithm consists of two decentralized Kalman filters and a strapdown navigator. The strapdown navigator processes the IMU measurements at a high update rate using mechanization equations [2]. The two decentralized filters are the GNSS-based positioning filter and the GNSS/INS integration filter:

- The GNSS-based positioning filter processes the GNSS measurements at a low update rate and is capable of providing a standalone, SBAS, DGPS or RTK solution.
- The integration filter runs at the same update rate as the GNSS-based positioning filter and combines the GNSS-based and IMU-based position and velocity solutions to determine the IMU sensor errors, amongst others.

The estimated errors are used to correct the incoming IMU measurements to improve the strapdown navigator solution. Therefore, the feedback-loop is especially important to improve results during periods of GNSS outage when only MEMS-based inertial sensors are used.

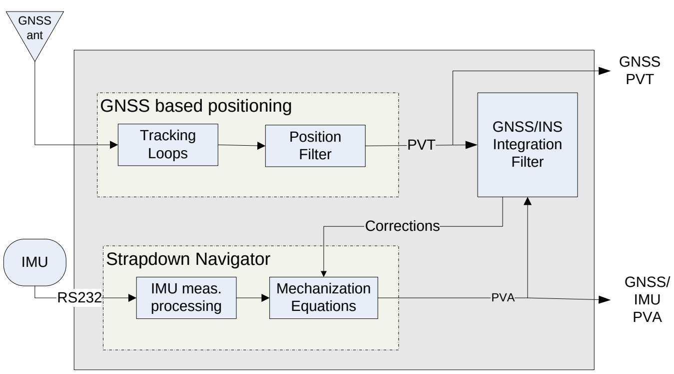

Figure 1 Block Diagram of a closed-loop, loosely-coupled integration strategy

CASE STUDY: AGRICULTURE APPLICATION

To evaluate the availability and accuracy of the solutions provided by the inertially aided AsteRx receiver, a measurement campaign was performed for an agriculture application during which the MEMS-based MMQ50 of Systron Donner was used. The PolaRx2eH GNSS receiver was used to provide a reference position, velocity and attitude. In order to have this reference continuously available, an open field was selected for this test. Outages, typically caused by dense vegetation surrounding the fields, were simulated during post-processing. To mimic operational conditions of real applications outages are simulated at the two locations shown in Figure 2.

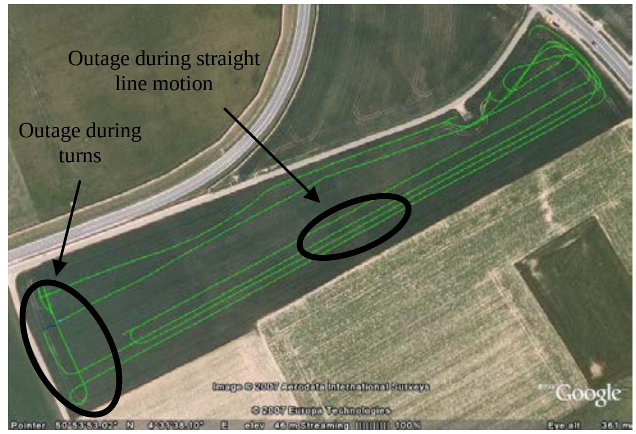

Figure 2 Test environment and trajectory – Steenokkerzeel (Belgium) ©Google

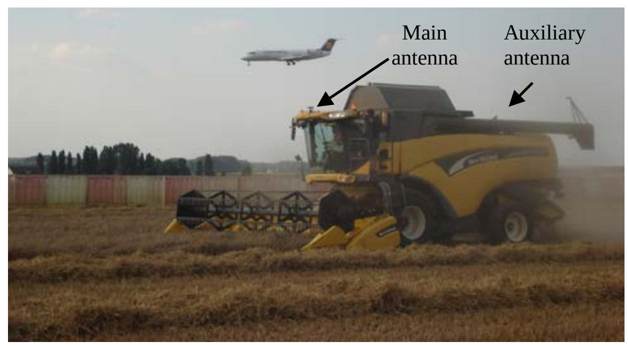

Figure 3 Combine harvester

The measurement campaign was held at fields in Steenokkerzeel (Belgium) on August 3rd, 2007. During the test, at least 8 satellites were continuously available, resulting in PDOP values of about 1.30. Figure 3 and Figure 4 show the equipment installed on the combine harvester:

