Integration of Inertial Measurements with GNSS
-NovAtel SPAN Architecture-

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ABSTRACT

As a GNSS system manufacturer, NovAtel is in a unique position to integrate external sensors such as inertial measurement units (IMU) in order to extend and enhance the usefulness of satellite navigation systems. For operational situations where navigation by GNSS only is either degraded or impossible, augmentation through the use of external sensors provides users with the required position and attitude solution accuracy and reliability.

Several companies have integrated GNSS with IMU data to generate a combined solution in the past. However, with the SPAN Technology developed by NovAtel, the combination of GNSS + INS is unique because the system is based on the NovAtel OEM4 GNSS technology for a GNSS centric design. Rather than considering the IMU to be aided by GNSS, the GNSS is enhanced by the IMU. By exploiting the company's GNSS system expertise, the integration of inertial measurements is done with a much tighter coupling because of access to the GNSS receiver core. Through the tight coupling of the inertial data with GNSS core functionality such as satellite tracking, RTK carrier phase positioning, and clock modeling, the system provides a full 3-dimensional position, velocity and attitude solution with virtually continuous availability.

This paper will discuss NovAtel's approach to INS/GNSS system architecture. Currently, the SPAN system supports two tactical grade IMUs: the Honeywell HG1700 AG58 and AG62. Recently work has been undertaken to evaluate the iMAR iIMU-FSAS within the SPAN system. The iIMU-FSAS is a tactical grade IMU as well, manufactured in Germany and subject to German export licensing. Results of the initial evaluation of the iIMU-FSAS integration are presented herein.

Tests were completed to assess the position, velocity, and attitude accuracy. Data was collected under clear GNSS conditions and controlled GNSS outages were applied. Errors after 10, 30 and 60 second GNSS outages are presented.

SPAN TECHNOLOGY OVERVIEW

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:

- 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
- ProPak-G2*plus*, with USB capability and an RS-232 or RS-422 interface

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

Figure 1 - *plus* Enclosures

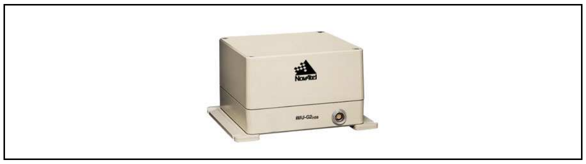
DL-4*plus* ProPak-LB*plus* ProPak-G2*plus*

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.

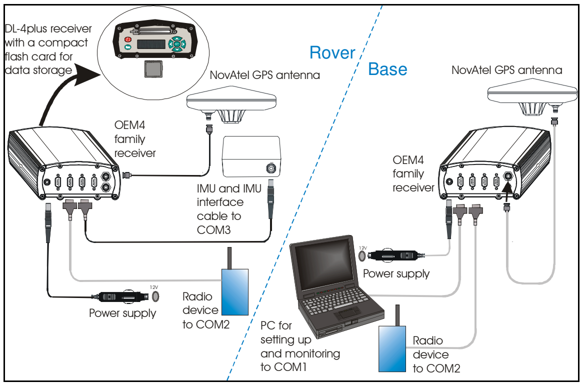
Figure 2 – IMU-G2 Enclosure



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.

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

Figure 3 - SPAN Setup



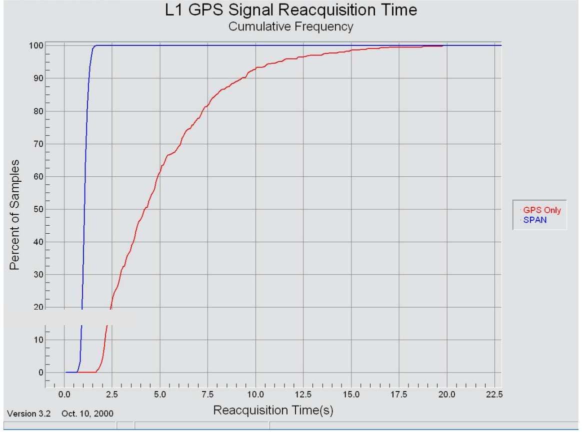
All system configuration is completed through the receiver's standard serial ports using simple commands and logs. The user can select what data is to be logged and enable various features. For example, the user can enter an IMU-GNSS antenna offset (the lever arm), or ask SPAN to solve for the lever 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. 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, 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 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 the 95th percentile of L1 GPS signal reacquisition is dramatically improved when running SPAN. Figure 4 shows the cumulative histogram of L1 signal reacquisition when testing a GNSS-only OEM4-G2 receiver against an OEM4-G2 receiver running SPAN.

