GPS/INS Integration with the iMAR-FSAS IMU

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SUMMARY

This paper discusses NovAtel's approach to GPS/INS system architecture and presents results from the Synchronized Position Attitude Navigation (SPAN) system. In addition to other IMU choices, the SPAN system integrates the iMAR-FSAS IMU, a German manufactured FOG based IMU, with high quality dual frequency GPS measurements. The performance of SPAN with the iMAR-FSAS will be discussed in herein. The iMAR-FSAS is equivalent to a tactical grade IMU, but it is designed for the civilian market and is subject to German export regulations. The majority of SPAN users utilize the system for mobile mapping applications, like Lidar mapping or aerial imaging.

The IMU integration is tightly coupled to the GNSS receiver core, with both the GNSS and inertial processing benefiting from the integration. The inertial processing provides a position, velocity, and attitude solution that is continuously available, even if GNSS signals are not. GNSS updates, in both the position and measurement domain, control the time dependent errors of the IMU. GNSS performance is improved with the integration of inertial measurements, allowing for faster signal reacquisition and faster return to a fixed integer carrier phase (RTK) solution after signal outage. SPAN provides a real-time solution computed on board the OEMV receiver, and a post-processed solution is also available using Waypoint's Inertial Explorer processing package from NovAtel's Waypoint Processing Group.

To demonstrate the performance of the integrated system incorporating the iMAR-FSAS IMU, results from testing in a land vehicle are presented. The test results show SPAN system performance with various levels of GPS aiding and with wheel sensor aiding during GPS outages. The benefits of a tightly integrated system will be demonstrated, along with the accuracy improvement gained with the addition of the wheel sensor. The navigation solution is also evaluated with respect to a navigation grade inertial navigation system to give an indication of absolute accuracy when GPS signals are fully available.

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1. INTRODUCTION

The Synchronized Position Attitude Navigation (SPAN) system is NovAtel's Global Navigation Satellite System – Inertial Navigation System (GNSS/INS) solution for applications requiring continuous position, velocity and attitude information. Using Inertial Measurement Unit (IMU) data in addition to GNSS, SPAN provides a high rate position, velocity and attitude solution which seamlessly bridges GNSS outages. The tight integration of the IMU to the receiver core improves GNSS performance by enabling faster signal reacquisition and quicker return to fixed integer status after a loss of GNSS signals.

While the real-time position, velocity and attitude solution is computed on-board the receiver, the solution and raw data can be simultaneously logged for post-processing. Post-processing of the GPS/INS data is performed by NovAtel 's Waypoint Inertial Explorer software package. Inertial Explorer builds on the high precision GNSS post-processor GrafNav. It is a loosely coupled integration of the GNSS and IMU data, and features a Rauch-Tung-Striebel (RTS) smoother (Gelb, 1974).

In this paper, the performance of the iMAR-FSAS integrated with SPAN is demonstrated. SPAN was introduced to the market with a Honeywell HG1700. As of fall 2006, SPAN now supports the iMAR FSAS and the Northrop Grumman LN200. The majority of SPAN users are involved in mobile mapping, either airborne applications like Lidar surveys or land applications like highway mapping. The iMAR-FSAS is manufactured in Germany, and is subject to German export regulations, making this IMU a very convenient choice for the European market. For land applications, the iMAR-FSAS offers an optional wheel sensor that is fully integrated into SPAN.

Data collected in a land vehicle is used to demonstrate the peformance of SPAN with the iMAR-FSAS. Analysis during periods of restricted GNSS availability shows how the growth of errors in the navigation solution can be limited by using carrier phase measuerments as updates to the inertial system, as well as with the wheel sensor. A Honeywell CIMU, a navigation grade IMU, was mounted in the test van in parallel to the iMAR-FSAS. The accuracy of the SPAN with iMAR-FSAS solution during full GNSS availability is assessed by comparison to the CIMU solution. A Honeywell HG1700 AG11 was onboard the test van as well, and the same comparison to the CIMU is performed to give an indication of iMAR-FSAS performance relative to it.

