Performance of a Deeply Coupled Commercial Grade GPS/INS System from KVH and NovAtel Inc.

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ABSTRACT

NovAtel Inc. and KVH Industries have jointly developed a commercial grade, single enclosure GPS/INS system. The integrated KVH CG-5100 IMU features fiber-optic gyros and MEMs accelerometers, and provides inertial data at 100 Hz. NovAtel's OEMV3 receiver is the GPS engine. Weighing 5.2 lbs, the combined system will feature the tightly coupled architecture that is a key characteristic of NovAtel's SPAN (Synchronized Position Attitude Navigation) technology. The GPS receiver provides aiding information for the INS, and is reciprocally aided by feedback from the INS to improve signal tracking. The feedback from the INS to the GPS engine is the deeply coupled aspect of the system. It is also tightly coupled. GPS measurements are used to update the INS filter, providing high quality aiding information whenever there are least two satellites available. The combined system has an optional wheel sensor, which is used to further aid the INS during times of reduced GPS availability in land vehicle applications.

The GPS/INS navigation solution is computed on-board the OEMV3 and is available in real-time. Raw data can be simultaneously logged for post-processing. For applications that need higher accuracy, post-processing can be performed with the Inertial Explorer software package, which features a fixed interval smoother.

This paper provides a preliminary performance assessment of the NovAtel-KVH GNSS/INS system. Results from real world data are presented. The analysis focuses on signal tracking performance and the accuracy of the GPS/INS solution, under favorable GPS conditions and under challenging GPS conditions.

INTRODUCTION

KVH and NovAtel have jointly developed a single enclosure GPS/INS system to offer the best integrated solution to the marketplace. KVH's patented FOG technology offers stable performance meant for the commercial market. Onboard the OEMV3, NovAtel's SPAN (Synchronized Position Atttitude Navigation) technology offers superior GPS tracking performance due to its unique tightly/deeply coupled integration of the GPS receiver and the IMU. By working together, KVH and NovAtel can offer a very robust commercial-off-the-shelf (COTS) system with a level of coupling typically only available in military systems,. Applications include airborne mapping, land vehicle mapping, robotics guidance, autonomous vehicles, motor sports tracking and precision agriculture.

The system computes a real-time GPS/INS solution and can simultaneously log raw data for post-processing. Waypoint's Inertial Explorer software package provides the post-processing capability. The joint system also supports wheel sensor input, allowing the user an additional aiding source that is already fully integrated for them.

In this paper, results from preliminary testing with the joint system are presented. Two tests were performed with the goal of showing the signal reacquisition benefit provided by the SPAN technology onboard the OEMV3, and the navigation performance possible with the KVH IMU. Both tests were conducted in a land vehicle, under normal driving conditions in suburban and urban environments.

SYSTEM DESCRIPTION

A single enclosure was designed to keep the system small and light, and make the installation as simple as possible. A prototype unit is shown below in Fig. 1. The system weighs 5.2 lbs (2.34 kgs), with dimensions of 6.67" x 6.0" x 3. 5" (170.2 x 152.4 x 89 mm). Communication with the system is through a 37 pin circular connector. Firmware can be loaded onto the OEMV3 and the CG-5100 through the 37 pin connector. Through the same connector, commands can be sent (for configuration for instance) and system output is logged. The smaller connector above the 37 pin connector is the antenna input. The entire system operates with an input voltage of 9-16 vdc and consumes less than 15 watts. Mounting holes and alignment holes are provided on the base plate of the unit. The centre of navigation is clearly marked on the exterior of the enclosure to allow precise measurement of the vector between the IMU and the GPS antenna (also referred to as the lever arm).

Fig. 1. Prototype KVH-NovAtel GPS/INS System

The enclosure also accepts odometer inputs from quadrature encoders as well as pulse and direction encoders. Accepted encoder inputs levels range from RS-422 signaling to battery voltage level pulses. An input pulse frequency in excess of 45 KHz is easily handled by the unit.

All system configuration is completed through the receiver's (OEMV3) standard serial ports, accessible through the 37 pin connector. Navigation computations are done on board the receiver. The IMU data is integrated with the GPS data and a continuous real time position, velocity and attitude solution is available to the user at up to 100 Hz. Raw data can be simultaneously logged for post processing. All previous SPAN features are supported in the KVH-NovAtel joint system. Post-processing capability is provided by the Waypoint Inertial Explorer software package.