- GNSS antennas, installed on the roof
  - 2 dual-frequency PolaNt
- GNSS receivers, installed in the cockpit behind the driver seat
  - 1 PolaRx2eH,
  - 1 AsteRx2
- IMU, installed in cockpit behind the driver seat
  - 1 MMQ50-200-400

The reference system, the PolaRx2eH, is a dual-frequency, dual-antenna GPS receiver capable of providing precise position, velocity, heading and pitch information at 10Hz. A PolaRx2 base station was installed in the vicinity of the field, providing differential corrections to compute the RTK reference position. The two antennas used to provide attitude reference were installed on the centerline of the harvester. One antenna was installed in front and was used as main antenna for all the GNSS receivers. The second antenna was installed in the back of the harvester and was used as auxiliary antenna for the PolaRx2eH (see Figure 3).

The AsteRx2 is a dual-frequency GPS/GLONASS receiver. The IMU is connected with this receiver through an RS232 interface. During the test, a standalone GNSS-based PVT was provided at 10Hz and the IMU measurements were recorded at 50Hz.

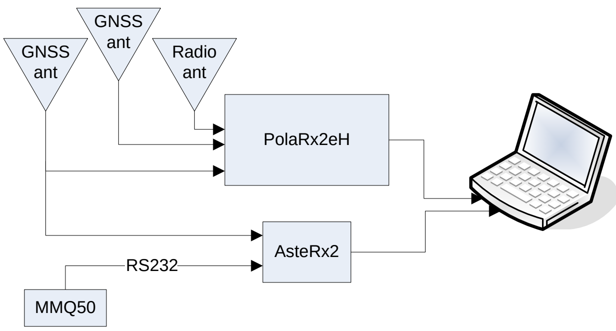

Figure 4 Schematic view of test setup

To avoid time correlation, the receiver is configured to provide an epoch-by-epoch GNSS PVT solution for usage in the integration filter. The AsteRx receivers allow the user to adapt the acceleration noise variances (the receiver dynamics) to allow the computation of a Kalman filter or an epoch-by-epoch GNSS PVT. When the Kalman filter is enabled, low-pass filtering effects and time-correlation may be introduced in the GNSS PVT and influence the integrated solution.

In-motion alignment, using GNSS-based horizontal velocity, has been used to determine the initial heading of the vehicle. The pitch and roll angles are assumed to be small and have been initialized to 0 deg.

PERFORMANCE ANALYSIS

The performance analysis will start with the discussion of the sensor biases since they have a major impact on the position and velocity error growth during GNSS outages. Besides the errors in the estimated sensor biases, the estimated attitude also influences the system's performance and will be analyzed next. The attitude estimation accuracy will be discussed when GNSS measurements are available, and during GNSS outages. Finally, the position estimation accuracy will be evaluated during GNSS outages.

For the analysis below, application independent algorithms have been used. This means that no motion constraints are taken into account to improve the results. The performance analysis will focus on the integrated system accuracy during periods of full GNSS outage. For the presented results, outages of up to 60 sec are simulated to investigate the long-term error behavior. Such a long outage period will typically not occur during agriculture applications. The length of GNSS outages will be limited due to the Fast-Acquisition-Unit (FAU) available in the AsteRx receivers. Therefore, depending on the environment, GNSS outages of 5 sec are expected.

SENSOR BIAS ESTIMATION ACCURACY

To evaluate the sensor bias estimation performance, the convergence time and the estimation accuracy are considered. Optimal sensor bias estimation can be performed during high-dynamic motions, such as fast turns. Since practical usage of the sensors in farmer applications does not allow this kind of motions, it has not been considered for this paper. Two types of low-dynamic motion, characteristic for most agriculture applications, can be distinguished as shown in Figure 5:

- Straight line motion at a nearly constant speed of about 1.2 m/sec
- 360° turns during which the harvester is slowly accelerating to speeds up to 3.5m/sec.