The benefits of phase and wheel updates in real-time are shown, as well as the impressive accuracy gains possible with the post-processed (RTS) smoother.

2. SPAN TECHNOLOGY

NovAtel's SPAN (Synchronized Position Attitude Navigation) Technology seamlessly integrates GNSS and inertial data for applications requiring greater functionality and reliability than traditional stand-alone GNSS can offer. With SPAN Technology, system integrators can build the system that meets their needs by starting with the NovAtel Propak-V3 receiver.

The OEMV-3 GNSS engine is a triple frequency board that includes L2C, GLONASS measurements and hardware support for the future L5 GPS frequency. It is a drop-in replacement for the OEM4-G2 with compatible commands and logs. The OEMV-3 has USB cability and an RS-422 or RS-232 interface. The ProPak-V3 also features integrated L-band corrections from geosynchronous satellites such as OmniSTAR and CDGPS. In addition the Propak-V3 features superior multipath mitigation, using PAC and Vision Correlator technologies.

The Propak-V3 is shown in Figure 1.

Figure 1 Propak-V3

Inertial data is added by choosing from one of four inertial measurement units

- the Honeywell HG1700 AG58, which has ring laser gyros (RLG) of approximately 1 degree/hour
- the Honeywell HG1700 AG62, which has RLGS of approximately 3-5 degree/hour
- the Northrop Grumman LN200, which has fiber optic gyros (FOG) of approximately 1 degree per/hour
- the iMAR-FSAS which has FOG of 0.75 degree/hour.

With SPAN Technology, integrating the GNSS receiver and inertial unit is simple. The IMU communicates with the receiver through one of the enclosure's standard serial ports. All system configuration is completed through the receiver's standard serial ports using simple commands and logs. The user can select what data is to be logged and enable various features. For example, the user can enter an IMU-GNSS antenna offset (the lever arm), or ask SPAN to solve for the lever arm on the fly. The result is a system that is operational within minutes of installation.

All navigation computations are done on board the receiver. The IMU data is integrated with the GNSS data and a continuous real time position, velocity and attitude solution is available to the user at up to 200 Hz. Raw data can be simultaneously logged for post processing. Post processing capability is provided by the Waypoint Inertial Explorer software package, which is described in the next section.

Building on the basic stand-alone mode with single point GNSS, more advanced positioning modes are offered for increased accuracy, including SBAS-corrected GNSS, Differential Global Positioning System (DGPS), and support for OmniSTAR and CDGPS correction services. For centimeter-level positioning accuracy, the real time kinematic RT-2® mode is available which requires corrections to be sent from a base via radio link. The SPAN filter uses GNSS position and velocity updates, and carrier phase updates are applied when insufficient satellites are available to provide a GNSS position. If available, wheel senor updates are also applied.

For added flexibility, the receiver can be operated independently to provide stand-alone GNSS positioning in conditions where GNSS alone is suitable. As a result, SPAN Technology provides a robust GNSS and inertial solution as well as a portable, high performance GNSS receiver in one system. The SPAN filter is considered tightly integrated, in that updates are applied in both the position or velocity domain, and the measurement domain with carrier phases. The GNSS and inertial filters are seperate but pass information between each other such that both the GNSS and the inertial solutions are improved. Figure 2 illustrates the general concept of SPAN's integration architecture. Other filter states beyond those shown may be utilized.

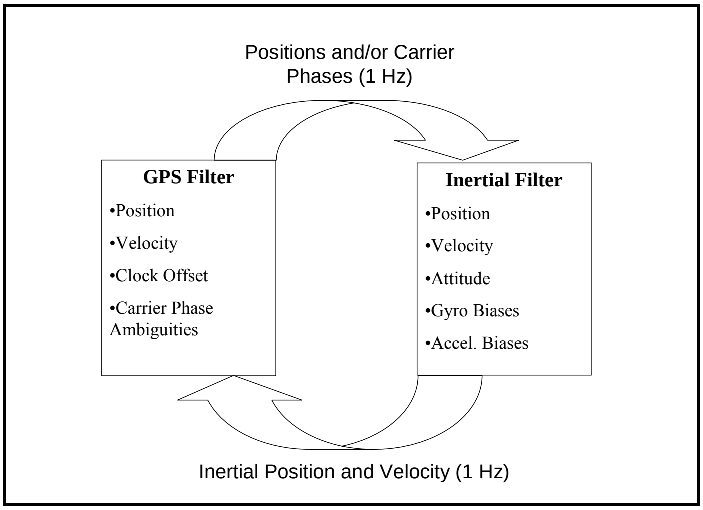


Figure 2 General Integration Architecture of SPAN

3. 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.