OEMV3 AND SPAN TECHNOLOGY

The OEMV3 offers the following positioning modes: single point, SBAS-corrected GPS (WAAS and EGNOS), L-Band corrections (OmniSTAR and CDGPS) and for centimeter-level positioning accuracy, the real time kinematic mode is available which requires corrections from a local base station receiver via radio link. The real time SPAN filter uses GPS position updates, velocity updates, carrier phase updates when insufficient satellites are available to provide a GPS position, and wheel updates as well if a wheel sensor is attached.

With typical GPS/INS integrations, the INS uses the GPS data as an aiding source to estimate and control the errors in the IMU. With SPAN, the INS is aided with the GPS data and the inertial solution is used to aid the GPS receiver as well, as shown in Fig. 2. This is the tightly, or deeply, coupled aspect of the SPAN architecture. There are many interpretations of what "deeply" and "tightly" mean [1]. SPAN can be considered deeply coupled since the signal tracking is being aided by the inertial solution. It can be considered tightly coupled as well, since the raw carrier phase measurements are used as updates to the INS filter. GPS signal reacquisition is dramatically improved when running SPAN. This is a key performance feature in restricted coverage environments, like urban canyons, where the user may only have a few seconds of satellite visibility before another blockage occurs. With SPAN technology, the user will be able to get GPS measurements in that small window of visibility. That means the INS will have shorter periods of free navigation and smaller errors, since the GPS is available more often for aiding.

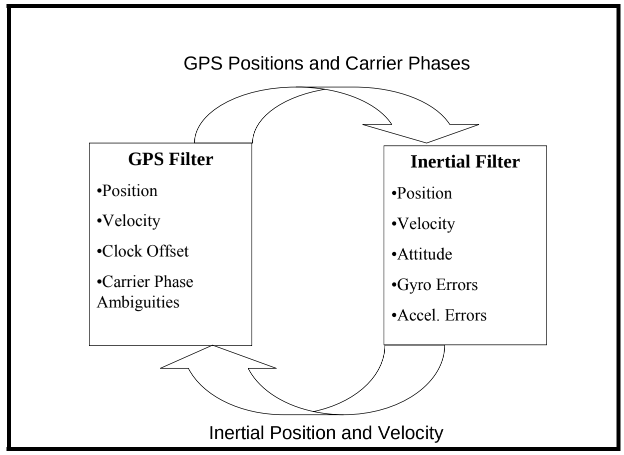

Fig. 2. SPAN Architecture

KVH IMU

The KVH CG-5100 IMU is based on the proven performance of the KVH DSP3000 FOG coupled to MEMS-based accelerometers. The overall IMU performance is superior to existing MEMS solutions and will be commercially available to the market. For this specific pairing, the IMU has been configured to output data at 100 Hz, although output rates up to 2 KHz are supported. The KVH IMU data is compensated for temperature effects and tagged to GPS time. All communication between the IMU and the OEMV3 is handled within the enclosure, transparently to the user.

KVH is the only FOG manufacturer in the world to fabricate 100% of the fiber used in its gyro products. More than 20 years of research into fiber design has resulted in the KVH E•Core® fiber, a proprietary class of D-shaped cross-section, non-stress induced fiber with an elliptical core. The temperature instability present in standard stress-induced fibers has historically precluded the use of FOGs in some applications. However, the elliptical core in E•Core fiber acts as an optical wave guide for the FOG sensing light, resulting in stable performance over a wide temperature range that make KVH FOGs extremely well-suited for navigation applications.

KVH employs patented Digital Signal Processing (DSP) technology in its FOG-based systems. This breakthrough design virtually eliminates temperature-sensitive drift and rotation errors. As a result, the CG-5100 is well suited for applications in which FOGs and accelerometers are combined to determine vehicle dynamic motions, as well as any application that requires precise measurement of rate or turning angle.

Utilizing a mature, all-fiber circuit, the KVH CG-5100 has no moving parts to maintain or replace so that the CG-5100 lasts longer, functions better and yields significant system life cycle savings.

The specifications of the KVH CG-5100 are given in tables 1 and 2.

