Marine Performance of NovAtel SPAN GNSS/INS Systems

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Abstract

NovAtel Inc. offers a high quality, tightly coupled GNSS/INS solution and has done so for nearly a decade through the SPAN® (Synchronized Position Attitude Navigation) product line. Historically, the SPAN GNSS/INS products have used traditional tactical grade IMUs, typically using FOG (Fiber Optic Gyro) or RLG (Ring Laser Gyro) technology. Recently, large strides have been made with MEMS (Microelectricalmechanical Systems) IMUs that have begun to make them viable for navigation purposes. They are very attractive devices due to their greatly reduced size, weight, and cost.

As the navigation technology is changing rapidly, so is the hydrographic survey market. IMUs are becoming smaller and more cost effective and so too are the multibeam sensors. Where just recently, all hydrographic survey vessels were equipped with expensive equipment, these new innovations allow for a more economical approach and lower threshold to entry. This technology is particularly attractive in shallow waters, where overall motion accuracy requirements are lower, and which account for a large part of the hydrographic market.

This paper explores the question of whether these technologies have developed to the point where shallow water surveys can be completed with smaller, simpler, and more economical sensor suites. In an attempt to answer this question, the performance of the SPAN solution operating in a shallow inland waterway survey will be presented.

Introduction

NovAtel SPAN is a tightly-coupled GNSS/INS system that pairs NovAtel GNSS receiver technology with a wide range of augmentation sensor options. SPAN was originally established utilizing high grade Inertial Measurement Units (IMU) built with Fibre Optic Gyroscope (FOG) or Ring Laser Gyroscope (RLG) technology. New developments in MEMS technology have enabled the use of smaller and less expensive sensor options while still providing high grade accuracy. However, low dynamic marine applications remain the challenge to real world performance of MEMS sensors, as it is more difficult to observe inertial errors in these environments. For this reason, the inertial filtering method plays a key role in the quality of the final solution. This paper presents a comparative analysis between SPAN and a competitor system both using tactical grade IMUs in a marine survey environment. It also explores the feasibility of using MEMS sensors for shallow water survey applications by comparing the performance of a MEMS IMU to a tactical grade FOG IMU using SPAN as the GNSS/INS engine.

When the GNSS solution is combined with IMU data, the absolute accuracy of the position and velocity from the GNSS solution compensates for errors in inertial measurements that accumulate over time. During instances when the GNSS solution is degraded or unavailable, as can be the case during inland hydrographic surveys, the stable relative position from the INS is used. The quality of the final processed bathymetric product relies heavily on the system's ability to mitigate position and attitude errors during real time data collection. Low dynamics and potential GNSS outages or blockages during a traditional inland survey present a challenge when estimating inertial errors. Therefore, it is important to investigate the impact that different grade sensors can have when considering system performance.

To establish a more robust understanding of sensor performance, this paper examines the real-time and post-processed implementation of a SPAN system with a tactical grade FOG IMU alongside a competitor system in a hydrographic survey test. These results will then be used to evaluate a second use case comparing a tactical grade IMU against a MEMS IMU in a marine environment. Navigation data in conjunction with bathymetry will be used to produce an analysis specific to the use of SPAN in hydrographic applications.

Test Area

Tests were conducted over the course of three days (November 12-14, 2013) along the Patuxent River near Solomons, Maryland aboard the NOAA R/V Bay Hydro II (Figure 1). The survey area encompasses a wide variety of bottoms and shoals that are ideal for carrying out a patch test. This allows for a very detailed analysis of the data. During these surveys, raw data was collected from each system to be able to adequately compare the SPAN solution with results produced by a competitor system. The November 14th dataset will be used for analysis.

Figure 1: NOAA R/V Bay Hydro II

Figure 2: SEAHORSE Geomatics Training and Development Vessel

Data from two additional inland surveys conducted three months prior in Portland, Oregon along the Columbia River will be used to evaluate the performance of a MEMS IMU using SPAN in a survey environment. These surveys were performed using the SEAHORSE Geomatics Training and Development Vessel (Figure 2). The river conditions during this test were calm, resulting in solutions that are representative of typical inland bathymetric multibeam surveys, but not rougher seas.