After the GNSS trajectory is created, Inertial Explorer processes the inertial data, implementing a loosely coupled integration that accepts wheel sensor updates as well. Rigorous quality control is applied to the GNSS positions before they are used to update the inertial processing. The GNSS and inertial processing share the same user interface. Plotting functionality is built in, with many analysis tools to help the user confirm the quality and accuracy of their results. For example, the user can plot GPS/INS misclosures or the separation between the forward and reverse solutions.

In the recent release of Inertial Explorer, an optimal fixed-interval smoother is implemented. A Rauch-Tung-Striebel (RTS) smoother is a standard tool in Inertial Explorer.

Waypoint GrafNav and Inertial Explorer are not limited to processing NovAtel data formats only. Waypoint software recognizes binary data from most GPS manufacturers. Provided the raw IMU data has been time tagged with GNSS time properly, Inertial Explorer can process delta velocity and delta theta measurements in the "generic IMU" data format defined. Users can define their own process noise values, allowing for custom filter tuning.

Inertial Explorer supports SPAN data, automatically recognizing the data format, and has predefined error models for IMUs integrated with SPAN.

4. iMAR-FSAS IMU

The iMAR-FSAS IMU has fiber optic gyros, and servo accelerometers. Its specifications are given in Table 1. When integrated with SPAN the raw IMU data is output at 200 Hz.

Table 1 iMAR-FSAS Specification

Gyro Rate Bias	0.75 deg/hr
Gyro Rate Scale Factor	300 ppm
Angular Random Walk	0.16 deg/√hr
Accelerometer Bias	1.0 mg
Accelerometer Linearity and Scale Factor	300 ppm
Velocity Random Walk	50 μG/√Hz

The iMAR-FSAS comes factory direct in a rugged enclosure with an external port for power supply, wheel sensor input, and data output. The iMAR-FSAS measures 128 x 128 x 104mm and is shown in Figure 3.

While the iMAR-FSAS specifications are similar to a tactical grade IMU, it has been designed for a civilian market. Additionally, it is manufactured in Germany and subject to

German export licensing. The delivery time for an iMAR-FSAS is generally much quicker than for other IMUs that are subject to export licensing from the US.

Figure 3 iMAR-FSAS IMU

4.1 Optional Magnetic Wheel Sensor

The iMAR-FSAS offers an optional magnetic wheel sensor. The wheel sensor consists of a magnetic strip with ticks every 25 mm, a sensor that reads the passing ticks, and small processor that converts the magnetic measurements into tick counts and velocity. The wheel sensor is integrated with the IMU, passing wheel velocity and tick count measures to the Propak-V3 to incorporate in the GNSS/INS processing. The wheel sensor is installed inside the vehicle's wheel rim. The user should calculate the number of ticks in the installed strip, and enter this parameter into their SPAN system. Any error in the number of ticks per wheel revolution entered, along with any changes in wheel circumference, will be absorbed by the wheel size scale factor in the SPAN filter.

5. TEST DESCRIPTION

The test vehicle was a mini-van. The data was collected on May 17, 2006 in Calgary, Alberta. An open sky trajectory was driven for approximately one and half hours, under normal driving conditions. The maximum vehicle speed was 110 km/hr and occasional stops were encountered due to traffic lights. The average base line length was 4 km. Figure 4 shows the trajectory of the test.

