Architecture and System Performance of SPAN -NovAtel's GPS/INS Solution

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ABSTRACT

As a GPS receiver manufacturer, NovAtel is in a unique position to build a GPS/INS navigation system. The Synchronized Position Attitude Navigation (SPAN) system is based on OEM4 receiver technology combined with an Inertial Measurement Unit (IMU). The IMU integration is tightly coupled with access to the GPS receiver core. The integrated system provides real time position, velocity and attitude. GPS outages can be seamlessly bridged, enabling more reliable navigation through challenging environments like urban canyons. Additionally, GPS performance is improved with the integration of inertial measurements, allowing for faster signal reacquisition and faster return to a fixed integer carrier phase solution after signal outage. The real time solution is computed on board the receiver and raw data can be simultaneously logged for post-processing. Post processing is performed by NovAtel's Waypoint Inertial Explorer package.

This paper discusses NovAtel's approach to INS/GPS system architecture. To demonstrate the performance of the SPAN system, data will be collected under real world conditions in a land vehicle. Test results will show system performance with various levels of GPS aiding and with wheel sensor aiding. The real time solution will be compared to the post-processed solution. Methods to deal with the constraints of real time will be discussed. The accuracy benefits of a post-processed solution will be demonstrated as well.

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, that 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, which features a RTS smoother.

In this paper, the performance of SPAN and Inertial Explorer is demonstrated using two datasets collected in NovAtel's test van.

The first dataset was collected in full availability GNSS conditions and the van was outfitted with a wheel sensor. Controlled outages were imposed in the GNSS data. Throughout the GNSS outages, position updates were not allowed but carrier phase updates and wheel sensor updates were. The errors over the outages were compared to determine how well aiding with carrier phase measurements and wheel sensor information can limit inertial error growth. The level of real-time errors with the various levels of aiding are also compared to the post-processed smoothed solution provided by Inertial Explorer.

The second dataset was collected in downtown Calgary. With its dense high rise buildings, Calgary's downtown is a very challenging environment with restricted GNSS availability and plenty of multipath. SPAN's performance is compared to a reference trajectory computed with navigation grade IMU data by Inertial Explorer.

Test results are discussed with a view toward operational performance. The benefits of phase and wheel updates in real-time are shown, as well as the impressive accuracy gains possible with the post-processed Rauch-Tung-Striebel (RTS) smoother.

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 first selecting one of three NovAtel GNSS receivers, each housing the OEM4-G2 engine:

- ProPak-G2*plus*, with USB capability and an RS-232 or RS-422 interface
- DL-4*plus*, with built-in memory card for data collection and integrated LCD and keypad for on-the-fly configuration
- ProPak-LB*plus*, featuring support for OmniSTAR and CDGPS correction data

Photos of each of the *plus* enclosures are shown below.

Fig. 1. ***plus*** **Enclosures**

Inertial data is added by choosing from one of two inertial measurement units, provided in NovAtel's IMU-G2 enclosure:

- IMU-G2$_{H58}$, containing Honeywell's HG1700 AG58 inertial measurement unit (IMU) which has Ring Laser Gyros (RLG) of approximately 1^{o}/hr.
- IMU-G2$_{H62}$, housing Honeywell's HG1700 AG62 IMU which has RLGs of approximately 10^{o}/hr.

The IMU-G2 enclosure is shown below.

Figure 2. IMU-G2 Enclosure

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. In the case of the DL-4*plus* and ProPak-G2*plus*, the IMU-G2 is powered directly from the receiver's power output. As a result, only a single cable is required from the receiver to the IMU to satisfy both communication and power requirements. For the ProPak-LB*plus*, a special cable has been designed to supply both the receiver and the IMU from a single power source.

Fig. 3 shows the SPAN setup with a DL-4*plus* and a base station.