Trajectories for each test area are shown in Figures 3 and 4.

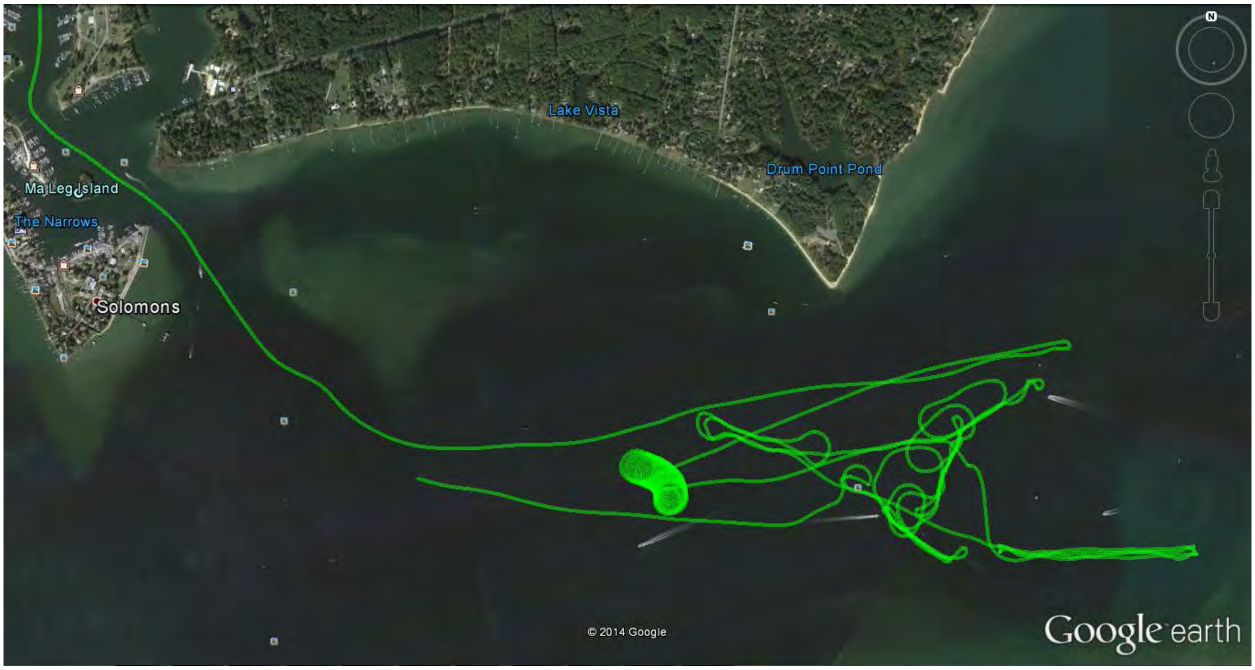

Figure 3: Patuxtent River Test Area Trajectory [1]

Figure 4: Columbia River Test Area Trajectory [2]

Equipment Overview

A NovAtel SPAN-SE receiver combined with a Northrup Grumman LN200 IMU was used for the Patuxent River Test. To make an equitable comparison to the competitor system, the SPAN-SE receiver was configured as a dual antenna model with ALIGN® GNSS dual antenna heading and with GPS+GLONASS tracking enabled.

Figure 5: SPAN-SE Receiver

Figure 6: LN200 IMU

All bathymetric data for the Patuxent River Test was collected aboard the NOAA R/V Bay Hydro II. Both the SPAN and competitor systems logged navigation and attitude data at the same time, with the competitor data being fed directly into HYPACK/HYSWEEP in real time. The Kongsberg EM2040 transducer was used to log range/angle, and across/along/depth data into the HYPACK software suite.

An iMAR IMU-FSAS was used as a reference system in the Columbia River Test. This test was conducted to demonstrate the difference between using a tactical grade IMU and a MEMS IMU on the SPAN platform. The MEMS sensor used was an IMU-IGM-S1, NovAtel's enclosure that houses the STIM300 IMU manufactured by Sensonor. Two separate SPAN receiver systems were used in this test. Both systems used NovAtel FlexPak6 GNSS receivers configured for GPS+GLONASS operation. NovAtel's ALIGN GNSS dual antenna heading functionality was also enabled for both systems. RTK corrections were provided in real-time using the Oregon Real-time GPS Network (ORGN) NTRIP service.