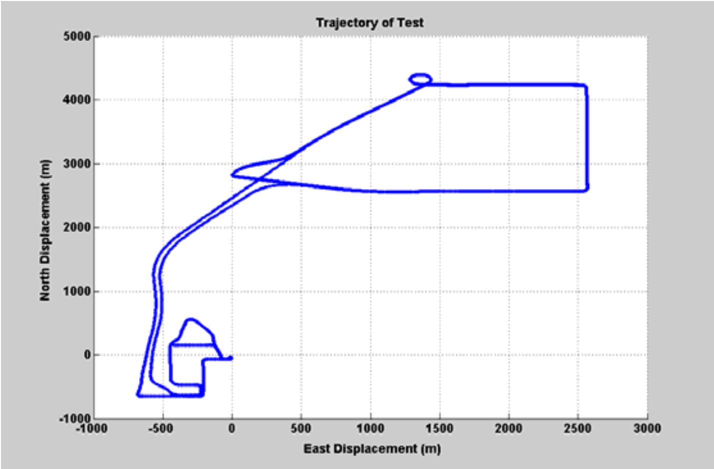


Figure 4 Test Trajectory

5.1 Equipment

The GNSS receiver under test was a NovAtel ProPak-V3. A GNSS-702 antenna was used for both the rover and the base station. The base station was set up on the roof of the NovAtel building. The iMAR FSAS was mounted in NovAtel's test van, with a lever arm of 0.31 m in the horizontal direction and 1.31 m in the vertical direction. The lever arm was surveyed using a total station and is known to within 1 cm. The magnetic wheel sensor described in the previous section was installed on the rear driver's side wheel of the test van.

In addition to the iMAR-FSAS, a Honeywell CIMU was installed in the van. The CIMU data was post-processed to provide a reference trajectory for evaluating the iMAR-FSAS performance. The specifications of the CIMU are shown in Table 2.

Table 2 CIMU Specifications

Gyro Rate Bias	0.0035 deg/hr
Gyro Rate Scale Factor	5 ppm
Angular Random Walk	0.0025 deg/√hr
Accelerometer Scale Factor	100 ppm
Accelerometer Bias	0.03 mg

A Honeywell HG1700 AG11 was also mounted in the test van. The SPAN with AG11 solution is compared to the CIMU solution as well, to give a comparison of the SPAN with AG11 and SPAN with iMAR systems under the same conditions. The SPAN with AG11 was also running on a Propak-V3 receiver. Table 3 shows the specifications of the HG1700 AG11 (now known as the AG58).

Table 3 Honeywell HG1700 AG11 (AG58) Specifications

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

5.2 Test Procedure

To show system performance with various levels aiding, controlled outages were inserted into the open sky test data. This processing was done offline; however, the algorithms used in the SPAN offline processing are implemented in the same way on board the receiver, and are exactly what would be used for the real-time solution.

The SPAN filter was allowed to converge before outages began. After the stationary alignment, there was approximately five minutes of vehicle motion before the first outage. No specific maneuvers were performed, just normal driving around the low-density commercial area surrounding NovAtel's building.

The controlled GPS outages were followed by 200 seconds of full GPS availability before the next outage was applied. A total of 36 outages were applied. Outages of 10, 30, 60 and 100 second duration were applied. The data was processed once using 10 second outages, and then again using 30, 60 and 100 second outages.

During the outages, various levels of aiding were allowed. When two or three satellites are available, a GNSS position cannot be computed without strict constraints. However, with a minimum of two satellites in view a carrier phase update can be applied. While not as powerful as a full position update, phase updates reduce inertial error growth significantly. In many urban canyon environments, 2 or 3 satellites may be available, resulting in one or two phase updates respectively. The benefit of this tight integration in SPAN is shown in the test results. The addition of the wheel sensor can also help to bridge periods of reduced GNSS availability.

Using an offline version of the SPAN firmware, the data was processed multiple times allowing the following updates: nothing for the duration of the outage, phase updates using 2 satellites, phase updates using 3 satellites, wheel sensor updates only, wheel sensor updates plus phase updates using 2 satellites, wheel sensor updates, plus phase updates using 3 satellites. The satellites selected for the phase updates are the satellites with the highest elevation to simulate real world conditions. In outages due to an urban canyon environment, or banked turns in an aircraft, the highest elevation satellites are the ones that remain available.