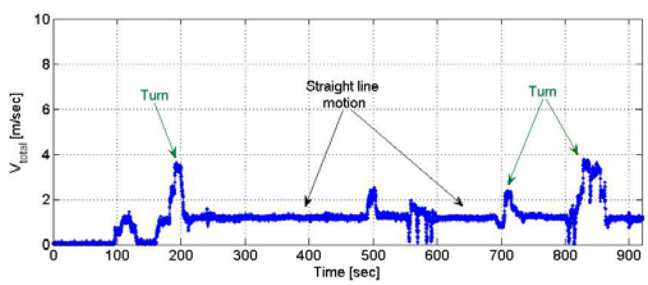

Figure 5 Total velocity during combine harvester operation

The capability to correctly estimate the sensor biases depends on the dynamics of the motion during operation and on the GNSS PVT mode. Table 1 gives an overview of the convergence time for the different sensor biases and the estimated sensor bias error during straight line motion (from 250 to 450 sec in Figure 5). The provided convergence time is the integration filter convergence time. For this prototype testing a standalone PVT solution is used, which is assumed to only increase the convergence time compared to the usage of other PVT modes such as SBAS, DGPS or RTK.

To analyze the sensor bias estimation accuracy, the mean of the measurements is used as an approximation of the reference since no real sensor bias reference is available. Therefore, the sensor bias estimation accuracy is analyzed during straight line motion at nearly constant speed. This makes it possible to compute the mean specific forces and angular rates, without being affected too much by the vehicle's motion. This approximated reference, however, has some limitations. An unknown small pitch and roll angle bias the reference since a small part of the gravity vector is also sensed by the X- and Y-accelerometer.

	Convergence Time [sec]	Mean measurement value	Error in estimated bias
Accelerometers			
X	35	0.2510 m/sec^2	0.0843 m/sec^2
Y	35	-0.0716 m/sec^2	0.1613 m/sec^2
Z	5	-9.6452 m/sec^2	0.0002 m/sec^2
Gyroscopes			
X	5	0.0522 deg/sec	-0.0007 deg/sec
Y	5	-0.1095 deg/sec	0.0032 deg/sec
Z	35	-0.1855 deg/sec	0.0265 deg/sec

Table 1 Mean IMU sensor measurements and error in estimated sensor bias during straight line motion

The horizontal motion is mainly determined by the X- and Y- specific forces and by the angular rate about the Z-axis. Due to the low variation in horizontal motion of the combine harvester and the low observability of the Z-gyroscope bias and the heading, these parameters are difficult to estimate. This results in a heading estimation error, which at its turn influences the bias estimation process of the X- and Y accelerometer. This is translated in longer convergence times and larger errors in the estimated sensor biases. As explained above, small pitch and roll angles influence the accuracy of the reference. Since the roll angle was larger than the pitch angle, the error in the reference will be larger for the specific forces about the Y-axis than about the X-axis. This explains the large difference between the estimated sensor bias errors of the X- and Y accelerometers. The sensor bias estimation accuracy for both sensors is probably about 0.08 m/sec^2.

The vertical motion is mainly determined by the Z-specific forces and by the angular rates about the X- and Y- axis. These sensor biases are less difficult to estimate, due to the used mathematical model. Consequently, smaller convergence times and smaller estimation errors are shown in the table. Small pitch and roll angles during the considered period also influence the accuracy of the Z-accelerometer reference. The actual error in the estimated bias for this sensor will probably be larger than the presented value.

ATTITUDE ESTIMATION ACCURACY

It is generally known that the position and velocity accuracy of a strapdown integrated system mainly depends on the attitude accuracy, amongst others, since it is used to transform the sensed body specific forces into the navigation frame. As for the bias estimation accuracy, the motion characteristics of the vehicle during operation influence the attitude estimation accuracy. Small and slow changes in horizontal motion makes especially the heading weakly observable and will consequently increase the difficulty of estimating the heading accurately.

Figure 6 and Figure 7 show the pitch and heading error respectively, using the attitude provided by the PolaRx2eH receiver as reference. Figure 6 shows that the error in the estimated pitch angle remains smaller than 1 deg during operation when GPS regularly is available. Figure 7 shows a considerable larger error in the heading estimate due to low vehicle dynamics during the test. The heading drift is higher when the vehicle drives on a straight line (200-500 sec and 600-500 sec). During turns, the heading error is only partially corrected due to the slow horizontal velocity and direction changes during these turns. As expected, the motion characteristics have a major impact on the heading estimation, while the impact on the pitch estimation remains negligible. Motion constraints could be used to limit the error growth of the heading estimate.