Figure 7: FlexPak6 GNSS Receiver

Figure 8: IMU-IGM-S1

Figure 9: iMAR FSAS

Bathymetric data for this test was collected using a pre-production NORBIT Wide Band Multibeam Sonar (WBMS). HYPACK/HYSWEEP was used for data collection in real time and multibeam data processing. Data collected from both systems was also post-processed using Waypoint Inertial Explorer software.

Table 1 - IMU Physical Specifications

	LN200	iMAR IMU-FSAS	IMU-IGM-S1
Dimensions (IMU)	89 mm D x 85 mm H	128 × 128 x 104 mm	45 × 39 × 22 mm
Dimensions (Enclosure)	135 × 153 × 130 mm	N/A	152 × 137 × 51 mm
Power Consumption	16 W (typical)	16 W (max)	2.5 W (typical)
Gyro Technology	FOG	FOG	MEMS

Table 2 - IMU Performance Specifications

	LN200	iMAR IMU-FSAS	IMU-IGM-S1
Gyro Bias Repeatability	1°/hr	0.75 °/hr	250 °/hr
Gyro Bias Instability	1°/hr	0.75 °/hr	0.5 °/hr (Allan Variance)
Gyro Scale Factor	100 ppm	300 ppm	500 ppm
Angular Random Walk	0.07 °/√hr	0.1 °/√hr	0.15 °/√hr
Accelerometer Bias Repeatability	1.5 mg	1 mg	10 mg (estimated)
Accelerometer Bias Instability	1.5 mg	1 mg	1 mg (estimated)
Accelerometer Scale Factor	1000 ppm	300 ppm	300 ppm

Performance Results

Patuxent River Test

The objective of the following test is to compare the degree of closeness, in terms of navigation and attitude, between the NovAtel SPAN solution and an industry competitor in a hydrographic survey application.

Raw data collected from both the NovAtel SPAN system and a competitor system was post-processed allowing for a more robust solution to be generated post-mission using forward and reverse processing, and smoothing techniques. The post-processed navigation and attitude solution from SPAN and the competitor were offset to be output at the same point and compared to one another. CARIS HIPS was used for post-processing bathymetry and imagery data from both systems.

The data was acquired over an optimum patch test area containing steep slopes, flat seabed, and large shoals. An overview of the area is shown in Figure 10.

Figure 10: Areas Surveyed in Patuxent River

For the purposes of analysis, the focus of the results will be on the three areas that are labeled in Figure 10: NW Wreck, Slope and Eastern Flat. An attitude comparison, the difference in the 10 cm CUBE (Combined Uncertainty Bathymetric Estimate) grids, and the effect of the propagated attitude at the sounding will be presented for the SPAN and competitor systems in each area.