The same 36 GPS outages were applied in the Waypoint Inertial Explorer software. Currently, Inertial Explorer utilizes wheel sensor updates, but not phase updates. It features a RTS smoother which processes the data forwards and backwards, creating an optimal solution.

The errors in the navigation solution over the outages are assessed by comparing to the trajectory computed with full GPS availability. The errors given are the root mean square (RMS) of the maximum differnce between the outage trajectory and the fully available GNSS trajectory over the duration of the outage.

For a measure of the accuracy of the SPAN system when GNSS signals are fully available, the SPAN solution was compared to the CIMU solution, which was a post-processed, smoothed solution. The CIMU is a navigation grade IMU, with specification two orders of magnitude better than the iMAR-FSAS and the AG11; therefore, any difference between the two navigation solutions is likely due to errors in SPAN IMUs. The comparison is done after the filter has converged and indicates "steady state" performance. Since it is very difficult to mount two IMUs perfectly in parallel, the CIMU solution was mathematically rotated to align to the body frame of the IMU under evaluation. The rotation angles between the CIMU and the second IMU were estimated by the mean difference in roll, pitch and heading throughout the test, and then used to rotate the CIMU solution and the comparison repeated.

6. TEST RESULTS

Tables 4 through 6 summarize the error growth in position, velocity and attitude, respectively, over all the outage periods when no wheel sensor updates were applied.

Table 4 SPAN with iMAR-FSAS Position Errors Over GNSS Outages Without Wheel Sensor Updates (m)

Aiding Level	GNSS Outage Length							
	10 s		30 s		60 s		100 s	
	2D	H	2D	H	2D	H	2D	H
0 Phase No Wheel	0.150	0.042	0.745	0.153	2.780	0.383	7.849	0.734
1 Phase No Wheel	0.147	0.042	0.670	0.153	2.297	0.380	6.018	0.722
2 Phase No Wheel	0.139	0.041	0.542	0.153	1.513	0.361	3.403	0.720

Table 5 SPAN with iMAR-FSAS Velocity Errors Over GNSS Outages Without Wheel Sensor Updates (m/s)

Aiding Level	GNSS Outage Length							
	10 s		30 s		60 s		100 s	
	2D	H	2D	H	2D	H	2D	H
0 Phase No Wheel	0.019	0.003	0.044	0.007	0.110	0.011	0.188	0.013
1 Phase No Wheel	0.018	0.003	0.041	0.007	0.092	0.011	0.142	0.013
2 Phase No Wheel	0.018	0.003	0.033	0.007	0.065	0.011	0.082	0.012

Table 6 SPAN with iMAR-FSAS Attitude Errors Over GNSS Outages Without Wheel Sensor Updates (degs)

Aiding Level	GNSS Outage Length											
	10 s			30 s			60 s			100 s		
	Pitch	Roll	Yaw	Pitch	Roll	Yaw	Pitch	Roll	Yaw	Pitch	Roll	Yaw
0 Phase No Wheel	0.005	0.006	0.012	0.009	0.007	0.019	0.012	0.011	0.035	0.012	0.013	0.043
1 Phase No Wheel	0.005	0.006	0.012	0.008	0.007	0.018	0.011	0.009	0.034	0.010	0.010	0.040
2 Phase No Wheel	0.005	0.006	0.012	0.007	0.006	0.016	0.008	0.007	0.032	0.009	0.008	0.038

Tables 7 though 9 summarize the error growth in position, velocity and attitude, respectively, over all 36 of the outage periods, this time applying the wheel sensor updates.