Figure 2 - 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.

To meet the needs of applications requiring different grades of inertial performance, NovAtel continues to add popular IMU choices to its SPAN Technology product line as well.

Various IMUs are evaluated for suitability to customer's needs and integration into the SPAN system. Recently, the iMAR iIMU-FSAS has been experimented with. While it is also a tactical grade IMU like the currently available HG1700, it is easier and quicker for customers outside of North America to obtain, due to its German manufacturer.

iMAR iIMU-FSAS

The iIMU-FSAS is a tactical grade IMU, featuring fiber optic gyros (FOG) and servo accelerometers. It is manufactured in Germany, thus being subject to German export regulations. Its specifications are given in Table 1.

Table 1 – iIMU-FSAS Specifications

Gyro Input Range	± 560 deg/s
Gyro Rate Bias	0.75 deg/hr
Gyro Rate Scale Factor	<300 ppm
Angular Random Walk	0.16 deg/hr
Accelerometer Range	± 5 g
Accel Linearity/Scale Factor	<300ppm
Accelerometer Bias	1.0 mg

The specifications for the HG1700 AG58 are given in Table 2, and are quite similar to the iIMU-FSAS.

Table 2 - HG1700 AG58 Specifications

Gyro Input Range	± 1000 deg/s
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

Given the similarity between the two IMUs, the iIMU-FSAS could be a suitable alternative for the HG1700 AG58.

Some interface modifications were required to integrate the iIMU-FSAS into the SPAN system. Extra processing steps and hardware were required to be able to interface between the IMU and the receiver; however, the processing flow remains unchanged from a standard SPAN system. This ad-hoc system was sufficient to preliminarily evaluate the performance of the iIMU-FSAS.

The iIMU-FSAS enclosure is shown in Figure 5. It's dimensions are 116 by 128 by 98 mm and it weights approximately 1700 grams.

Figure 5 – iIMU-FSAS Enclosure

The iIMU-FSAS provides data at an output rate of up to 500 Hz and can be synchronized to an external clock. Full power conditioning (10-34 V DC, < 16 W) is used, and the iIMU-FSAS is designed to operate in harsh environments. The unit is currently used in many applications such as: airborne surveying and stabilization (i.e. LIDAR), pipeline surveying, automotive testing and vehicle dynamics analysis, AUV (autonomous underwater vehicle) guidance, helicopter glide path, and stabilization on naval vessels. Compared to the HG1700 the iIMU-FSAS shows a more than times 20 longer lifetime (HG1700 has 500 hrs operational time warranted). For more information see www.imar-navigation.de.

TESTING OVERVIEW

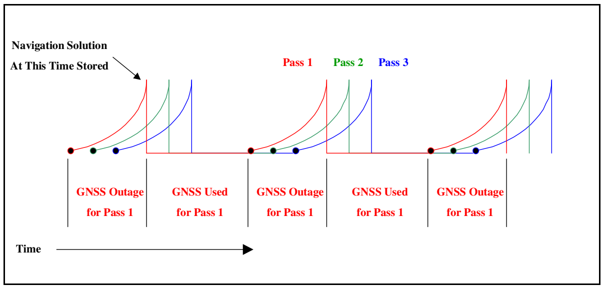
The goal of the testing was to evaluate the performance of SPAN with the iIMU-FSAS as the IMU choice. Performance with the HG1700 AG58 is documented in "SPAN Technology Performance during GNSS Outages", available at www.novatel.com.

A higher quality IMU was not available to serve as a control system to compare the iIMU-FSAS results to. Therefore, the navigation solution after controlled GNSS outages was compared to the navigation solution obtained with full GNSS availability to evaluate the performance. The outage lengths were chosen to be 10, 30 and 60 seconds.

