Performance Differentiation in a Tightly Coupled GNSS/INS Solution

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BIOGRAPHIES

Ryan Dixon is the Chief Engineer of the NovAtel Synchronized Position Attitude Navigation (SPAN) GNSS/INS products, with a focus on enhancing NovAtel sensor fusion technology and overseeing the long term direction of the product line. Ryan joined NovAtel in 2005 after completing a B.Sc. in Geomatics Engineering at the University of Calgary. He moved into the SPAN development group in 2008, becoming a technical lead in 2010 and chief engineer in 2013. His knowledge and experience in integrating inertial measurement technology, from navigation grade to commercial microelectrical mechanical system (MEMS) with GNSS technologies, has developed a wide range of augmented positioning solutions for both ends of the cost and performance spectrum.

Mike Bobye is a Principal Geomatics engineer at NovAtel Inc. He has been involved with NovAtel Inc since 1997 and joined full time in 1999 after completing his B.Sc. in Geomatics Engineering from the University of Calgary. Mike has a deep breadth of knowledge in GNSS, GNSS/INS integration, and embedded software development. He was a member of the original research team that created the first GPS/INS integration at NovAtel in 2000, and has developed several patented methods for improving reliability and robustness of GNSS/INS products. During the early development of GPS/INS, he investigated the use of MEMs IMUs in the system (2003) and has recently returned his focus to MEMs IMU implementation within the now consistently proven SPAN product line.

ABSTRACT

It can be a difficult task trying to determine what kind of GNSS/INS solution will meet the needs of a specific application. Rapid advances in MEMS IMU technology and a proliferation of suppliers have narrowed the cost performance gap considerably when compared with larger and more expensive sensors. However, it has also made the process of selecting an appropriate solution more difficult than ever before. Negotiating the world of IMU specifications and correlating that to performance of the final product can be daunting, as the differences between MEMS sensors are not always apparent in the specification sheets. Furthermore, there are still some applications and performance metrics that require accuracy levels that can only be achieved with more precise sensors.

This paper will present what kind of performance is achievable using NovAtel's SPAN GNSS/INS sensor fusion technology across a range of IMUs. The IMUs investigated have all undergone significant scrutiny and are determined to be amongst the best in their respective performance categories. The process of negotiating the IMU market is a topic worthy of its own paper.

The IMU analysis presented herein will be further broken down by a selection of scenarios that highlight different performance criteria. This is intended to help clarify both what performance is possible for each sensor using SPAN technology and to provide guidelines on how to select an appropriate solution for different applications.

SPAN technology has also adapted and grown in order to deliver the most accurate solution possible in each application with each IMU type. Some improvements will be explored, including the concept of filter profiles, specifically the one for land vehicles. This is an enhanced approach to dead reckoning, applying constraints and additional updates by environment.

INTRODUCTION

The market for Inertial Navigation Systems (INS) is rapidly changing. The number of available options in INS systems has grown substantially over the last several years. Major advances have been made not only in IMU technology, but also in the ability to exploit sensor information to its fullest extent. In both cases, the largest impact can be seen in the MEMS (Micro Electrical Mechanical Systems) sensors. MEMS sensors are typically much smaller, lower power, and less expensive than traditional IMUs. The net result of these improvements is a proliferation of INS systems at much lower cost than were previously available and therefore greatly increased accessibility to technology that has historically seen limited deployment. Selecting the appropriate sensor and fusion solution for a particular application can be very challenging due to the large and confusing spectrum of solutions.

NovAtel Inc. offers a high quality, tightly coupled GNSS/INS solution through the SPAN (Synchronized Position Attitude Navigation) product line. A range of carefully selected IMUs encompassing a wide spectrum in size, weight, power, cost, and of course performance, are available as companion sensors to NovAtel GNSS cards. This paper will focus on the achievable performance with the SPAN GNSS/INS system using different classes of IMUs in some typically challenging scenarios.

Not only will the IMUs be examined, but also new enhancements to SPAN technology such as the use of INS profiles. The concept of INS profiles will be analysed by applying environment specific constraints, and their overall effect amongst the different classes of IMU sensors under varying conditions. External updates however, such as odometers or dual antenna setups are considered out of the scope of this analysis and are not used. These external aiding sensors are extremely helpful in many cases and are available to use with a NovAtel SPAN system, but this paper seeks to evaluate what performance can be achieved without such aids.

Real world test results will be examined using a selection of IMUs with the latest NovAtel SPAN algorithms to illustrate what kind of performance can be achieved with different sensors in difficult conditions. Despite their major advances over the past few years, there are many challenges involved with utilizing MEMS technology to provide a robust navigation solution, particularly during limited GNSS availability or low dynamics. The measurement error characteristics of these devices have improved dramatically, but are still much larger and more difficult to estimate than traditional sensors. Advancements in SPAN sensor fusion algorithms have enabled these smaller sensors to achieve remarkable performance, especially in applications where environmental conditions allow for additional constraints to be applied.

All testing was carried out in a ground vehicle with a primary focus on providing the effects of overall performance when applying various pre-defined profiles. The test scenarios were selected in such a way as to provide results for ideal, poor, and completely denied GNSS coverage. This is intended to not only provide an overview of what performance can be achieved, but also to act as a guide when attempting to select an IMU and GNSS/INS system for particular applications.

EQUIPMENT TESTED

NovAtel SPAN technology on the NovAtel OEM7 receiver is the testing and development platform for this discussion. New NovAtel OEM7700 GNSS receiver cards were paired with a selection of IMUs in different performance categories.

Since the OEM7 platform is capable of tracking all GNSS constellations and frequencies, each receiver was configured to use triple frequency, quad-constellation RTK positioning. They were coupled with a NovAtel wideband Pinwheel antenna capable of tracking, GPS L1/L2/L5, GLONASS L1/L2, BeiDou B1/B2 and Galileo E1/E5b signals.

The following list of IMUs was selected for evaluation based on the cross-sectional coverage of size, power and cost.

