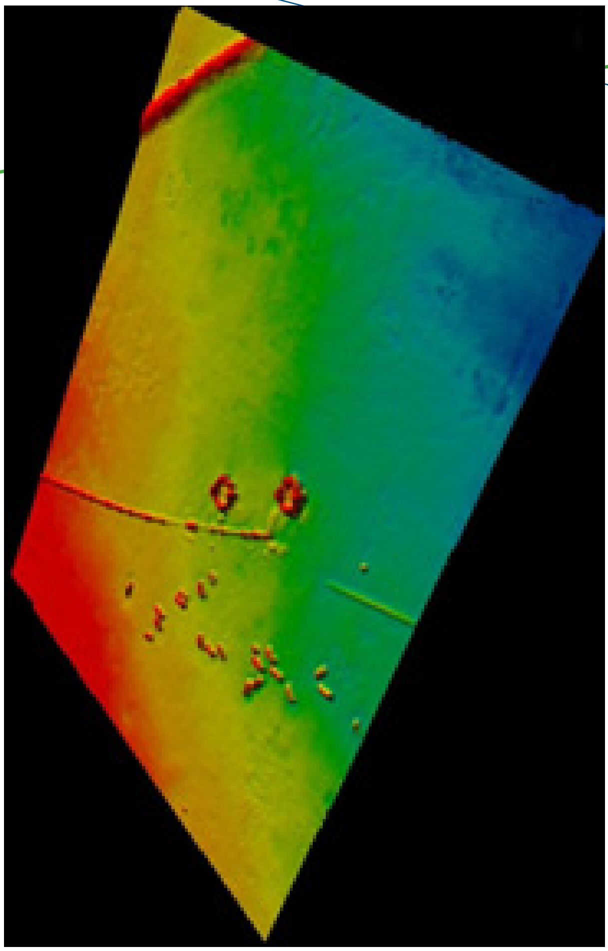


NovAtel's SPAN® Technology for Marine Environments—Featuring Heave Filter

Performance Analysis—March 2012

Abstract

This paper details the testing of NovAtel's SPAN® GNSS/INS technology against a competitive navigation system in a marine environment. The testing confirms that SPAN technology, featuring a reliable heave filter, is an excellent alternative to existing heave compensation systems. Tests were conducted specifically to analyze results for multi-beam hydrographic survey applications.

Two NovAtel SPAN-SE™ receivers were tested utilizing different grades of inertial measurement units (IMUs). Data from the NovAtel and competitive systems was collected simultaneously using Reson PDS2000 software. This ensured that resulting sea floor images would be assembled under identical GNSS and sea conditions.

Test Overview

Data for the performance analysis was collected on a survey vessel, in the Santa Barbara harbour on November 8th and 9th, 2011.

The following details test methodology and compares the real time results of the three systems. Performance of each navigation solution is compared as well as the resulting sea floor Digital Terrain Model (DTM) image produced.

Equipment Overview

Two NovAtel SPAN-SE receivers were used for testing. One SPAN-SE used a tactical grade LN200-L IMU and the other used a commercial grade IMU-CPT™.

The firmware used on the SPAN-SE receivers was the release candidate for the latest firmware version including beta versions of the heave filter and low dynamics (marine) error modeling. Both SPAN-SE units were configured for GPS+GLONASS.

A Reson SeaBat 7125 multi-beam system was used, operating at 400 kHz in high density beam mode.

About SPAN

SPAN™ technology tightly couples NovAtel's OEM precision Global Navigation Satellite System (GNSS) receivers with robust IMUs to provide continuously available, 3D position, velocity and attitude—at data rates up to 200 Hz. When combined, the two navigation techniques augment and enhance each other with the absolute position and velocity accuracy of the GNSS compensating for the errors in the IMU measurements that occur over time. The stable relative position of the INS is used to bridge times when the GNSS solution is degraded or unavailable such as in a busy port environment.

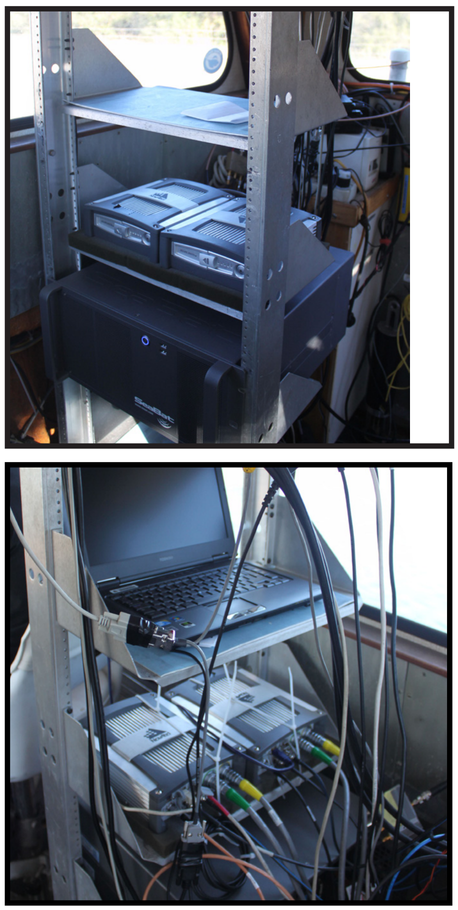
While data for this performance analysis was collected in real-time, NovAtel's SPAN technology offers post-processing capabilities through its Waypoint® software. SPAN products allow for the collection of raw GNSS and IMU measurement data for later use. Inertial Explorer® software uses the stored measurement data, post-mission, to generate a more accurate solution than is possible in real-time.