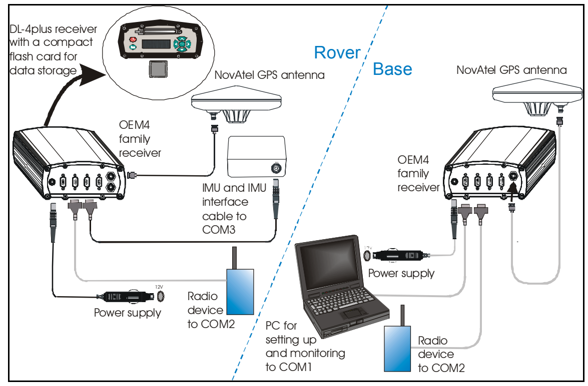

Fig. 3. SPAN Setup

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 100 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. Logged IMU data is time stamped with GNSS time. The DL-4*plus* and Propak models log data through a serial port to another device, like a laptop computer. With the DL-4*plus*, raw data can also be logged to the built in memory card.

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.

The optimized GNSS/INS integration results in faster satellite reacquisition and RTK solution convergence. Testing has shown L1 GPS signal reacquisition is dramatically improved when running SPAN.

Fig.4. shows the cumulative histogram of L1 signal reacquisition when testing a GNSS-only OEM4-G2 receiver against an OEM4-G2 receiver running SPAN. With SPAN running, 95% of L1 GPS signals are reacquired in just over 1

second after signal obstruction ends, compared to approximately 11 seconds without SPAN.

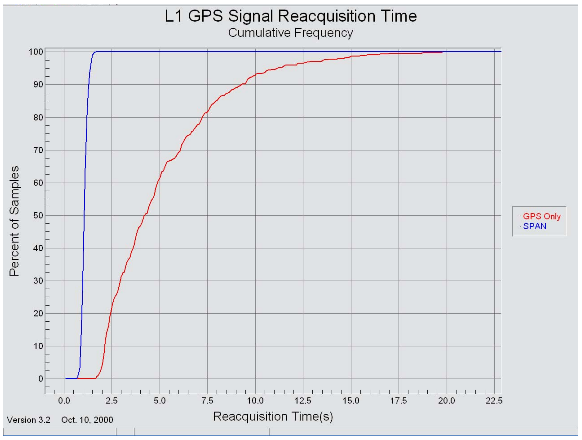

Fig. 4. L1 Signal Reacquisition Histogram

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.

Since the system is based on NovAtel's standard GNSS receivers rather than custom components, integrators can easily add inertial capability to their systems after their initial receiver purchase. Existing IMU-capable receivers can be enabled to support an IMU through a quick firmware upgrade in the field. Combined with the availability of multiple receiver models and accuracy levels, this ensures that SPAN Technology can adapt and evolve as positioning requirements change.

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. 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 upcoming release of Inertial Explorer, an optimal fixed-interval smoother is implemented. A Rauch-Tung-Striebel (RTS) smoother will be a standard tool in Inertial Explorer [1]. The Inertial Explorer results presented in this paper were obtained using a beta version of the next software release, tentatively scheduled for June 2006.

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 a predefined error model for SPAN users.

TEST DESCRIPTON

To demonstrate the performance of SPAN and Inertial Explorer, data was collected under real world conditions. Two tests were performed.

The first test collected data under good GNSS availability conditions. This "open sky" dataset is used to show the effect of various levels of aiding over controlled GNSS outages. During the open sky data set, the test vehicle was equipped with a wheel sensor.