TABLE 1

KVH CG-5100 FIBER OPTIC GYRO SPECIFICATIONS

Offset	20 deg/hr
Repeatability (turn-on to turn-on, 1 σ)	3 deg/hr
Stability (constant temperature, 1 σ)	1 deg/hr
Angular Random Walk (max)	0.07 deg/√hr
Scale Factor Error over temperature	500 ppm
Linearity	1000 ppm
Range	375 deg/s
Alignment	8 mrad

TABLE 2

KVH CG-5100 ACCELEROMETER SPECIFICATIONS

Offset	50 mg
Repeatability (turn-on to turn-on, max)	0.75 mg
Stability (over 48 hrs, 1 σ)	0.25 mg
Velocity Random Walk (max)	0.053 m/s/√hr
Scale Factor Error	4000 ppm
Linearity	3000 ppm
Range	10 g
Alignment	10 mrad

WAYPOINT INERTIAL EXPLORER

Inertial Explorer is an extension of the popular GrafNav GNSS post processing software. GrafNav is a high-precision GNSS post-processor, supporting multiple base stations and featuring very reliable on-the-fly (OTF) kinematic ambiguity resolution (KAR) for single and dual frequency data. The GNSS data can be processed forwards and backwards and combined for an optimal solution. A Rauch-Tung-Striebel (RTS) smoother is a standard tool in Inertial Explorer [2].

TEST DESCRIPTON

Two tests are presented herein. The first test was conducted in open sky conditions. The second test was collected in downtown Calgary, Alberta, a typical urban environment. The test setup was similar for both tests. The KVH-SPAN system was installed in a minivan, securely mounted to the floor. A NovAtel GNSS-702 antenna was mounted on the roof of the van. The vector between the IMU centre and GPS antenna was accurately surveyed using a total station and is considered known to within 1 cm. The antenna was split between the KVH-SPAN system and an OEMV3 in GPS only mode. Data was logged from both receivers to a laptop, using the serial ports of the receivers. Additionally, an OEMV3 SPAN enabled receiver with tactical grade IMU was mounted in the van. This tactical grade SPAN system logged raw data for post-processing in Inertial Explorer to use as a reference to evaluate the positional error of the KVH SPAN system. The tactical grade reference IMU specifications are given in Table below.

TABLE 3

REFERENCE IMU SPECIFICATIONS

Gyro Rate Bias (total)	1.0 deg/hr
Gyro Rate Scale Factor	150 ppm
Angular Random Walk	0.125 deg/hr
Accelerometer Linearity	500 ppm
Accelerometer Scale Factor	300 ppm
Accelerometer Bias (total)	1.0 mg

Signal Reacquisition Test Procedure

To evaluate the signal reacquisition benefits of the deep coupling of the KVH-NovAtel system, an open sky route was driven with specific signal blocking commands sent simultaneously to both the SPAN enabled (KVH) receiver and the GPS only receiver. The signal blocking command forces the receiver to drop all the signals tracked, and then wait 10s before starting to reacquire all available GPS signals. A total of 50 such signal block commands were sent, separated by 100s. The full test was just over 1.5 hours in duration.

The van was driving in a suburban area on the edge of Calgary, Alberta, Canada, following all normal traffic conditions. Vehicle speeds varied from 50 – 110 km/hr. Occasional stops occurred at traffic lights. The vehicle speed and azimuth during the signal reacquisition test is show in Fig. 3.

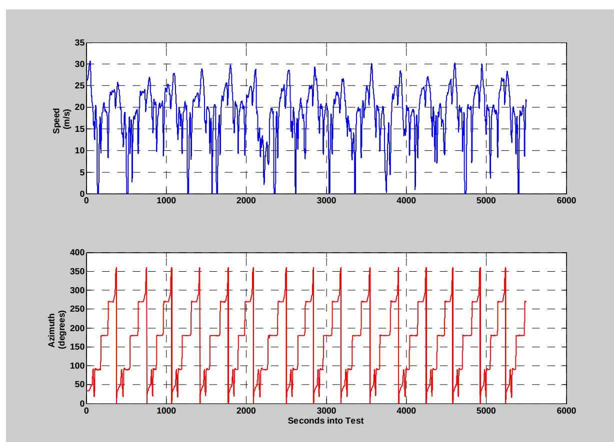

Fig. 3. Speed and Azimuth During Signal Reacquisition Test

To start the test, a kinematic alignment was performed using GPS velocities. After approximately 10 minutes of driving to allow the GPS/INS solution to converge, the signal blockages were started.

After this open sky test, the reference IMU data was post-processed in differential mode in Inertial Explorer. The real-time single point KVH SPAN attitude solution was differenced with the reference attitude solution to give an indication of the KVH SPAN attitude errors. Because the KVH and reference IMUs could not be mounted precisely aligned, there was a mean difference between the attitude solutions due to the physical mounting differences.