NovAtel Test Equipment

Model Information

1. SPAN-SE-D with LN200-L
   - Receiver Model - Dual antenna input
     OEMV3 (GPS 1): GPS+GLONASS
     Dual frequency ALIGN Master
     OEMV2 (GPS 2): GPS+GLONASS
     Dual frequency ALIGN Rover
   - IMU: 200Hz output rate
2. SPAN-SE-D with IMU-CPT
   - Receiver Model - Dual antenna input
   OEMV3 (GPS 1): GPS+GLONASS
   Dual frequency ALIGN Master
   OEMV2 (GPS 2): GPS+GLONASS
   Dual frequency ALIGN Rover
   - IMU: 100Hz output rate

Figure 1: Installed Test Equipment - Front and Back



Product Highlights

Receiver: SPAN-SE

- Built in data logging
- Secondary receiver built in and automatically configured for dual antenna
- Ruggedized enclosure with Status LEDs
- Full GPS+GLONASS constellation

Receiver: SPAN-SE + LN200

- Higher grade IMU (best attitude/solution stability)
- 200 Hz data rate

Receiver: SPAN-SE + IMU-CPT

- Lower grade IMU (worse attitude performance in slower vessels)
- Cost effective with noexport restrictions
- 100 Hz data rate

IMU Mounting

The competitor's IMU was pre-installed on the vessel utilizing a metal IMU mount under the floor boards, near the cabin door. For testing purposes, a wood mounting board was added for the two NovAtel IMUs. **Figure 2** shows the NovAtel mounting board lifted out of place to reveal the top of the competitor's LN200. When bolted on, the plate fits so the IMUs were all aligned on the X or across-ship axis.

Axis Mounting

The SPAN LN200 IMU was mounted with the Y axis positive along the forward axis of the vessel, Z axis positive up and X axis positive to vessel starboard. To accommodate the limited space on the mounting board, the IMU-CPT was mounted with a 90° rotation about Z so the X axis was positive along the vessel and Y axis was positive to port.

Rotation Compensation

The rotation was compensated for in the real-time solution by using standard NovAtel commands but remains evident in the raw data. See **Figure 3** for axis definitions.

Sensor Offset

There was a clear sensor offset between the SPAN mounting board and the properly aligned competitor's LN200. This was compensated for during the patch testing and all navigation results are presented with this physical offset mathematically removed.

Figure 2: IMU Mounting

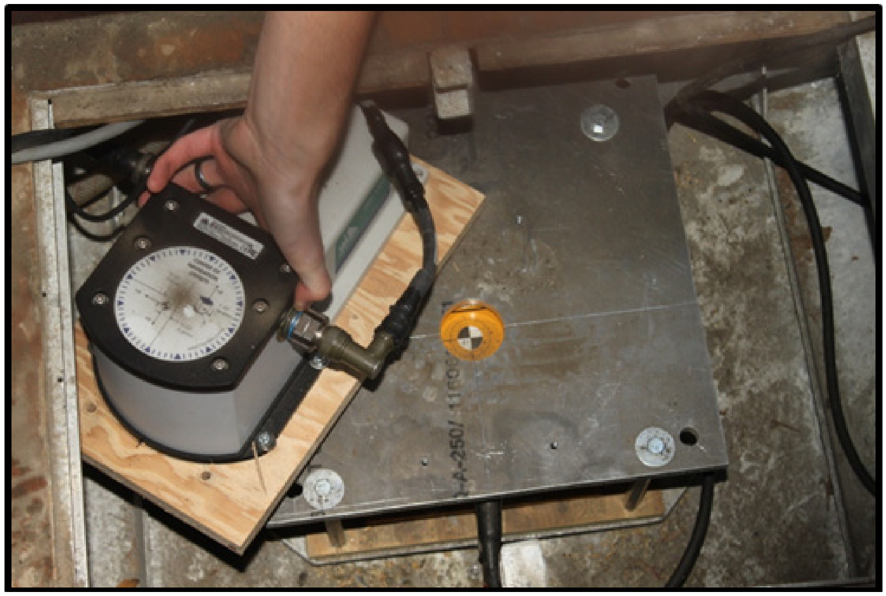
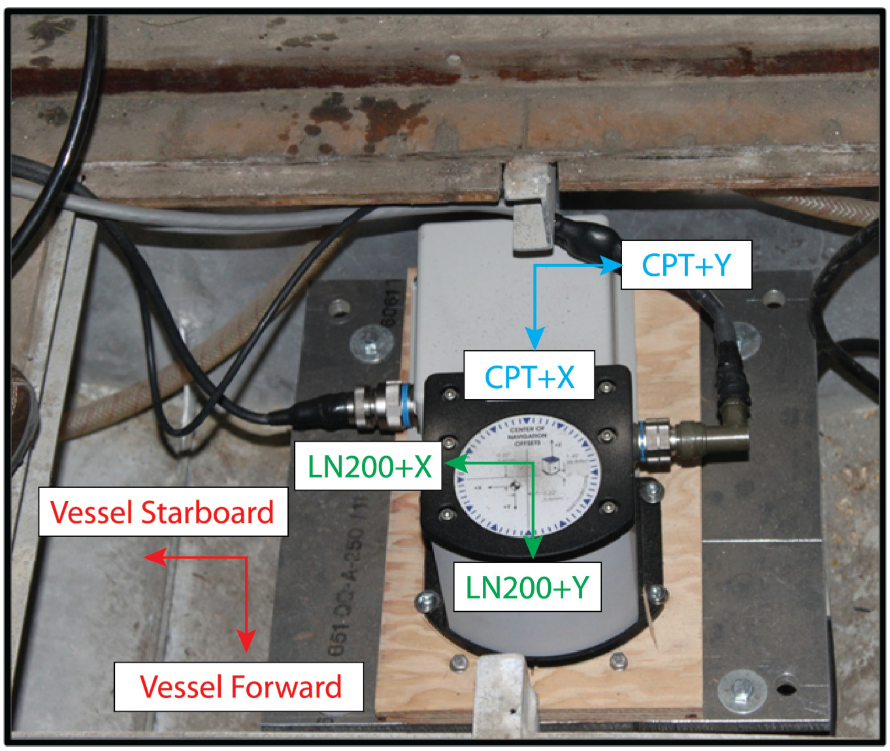