Table 7 SPAN with iMAR-FSAS Position Errors Over GNSS Outages With Wheel Sensor Updates (m)

Aiding Level	GNSS Outage Length							
	10 s		30 s		60 s		100 s	
	2D	H	2D	H	2D	H	2D	H
0 Phase With Wheel	0.144	0.042	0.754	0.154	2.58	0.393	6.783	0.734
1 Phase With Wheel	0.142	0.042	0.713	0.153	2.275	0.380	3.458	0.722
2 Phase With Wheel	0.140	0.042	0.577	0.153	1.570	0.360	2.945	0.720
Smoothed With Wheel	0.014	0.003	0.027	0.006	0.201	0.032	0.363	0.047

Table 8 SPAN with iMAR-FSAS Velocity Errors Over GNSS Outages With Wheel Sensor Updates (m/s)

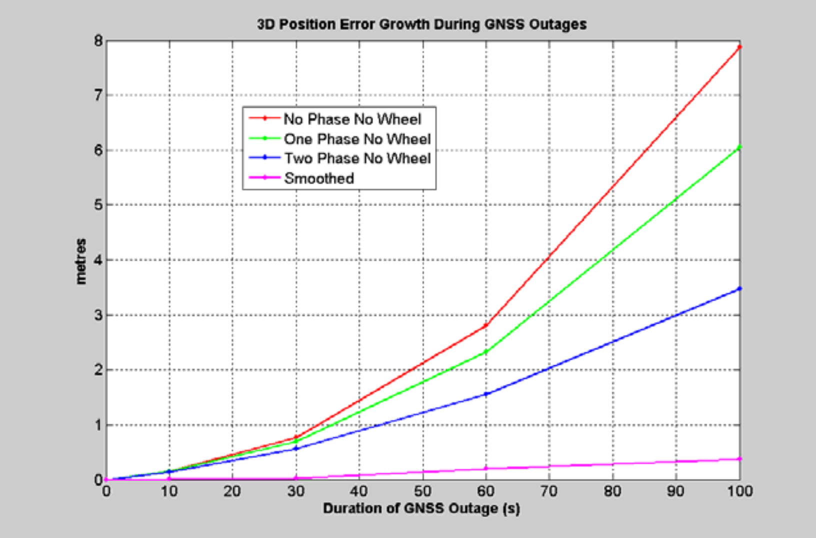
Aiding Level	GNSS Outage Length							
	10 s		30 s		60 s		100 s	
	2D	H	2D	H	2D	H	2D	H
0 Phase No Wheel	0.018	0.003	0.047	0.007	0.105	0.012	0.162	0.014
1 Phase No Wheel	0.018	0.003	0.044	0.007	0.093	0.012	0.082	0.012
2 Phase No Wheel	0.017	0.003	0.036	0.007	0.065	0.012	0.066	0.012
Smoothed With Wheel	0.002	0.000	0.002	0.000	0.005	0.001	0.008	0.001

Table 9 SPAN with iMAR-FSAS Attitude Errors Over GNSS Outages With Wheel Sensor Updates (degs)

Aiding Level	GNSS Outage Length											
	10 s			30 s			60 s			100 s		
	Pitch	Roll	Yaw	Pitch	Roll	Yaw	Pitch	Roll	Yaw	Pitch	Roll	Yaw
0 Phase With Wheel	0.005	0.006	0.012	0.0010	0.007	0.018	0.012	0.010	0.036	0.013	0.010	0.043
1 Phase With Wheel	0.005	0.006	0.011	0.009	0.008	0.017	0.010	0.009	0.033	0.009	0.008	0.038
2 Phase With Wheel	0.005	0.006	0.011	0.008	0.007	0.016	0.006	0.008	0.031	0.009	0.007	0.036
Smoothed With Wheel	0.002	0.001	0.003	0.002	0.001	0.004	0.004	0.004	0.009	0.009	0.005	0.009

To clearly illustrate the effect of the phase updates on the position error growth, the data from table 4 is plotted in figure 5. The smoothed trajectory is included as well, to emphasize the accuracy gains possible with Inertial Explorer's RTS smoother.

Figure 5 Position Error Growth Over GNSS Outages



For an indication of the steady state performance of the SPAN with iMAR-FSAS, the SPAN solution was compared to a post-processed trajectory estimated with the CIMU data. The same comparison was done with another SPAN integrated with a HG1700 AG11. Table 10 gives the differences between the iMAR-FSAS and AG11 solutions and the CIMU solution.