1. NW Wreck

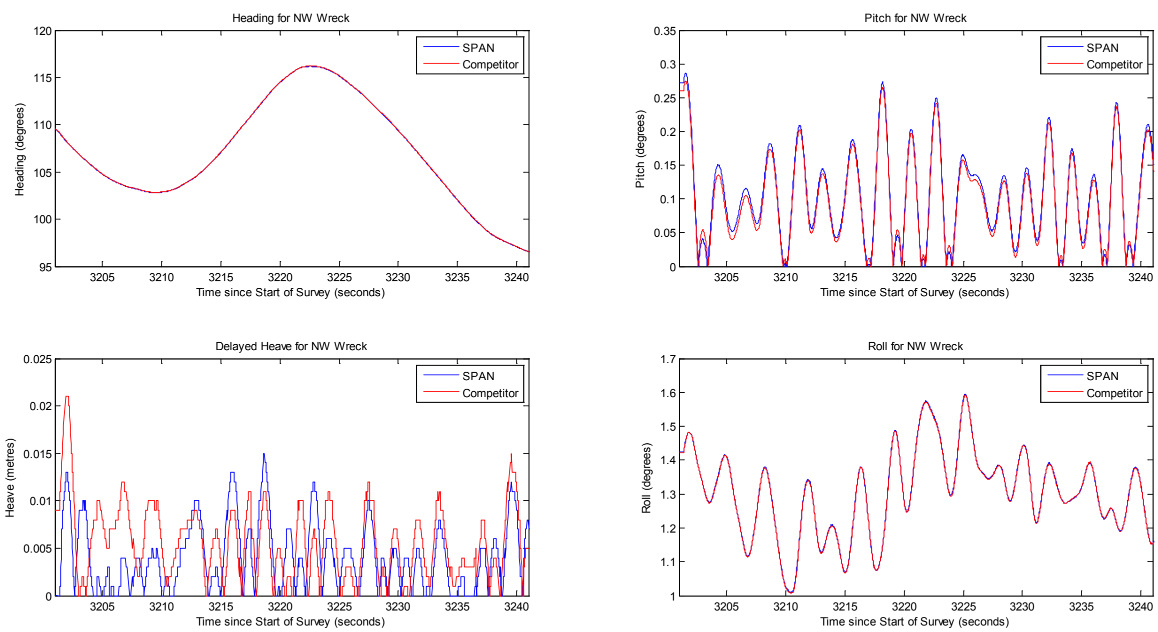

Figure 11: Attitude plots for NW Wreck Area

Table 3 - Observed RMS difference of SPAN and competitor

Survey Area	Position RMS (m)		Attitude RMS			
	2D	Depth	Pitch (°)	Roll (°)	Azimuth (°)	Heave (m)
NW Wreck	0.044	0.012	0.004	0.007	0.048	0.006

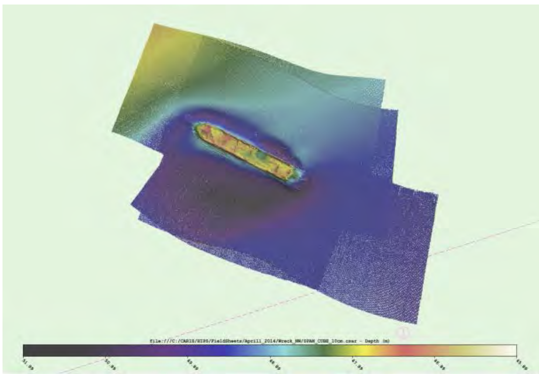

Figure 12: 10cm CUBE grid with SPAN

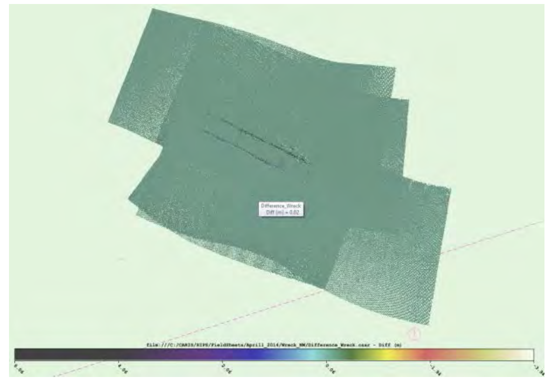

Figure 13: 10cm grid difference between SPAN and Competitor

Table 4 - Sounding-to-Sounding difference between SPAN and competitor

	Number of Soundings	|max diff| (m)	Mean of difference (m)	σ difference (m)
Difference in 2D positioning	577068	0.09	0.036	0.023
Difference in depth	577068	0.034	0.0073	0.009