Figure 3: IMU Mounting Axis Detail



Antenna Mounting

Both the SPAN and competitor's systems operated with dual GNSS antenna setups. The competitor's system had two antennas mounted on a rigid metal bracket with a separation baseline of approximately 1.6 m. To avoid interference, two separate NovAtel antennas were installed by clamping wood base plates to the vessel roof. The NovAtel antenna baseline was approximately 2.1 m and was used for both SPAN systems. Both antenna setups were mounted in the across track direction with respect to vessel forward. See **Figure 4** for details. The SPAN systems used the starboard antenna as the primary antenna.

The vessel reference point is the competitor's IMU reference point. The competitor's lever arms were previously surveyed for this vessel. The relative offsets for the NovAtel IMUs and antennas were measured (tape measure) to extrapolate the surveyed lever arms for the SPAN systems. IMU center offsets were also measured with a tape measure. Lever arms used are listed in **Table 1** and sensor offsets are listed in **Table 2**. These are expressed in IMU body frame which is defined as follows:

- Y is positive in the forward direction of the vessel
- Z is positive up
- X completes the right handed system positive to starboard
- IMU-CPT body frame is rotated by 90° about Z

Figure 4: Antenna Mounting

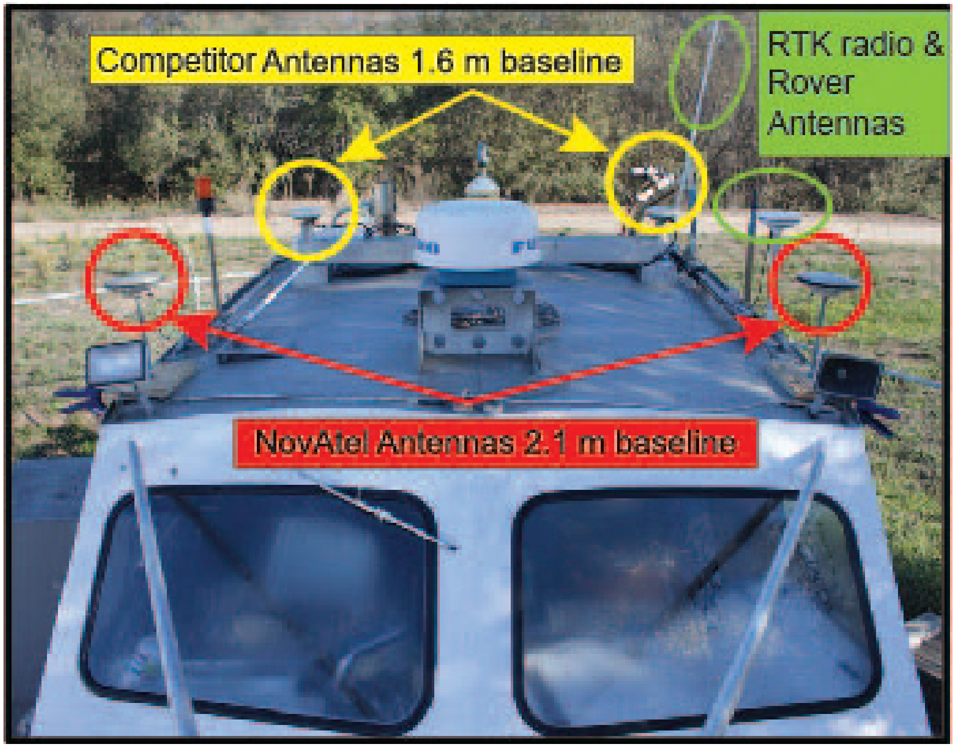


Table 1: Lever Arms				
System	**Lever Arm**	**X (m)**	**Y (m)**	**Z (m)**
Competitor IMU	Starboard Antenna	0.771	0.265	2.451
	Port Antenna	-0.799	0.265	2.438
SPAN LN200	Starboard Antenna (Primary)	1.01	1.71	2.35
	Port Antenna	-1.05	1.71	2.34
SPAN IMU-CPT	Starboard Antenna (Primary)	1.91	-1.01	2.38
	Port Antenna	1.91	1.05	2.37

Table 2: IMU Center of Navigation Offsets				
From	**To**	**X (m)**	**Y (m)**	**Z (m)**
SPAN LN200	Competitor IMU	0	-0.02	-0.074
SPAN CPT	Competitor IMU	0	0.18	-0.034
SPAN CPT	SPAN LN200	0	0.20	0.04
Competitor IMU	SeaBat 7125	-1.578	-0.9825	-0.7175
Competitor IMU	Water line	N/A	N/A	0.254

Test Area

Testing occurred in southern California, off the coast of Santa Barbara at depths of 20 m and 50 m. The twenty metre survey area was located approximately 1.8 kilometres south-east of the Santa Barbara harbour. The fifty metre survey area was located approximately 3.5 kilometres south-west of Santa Barbara harbour.