Table 10 RMS Errors of SPAN with iMAR-FSAS and SPAN with AG11

		iMAR-FSAS	**HG1700 AG11**
Position Difference RMS (m)	North	0.038	0.030
	East	0.034	0.037
	Height	0.033	0.030
Velocity Difference RMS (m/s)	North	0.007	0.005
	East	0.008	0.006
	Height	0.005	0.007
Attitude Difference RMS (degrees)	Roll	0.011	0.011
	Pitch	0.014	0.012
	Yaw	0.038	0.031

7. DISCUSSION

7.1 Phase Updates and Wheel Sensor Aiding

The GNSS outage testing shows the error growth in position, velocity, and attitude when GNSS positions are not available for updating the SPAN filter. Time differenced carrier phase measurements are used as updates as well. As shown in figure 5, the phase updates are very powerful in controlling the error growth between position updates. The tight integration allows for full exploitation of all information available in the GNSS signals, and improves the GNSS signal tracking and RTK performance. The phase updates keep the variance of the inertial solution low, which provides valuable information to guide the signal tracking loops and to help define the carrier phase ambiguity search space.

The phase updates are available to any platform, airborne or land, and do not require any additional equipment installation.

If using a land vehicle, wheel sensor updates can be used to aid the SPAN filter. In the testing presented here, the wheel sensor did not improve the navigation solution until the outage periods were 60 to 100 seconds in length. The wheel sensor updates are modeled as a position displacement, thusly showing the most improvement in the position domain. The wheel sensor resolution is 25 mm. The GNSS positioning mode was RTK for this test, which is the most accurate form of GNSS positioning. The baseline was approximately 4 km on average, yielding rover positions of centimeter level accuracy. The SPAN filter did not allow the wheel sensor updates to significantly contribute until the position variance became larger than that of the variance on the wheel sensor updates.

If a lower quality GNSS positioning mode had been used, like single point or differential pseudorange positioning, the wheel sensor updates would have had a much larger effect over shorter GNSS outages. Conversely, if the wheel sensor was of a higher resolution, like an optical encoder with millimeter level resolution, it also would have had a larger effect during shorter outages, as shown in (Kennedy et al, 2006). The iMAR magnetic wheel sensor also provides a wheel velocity measurement which is a more precise measurement than the tick counts, due to the way it is computed. If the wheel sensor update was modelled in the velocity domain, the more precise velocity measurement would be a stronger aid during GNSS outages than the difference in tick counts.

7.2 Steady State Performance

The comparison of the SPAN with iMAR-FSAS solution to the CIMU navigation solution gives a more absolute measure of the accuracy achieved. The CIMU data was post-processed, using a GNSS trajectory that combined forward and backward passes through the data. The SPAN results used the RTK solution computed onboard the Propak-V3. Since both the CIMU and the SPAN filters were being updated with GNSS positions at 1 Hz, the differences between the two trajectories in the position and velocity domain are dominated by the differences in GNSS positions used, and the noise level of the GNSS positions.

The attitude is not as closely tied to the GNSS solution used. The comparison in the attitude domain shows the error of the SPAN with iMAR attitude, or in other terms, it shows the typical accuracy a user could expect from the SPAN with iMAR during good GNSS availability and moderate dynamics. The SPAN with iMAR roll and pitch error are both under 1 arc minute, while the yaw error was 2.3 arc minutes. This attitude performance is equivalent to what the Honeywell AG58 supplies (NovAtel, 2005), and meets the needs of many mobile mapping applications.

8. SUMMARY

In summary, NovAtel Inc. is pleased to introduce another IMU choice with the SPAN system. The SPAN system is a tightly integrated solution for applications requiring continuous position, velocity and attitude information. Testing has shown the iMAR-FSAS can provide performance similar to that of the Honeywell HG1700 AG11/AG58. The iMAR-FSAS is an attractive IMU option for the European market, as it is German manufactured and subject to German export regulations.

9. ACKNOWLEDGMENTS

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