2. Slope Area

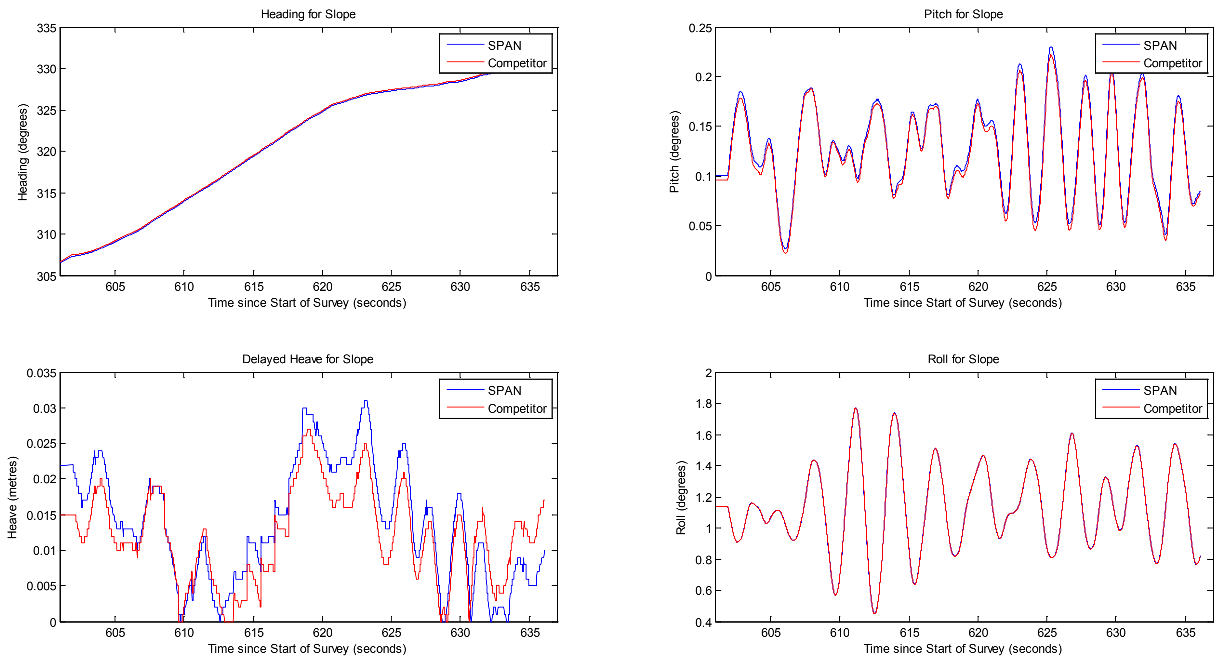

Figure 14: Attitude Plots for Slope Area

Table 5 - Observed RMS difference of SPAN and competitor

Survey Area	**Position RMS (m)**		**Attitude RMS**			
	2D	Depth	Pitch (°)	Roll (°)	Azimuth (°)	Heave (m)
Slope	0.044	0.031	0.003	0.004	0.120	0.003

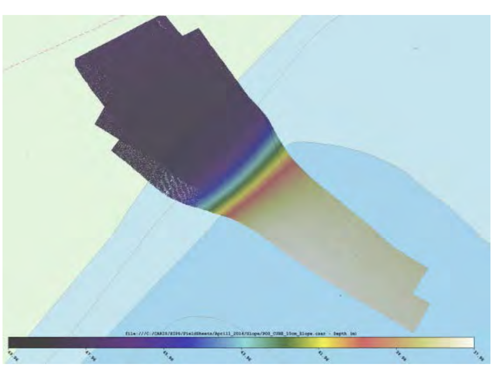

Figure 15: 10cm CUBE grid with SPAN

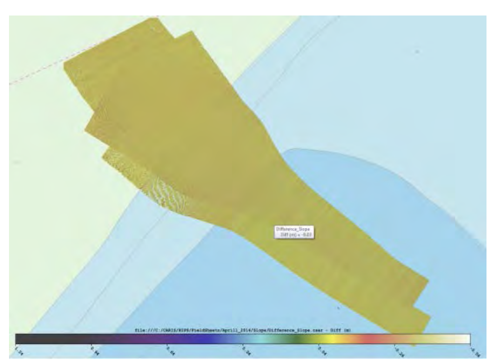

Figure 16: 10cm grid difference between SPAN and competitor

Table 6 - Sounding-to-Sounding Difference between SPAN and competitor

	Number of Soundings	|max diff| (m)	Mean of difference (m)	σ difference (m)
Difference in 2D positioning	2107549	0.09	0.034	0.027
Difference in Depth	2107549	0.062	0.0295	0.0088