Urban Canyon Test Procedure

In the second test, the van was driven through real obstructions, namely downtown Calgary. Both receivers were in single point mode. The real-time trajectory computed onboard the SPAN enabled OEMV3 (KVH) was logged at 10 Hz, in addition to the raw IMU data at 100 Hz for post-processing evaluation.

A base station was setup on the roof of the NovAtel building, approximately 10km from the test area in downtown Calgary. This base station data was used to post-process in differential mode.

Fig. 4 shows a plot of the route taken through downtown, overlaid on GoogleEarth imagery.

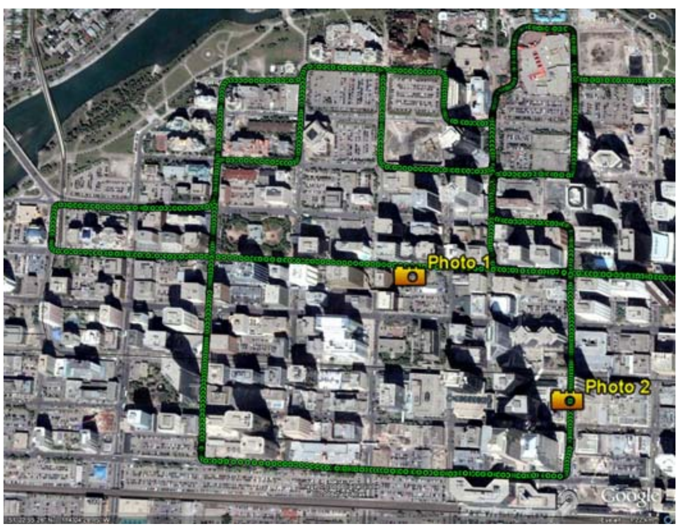

Fig. 4. Test Route Through Downtown Calgary

The small camera icons in Fig. 4 indicate the location that the photos shown in Fig. 5 and 6 were taken. As the photos illustrate, the test was undertaken in fully urban conditions, with severe multipath and obstructions.

Fig. 5. Photo 1 of Downtown Test Route

Normal driving behaviors were followed, only stopping as directed by traffic control signals. Vehicle speed varied from 0 – 50 km/hr. The duration of the test was just over 0.5 hr.

Fig. 6. Photo 2 of Downtown Test Route

TEST RESULTS

The results from the open sky test are presented first, followed by the downtown test.

Signal Reacquisition Test Results

The signal reacquisition performance of the SPAN enabled (KVH) receiver and the GPS only receiver is shown in Fig. 7.

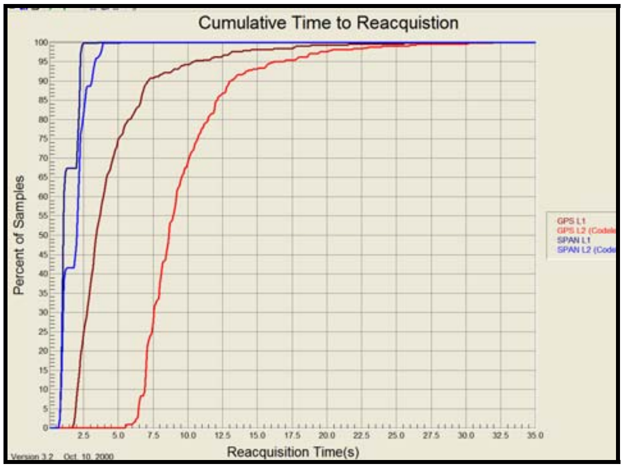

Fig. 7. Signal Reacquistion of SPAN Enabled Receiver (blue) and GPS Only Receiver (red)

Table 4 gives more detail about the reacquisition behavior of the SPAN enabled receiver and the GPS only receiver. For example, the 50% statistic for the SPAN L1 means that 50% of the time all the L1 signals were tracked by the SPAN enabled receiver in 1.1s or less. The statistics were computed over 50 signal blockages.