The impact of using a Kalman filtered or an epoch-by-epoch (or least-squares) GNSS PVT is mainly visible in the error of the heading estimate (Figure 7). The differences in heading estimates are caused by low-pass filtering effects and correlation between the used GNSS PVT in the integration filter.

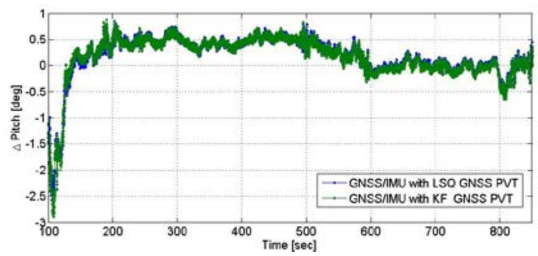

Figure 6 Pitch error, using PolaRx2eH reference

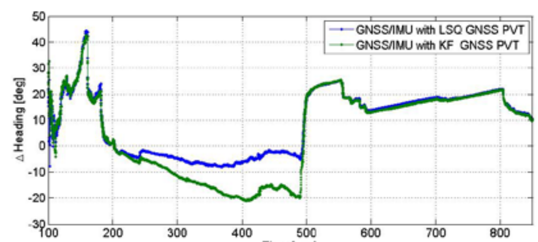

Figure 7 Heading error, using PolaRx2eH reference

Some applications require attitude to transform the provided GNSS antenna position to a position on the vehicle that is required, for example to allow more accurate automated vehicle guidance. Especially the roll and pitch angles are of importance. The results presented in this paper show that the pitch error remains smaller than 1 deg during operation when GPS is available. This accuracy, however, may not be sufficient to correct the position accurately.

ATTITUDE ACCURACY DURING GNSS OUTAGES

The attitude accuracy during GNSS outages is shown in Figure 8 to Figure 10. For heading and pitch error computation, the PolaRx2eH receiver is used as reference. No roll reference is available from an independent system and therefore, the roll angle error has been computed using the AsteRx2/IMU solution obtained while no outage was simulated. Table 2 shows the maximum attitude errors during the 60 sec GNSS outages.

The accumulating attitude error during the outages is limited, which shows the good drift characteristics of the used gyroscopes. Nevertheless, the heading estimate is drifting away faster from the reference than the pitch and roll during a GNSS outage. This indicates that the bias of the angular rate sensor about the z-axis has not fully been estimated, as expected because of the weak observability of this parameter. The figures also show that the error growth behavior depends on the motion during the outage. This is caused by correlation between the estimated state elements, which depends on the motion characteristics.

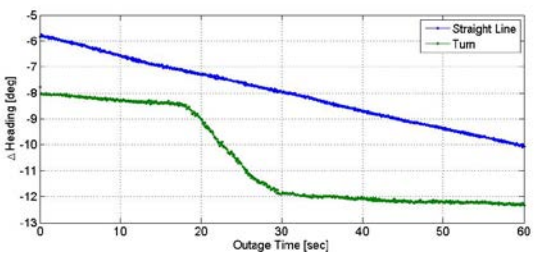

Figure 8 Heading error during GNSS outages, using PolaRx2eH reference

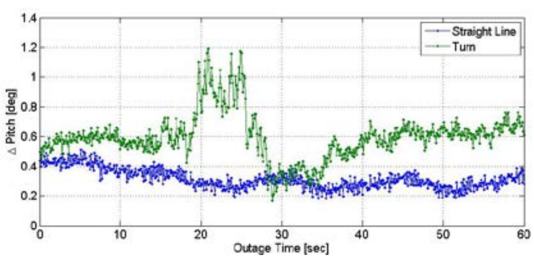

Figure 9 Pitch error during GNSS outages, using PolaRx2eH reference

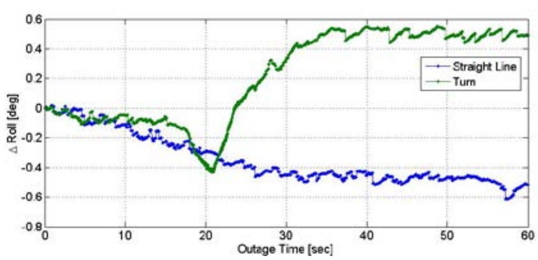

Figure 10 Roll error during GNSS outages, using GNSS/IMU reference

	Max. absolute error		**Max. difference with initial error**	
	Straight Line	*Turn*	*Straight Line*	*Turn*
Heading	10.10 deg	12.33 deg	4.37 deg	4.30 deg
Pitch	0.51 deg	1.20 deg	0.25 deg	1.23 deg
Roll	0.61 deg	0.55 deg	0.61 deg	0.55 deg