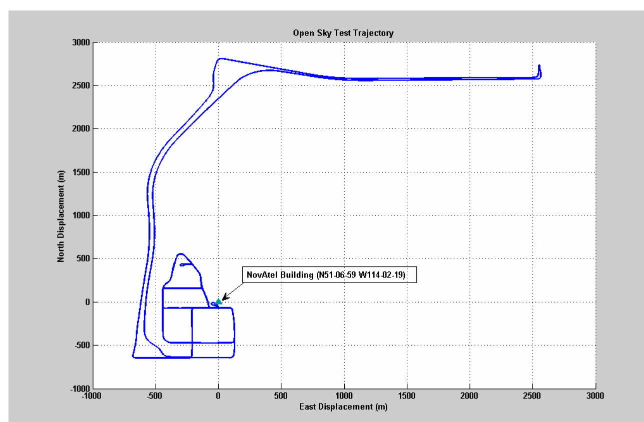

Fig. 5. Open Sky Test Trajectory

The second test collected data in a challenging GNSS environment – downtown Calgary which provides extreme urban canyon situations with very restricted GPS availability. The test van was driven around the streets of downtown Calgary for approximately one hour. A navigation grade IMU was employed to provide a reference trajectory. Fig.6 is a photograph taken on the test route.

Fig.6 . Section of the Downtown Test Route

Equipment

The test setup was similar for both tests. The SPAN system was installed in a minivan. The GNSS antenna, GNSS receiver and IMU were mounted in a van and data was logged from the receiver's serial ports to a laptop PC for storage and processing. The vector between the IMU centre and GPS antenna was accurately surveyed using a total station and is considered known to within 1 cm. A base station was set up to provide DGPS and RTK corrections.

GNSS Receivers and Antenna

The GNSS receiver under test was a NovAtel ProPak-G2, containing the OEM4-G2 engine. 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 average baseline length was less than 10 km for both tests.

Inertial Measurement Units

The IMU under test was a Honeywell HG1700 AG11, which is a 1 degree/hour tactical grade IMU. (The HG1700 1 degree/hour unit is currently referred to as an AG58 but this unit is an AG11.) An AG11 was used in both the open sky and the downtown tests. The specifications for an AG11/AG58 are given in Table 1.

TABLE 1
HG1700 AG11 SPECIFICATIONS

Gyro Rate Bias	1.0 deg/hr
Gyro Rate Scale Factor	150 ppm
Angular Random Walk	0.125 deg/√hr
Accelerometer Range	± 50 g
Accelerometer Linearity	500 ppm
Accelerometer Scale Factor	300 ppm
Accelerometer Bias	1.0 mg

In the second test conducted in downtown Calgary, a Honeywell CIMU was also installed in the van. The CIMU data was post-processed using Waypoint's Inertial Explorer package. This served as a reference trajectory to compare the real-time SPAN solution using the AG11. The specifications for a CIMU are given 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 Range	± 30 g
Accelerometer Scale Factor	100 ppm
Accelerometer Bias	0.03 mg

Wheel Sensor

For the "open sky" test, an optical encoder wheel sensor was mounted on the rear driver's side wheel of the van. Intermediary processing was performed to sum up the tick counts and provide that cumulative sum to the OEM4-G2 receiver at 1Hz. The wheel sensor has a resolution of 2000 ticks per revolution, with the wheel circumference on the test van being about 2.0 m.

When wheel sensor data is available, a wheel scale factor state is added to the SPAN filter. The wheel scale factor allows for changes in the wheel size during the test.

Open Sky 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 30 outages were applied. Outages of 10, 30 and 60 second duration were applied. The data was processed once using 10 second outages, and then again using 30 and 60 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 also helps 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 same 30 GPS outages were applied in the Waypoint Inertial Explorer software. Inertial Explorer utilizes wheel sensor updates, but not phase updates. It does feature 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.

Urban Canyon Test Procedure

To demonstrate SPAN's real-time performance under very challenging GNSS conditions, the test van was driven through downtown Calgary with a Honeywell CIMU mounted in parallel. The CIMU data was post-processed using Inertial Explorer which used the RTS smoother. The wheel sensor was not used in this test.

The real-time SPAN with the AG11 IMU trajectory is differenced with the CIMU post-processed smoothed trajectory. These differences are considered the error of the real-time SPAN solution.

TEST RESULTS

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

Open Sky Data with Controlled Outage Test Results

The errors of the position, velocity and attitude solution over the outages are given in Tables 3 through 10. The errors given are the root mean square (RMS) of maximum error over the duration of the outage. The difference between the outage trajectory and the trajectory estimated with all available GPS signals is considered the error.