- Epson G320
    - Low power, small size MEMS IMU
- Litef µIMU-IC
    - Larger tactical grade performance IMU still based on MEMS sensors
- Litef ISA-100C
    - Near navigation grade IMU using Fiber Optic Gyros (FOG).

Although all of the above IMUs are excellent performers in their class and are capable of providing a navigation quality solution, the intent is to show the potential limitations that might arise due to the intended application. Along this line of thinking, it should also be noted that some applications require a higher degree of accuracy than can be achieved in real-time. For these applications NovAtel offers a post-processing solution via Waypoint Inertial Explorer.

It is difficult to compare IMU specifications directly from data sheets because each manufacturer tends to provide the information in slightly different ways.

Table 1 highlights a few key physical and performance parameters of the selected IMUs. The size and power listed in the table is for the standalone sensor. Hardened

NovAtel IMU enclosures are available which provide additional environmental and electrical robustness.

	G320	µIMU-IC	ISA-100C
Physical Characteristics			
Size (mm)	24x24x10	85dx60h	180x150x137
Power (W)	0.1	8	18
Gyroscopes			
Bias Repeatability (°/hr)	1800	10	0.5
Bias Instability (°/hr)	3.5	6	0.5
ARW (°/√hr)	0.1	0.3	0.012
Accelerometers			
Bias Repeatability (mg)	15	3	1.25
Bias Instability (mg)	0.1	0.01	0.01
VRW (m/s/√hr)	0.05	0.05	0.01

Table 1 – IMU Characteristics

INS PROFILES

GNSS and IMU sensors are only one part of the overall INS system performance. The algorithms used to exploit the available sensor data to its utmost capability are equally as important. In this regard, several improvements have been made to the existing SPAN INS algorithms to enhance performance under a variety of scenarios.

The largest addition to the SPAN product line is the introduction of INS profiles. That is, environment and vehicle specific modeling constraints can be utilized to enhance the filter performance. For example, the “land” profile, which will be examined in depth in this paper, is intended for use with ground vehicles that cannot move laterally. The assumptions introduced for land vehicles however, are not necessarily valid for different forms of movement, such as those experienced by a helicopter for example. Therefore, profiles have been implemented via command and controlled as required by the user, allowing for maximum performance depending on the application at hand.

The land profile is analogous of what has historically been identified as dead reckoning [1]. It is a method which uses a priori knowledge of typical land vehicle motion to help constrain the INS error growth. Or in other words, it makes assumptions on how land vehicles move to simplify inertial navigation from a six degree of freedom system to something closer to a distance/bearing calculation. The land profile takes the concept of dead reckoning, models it as an update type into the inertial filter and adds a few additional enhancements.

The following sub-sections will explore some of the filter enhancements offered under the land profile.

Velocity Constraints

Amongst other optimizations, the land profile enables velocity constraints based on the assumption of acceptable vehicle dynamics. This includes limiting the cross track and vertical velocities of the vehicle. Of all the enhancements, this is the one most colloquially referred to as dead reckoning.

Using the current INS attitude (R_b^l), the vehicle attitude (R_v^l) is estimated by applying the measured or estimated IMU body to vehicle direction cosine (R_b^v). From this the pitch and azimuth for the vehicle is estimated.

$$R_v^l = R_b^l R_b^{vT} \tag{1}$$

$$Pitch_{vehicle} = \tan^{-1}\left(\frac{R_v^l(2,1)}{(R_v^l(2,0)^2 + R_v^l(2,2)^2)^{\frac{1}{2}}}\right) \tag{2}$$

$$Roll_{vehicle} = \tan^{-1}\left(\frac{-R_v^l(2,0)}{R_v^l(2,2)}\right) \tag{3}$$

$$Heading_{vehicle} = \tan^{-1}\left(\frac{-R_v^l(0,1)}{R_v^l(1,1)}\right) \tag{4}$$

Using the magnitude of the measured INS velocity in conjunction with the derived vehicle orientation, the vehicle velocity is computed allowing the expected vertical velocity and cross-track to be constrained.

$$V_{l_{vehicle}} = \begin{bmatrix} Vel_{Sys}\sin(Azimuth_{vehicle}) \\ Vel_{Sys}\cos(Azimuth_{vehicle}) \\ Vel_{Sys}\sin(Pitch_{vehicle}) \end{bmatrix} \tag{5}$$

$$V_{v_{vehicle}} = {R_v^l}^T V_{l_{vehicle}} \tag{6}$$

A velocity vector update is then applied to the inertial filter to constrain error growth. The effects of this method are expected to be most apparent in extended GNSS outage conditions when the INS solution must propagate with no external update information.

Phase Windup Attitude Updates

Some applications are inherently difficult for inertial sensors due to the fact that these systems are reliant on measuring accelerations and rotations in order to observe IMU errors. When travelling at a constant bearing and speed, separating IMU errors from measurements becomes challenging, so any application that does not provide meaningful dynamics is more demanding on inertial navigation algorithms. This type of condition commonly appears in applications such as machine control, agriculture, and mining.

Gravity is a strong and fairly well known acceleration signal, so the real difficulty in this type of environment is managing the attitude, and especially azimuth, errors. Attitude parameters become very difficult to observe when the system experiences insignificant rotation rates about its vertical axis [2].

External inputs are used for providing input during low dynamic conditions when rotational observations are weaker. These are particularly helpful in constraining angular errors and include the same types used to assist in initial alignment; dual antenna GNSS heading, course over ground (CoG), magnetometers, etc. However, as the goal of this testing is to demonstrate the achievable performance from a single antenna GNSS system, this type of external aid was specifically omitted.

Utilizing the NovAtel patented technique for determining relative yaw from phase windup, the system is able to distinguish between true system rotation and un-modeled IMU errors during times of limited motion [3]. This is a novel way to extract additional information out of existing sensors rather than adding more equipment and complexity.