3. Eastern Flat Area

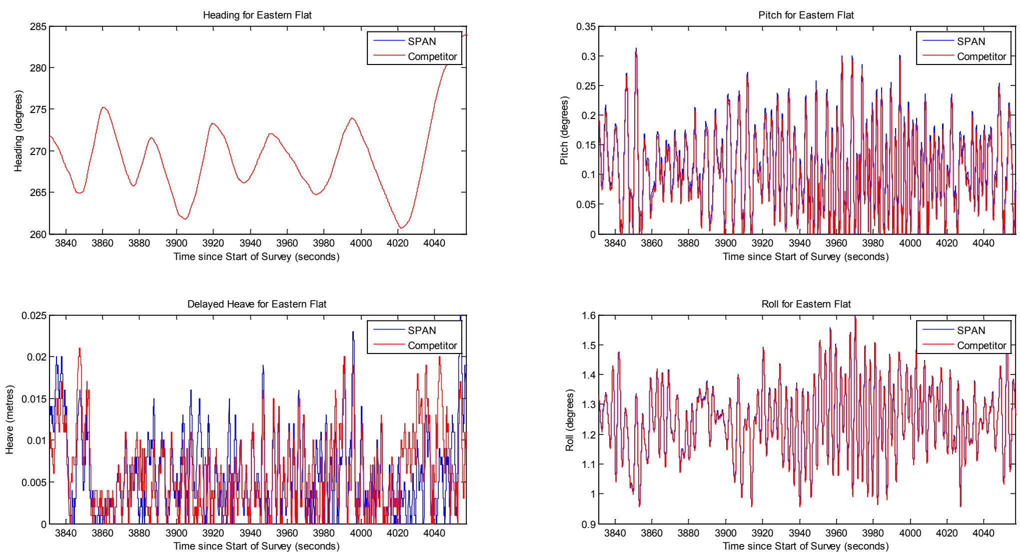

Figure 17: Attitude Plots for Eastern Flat Area

Table 7 - Observed RMS difference of SPAN and competitor

Survey Area	**Position RMS (m)**		**Attitude RMS**			
	2D	Depth	Pitch (°)	Roll (°)	Azimuth (°)	Heave (m)
Eastern Flat	0.027	0.044	0.004	0.009	0.012	0.003

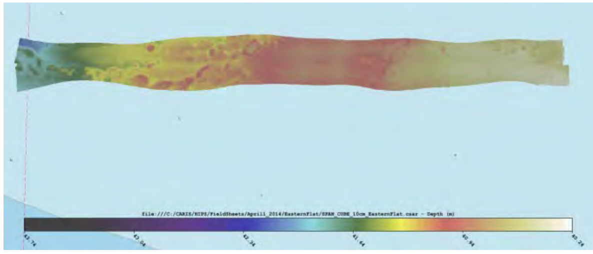

Figure 18: 10cm CUBE grid with SPAN

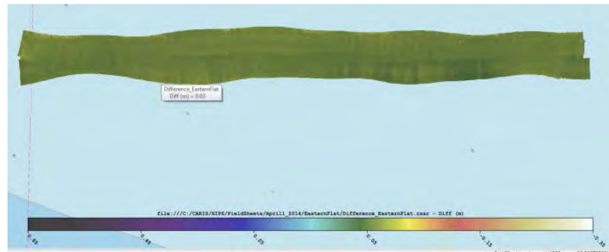

Figure 19: 10cm CUBE grid between SPAN and competitor

Table 8 - Sounding-to-Sounding Difference between SPAN and competitor

	Number of Soundings	|max diff| (m)	Mean of difference (m)	σ difference (m)
Difference in 2D positioning	9622120	0.07	0.025	0.009
Difference in Depth	9622120	0.026	0.0439	0.0068

The differences between the SPAN system and the competitor are very small. The largest pitch and roll differences were seen in the Eastern Flat area at 0.004° and 0.009° RMS, respectively. Position differences also show strong agreement with a max difference error of 0.044m RMS in the NW Wreck and Slope areas. And, though the test was conducted in calm waters the heave output by both systems agree strongly to 0.006m RMS in the NW Wreck and 0.003m RMS in the Slope and Eastern Flat areas. This strong agreement demonstrates similar performance between both systems, which leads to an expectation of very similar bathymetry results.