For the real-time results, the maximum error occurs at the end of the outage. For the post-processed smoothed results, the maximum error occurs around the middle of the outage. To illustrate this, Fig.7 is an example of a 60 second GNSS outage taken from the open sky data set.

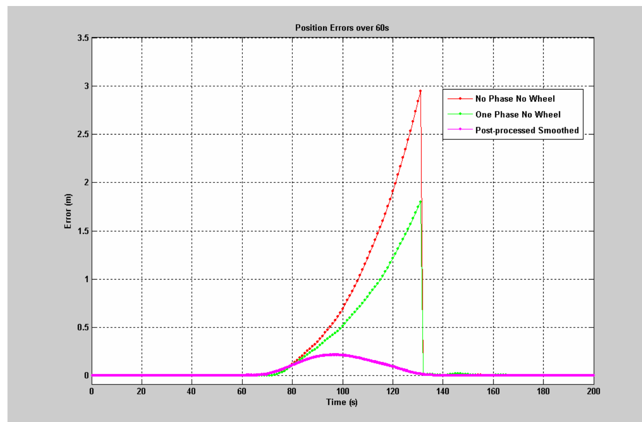

Fig.7. 3D Position Error Over 60s, Outage #1

The values presented in Tables 3 through 10 are the root mean square of the maximum error over all 30 outage periods. The horizontal error is labeled as 2D in the tables. The vertical error is labeled as H.

Table 3 shows the errors in position when the wheel sensor updates are not applied.

TABLE 3
POSITION ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (m)

Aiding Level	Outage Length					
	10 s		30 s		60s	
	2D	H	2D	H	2D	H
No Phase No Wheel	0.12	0.06	0.70	0.18	3.09	0.48
1 Phase No Wheel	0.11	0.06	0.53	0.17	1.96	0.41
2 Phase No Wheel	0.10	0.06	0.43	0.15	0.96	0.33
Smoothed	0.01	0.01	0.05	0.02	0.27	0.12

Table 4 follows from Table 3, showing the velocity errors over the outages when the wheel sensor data is not applied.

TABLE 4
VELOCITY ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (m/s)

Aiding Level	Outage Length					
	10 s		30 s		60s	
	2D	H	2D	H	2D	H
No Phase No Wheel	0.016	0.003	0.044	0.007	0.128	0.015
1 Phase No Wheel	0.014	0.003	0.033	0.007	0.082	0.013
2 Phase No Wheel	0.014	0.003	0.027	0.006	0.043	0.011
Smoothed	0.001	0.000	0.002	0.001	0.003	0.002

Table 5 gives the roll and pitch errors over the outages, again without any wheel sensor aiding.

TABLE 5
ROLL AND PITCH ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (degs)

Aiding Level	Outage Length					
	10 s		30 s		60s	
	Roll	Pitch	Roll	Pitch	Roll	Pitch
No Phase No Wheel	0.004	0.005	0.008	0.007	0.014	0.015
1 Phase No Wheel	0.004	0.004	0.006	0.005	0.009	0.012
2 Phase No Wheel	0.004	0.004	0.006	0.005	0.006	0.009
Smoothed	0.002	0.002	0.004	0.004	0.007	0.008

Finally, Table 6 summarizes the heading errors without wheel sensor updates being applied during the outages.

TABLE 6
HEADING ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (degs)

Aiding Level	Outage Length		
	10 s	30 s	60s
	Heading	Heading	Heading
No Phase No Wheel	0.007	0.013	0.027
1 Phase No Wheel	0.006	0.013	0.026
2 Phase No Wheel	0.006	0.012	0.025
Smoothed	0.003	0.008	0.016

Tables 7 through 10 show the errors when the wheel sensor updates are applied. They compare directly to Tables 3 through 6, and illustrate the impact of adding a wheel sensor update during the GNSS outages.

Table 7 shows the horizontal and height errors over the outages when wheel updates are applied.