The principal of using phase windup in this way is summarized in equation (7).

$$\Delta Yaw_{pwu} = \frac{2\pi((\varphi^{1}_{\lambda_1} - \varphi^{1}_{\lambda_2}) - (\varphi^{0}_{\lambda_1} - \varphi^{0}_{\lambda_2}))}{\lambda_1 - \lambda_2} \qquad (7)$$

The phase windup update is used to constrain azimuth error growth during low dynamic conditions that are typically not favorable to inertial navigation. However, it does require uninterrupted GNSS tracking and is therefore not applicable in benign environments. This approach is expected to show the greatest benefit in low dynamic conditions and be directly attributable to azimuth accuracy but only in conditions where GNSS availability is relatively secure.

Robust Kinematic Alignments

Realistically, IMUs with gyro biases greater than 15 degrees per hour are unable to reliably perform gyro compassing for initial coarse alignment estimation. This is because they cannot distinguish sensor errors and noise from earth rotation [2], which means they are reliant upon other means to acquire an initial attitude to complete the alignment process.

Attitude can be injected from external input methods such as user commands, fixed dual antenna GNSS heading, magnetometers, etc. One method that does not require additional sensors beyond a single GNSS antenna is to use the GNSS course over ground to inject as the initial azimuth. This process is referred to as a kinematic alignment as it requires movement to provide a meaningful course over ground measurements. Another issue with kinematic alignments is that they require some assumptions be made about the vehicle movement. Pitch angles can be measured, but poorly, and roll angles are not measurable at all. Therefore, both roll and pitch are typically assumed to be zero. This is an acceptable solution on flat surfaces, but breaks down on slopes such as hills or climbing in an aircraft. Kinematic alignments must also make assumptions about the vehicle movement in order to resolve the directional ambiguity. Assuming that the vehicle is accelerating along its forward axis is common. So accelerating in reverse (say, backing out of a parking stall) or sideways like a helicopter or quad-copter can cause problems.

Of the three sensors tested, only one was not capable of performing a static alignment. The Epson G320 relied instead on completing the initial alignment by using the kinematic alignment method that was described.

To help alleviate some of the inherent weaknesses with kinematic alignments, and to simplify the user experience, NovAtel has implemented an enhanced robust kinematic alignment routine. This routine allows for a few major advantages; aligning in reverse is now both detectable and correctable, and kinematic alignments can be achieved at lower velocities than previously required. In addition to this, independent short static routines were added to allow estimation of roll and pitch angles prior to a kinematic alignment. Due to the strong gravity observation, even an IMU incapable of gyro compassing can roughly determine their roll and pitch, thus eliminating the previous zero roll/pitch assumptions and allowing robust kinematic alignments on slopes.

It should also be noted that the INS solution is available prior to the directional ambiguity being resolved, with all feedback of the current alignment state available. This provides the user with a greater flexibility to decide what is acceptable for their application, allowing for quick, robust alignment without the need of following detailed initialization procedures.

The alignment robustness improvements are not expected to be directly observable in the testing conducted for this paper.

TEST SETUP

All GNSS receivers and IMUs were setup in a single test vehicle and collected simultaneously for all scenarios. IMUs were mounted together on a rigid frame and all receivers ran the same OEM7 firmware build that were connected to the same antenna.

The tests were conducted using a single GNSS antenna with no additional augmentation sources, such as distance measurement instrument (DMI) or wheel sensor. These are extremely helpful in aiding the solution, but as previously mentioned this testing seeks to demonstrate the possible performance without the benefit of additional aiding sources. Dependence on aiding sources is a very important distinction when comparing such systems.

The GNSS positioning mode used was RTK via an NTRIP feed from a single base station with baselines between 5-30Km. This was done to try to minimize GNSS positioning differences between the three systems. L-band correction signals were not tracked and PPP positioning modes were not enabled.

A basic setup diagram of each system under test can be seen below in Figure 1.

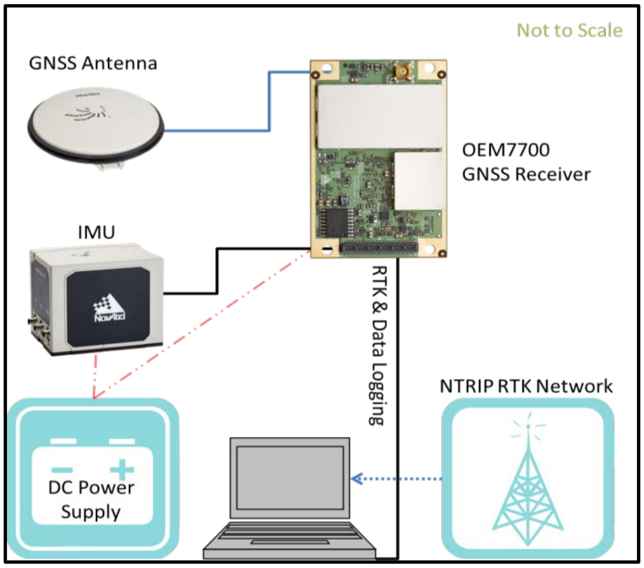

Figure 1 – Equipment Setup

TEST SCENARIOS

Three test scenarios will be examined using all the equipment and algorithms described above. They are; urban canyon, low dynamics, and parking garage. All three test scenarios are conducted to illustrate the tradeoffs when using different sensors and different SPAN algorithm modes.

The urban canyon test is designed to show the performance of the system in restricted GNSS conditions. The challenge to this scenario is to maintain a high accuracy solution when GNSS positioning becomes intermittent or even unavailable.

The low dynamics test is intended to illustrate the benefits of the land profile, and specifically the phase windup azimuth updates in maintaining the azimuth accuracy.

The parking garage test will show the efficacy of the velocity constraint models over the different IMU classes as the extended outage provides no external information to the INS filter whatsoever. Again, no other aiding sources were used.

Urban Canyon Test

The urban canyon environment has been and remains one of the strongest arguments in favor of using GNSS/INS fusion in a navigation solution. Because urban canyons are common, densely populated, and of course a demanding GNSS environment, they represent both an important and challenging location to provide a reliable navigation solution. Typically they contain major signal obstructions, strong reflectors, and complete blockages (depending on the city). For this reason they provide an excellent use case for INS bridging to maintain stability of the solution.