Figure 5: 20 m Survey Area

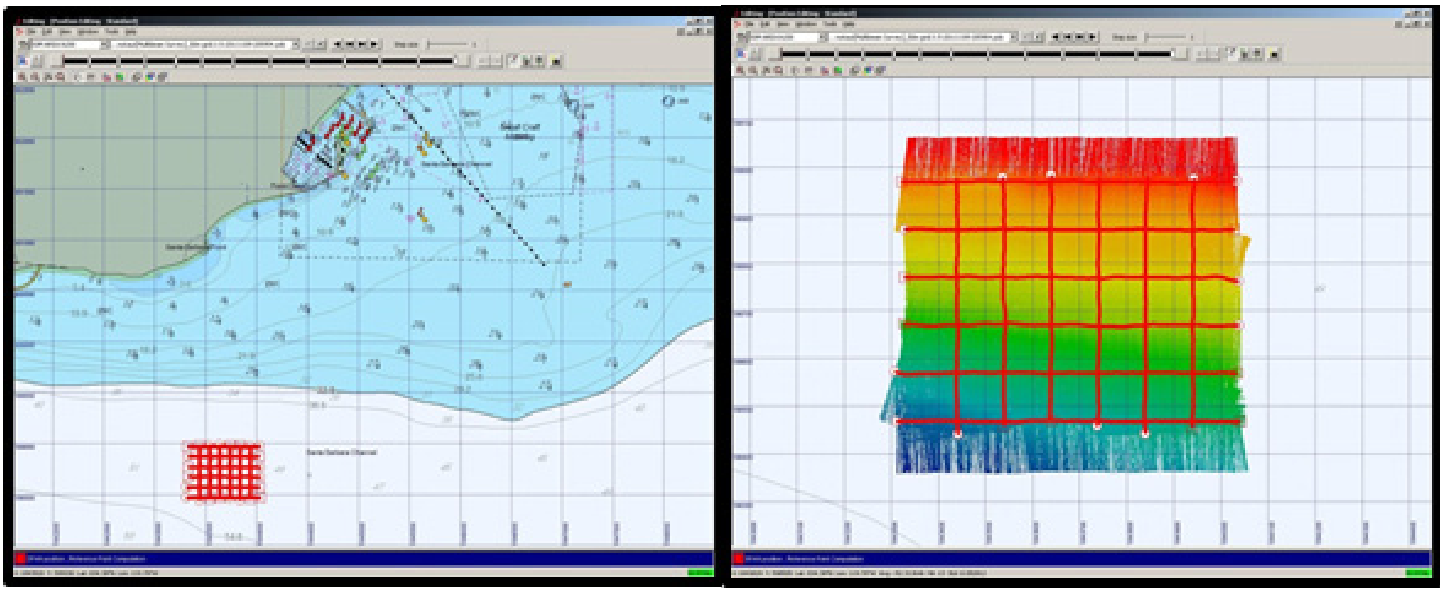
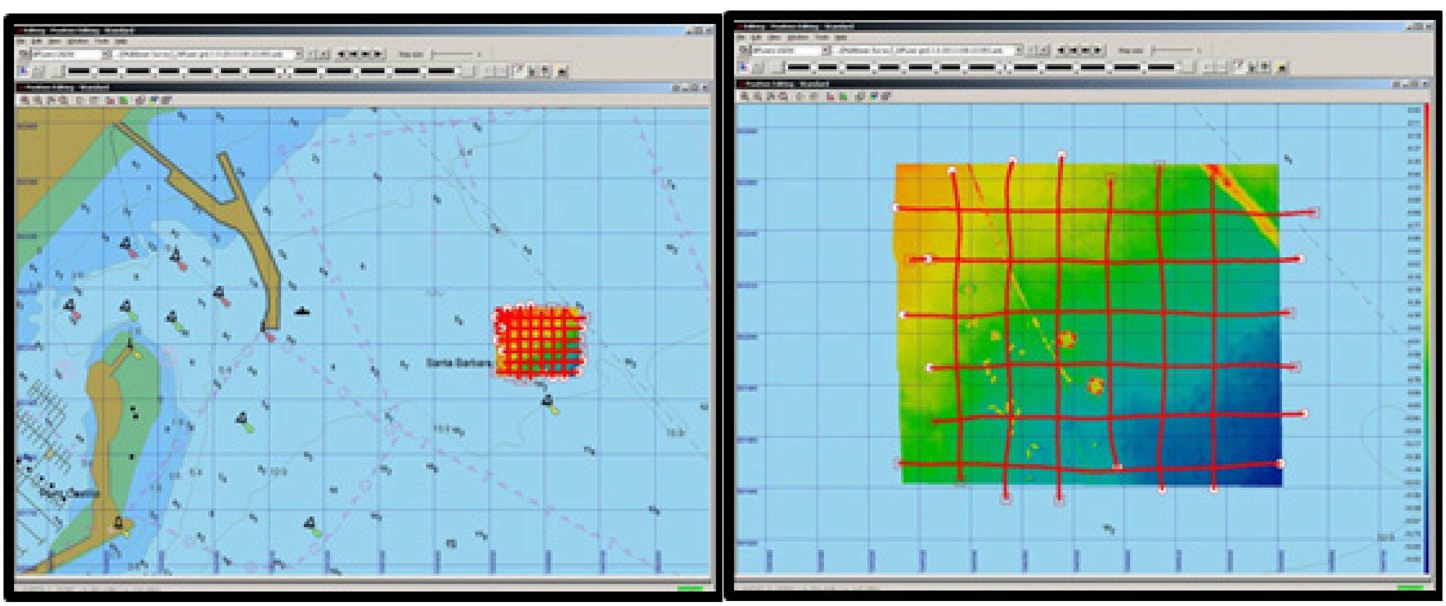


Figure 6: 50 m Survey Area



Diffusers Survey Area

The diffusers area is located very near to the Santa Barbara harbour in water depths of approximately 10 metres. This area was used primarily to perform calibration patch test for the system with the three IMUs.