The way the outages are applied is somewhat novel, and warrants a thorough explanation. To begin, a data set is collected under good GNSS conditions, meaning high availability of signals with few obstructions. The GNSS outages are applied in post processing. (Note that the algorithms used in the post processing are implemented in the same way on board the receiver and are exactly what would be used for the real time solution.)

Once the navigation filter has reached steady state, which is usually a few minutes after motion has been initiated, the outages are applied. No GNSS updates are allowed to the filter for the length of the outage, and then a recovery period of 200 seconds is applied where GNSS updates are allowed, followed by another outage with no GNSS updates. This process is repeated until the end of the dataset is reached. The data is processed in this manner repeatedly, with the initial outage progressing forward by one epoch on each pass. The navigation solution is stored at the end of each outage for each pass through the data. This method of testing is referred to as "sweep testing". Figure 6 below shows the method graphically.

Figure 6 - Sweep Testing Methodology



It is a computationally intensive method. For 60 second outages with 200 second recovery periods, the data set will be processed 260 times, resulting in an outage ending at every epoch of the data set after the initial start of the outages. By calculating the outage results for every part of the data set, error growth under different dynamics (such as traveling in a straight line, turning, stopping) is included in the performance evaluation.

The sweep results are compared to the navigation solution computed with full GNSS availability. The RMS of the difference between the two solutions is computed, and represents the average expected error after an outage of the length used in the sweep testing.

A test van was driven in the vicinity of NovAtel's office in Calgary, Alberta, Canada. Favorable GNSS conditions were insured by driving a route along open highways and areas with low buildings only. Satellite availability was good, with only brief interruptions from driving under highway overpasses.

EQUIPMENT

Testing was completed using NovAtel GNSS receivers and an iMAR iIMU-FSAS. The GNSS antenna, GNSS receiver and IMU were mounted in a van and data was logged from the receiver’s serial ports to a PC for storage and processing. A base station was set up to collect DGPS and RTK corrections.

GNSS Receiver and Antenna

The GNSS receiver under test was a NovAtel ProPak-G2, containing the OEM4-G2 engine. A GNSS-702 antenna was used. The antenna to IMU offset was measured to within 5 centimeter. There were no fiducial marks on the iIMU-FSAS enclosure, so the lever arm was measured to the center of the iIMU-FSAS.

Inertial Measurement Unit

The iIMU-FSAS is a tactical-grade, fiber optic gyro based IMU manufactured by iMAR. Specifications are given in Table 1. The IMU was mounted to the roof rack of the van, within 0.6 m of the GNSS antenna.

Base Station Receiver and Antenna

To provide DGPS and RTK corrections, a ProPak-G2 receiver was set up on the roof of the NovAtel building with a GNSS-702 antenna. The average baseline length between the test van and the base station during the testing was approximately 6 km.

Software

Results shown are for data generated using the INS Results shown were generated using the algorithms that run in real-time on board SPAN’s OEM4-G2 receiver. For the controlled GNSS outage sweep testing described previously, the data was processed offline. The offline software contains the same algorithms used by the firmware on board the receiver.

TEST RESULTS

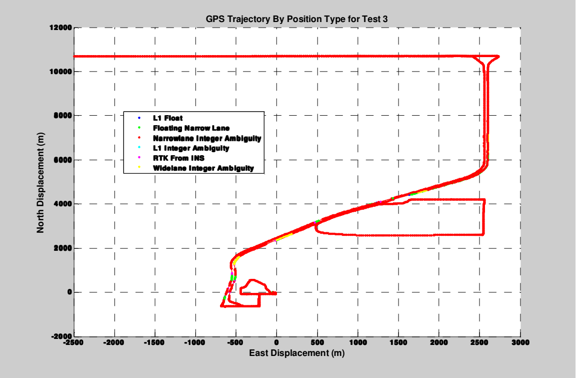
Three datasets were collected. Table 3 summarizes the test data.

Table 3 -Data Sets Collected

Test	Date Collected	Duration
1	August 22, 2005	49 mins
2	September 9,2005	80 mins
3	September 14, 2005	76 mins

A similar route was driven for each dataset. Figure 6 below shows the trajectory of the third test, which is representative of all three tests. Multiple laps of this route were made. Note that Figure 7 is color coded by GPS position type. The majority of GPS positions were computed with narrowlane fixed integer ambiguities.