To compare the bathymetric results, the 10cm CUBE grids for each area were computed using the navigation data from both systems and then compared. The grid differences and the sounding-to-sounding analysis demonstrate the effect of the position and attitude differences of the navigation systems on the sea floor images. The grid difference figures illustrate that the difference between both systems are very small on the final product. The largest differences are observed around steep shoals or edges; however this can be attributed to the gridding process where soundings near the sharp features may be used in non-overlapping grid notes. A direct sounding-to-sounding comparison is a more robust test that removes the errors introduced by the gridding process. See tables 4, 5, and 6 for a summary of sounding-to-sounding comparisons for each area. Using this comparison method, the largest standard deviation is seen in the slope area and amounts to only 2.13cm in northing.

There is also no apparent correlation between the sounding differences over the water depth. For example, the NW Wreck is the deepest area yet the accuracy of its difference between SPAN and the competitor are smaller than that of the Slope Area which is considerably shallower. If there were significant attitude discrepancies between the SPAN system and competitor then they would become much more apparent as water depth increases. The fact that they do not is another indication of the similarity of the solutions.

The results from this test show that SPAN systems using tactical grade IMUs are able to provide the attitude accuracy that is required in marine survey applications, when compared to similar competitor products. Now that the performance of SPAN technology using tactical grade IMUs has been validated, the Columbia River Test will be discussed to evaluate the expected performance when using a MEMS IMU.

Columbia River Test

This test demonstrates the performance of SPAN using a MEMS IMU in the context of a hydrographic survey. These results demonstrate that SPAN continues to provide an accurate position and attitude solution integrating smaller and more cost effective MEMS IMUs.

Navigation results for this test were achieved by comparing the real-time and post-processed solution from the IMU-IGM-S1 to the post-processed IMU-FSAS results. Given the performance of the IMU-FSAS, the post-processed results from this IMU serve as the reference for this test.

Table 9 below shows the RMS differences for the IMU-IGM-S1 real-time and post-processed solutions when compared to the reference solution of the IMU-FSAS. The azimuth error stands out as the largest separation in performance, which is an expected result when comparing IMUs of different performance levels. Inertial navigation relies on the ability to observe sensor errors, and the vertical gyroscope is the most difficult axis to observe in that respect, particularly in a low dynamics application such as marine survey.

Table 9 - Observed Difference of IMU-IGM-S1 and IMU-FSAS [3]

Positioning Mode	Position RMS (m)		Velocity RMS (m/s)		Attitude RMS (°)		
	2D	Height	2D	Vertical	Pitch	Roll	Azimuth
Real Time	0.08	0.05	0.010	0.009	0.014	0.014	0.071
Post-Processed	0.01	0.02	0.003	0.004	0.010	0.010	0.053

An important component of a successful hydrographic survey is the system's ability to correct for any heave motion in the data. This particular survey was conducted on an inland waterway, with minimal heave. However, the results computed by NovAtel SPAN's heave filter for each IMU demonstrate that it is able to separate the effect of vessel acceleration or turning from real heave. Both sensors were able to detect that there was very little heave during this test. Table 10 shows the RMS heave differences and Figure 20 shows the post-processed heave computed with the IMU-IGM-S1 and IMU-FSAS. In all cases, the RMS heave measurements and differences are below 5cm [3].

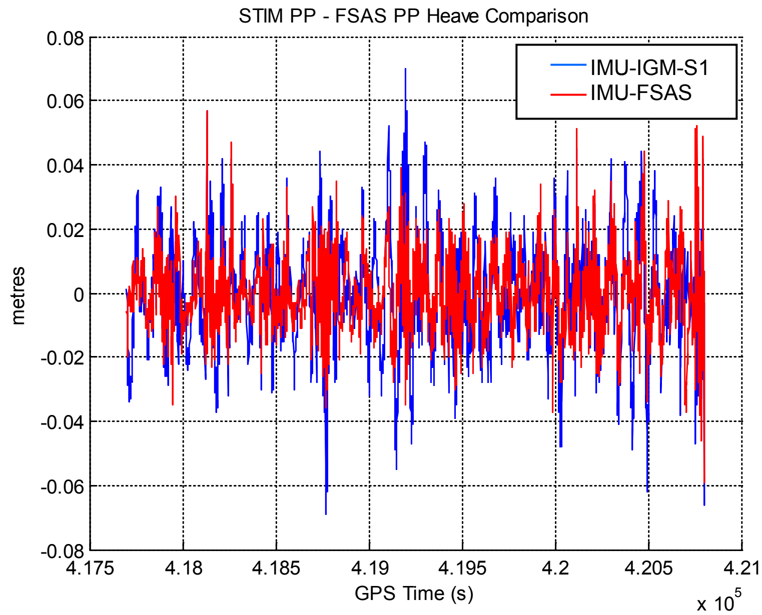

Figure 20: Heave Comparison [3]