Patch Test

Each time a system is re-configured or moved in the vessel, a patch test over a known artifact is completed to remove IMU angular offsets and data latency. For the November 9th data the patch test was performed over an oil pipeline. It was run twice for verification and all results matched to within 0.15° except for the competitor's IMU azimuth. The competitor's azimuth was pre-installed and properly mounted and therefore should have produced stable results. However, azimuth or yaw offsets are notoriously difficult to derive accurately. Refer to **Table 3** for detailed data.

Figure 7: Diffusers Survey Area (vicinity of Santa Barbara Harbour)

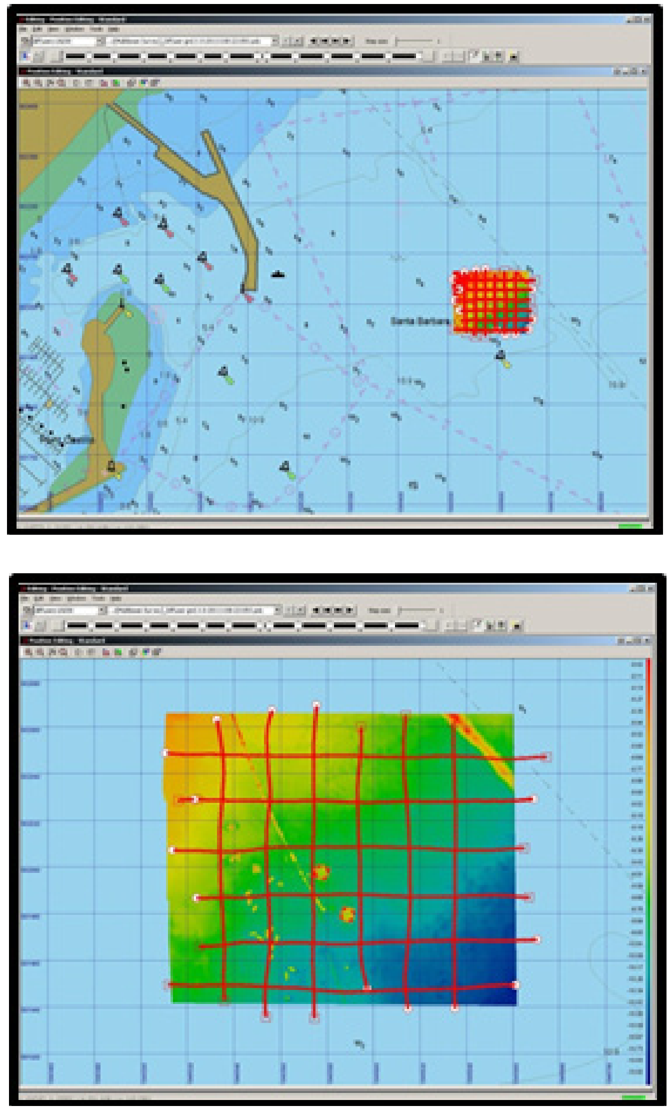


Table 3: Patch Test Angular Offsets				
System	**Patch Test**	**Pitch (Deg) (+ Port Up)**	**Roll (Deg) (+ Bow Up)**	**Yaw (Deg) (+ Starboard)**
Competitor	1	+0.88	-1.64	-1.23
	2	+0.89	-1.76	-1.58
	Difference	**0.01**	**0.12**	**0.35**
SPAN LN200	1	+0.78	+0.36	-0.25
	2	+0.79	+0.38	-0.28
	Difference	**0.01**	**0.02**	**0.03**
SPAN IMU-CPT	1	+0.79	+1.47	-1.07
	2	+0.84	+1.55	-0.96
	Difference	**0.05**	**0.08**	**0.07**

Navigation Performance Analysis

This section discusses the navigation performance of the three systems. Specifically attitude and heave performance is evaluated. All three systems are comparable (especially the two LN200 systems) therefore the differences between systems contain relative error from both. The test does not provide the absolute error but is a good indication of the similarity of the solutions.

Real Time Results

Due to base station difficulties and the slightly different offset positions used (both IMUs were configured to provide position at IMU reference point), the position of each system is not compared. However, as both systems used Real Time Kinematics (RTK) corrections, the position differences are expected to be centimetre level and any large errors in positioning would display in the processed sea floor maps. As the attitude and heave solutions are most significant, the comparison focuses on them.

In order to deliver the closest possible comparison, output data from each system is synchronized by interpolating one solution to the other. The mean offsets for attitude were also removed to eliminate the physical offset bias from each system. Refer to **Figure 8**.

Results cover the entire set of data collected on November 9th. This includes the 50 m and 20 m survey areas as well as transit time in between. The start and end times of the data were trimmed slightly to reflect that all systems were operational.

A five minute sample of the heave solution (**Figure 9** and **Figure 10)** clearly shows the trends between systems. The five minute sample was taken from GPS time 336000 to 336300 which occurs during the largest sea swell conditions encountered when surveying the 50 m area.

Table 4 shows the difference in performance between a SPAN + IMU-CPT and the competitor's system.