TABLE 7
POSITION ERRORS OVER GPS OUTAGES
WITH WHEEL SENSOR UPDATES (m)

Aiding Level	Outage Length					
	10 s		30 s		60s	
	2D	H	2D	H	2D	H
No Phase With Wheel	0.11	0.06	0.56	0.18	1.45	0.48
1 Phase With Wheel	0.10	0.06	0.31	0.17	0.67	0.39
2 Phase With Wheel	0.10	0.06	0.25	0.15	0.47	0.29

Velocity errors with wheels sensor updates applied are given in Table 8.

TABLE 8
VELOCITY ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (m/s)

Aiding Level	Outage Length					
	10 s		30 s		60s	
	2D	H	2D	H	2D	H
No Phase With Wheel	0.015	0.003	0.035	0.007	0.067	0.014
1 Phase With Wheel	0.014	0.003	0.021	0.007	0.037	0.012
2 Phase With Wheel	0.013	0.003	0.017	0.006	0.024	0.010

Table 9 gives the roll and pitch errors during the outages when wheel sensor aiding is used, followed by Table 10 which contains the heading errors.

TABLE 9
ROLL AND PITCH ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (degs)

Aiding Level	Outage Length					
	10 s		30 s		60s	
	Roll	Pitch	Roll	Pitch	Roll	Pitch
No Phase With Wheel	0.004	0.005	0.006	0.006	0.008	0.011
1 Phase With Wheel	0.004	0.004	0.005	0.004	0.005	0.009
2 Phase With Wheel	0.004	0.004	0.004	0.004	0.005	0.007

TABLE 10
HEADING ERRORS OVER GPS OUTAGES
WITHOUT WHEEL SENSOR UPDATES (degs

Aiding Level	Outage Length		
	10 s	30 s	60s
	Heading	Heading	Heading
No Phase With Wheel	0.007	0.013	0.027
1 Phase With Wheel	0.006	0.012	0.024
2 Phase With Wheel	0.006	0.012	0.024

Fig.8, 9, and 10 graphically show the data from Tables 3 through 6, which is the error growth over GNSS outages without wheel sensor aiding. For ease of comparison, Fig. 11, 12 and 13 show the data from Tables 7 through 10, which is the error growth over GNSS outages with wheel sensor aiding. The scale of the figures is the same.