TABLE 4

REACQUSITION TIMES FOR L1 AND L2 (SECONDS)

Statistic	L1	SPAN L1	L1 % Reduction	L2	SPAN L2	L2 % Reduciton
Min.	1.7	0.7	59%	5.5	0.8	85%
Mean	4.5	1.4	69%	9.6	1.8	81%
Max.	26.5	3.6	69.%	31.5	5.1	83%
Std. Dev.	3.2	0.6	81%	3.6	0.8	78%
50%	3.5	1.1	69%	8.7	2.1	76%
68%	4.5	2.1	53%	10.0	2.2	78%
75%	5.1	2.1	59%	10.8	2.3	79%
80%	5.9	2.2	63%	11.5	2.5	78%
95%	10.6	2.3	78%	17.0	3.4	80%

The real-time single point KVH SPAN attitude solution was differenced with the reference solution.

TABLE 5

KVH SPAN ATTITUDE ERRORS WITH RESPECT TO REFERENCE SOLUTION

Statistic	Roll (deg)	Pitch (deg)	Heading (deg)
Mean	0.418	-0.234	-0.532
Std. Dev.	0.017	0.018	0.125

Note that the mean difference is likely caused by physical mounting differences between the KVH and reference IMUs. The IMUs were not aligned precisely during installation.

Downtown Test Results

There was a total of 2041s of the test in true downtown, urban canyon conditions. GPS data was logged at 1 Hz on both receivers. During the test, the SPAN enabled (KVH) receiver tracked and logged more signals than the GPS only receiver for 1005 s, providing access to additional signals during 49% of the test. Table 6 gives the cumulative lock time (over all PRNS tracked) for both receivers. Table 7 presents the total number of 1 Hz carrier phase measurements made by each receiver. Table 8 summarizes the updates applied to the INS filter during the test.

TABLE 6

CUMULATIVE LOCK TIMES (SECONDS)

Receiver	L1	L2
GPS Only	9643.98	8423.82
SPAN	10466.37	9427.26
% Improvement With SPAN	9%	12%

TABLE 7

TOTAL NUMBER OF 1HZ OBSERVATIONS (L1 AND L2 COMBINED)

Receiver	L1+L2
GPS Only	19521
SPAN	21790
% Improvement With SPAN	12%

TABLE 8

NUMBER OF INS FILTER UPDATES APPLIED (2041 TOTAL EPOCHS)

Position Update	1557
Delta Phase Update	1221
Only Delta Phase Update	251
Zero Velocity Update	288
No Update	210

Note that SPAN automatically detects and applies zero velocity updates. Also, SPAN will not perform an update while the vehicle is stationary; thus, the epochs where only a phase update was applied are epochs when this was the only type of update available. Also, not every available GPS position is used to update the INS filter. Only GPS positions that pass the quality checks are allowed to update the INS filter. Delta phase updates are also checked rigorously before they are allowed to update the filter, to avoid using a multipathed phase measurement as an update.

Fig. 8 shows the type and frequency of various updates to the INS filter.