Figure 8: SPAN + IMU-CPT vs Competitor (Mean Offset Removed)

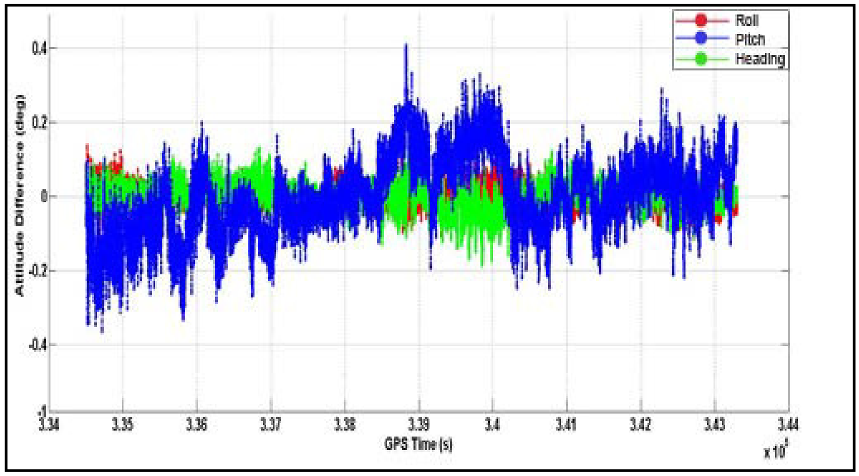


Figure 9: SPAN Real Time IMU-CPT vs Competitor Heave Differences (5 minute sample)

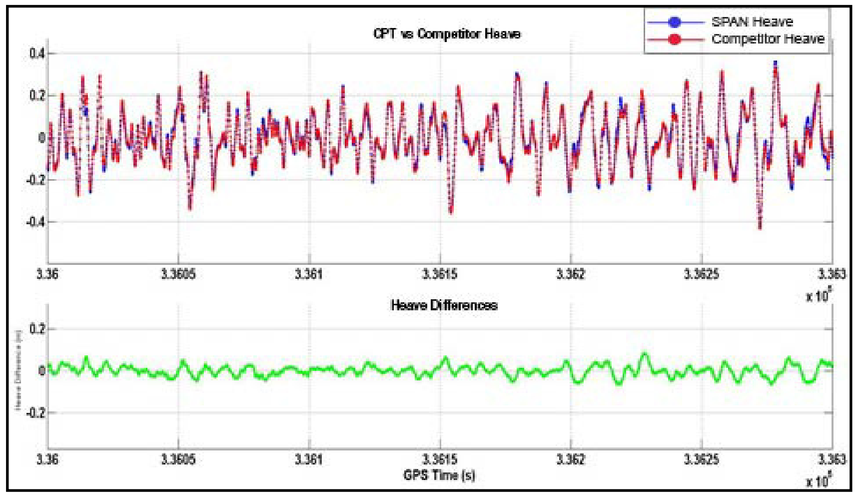


Figure 10: IE Post-Processed CPT vs Competitor Heave Differences (5 minute sample)

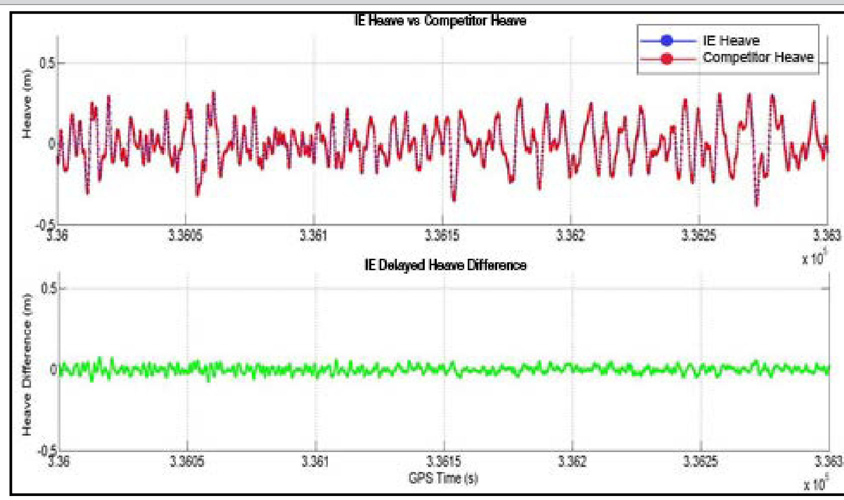


Table 4: SPAN IMU-CPT vs Competitor Difference Standard Deviation

Pitch (deg)	Roll (deg)	Heading (deg)	Real Time Heave (m)	IE Heave to Delayed Heave (m)
0.033	0.026	0.104	0.030	0.021

Final Sea Floor Map Results

The final sea floor map results were created by Reson's PDS2000 software using the data collected natively to their SeaBat system from all three navigation systems.

The target accuracy for this system in a typical survey is 0.25% of water depth. Therefore, the 20 m area target accuracy is 5 cm and the 50 m area target accuracy is 12.5 cm. Many factors other than the navigation solution account for these results. Dominant amongst these errors is the sound velocity profile through the water. Another potential contributing factor to the final results is the quality of the measured lever arms and IMU offsets. The lever arms for the competitor's system were surveyed in and both antennas and the IMUs were mounted on solid metal brackets. For temporary testing purposes, the SPAN IMUs were mounted on a plywood board near the competitor's IMU and the antennas were attached to the roof with all offsets measured with a tape measure.