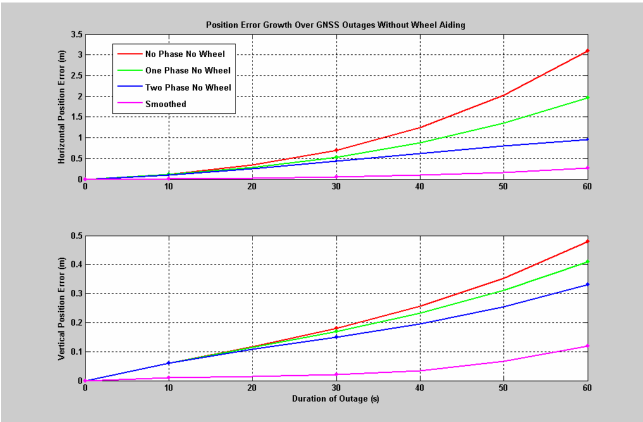

Fig. 8. Position Error Growth Over GNSS Outages without Wheel Sensor Aiding

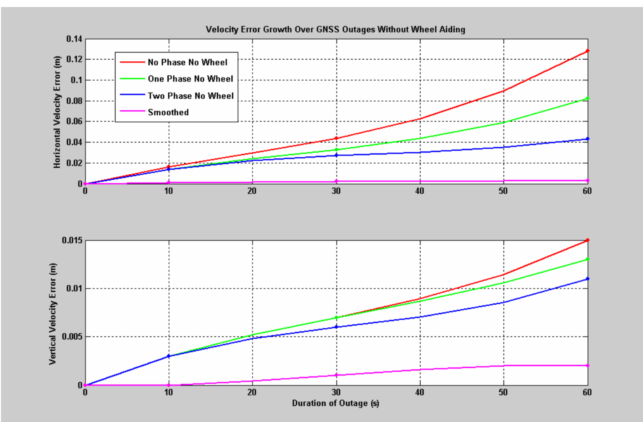

Fig. 9. Velocity Error Growth Over GNSS Outages without Wheel Sensor Aiding

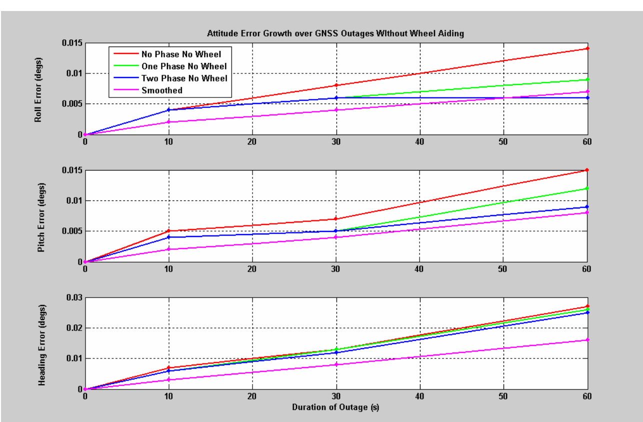

Fig. 10. Attitude Error Growth Over GNSS Outages without Wheel Sensor Aiding

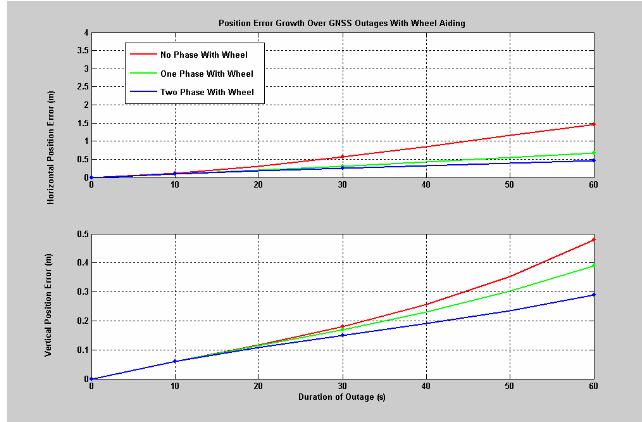

Fig. 11. Position Error Growth Over GNSS Outages with Wheel Sensor Aiding

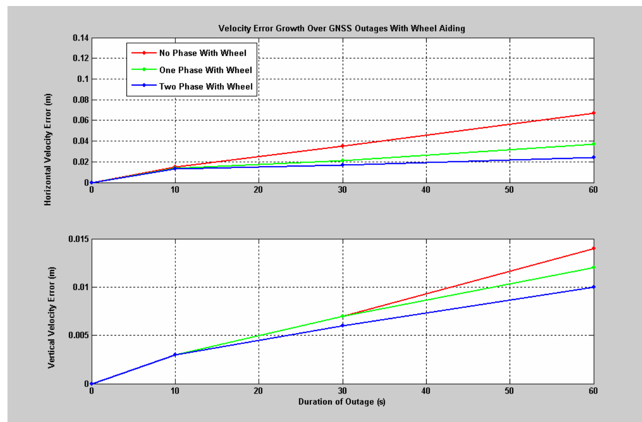

Fig.12. Velocity Error Growth Over GNSS Outages with Wheel Sensor Aiding

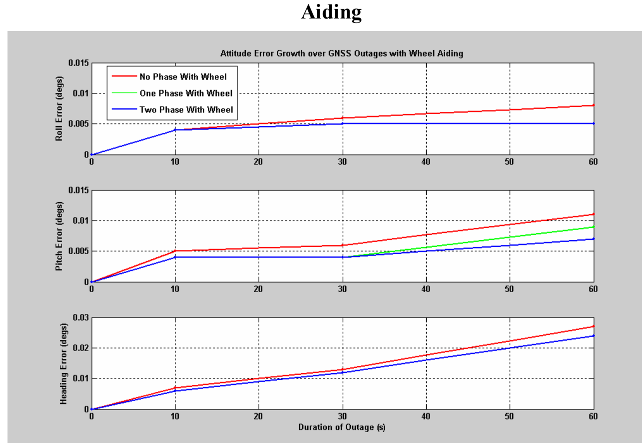

Figure 13 Attitude Error Growth Over GNSS Outages with Wheel Sensor Aiding

In Fig.13., note that the "one phase with wheel" line is not missing from the roll and heading plots. It is merely covered up by the "two phase with wheel" line. The values are the same to three decimal places, rounded.

Downtown Test Results

The route driven through downtown Calgary presented a very challenging GPS environment. Satellite visibility was severely restricted and multipath levels were high. In these conditions, GPS only navigation is nearly impossible. Fig. 14 shows an overlay of the SPAN trajectory over top of the GPS only trajectory. Many of these GPS epochs were flagged as integrity errors by the OEM4-G2. Note that the GPS trajectory does not capture the route along some of the east-west streets shown in the central area of Fig.14.

SPAN does an excellent job of rejecting the erroneous GPS positions and bridging GPS outages, maintaining a reliable trajectory. The loop through the central part of downtown was driven repeatedly to be able to assess consistency, and to accumulate a sufficient amount of test time.