During most urban canyon environments, it is typically rare to incur total GNSS outages of more than 30 seconds. Therefore, this scenario examines the stability of the solution in continuously degraded, but not generally absent GNSS. In this case, the coupling technique of the inertial algorithms rather than quality of the IMU dominates achievable position accuracy.

The OEM7 platform is capable of tracking all GNSS constellations and frequencies. This provides a significant benefit to test scenarios, such as the urban canyon, where the amount of visible sky is significantly restricted. In this case, the more satellites that are observable, the more SPANs tightly coupled architecture can exploit the partial GNSS information. This was covered in greater detail in past publications [4].

Though position accuracy between IMUs is less apparent in this condition, attitude results remain separated by IMU quality, which is a major consideration for some mapping applications such as those using LiDAR or other sensors where a distance/bearing calculation must be done for distant targets.

Test data for this scenario was collected in downtown Calgary, Canada. The trajectory, seen in figure 2, includes several overhead bridges for brief total outages and some very dense urban conditions.

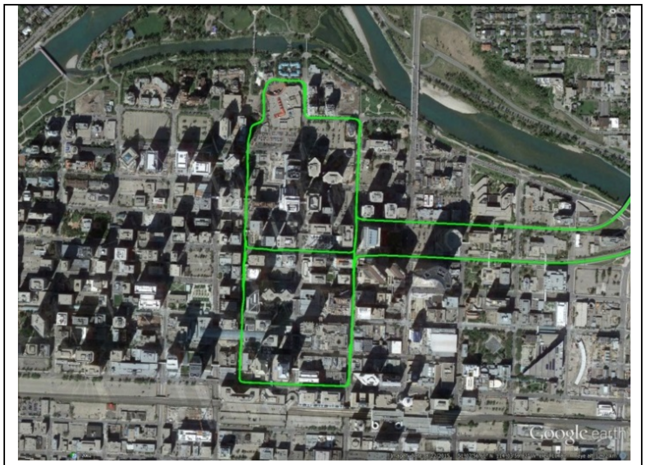

Figure 2 – Urban Canyon Test Trajectory [5]

Table 2 below shows the RMS error results of the three systems running both the default and land profiles. The first thing to notice is that the errors are differentiated by IMU category, though the differences are fairly small in the position domain thanks to the tightly-coupled architecture. However, because GNSS information is partially available, the differences seen in activating the land profile are fairly modest, especially as the IMU performance rises.

RTK - Urban Canyon - Partial GNSS								
Profile	**IMU**	**2d Pos (m)**	**Hgt (m)**	**2d Vel (m/s)**	**Up Vel (m/s)**	**Roll (deg)**	**Pitch (deg)**	**Az (deg)**
default	G320	2.44	0.98	0.04	0.01	0.02	0.02	0.14
	µIMU	0.79	0.76	0.02	0.01	0.01	0.01	0.05
	100C	0.49	0.23	0.02	0.01	0.01	0.02	0.03
land	G320	1.70	0.55	0.05	0.01	0.02	0.02	0.12
	µIMU	0.78	0.78	0.02	0.01	0.01	0.01	0.05
	100C	0.47	0.23	0.02	0.01	0.01	0.02	0.03

Table 2 – RTK RMS Errors for Urban Canyon

As the clearest benefits of the land profile are seen on the Epson IMU, these will be explored graphically in figures 3 thru 5 below. Figure 3 shows the position domain, and the RMS differences can be seen in a few cases where the default mode errors increased faster than the land profile. An example of this divergence is most obvious around the 1500 second mark of the test during periods GNSS is most heavily blocked.

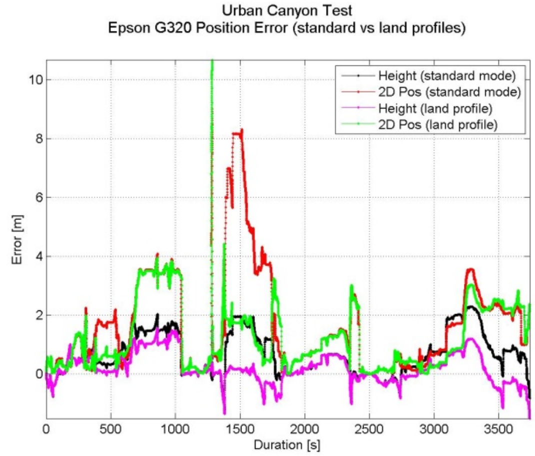

Figure 3 – Epson G320 Position Error (std vs land)

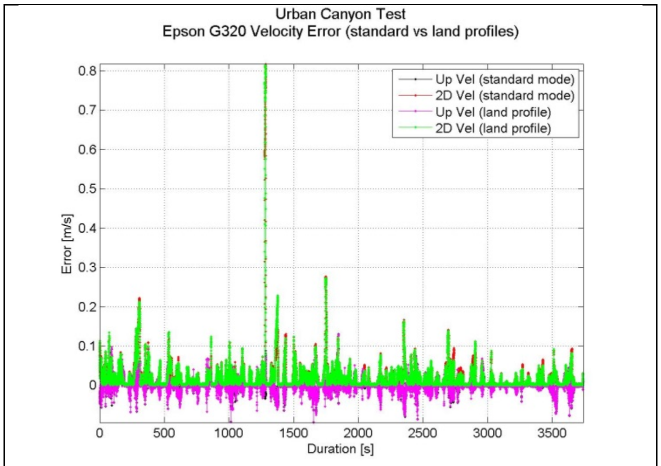

Figure 4 – Epson G320 Velocity Error (std vs land)