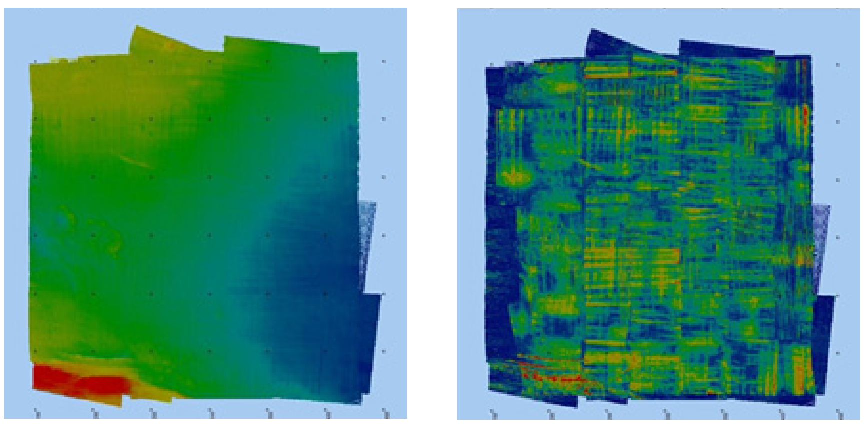
The following sections present results for the 20 m, 50 m and diffuser areas including some undesirable operations in an attempt to stress each system.

20 m Survey Area Results

The 20 m results from the three systems are shown below. Systems used a 0.5 m DTM size and contain millions of data points. The standard deviation of the sea floor image averaged over approximately 475,000 values for each system.

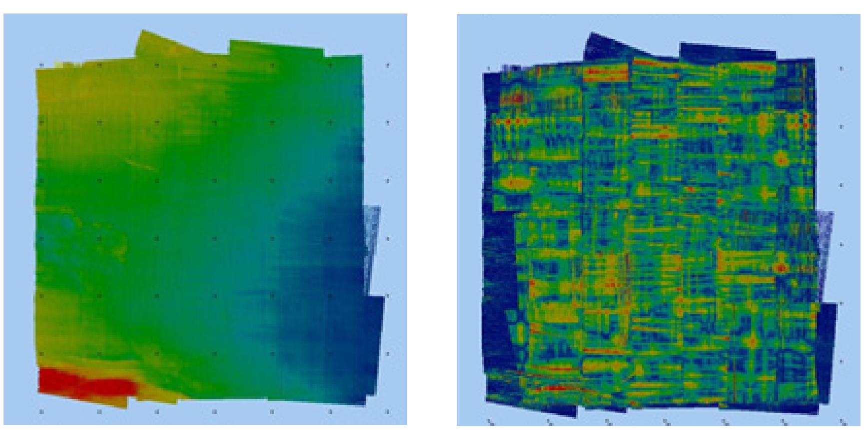
The desired accuracy at this depth is 5 cm. All three systems performed within the target accuracy and were well within a centimetre of each other. This is a remarkably small difference when all factors, from system setup to different error sources, are considered.

Figure 11: 20 m Competitor Results



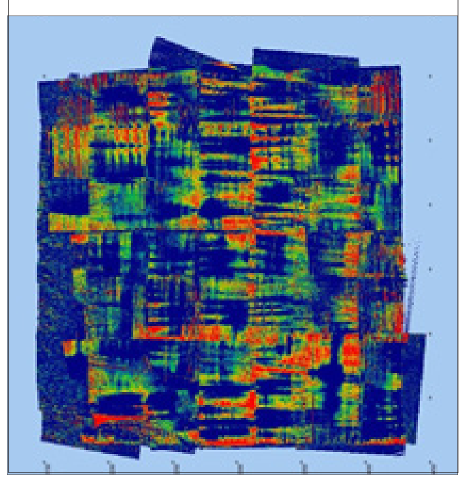
0.5 m DTM Image | **Standard Deviation per cell (red is 10 cm)**

Figure 12: 20 m SPAN-SE + IMU-CPT Results



0.5 m DTM Image | **Standard Deviation per cell (red is 10 cm)**

Figure 13: Difference between SPAN-SE + LN-200 and SPAN-SE + IMU-CPT

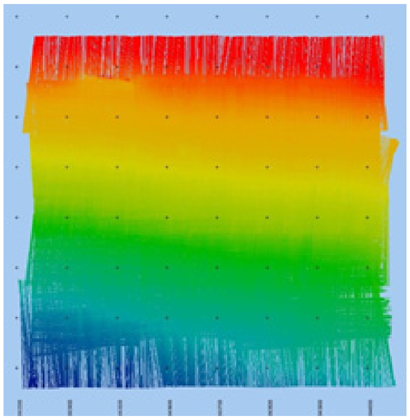


Standard Deviation Difference Blue 0, Red 0.03 m

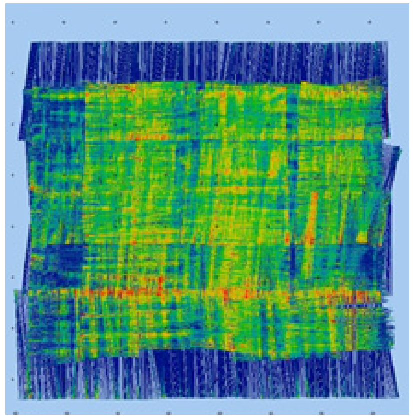
50 m Survey Area Results

The 50 m results from the three systems are shown below. Systems used a 1 m DTM size and contain millions of data points. The standard deviations of all three systems surpass the desired accuracy of 12.5 cm for the 50 m depth area. The average separation is also within 1 cm for all three systems.