Table 2 Maximum attitude error during 60 sec GNSS outages using epoch-by-epoch GNSS PVT

POSITION ACCURACY DURING GNSS OUTAGES

Unlike the attitude errors, the position errors are growing rapidly during a GNSS outage period. The position accuracy is shown in Figure 11, Figure 12 and Table 3. The horizontal position error contributes most to the total position error, due to the contribution of estimation errors in the estimated sensor biases as well as in the estimated attitude. The outages were generated during straight line motion at constant speed and during a turn. Due to different dynamics during these periods, different error propagation behaviour can be seen. The values that are presented here are as expected for the considered IMU and vehicle dynamics.

The impact of using a Kalman filtered or an epoch-by-epoch (or least-squares) GNSS PVT is, besides in heading, also visible in the position estimates. Due to differences between both computed GNSS PVT's, the integrated result is also slightly different as expected when the GNSS PVT is available. During GNSS outage, however, Figure 11 and Figure 12 show differences in error growth and the errors for the Kalman filtered solution seems to be the largest. However, the behavior during the turn shall be investigated in more detail, since the Kalman filtered solution seems to follow the actual turn more closely than the integrated solution based on the epoch-by-epoch GNSS PVT. This may indicate that the filter parameters for the epoch-by-epoch solution are not yet optimal for the considered application.

These results show that only short outages are acceptable for most agriculture applications when the MMQ50 is used. On the AsteRx receivers, a Fast-Acquisition-Unit (FAU) is available which allows re-acquisition within 1 sec after full GNSS outage. This feature reduces the maximum length of outage periods.

Figure 13 shows that the integrated solution smoothes the GNSS-based solution, when GNSS is regularly available. It is also expected that for periods with partial GNSS outages and with signal quality degradation the system will improve the position accuracy by providing a non-delayed smoothed result, which will be useful for automated vehicle guidance systems.

	GNSS outage period [sec]	Compared to standalone GNSS Position [m]		
		2D	Up	3D
Straight Line	10	1.48	0.36	1.53
	15	2.47	0.36	2.50
	20	5.59	0.065	5.58
	30	16.80	0.83	16.82
	60	99.36	9.47	99.81
Turn	10	3.00	0.26	3.01
	15	5.04	0.19	5.04
	20	7.97	0.43	7.98
	30	8.50	1.38	8.61
	60	12.72	4.93	13.66

Table 3 Position accuracy during GNSS outages setting using epoch-by-epoch GNSS PVT

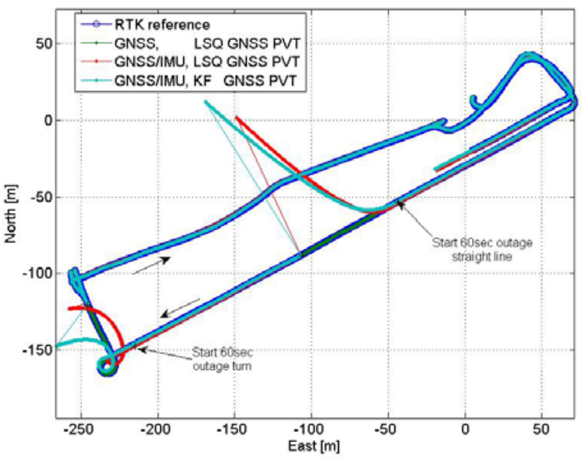

Figure 11 Horizontal trajectory with 60 sec outage (black arrows indicate driving direction)