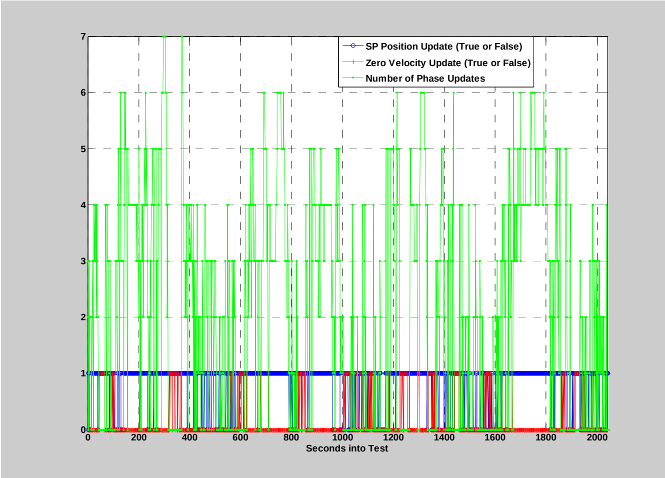

Fig. 8. Updates Applied during Downtown Test

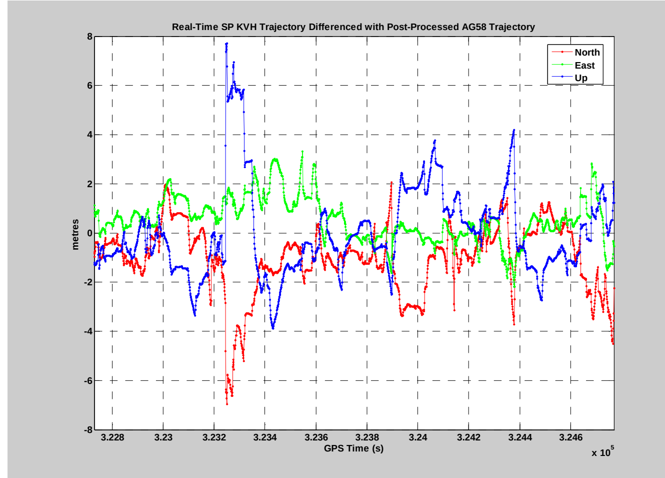

Fig. 10. Real-time Single Point KVH Positions Differenced with Inertial Explorer Post-processed AG58 Positions

The test route went through very challenging GPS conditions. Fig. 9. shows the GPS only trajectory with the real-time KVH GPS/INS trajectory. The GPS positions are quite erratic due to extreme multipath conditions and direct reflected signals.

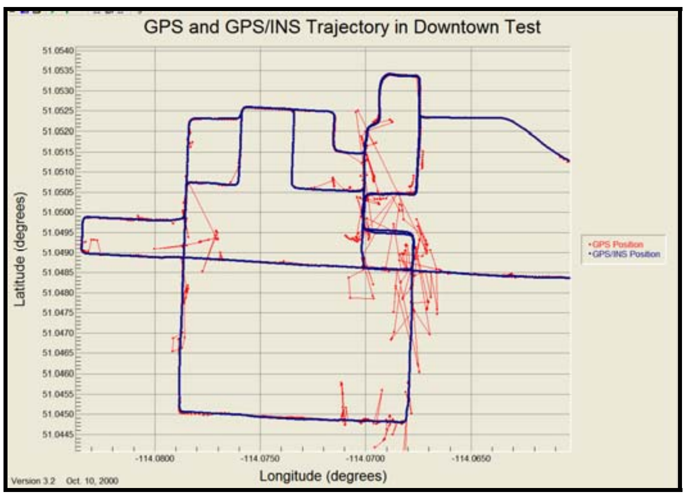

Fig. 9. GPS and KVH GPS/INS Real-time Trajectories During Downtown Test (Single Point Mode)

To evaluate the accuracy of the positioning solution, the KVH real-time single point trajectory was differenced with the reference trajectory post-processed in differential mode in Inertial Explorer. Fig.10 is a plot of those differences.

The statistics of the position differences shown in Fig. 10 are given in Table 9.

TABLE 9

DIFFERENCES BETWEEN REAL-TIME SINGLE POINT KVH POSITIONS AND POST-PROCESSED AG58 POSITIONS (METRES)

Statistic	East (m)	North (m)	Height (m)
Mean	0.55	-1.06	-0.01
Std. Dev.	0.90	1.39	1.81
RMS	1.06	1.75	1.81
RMS 2D	2.04		N/A
RMS 3D	2.73		

The post-processed reference solution is at least an order of magnitude better than the real-time single point solution. The post-processed reference was processed in differential mode, and the fixed interval smoother featured in Inertial Explorer was employed to optimally minimize the errors.

TABLE 10

QUALITY MEASURES FOR POST-PROCESSED REFERENCE POSITIONS

Statistic	East (m)	North (m)	Height (m)
Mean Reported Std. Dev.	0.087	0.099	0.163
Max. Reported Std. Dev.	0.427	0.444	0.388
RMS of Reported Std. Dev	0.129	0.146	0.132

Fig. 11 shows the errors in the real-time KVH solution with the error envelope given by 3 times the reported standard deviation.