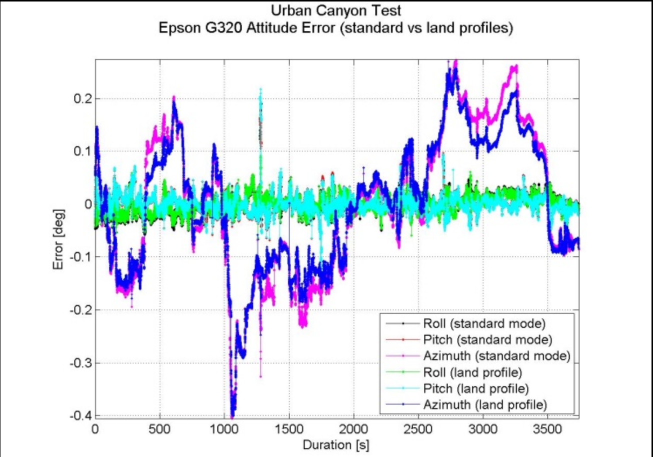

Figure 5 – Epson G320 Attitude Error (std vs land)

Low Dynamics Test

The low dynamics test is designed to emulate conditions experienced by machine control, agriculture, and mining applications. In this situation GNSS availability is generally not the limiting factor and can be used to control the low frequency position and velocity errors of the INS system. The difficulty is managing the attitude, especially azimuth, errors because attitude parameters are very hard to observe without significant rotations or accelerations.

The low dynamics test was collected in an open sky environment and consisted of traveling in a straight line on a rural road for roughly 2km at an average speed of 10-15km/h.

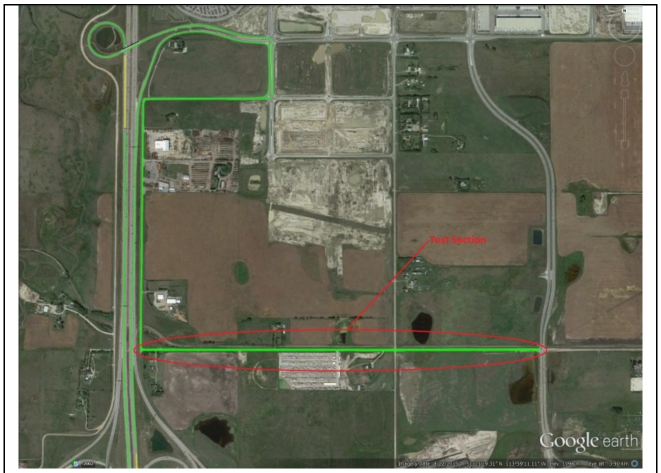

Figure 6 – Low Dynamics Test Trajectory [6]

As this type of scenario provides little physical impetus, the azimuth and gyroscope biases are not observable. The reason for this is due to the use of the first order differential equations to estimate the navigation system errors [7]. Essentially the differential equations define how the position, velocity and attitude errors change (grow) over time based on each other and the IMU errors. The observability of a particular update is tied to additional states thru the off diagonal elements of the derived transition matrix with the accelerations and rotations experienced by the system.

The overall RMS solution errors for RTK are provided in Table 3 below. As evident by the results presented, the position and velocity errors are clearly constrained by the continuous RTK level GNSS position regardless of whether the land profile is enabled or not. The real differentiator in the land profile is the attitude performance due to the use of phase windup as a constraint. Moreover, the attitude improvements are certainly tied to IMU quality.

The Epson G320 exhibited a noticeable improvement in the attitude performance, while the higher performance IMUs did not. This is not entirely unexpected as the precision of the phase windup is lower than that of the higher grade IMUs.

RTK - Low Dynamics - Full GNSS								
Profile	**IMU**	**2d Pos (m)**	**Hgt (m)**	**2d Vel (m/s)**	**Up Vel (m/s)**	**Roll (deg)**	**Pitch (deg)**	**Az (deg)**
default	G320	0.03	0.02	0.01	0.01	0.01	0.01	0.20
	µIMU	0.02	0.02	0.01	0.01	0.01	0.01	0.07
	100C	0.03	0.02	0.01	0.01	0.01	0.01	0.05
land	G320	0.03	0.02	0.01	0.01	0.01	0.01	0.13
	µIMU	0.02	0.02	0.01	0.01	0.01	0.01	0.07
	100C	0.03	0.02	0.01	0.01	0.01	0.01	0.05

Table 3 – RTK RMS Errors for Low Dynamics

Looking at the data graphically, figure 7 below shows the effect of land profile on positioning performance in this scenario. The two solutions are indistinguishable on the plot, and are all within standard RTK level error bounds as was indicated in the RMS table.

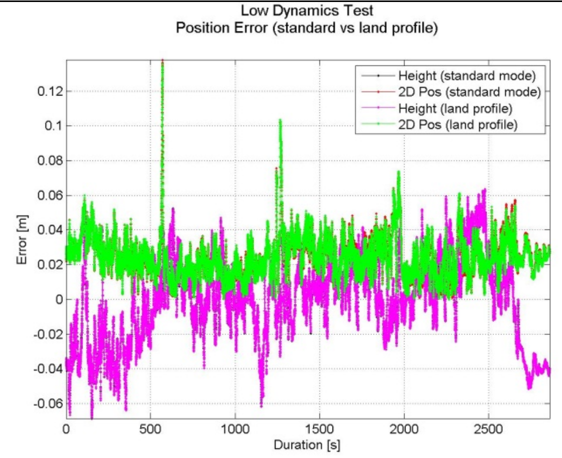

Figure 7 – Low Dynamic Epson G320 Position Errors

Figures 8 thru 10 show the attitude accuracy with and without the land profile enabled. In this case the attitude error accumulation can be seen in all three IMUs, though note the scale is different in each plot. Only figure 7 with the Epson data shows a difference as table 3 indicated where the azimuth drift is clearly constrained. All the sharp corrections in each plot correspond to the vehicle turning around at the end of each 2Km line and illustrates how much more powerful a rotation observation can be in azimuth accuracy overall.