Figure 7 - GPS Trajectory for Test 3



Lever Arm Estimation

The SPAN filter allows the user to estimate the lever arm if it has not or cannot be measured. In this case, the lever arm was measured by tape measure to the center of the iIMU-FSAS enclosure. Since both the antenna and the IMU were on the roof rack of the test van, measuring by tape measure was an easy option.

To see how well the lever arm could be estimated with the SPAN filter, no lever arm was entered and the filter was asked to solve for one. The results of the lever arm estimation are given in Table 4 below.

Table 4 - Lever Arm Estimates

	x (m)	y (m)	z (m)	Solved in
Test 1 Est.	0.57	0.01	0.19	822 sec
Test 2 Est.	0.59	-0.03	0.21	393 sec
Test 3 Est.	0.56	-0.02	0.18	718 sec
Measured	0.60	0.0	0.14	N/A

No special maneuvers were performed in any of the tests. The vertical component of the lever arm (z) is the least observable since motion in the vertical direction is quite minimal in a van. The lever arm estimate will converge faster with more changes in velocity. Driving an "s" pattern or "figure-eights" will aid the estimation of the horizontal components of the lever arm.

Outage Testing

The outage testing was performed with outages of 10, 30 and 60 seconds. Tables 4 through 6 give the results of the sweep testing for each data set.

Table 4 – Test 1 Solution Error Over GNSS Outages – RTK Mode

		Outage Length		
		10 s	**30 s**	**60 s**
Position Error (m RMS)	**Lat**	0.096	0.662	2.761
	Long	0.105	0.760	3.427
	Height	0.023	0.104	0.307
Velocity Error (m/s RMS)	**East**	0.015	0.045	0.105
	North	0.016	0.053	0.136
	Up	0.002	0.006	0.010
Attitude Error (deg RMS)	**Roll**	0.008	0.014	0.020
	Pitch	0.006	0.010	0.015
	Azimuth	0.009	0.018	0.028

Table 5 – Test 2 Solution Error Over GNSS Outages – RTK Mode

		Outage Length		
		10 s	**30 s**	**60 s**
Position Error (m RMS)	**Lat**	0.116	0.748	2.522
	Long	0.139	0.854	2.920
	Height	0.051	0.134	0.373
Velocity Error (m/s RMS)	**East**	0.018	0.051	0.097
	North	0.021	0.056	0.104
	Up	0.003	0.007	0.011
Attitude Error (deg RMS)	**Roll**	0.008	0.012	0.012
	Pitch	0.009	0.014	0.017
	Azimuth	0.009	0.020	0.030

Table 6 – Test 3 Solution Error Over GNSS Outages – RTK Mode

		Outage Length		
		10 s	**30 s**	**60 s**
Position Error (m RMS)	**Lat**	0.097	0.623	2.551
	Long	0.096	0.659	2.631
	Height	0.028	0.100	0.294
Velocity Error (m/s RMS)	**East**	0.014	0.041	0.095
	North	0.014	0.044	0.098
	Up	0.002	0.005	0.009
Attitude Error (deg RMS)	**Roll**	0.006	0.010	0.013
	Pitch	0.006	0.010	0.014
	Azimuth	0.009	0.020	0.034

Graphically, the error growth over time for position velocity and attitude are represented in Figures 8 to 10.