Table 10 - Estimated Heave Differences [3]

Scenario	RMS Heave Difference (cm)
IMU-IGM-S1 Real Time vs. iMAR FSAS Real Time	3.3
IMU-IGM-S1 Real Time vs. iMAR FSAS Post Processed	3.4
IMU-IGM-S1 Post Processed vs. iMAR FSAS Post Processed	1.4

Conclusion

NovAtel's SPAN product line integrates a wide range of augmentation sensors to provide the system performance that is required for different hydrographic survey applications. The results presented in this paper are an indication of the high quality that can be accomplished with post-processed NovAtel SPAN data compared to a post-processed solution generated by an industry competitor. In addition, data from an independent test is presented to demonstrate the performance of a MEMS IMU with a new generation SPAN receiver. By staying on the cutting edge of technology, SPAN is able to offer solutions that are comparable to tactical grade systems utilizing smaller and less expensive MEMS IMUs.

Errors inherent to an inertial system are difficult to estimate in low dynamic applications, such as hydrographic survey. In order to demonstrate the effects of these errors on the bathymetry data, CUBE grid comparisons and direct sounding-sounding differences between the SPAN and competitor systems were presented. Traditionally, high grade IMUs have been used in high precision marine applications, but as sensors are becoming smaller and more robust, other options, such as MEMS IMUs, can be considered. Mitigating position and attitude errors in real-time is a key component of success in any hydrographic application. Because SPAN is a tightly coupled GNSS/INS solution that combines the GNSS solution with IMU data, it utilizes the absolute accuracy of the position and velocity from GNSS, and the stable relative accuracy from the INS to provide a continuously available position, velocity, and attitude solution. The results presented in this paper demonstrate that SPAN can be paired with both high grade FOG and entry level MEMS IMUs to provide an accurate solution for position and attitude navigation in the hydrographic market.

The Patuxent River test illustrates a strong agreement between the navigation solutions provided by SPAN and a competitor system. With very similar navigation solutions, the resultant bathymetric data also compared extremely well. The CUBE grid differences are a good indication of the effect of the different navigation and attitude solutions on final bathymetric products. Even though the difference in flat terrain was quite small, there were big depth differences seen in areas of steep shoals but this expected because of the nature of the gridding process. The sounding-to-sounding comparison shows the effect of attitude, propagated at each sounding, for each area of interest. These comparisons offered high quality results, with the standard deviation of the difference in soundings being less than or equal to 2.3 cm.

The Columbia River Test conducted in Portland benchmarks the performance of a MEMS IMU against a traditional FOG IMU. The IMU-IGM-S1 produced a post-processed position solution with a difference of 0.01 m (2D RMS) from the same solution produced by a high performance FOG IMU. The attitude differences were 0.010° RMS in roll and pitch, and 0.053° RMS in heading. Post-processed heave performance showed a 1.4 cm RMS difference between the two solutions. The results of these tests tell us that, with the improvements made in MEMS technology in conjunction with the ongoing development of the SPAN engine, lighter and less expensive sensors have become a viable option for shallow water survey applications in the hydrographic market. Given the performance of SPAN with the IMU-IGM-S1, it is reasonable to embed the small inertial sensor into a sonar head to create a compact solution for shallow water applications that is both cost effective and accurate.

References

[1] *Source:* “Figure 3: Patuxtent River Test Area Trajectory”, **Google Earth**. April 7, 2014.

[2] *Source:* “Figure 21: Columbia River Test Area Trajectory”, **Google Earth**. April 7, 2014.

[3] R. Dixon, M. Mutschler, “Performance of a Tightly-Coupled GNSS/INS System in a Marine Environment Using MEMS Sensors”, in Proceedings of Oceanology International China, September 3-5, 2013, Intex, Shanghai.