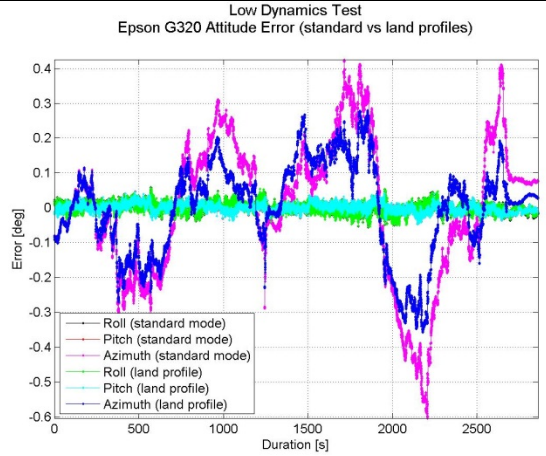

Figure 8 – Epson G320 Attitude Error (std vs land)

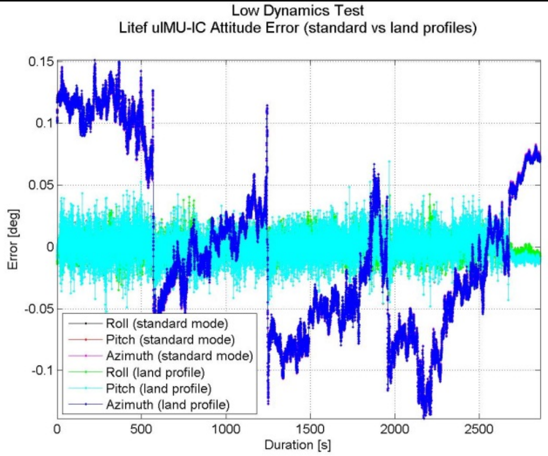

Figure 9 – Litef µIMU-IC Attitude Error (std vs land)

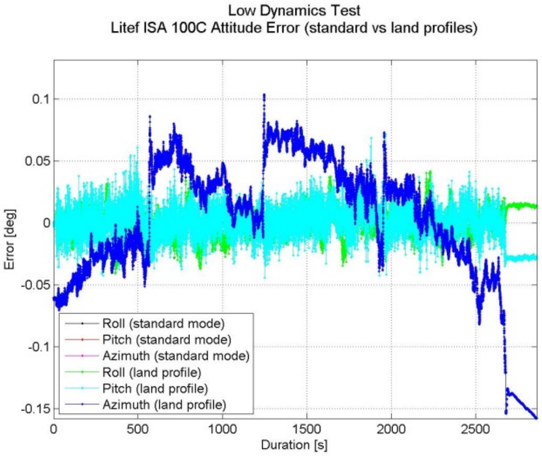

Figure 10 – Litef ISA 100C Attitude Error (std vs land)

Parking garage Test

The parking garage test was carried out at the YYC airport and was selected to show the INS solution degradation during extended complete GNSS outages. The test consisted of an initialization period in open sky conditions to allow the SPAN filter time to properly converge, followed by a 500 second period within the parking garage. During the interval within the parking garage there were no GNSS measurements available.

The following figure provides a trajectory of the test environment. The time spent inside the parking structure is evident on the center bottom of the image.

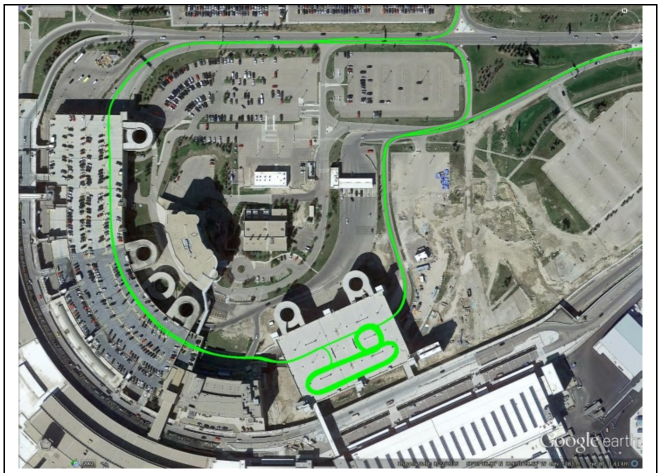

Figure 11 – Parking Garage Test Trajectory [8]

Unlike urban canyon environments that contain partial GNSS information, this exhibits an extended period of complete GNSS outage. During this type of scenario, the IMU specifications provided in Table 1 become much more significant. IMU errors directly translate to the duration the solution can propagate before the accumulated low frequency errors of the IMU grow to unacceptable levels. System performance during the outage degrades according to the system errors at the time of the outage and the system noise. The velocity errors increase linearly as a function of attitude and accelerometer bias errors. The attitude errors will increase linearly as a function of the un-modeled gyro bias error. The position error is a quadratic function of accelerometer bias and attitude errors.

Position results from each IMU are shown below in figures 12 to 14. All plots show the error with the land profile on and off. These clearly show the second order position degradation in the system that occurs in standard mode when GNSS measurements are not available.

It is also obvious via the y-axis scale on each plot how the individual IMU specifications are reflected in the INS performance during prolonged outages, when no external inputs are available to control the error growth.

By enabling the land profile, the filter constrains IMU errors by utilizing a velocity model for wheeled vehicles. With the constraints the position errors are startlingly reduced for the Epson G320 and then progressively less impactful as the IMU quality increases in the µIMU and the ISA-100C, respectively. This makes sense as the IMU error growth is progressively smaller in those IMUs, so the effect of mitigating them is also reduced.

One notable anomaly in the plots is explained by a self-detected zero velocity update (ZUPT) which occurred around the 425 second mark of the test. Much more apparent in the standard mode, this allowed the system errors to be corrected and resulted in a noticeable improvement in the INS solution. This ZUPT was detected only in the ISA-100C and µIMU, which is why there are no apparent effects on the Epson. Detecting a ZUPT relies on the solution quality and is more difficult to detect as the velocity estimates drift, which is why the Epson solution was unable to detect it in standard mode.