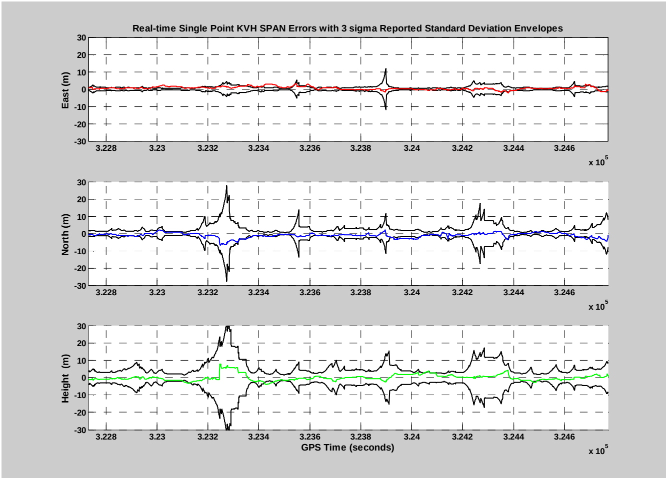

Fig. 11. Real-time KVH Position Errors with 3 sigma Error Envelope

DISCUSSION

As with the other IMUs compatible with SPAN technology, the KVH SPAN system provides excellent signal reacquisition performance. In 95% of the samples, the SPAN with KVH receiver was tracking all available L1 signals in just over 2 seconds, compared with nearly 11 s for the GPS only receiver. On the SPAN with KVH receiver, there is very little delay in reacquiring the L2 signal after L1 is reacquired. On average, the SPAN with KVH receiver reacquired all L2 signals within 0.4s of L1 recovery, while the GPS only receiver took 5.1s to acquire the L2 after L1. RTK ambiguity resolution can begin much faster with the SPAN receiver, since the L2 signals are available much faster. As a result, the SPAN system has many more high quality GPS measurements available to produce high quality fixed integer position solutions. This keeps the INS error to a minimum by keeping the GPS outages shorter.

Many GPS/INS systems may use an OEMV3 receiver to time stamp the IMU data. However, OEMV3 data plus IMU data is not the same as SPAN data. Due to the symbiotic nature of the SPAN tight/deep coupling, a SPAN enabled receiver can track substantially more GPS signals during conditions of intermittent blockages. With more GPS signals, the INS filter is more frequently updated, resulting in a much stronger navigation solution since free navigation periods are minimized. A commercial gradeIMU in a SPAN system can perform as well as a high quality IMU loosely coupled with a GPS receiver, because the GPS outages experienced by the SPAN system are much shorter.

Using delta phase updates are also another key feature of the SPAN system. Carrier phase measurements differenced over the current and previous epoch provide a very accurate measure of position displacement. This process is sometimes referred to as satellite odometry [3]. As long as 2 satellites remain in view, the SPAN filter has access to update measurements with just a few millimeters of variance. As shown in Fig. 5, the SPAN system in single point mode performs phase updates frequently, exploiting the high quality carrier phase measurements when only a pseudorange position is available.

Especially in high multipath environments, GPS based updates to the INS filter must pass quality checks to ensure that erroneous updates are not applied. The SPAN firmware on the OEMV3 automatically detects and rejects poor quality position and delta phase updates. The SPAN firmware also continuously monitors the IMU data to automatically detect moments of zero velocity, and applies zero velocity updates whenever possible. As reported in Table 8 there were only 210 s (of a total of 2041 s) when no update was available for the INS filter to use.

The attitude comparison of the real-time single point KVH solution to the post-processed reference solution gives a slightly pessimistic measure of the KVH errors. The post-processed reference solution is accurate to approximately 0.013 degrees in roll and pitch and 0.031 degrees in azimuth. The KVH attitude accuracy is therefore slightly under 0.018 degrees (~1 arcmin) in roll and pitch, and 0.125 degrees (7.5 arcmin) in azimuth.

The positional standard deviation reported by SPAN is an accurate portrayal of the accuracy achieved by the system. The post-processed reference solution is under 15cm RMS standard deviation in each direction, as reported by Inertial Explorer. Previous comparisons to an external reference has shown that the reported standard deviations that Inertial Explorer reports are realistic [4]. The difference between the real-time single point KVH solution and this reference solution can be considered the errors of the real-time single point KVH solution. As shown in Fig. 11, the actual errors fall within the bounds of a 3 sigma (or 95% confidence) envelope defined by the reported standard deviations.

The KVH-OEMV3 SPAN system is still undergoing development, with further refinements to the GPS/INS filter expected.

SUMMARY

The KVH-NovAtel single enclosure, deeply coupled GPS/INS system offers a robust real-time navigation solution. Post-processing with Inertial Explorer is available for the best accuracy solution possible, using the smoother.

As shown in the preliminary testing presented herein, the KVH-OEMV3 SPAN system offers remarkable signal tracking and reacquisition performance, resulting in many more GPS measurements available for use in the GPS/INS filter.

The KVH-OEMV3 SPAN system is a purely commercial system and as such falls under commercial export guidelines. Using only off-the-shelf technology, the KVH-OEMV3 SPAN system offers excellent performance at a reasonable price.

ACKNOWLEDGEMENTS

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