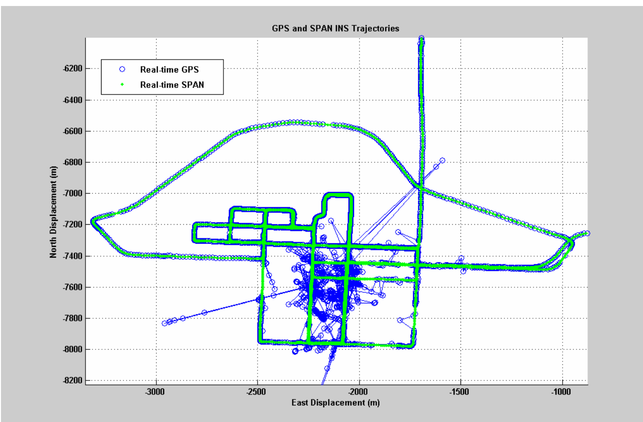

Fig. 14. GPS Only and SPAN Trajectory During the Downtown Test

During the test, the SPAN position, velocity and attitude solution was available 100% of the time. In the portion of the test that was in the heart of downtown, differential pseudorange positions were unavailable 47% of the time, while RTK positions were unavailable 95% of the time. RTK is not possible due to the few number of satellite available and poor signal quality from the high multipath environment.

The average time between pseudorange positions was approximately 15 seconds, with a maximum outage time of 75 seconds. Although 15 seconds does not seem like a very long outage, there was very little recovery time between outages. After a 15 second outage, there was often only one epoch with a pseudorange position before there was another outage of several seconds duration. Also, many of the pseudorange positions were poor quality and would not be strong update measurements or could be rejected entirely if they fail the quality control checks.

The RMS errors of the real-time SPAN with AG11 solution with respect to the post-processed smoothed CIMU solution are shown in Table 11.

TABLE 11
RMS REAL-TIME SPAN AG11 ERROS IN DOWNTOWN CALGARY

Position Error (m RMS)	**North**	0.59
	East	0.31
	Height	0.72
Velocity Error (m/s RMS)	**North**	0.014
	East	0.013
	Up	0.010
Attitude Error (deg RMS)	**Roll**	0.020
	Pitch	0.016
	Azimuth	0.072

Table 12 gives the maximum deviation of the real-time SPAN solution from the smoothed CIMU solution.