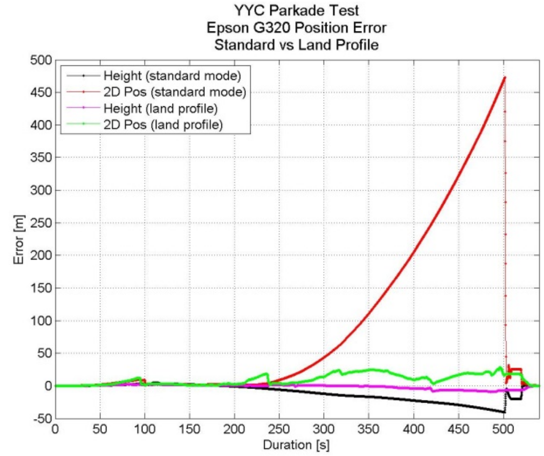

Figure 12 – Epson G320 Position Error (std vs land)

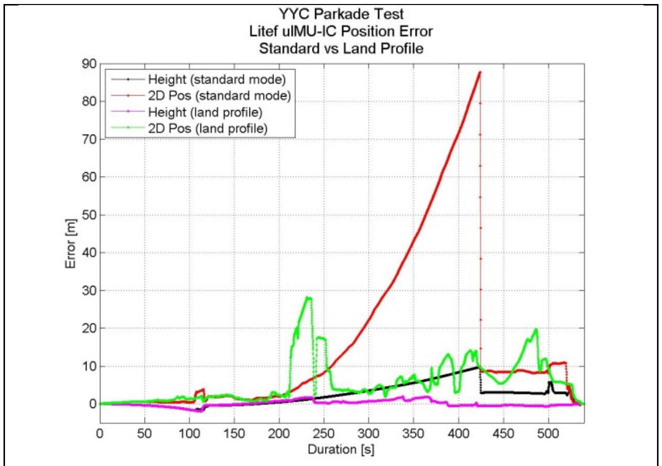

Figure 13 – Litef µIMU IC Position Error (std vs land)

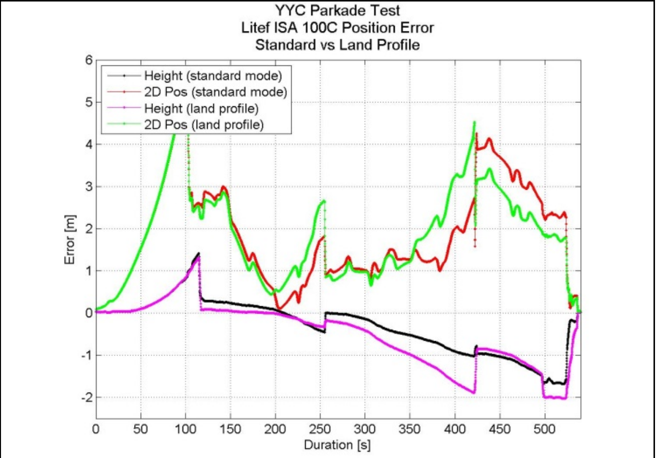

Figure 14 – Litef ISA 100C Position Error (std vs land)

Moving on from the position domain to the velocity domain, similar performance improvements relating to the use of the land profile can be seen in Figures 15 to 17 below.

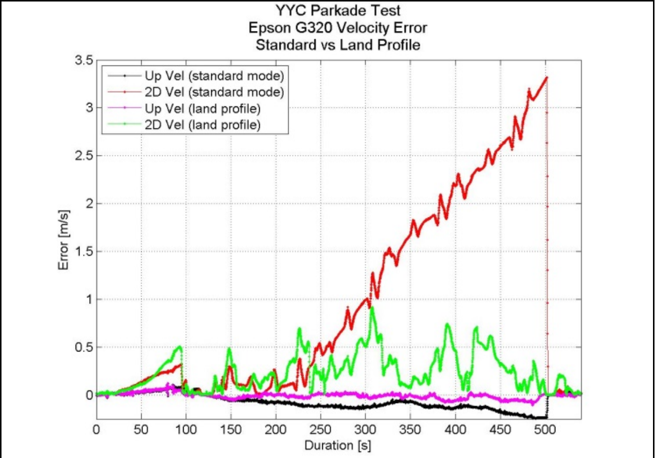

Figure 15 – Epson G320 Velocity Error (std vs land)

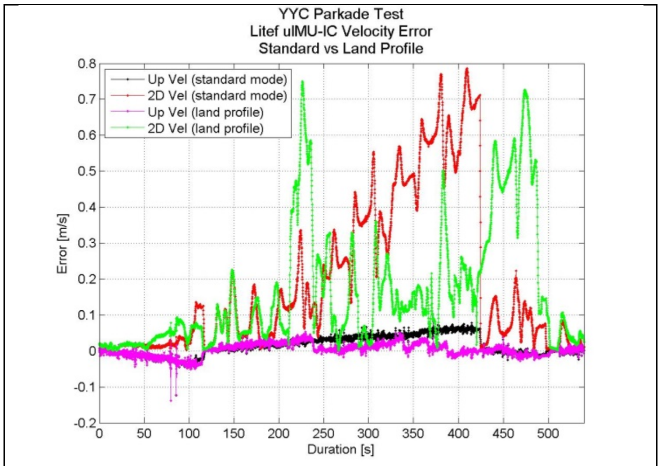

Figure 16 – Litef µIMU IC Velocity Error (std vs land)

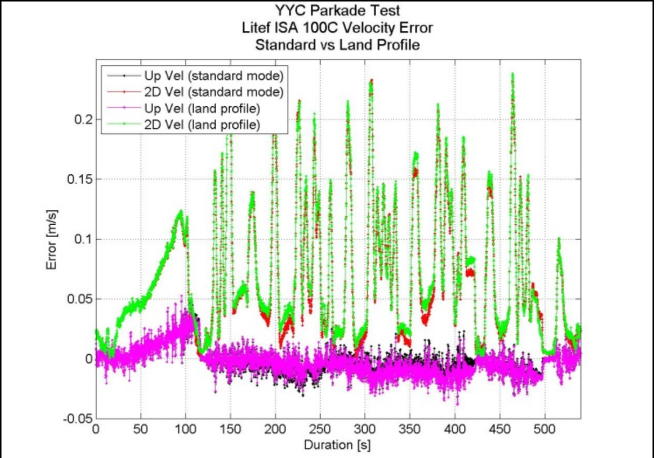

Figure 17 – Litef ISA 100C Velocity Error (std vs land)

As with position, the improvements in velocity are more significant with lower IMU specifications. This is due to the fact that the land profile was initially implemented to improve the performance of these units specifically.