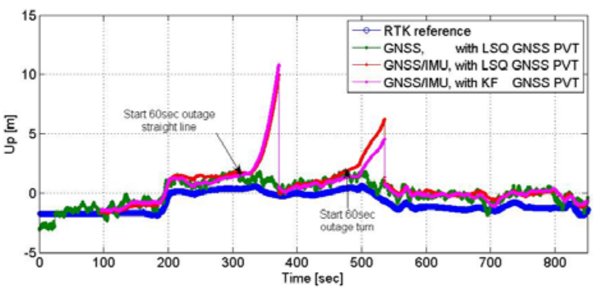

Figure 12 Vertical trajectory with 60 sec outages

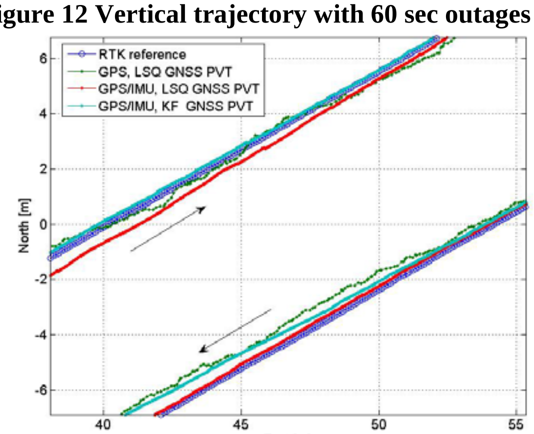

Figure 13 Detail of horizontal trajectory (black arrows indicate driving direction)

CONCLUSIONS

Septentrio has developed a prototype AsteRx/IMU receiver for usage in industrial applications to overcome the limitations of using a GNSS-only solution in this kind of applications. The usability of GNSS/IMU receivers in industrial applications is determined by the motion characteristics, the operational environment and the accuracy requirements. Therefore, the AsteRx/IMU receiver is a scalable solution. For the prototype, the high-end AsteRx receiver is loosely integrated with the MEMS-based MMQ50 IMU of Systron Donner and uses application independent algorithms. The goal of the integrated system is to increase the availability of a position and velocity solution over a GNSS-only solution, during operation near obstructions, without decreasing the position accuracy when a GNSS navigation solution is available.

The performance of the AsteRx/IMU receiver has been verified using an agriculture application, which is characterized by low-dynamic motion. The GNSS/IMU integrated system reduces the effects of some GNSS errors on the position solution and also provides a pitch and roll angle within 1 deg accuracy limits. The heading, in contrary, contains large errors due to a growing error caused by low-vehicle dynamics. During GNSS-outages of up to 60sec, the attitude error remains limited to maximum 5deg. The position error growth during these outages has been demonstrated to depend on the vehicle motion. When the outage occurs during straight line motion, the largest position error is encountered and is about 17m after 30sec outage.

The presented results are promising and indicate that an AsteRx receiver can provide an accurate navigation solution during a full GNSS outage period of a few seconds when coupled to a MEMS-based IMU. For longer outages, new integration algorithms will be developed to improve the accuracy. Application dependent parameters and motion constraints will be taken into account.

ACKNOWLEDGMENTS

The authors are thankful to CNH and the University of Leuven (Belgium) for the cooperation on the test campaign and the provision of the combine harvester and driver. The authors also would like to thank Jan Leyssens, Septentrio's application engineer, who arranged the test facilities and test setup.

REFERENCES

[1] El-Sheimy, N., *Inertial Techniques and INS/DGPS Integration*, ENGO 623 Course

Notes, Department of Geomatics Engineering, University of Calgary, 2004.

[2] Titteron, D.H. and Weston, J.L., *Strapdown Inertial Navigation Technology*, Peter Peregrinus Ltd, 1997

[3] Scherzinger, B., Petovello, M., Lachapelle, G., *What are important considerations when selecting the type and quality of IMU for integration with GNSS?*, Inside GNSS, May/June 2007, pg. 36-38

[4] Systron Donner, *Datasheet MMQ50 IMU*, http://www.systron.com/PDFS/datasheets/MMQ50-200-400.pdf

[5] Jaffe, R., Aston, T., Madni, A.M., *Advances in Ruggedized Quartz MEMS Inertial Measurement Units*, PLANS 2006, pg. 390-399

[6] Gebre-Egziabher, D., Petovello, M., Lachapelle, G., *What is the difference between 'loose', 'tight', 'ultra-tight' and 'deep' integration strategies for INS and GNSS?*, Inside GNSS, January/February 2007, pg. 28-33

[7] Salytcheva, A.O., *Medium Accuracy INS/GPS Integration in Various GPS environments*, UCGE Report Number 20200, Department of Geomatics Engineering, University of Calgary, September 2004