Figure 14: 50 m Competitor Results

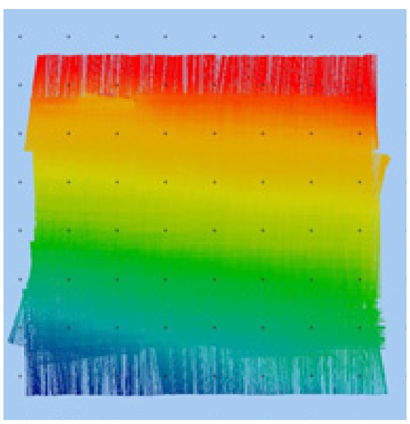


1 m DTM

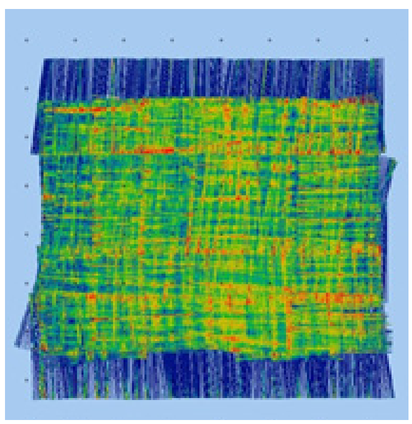


Standard Deviation per cell (red is 20 cm)

Figure 15: 50 m SPAN-SE + IMU-CPT Results

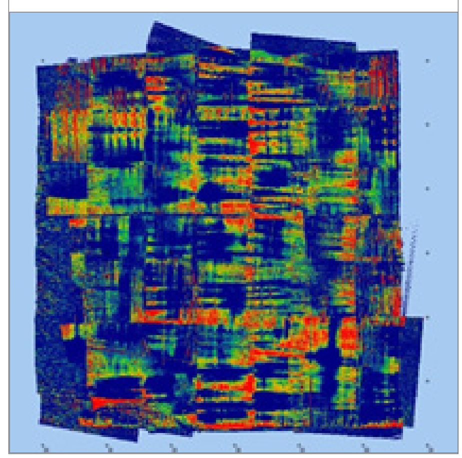


1 m DTM



Standard Deviation per cell (red is 20 cm)

Figure 16: Difference between 50 m SPAN-SE + LN200 and SPAN-SE + IMU-CPT Results



Standard Deviation Difference Blue 0, Red 0.03 m

Navigation Performance

The attitude solutions of the three systems are comparable. Roll and pitch are within 0.06° (4 arc-minutes) in all cases. Heading separation was slightly higher but Root Mean Squared (RMS) remains within 0.2° (12 arc-minutes). When considering the temporary nature of the SPAN mounting, this is a very strong result. If the SPAN system had been installed with greater precision (surveyed lever arms and proper mounting) the difference between the systems would likely be reduced further.

The heave solution between the three systems compare to an RMS of less than 3 cm. From these observations, the heave solutions output by SPAN and the competitor were virtually indistinguishable.

The IMU-CPT performed extremely well in this test, competing very favorably with the two LN200 systems—an excellent result for this sensor. However, the test was performed under optimal conditions for the commercial grade IMU-CPT. The survey vessel was relatively small and agile and the survey lines were relatively short (longest approximately 5 minutes). A slower survey vessel and/or surveys involving longer straight survey lines may experience slightly poorer performance with the CPT sensor set, particularly heading.

Final Sea Floor DTM Results

Reflective of the navigation results, final sea floor images are similar. In both the 20 m and 50 m survey areas, overall standard deviations from all systems were below 10 cm and overall differences are less than 2 cm.

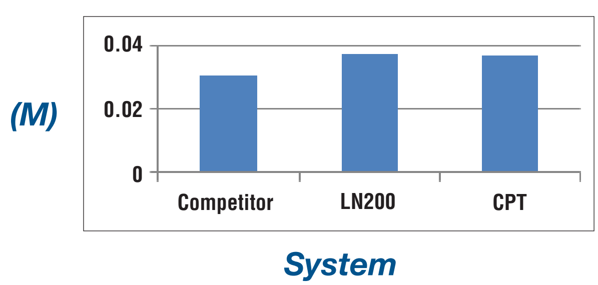
In all cases, the sea floor images produced are within 10 cm of each other. A good portion of the difference likely comes from the tape measured sensor offsets.

Even without factoring in the set up differences, results are extremely similar. Given time to properly mount both systems, it is likely the difference between final solutions would be even smaller.

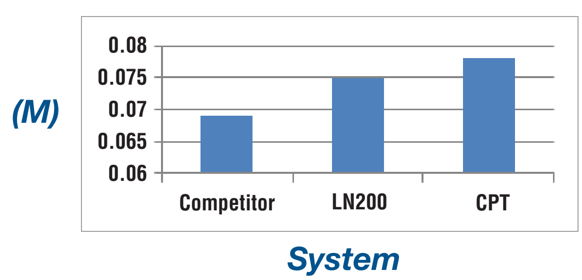
Conclusion

The SPAN-SE with either the LN200 or IMU-CPT sensors proved a very good alternative to the competitive system as the navigation component of this multi-beam sensor setup. The final results from the three systems were nearly indistinguishable despite the quick setup of the SPAN systems and the pace of development of the Reson software drivers for the SPAN products.

20 m Area of Standard Deviation



50 m Area of Standard Deviation



SPAN with IMU-CPT performance in larger, slower moving vessels or over longer survey lines may experience larger errors (mostly in heading) than the results found of this testing. However, under these test conditions the SPAN + IMU-CPT performance proved comparable to a system using a tactical grade and export restricted LN200 IMU.

For more information on the NovAtel range of SPAN systems, including non-ITAR tactical grade IMU's, please visit:

http://www.novatel.com/products/span-gnss-inertial-systems/

March 2012

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