TABLE 12
MAXIMUM REAL-TIME SPAN AG11 ERRORS IN DOWNTOWN CALGARY

Position Error (m)	**North**	4.23
	East	1.91
	Height	2.80
Velocity Error (m/s)	**North**	0.162
	East	0.140
	Up	0.126
Attitude Error (deg)	**Roll**	0.122
	Pitch	0.140
	Azimuth	0.377

DISCUSSION

In real-time all aiding sources must be exploited to limited inertial error growth during GNSS outages. Reviewing Figs. 8 and 11, it is apparent how effective the phase updates are. Over the 60 seconds outages, a single phase update (computed from carrier phase measurements to two satellites) reduces the horizontal position by 37% from 3.09 m to 1.96m. With three available satellites and two phase updates applied, the 60 second error growth is limited even further to only 0.96m in the horizontal direction. For a real-time user with three satellites in view, an error of 0.96m is much easier to tolerate than one of 3.09m which is what would be expected from a loosely coupled real-time implementation.

The addition of the wheel sensor controls errors during the outages even more. Over the 60 second outages, aiding with the wheel sensor and no phase updates reduces the horizontal error by 55%, compared to the error resulting with no aiding during the outage. Thus, the wheel sensor offers even more error control than a single phase update, but this is not an "either or" situation. The wheel sensor update combined with phase updates provides the filter with strong geometry to constrain the error growth. Applying one phase update along with the wheel sensor updates leads to an RMS error of only 0.67m over the 60 second outages.

The wheel sensor is a beneficial addition to the system; however, it is another piece of hardware that must be installed and maintained. Wheels sensors are also only of use to land vehicles. The phase updates offer impressive error reduction and can be applied to any vehicle. The tight integration of SPAN is key to achieving a reliable trajectory in real-time.

All the information available from the GNSS signals is leveraged, and in turn the improved inertial solution helps the GNSS signal tracking.

In the Inertial Explorer post-processing, a loosely coupled integration is employed. While the errors in a loosely coupled integration will grow larger in the forward direction, the backwards pass through the data that performs the smoothing reduces the error significantly. Over 60 second outages, the RMS horizontal position error of the smoothed trajectory is 0.27m. This is 40% of the error of the real-time solution that used phase updates from three satellites and wheel sensor updates. For any application that allows post-processing, the smoother provides an excellent solution.

The downtown test demonstrated how well SPAN can withstand GNSS outages and poor quality GNSS positions. The RMS position error is less than one metre, in each direction and in three dimensions. If the maximum northing, easting and height errors occurred at the same instant, the maximum three dimensional position error would have been 5.4 m. Having an error of only 5.4 m is much better than having no position at all if the user was relying on GNSS only. In many areas of the downtown test, there were no GNSS positions available for extended periods. Note the east-west streets evident in Fig. 14 from the SPAN trajectory that are not existent in GNSS only trajectory.

Some areas of the downtown test route did afford reasonable GNSS conditions. The errors in the inertial solution are time dependent. As time increases from the last high quality GNSS position update, the inertial errors will grow, making it more difficult to reject bad GNSS positions or maintain a reliable trajectory. For good performance in restricted GNSS conditions, SPAN must have sufficient time for alignment and for the filter to converge. This can be achieved in five to ten minutes of motion in full availability GNSS conditions.

SUMMARY

In summary, SPAN and Inertial Explorer provide a complete GPS/INS solution.

In real-time, the tightly integrated approach controls errors much better than a loosely coupled approach, as demonstrated by the error growth over GNSS outages when different levels of aiding were applied. Phase updates are often readily available, even in restricted GNSS environments, and they represent a maximal exploitation of information from GNSS. The addition of a wheel sensor allows a further reduction in error. For post-processed applications, Inertial Explorer's RTS smoother provides a high accuracy solution, optimally combining forward and reverse processing.

SPAN's real-time navigation solution, raw data logging and improved GNSS performance, along with the high accuracy post-processing software from Inertial Explorer is NovAtel's complete GPS/INS toolbox.

REFERENCES

[1] A. Gelb, *Applied Optimal Estimation*. Cambridge, MA: The M.I.T. Press, 1974.