The azimuth error degrades slightly for the land profile in Table 4. There are a few reasons for this. The land profile velocity constraints tend to push unaccounted error into the attitude rather than position, and in the case especially of the µIMU, the ZUPT near the end of the outage period had a dramatic effect on the filter estimates. In most cases, the tradeoff of slightly larger azimuth errors versus greatly reduced position errors in long GNSS outages can be considered very advantageous.

Figures 18 to 21 provide the standard vs land profile attitude errors.

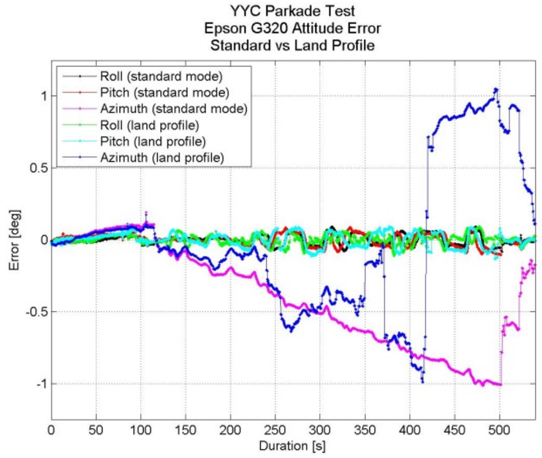

Figure 18 – Epson G320 Attitude Error (std vs land)

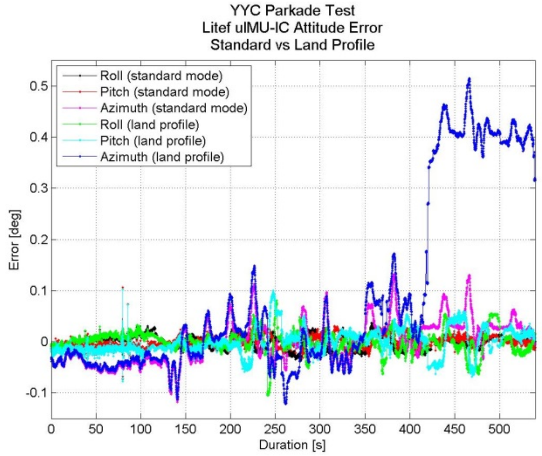

Figure 19 – Litef µIMU IC Attitude Error (std vs land)

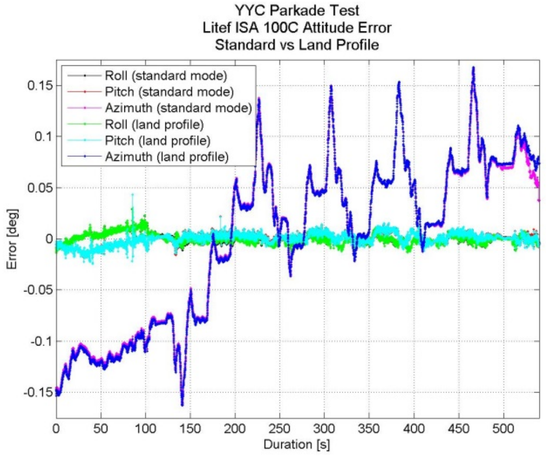

Figure 20 – Litef ISA 100C Attitude Error (std vs land)

A summary of all the 1-sigma RMS error statistics are provided in Table 4.

RTK - Parkade - GNSS Denied (500s)								
Profile	**IMU**	**2d Pos (m)**	**Hgt (m)**	**2d Vel (m/s)**	**Up Vel (m/s)**	**Roll (deg)**	**Pitch (deg)**	**Az (deg)**
default	G320	157.01	15.99	1.38	0.11	0.04	0.04	0.35
	µIMU	27.02	3.59	0.29	0.03	0.01	0.01	0.04
	100C	2.18	0.70	0.09	0.01	0.00	0.01	0.08
land	G320	12.50	3.48	0.30	0.03	0.03	0.05	0.50
	µIMU	8.19	0.77	0.24	0.02	0.02	0.02	0.18
	100C	2.15	0.89	0.09	0.01	0.00	0.01	0.08

Table 4 – RTK RMS Errors Parking garage (500s)

RESULTS & CONCLUSIONS

In testing a range of IMUs in some challenging scenarios, this paper has sought to illustrate what kind of performance is achievable using each kind of system. An added complexity is looking at what affect certain inertial constraint algorithms have on this solution.

Although low cost MEMs IMUs are continuing to greatly improve in quality and stability, the end application is still highly correlated to the overall performance of a selected INS system. For a great many applications, the MEMS devices in combination with a robust inertial filter can meet requirements and provide excellent value. However, some applications continue to require higher end sensors, and possibly post-processing to meet their needs.

The ability of SPAN to utilize partial GNSS measurements such as pseudorange, delta phase and vehicle constraints means even low cost MEMs are capable of providing a robust solution in challenging GNSS conditions. However, this tightly-coupled integration is limited in cases where GNSS is completely denied or when in low dynamic conditions.

INS profiles using velocity constraints, phase windup, and robust alignment routines have been shown to provide substantial aid to the INS solution in tough conditions, such as GNSS denied or low dynamics. These improvements were shown to exhibit greater impact as the IMU sensor precision decreases. These abilities in conjunction with the existing tightly coupled architecture of SPAN and the ever increasing accuracy of MEMS IMUs indicate that robust GNSS/INS solutions will continue to proliferate at lower cost targets. However, very precise applications such as mapping will continue to rely on higher quality sensors to meet strict accuracy requirements.

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[6] *Source:* "Figure 6. Low Dynamics Test Trajectory", **Google Earth**. August 22, 2015. July 12, 2016.
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[8] *Source:* "Figure 11. Parking Garage Test Trajectory", **Google Earth**. August 22, 2015. July 12, 2016.