Figure 8 - Position Error Growth During Complete GNSS Outages

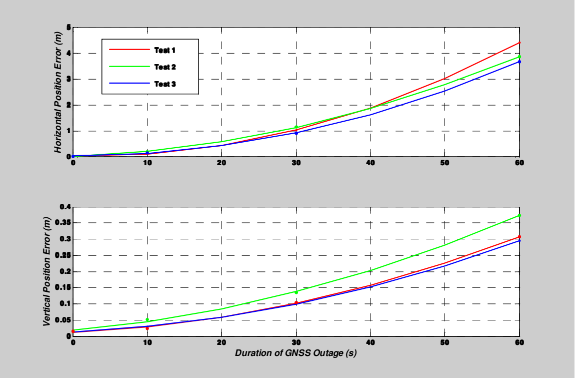


Figure 9 - Velocity Error Growth During Complete GNSS Outages

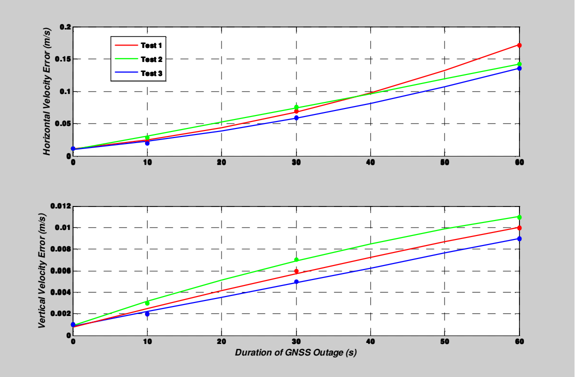
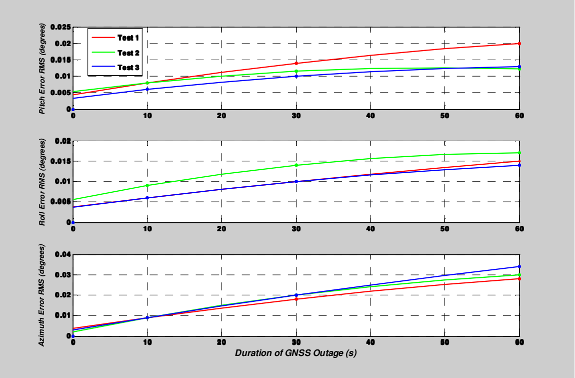


Figure 10 - Attitude Error Growth During Complete GNSS Outages



DISCUSSION

These initial results with the iIMU-FSAS are quite promising. The preliminary testing presented herein was the first attempt at integrating this IMU. The

SPAN filter was not tuned for the iIMU-FSAS. The process noise values developed for the HG1700 AG11 were used for the iIMU-FSAS. Reviewing the specifications given for each IMU in Tables 1 and 2, it is apparent that they are very similar units. However, the HG1700 uses RLGs and the iIMU-FSAS using FOGs. These two types of gyros could have different noise characteristics, as they measure angular rates by different methods. The angular random walk of the iIMU-FSAS gyros is also higher than that of the HG1700's. On the other hand, the HG1700 shows significant mechanical vibration due to the dithering of the internal ring laser gyros while the iIMU-FSAS offers silent operation without any mechanical induced noise on the inertial sensors. Also, the angular resolution of the iIMU-FSAS is 20 times higher than those of the HG1700. It is expected that improvements in the iIMU-FSAS results could be achieved with filter tuning.

Additionally, improvements in how the iIMU-FSAS interfaces with the receiver can be made. An ad-hoc system was used to request and receive IMU data through the receiver. It was a temporary setup for the purpose of doing an initial evaluation. Data latency issues may be present, which would lessen the overall performance of the iIMU-FSAS.

SUMMARY

The addition of inertial functionality to a GNSS system results in improved data availability and reliable operation in conditions where GNSS alone is inadequate. During times of insufficient satellite visibility, SPAN Technology is able to continue providing position, velocity, and attitude data. GNSS performance is enhanced, with faster reacquisition times and faster return to fixed integer mode after signal loss.

The SPAN system is based on standard NovAtel GNSS receivers that are enabled to incorporate an IMU as an external sensor. All navigation computations are done on board the receiver, and raw data can be simultaneously logged for post processing as well. Currently, the HG1700 AG58 and AG62 are the commercially available IMU choices with SPAN. NovAtel continues to evaluate other IMUs for potential inclusion as supported IMU types.

The iMAR iIMU-FSAS was successfully tested within the SPAN architecture. This was a first attempt at integrating the iIMU-FSAS. Even without any specific filter tuning, three dimensional position error is just over 1 meter after 30 seconds without any GNSS. Performance improvements are expected with adaptation of the process noise values, and an improved interface between the IMU and the receiver. The iIMU-FSAS has the potential to be an ideal alternative to the HG1700 AG11, especially in markets outside North America and in applications where a long lifetime is required.

Particularly for very high accuracy applications, iMAR's ring laser gyro based INS iNAV-RQH with an angular random walk of 0.0018 deg(sqrt(hr) will be integrated into the SPAN architecture for evaluation.