NovAtel's SPAN® Land Vehicle

Performance Analysis—May 2017

Abstract

In its simplest form, dead reckoning is the estimation of a position without any external input save a starting point. In this forum external input generally refers to GNSS satellites and dead reckoning as the positioning through a GNSS outage.

Without external input, dead reckoning is inherently dependent on assumptions of velocity and heading to propagate the position. The simplest form of course would be the assumption of constant velocity and heading.

Dead reckoning solutions have evolved by integrating inertial and directional sensors to provide more local input and improve the solution propagation. This however is not a perfect method as inertial sensors have their own errors which grow exponentially over time. The error growth rate depends on the accuracy and cost of the IMU used. This means the next major evolution of dead reckoning performance is how well the system is able to interpret all the measurement information from the various local sensors to minimize the error growth.

This article aims to quantify the performance of the latest NovAtel innovations in dead reckoning—SPAN Land Vehicle. Land Vehcile performance was first introduced at ION GNSS+ 2016. The basic premise of it is to control inertial error growth based on assumptions about vehicle dynamics to constrain lateral and vertical vehicle movement on land.

Though the focus of this paper, Land Vehicle methodology is not limited to only GNSS outage dead reckoning, but contains innovations for different conditions as well. Innovations such as NovAtel's patented Antenna Phase Windup technology to provide additional heading information based on rotation of the antenna, for example. More information on these other enhancements can be found in the ION2016 paper (www.novatel.com/assets/Documents/Papers/Performance-Differentiation-in-a-Tighlty-Coupled-GNSS-Solution.pdf).

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.

Percent Error Over Distance Travelled

Before we explore dead reckoning performance of Land Vehicle, the Percent Error over Distance Traveled (EDT) specification needs to be discussed.

The most common measure of dead reckoning performance is EDT. This is at odds with the typical inertial method of measuring error growth over time (recall that inertial sensor error growth is exponential with respect to time). The constraints described above are applied to allow for extended dead reckoning and change the error growth characteristics of the system. Still, there are some important nuances about the EDT statistic that bear some discussion.

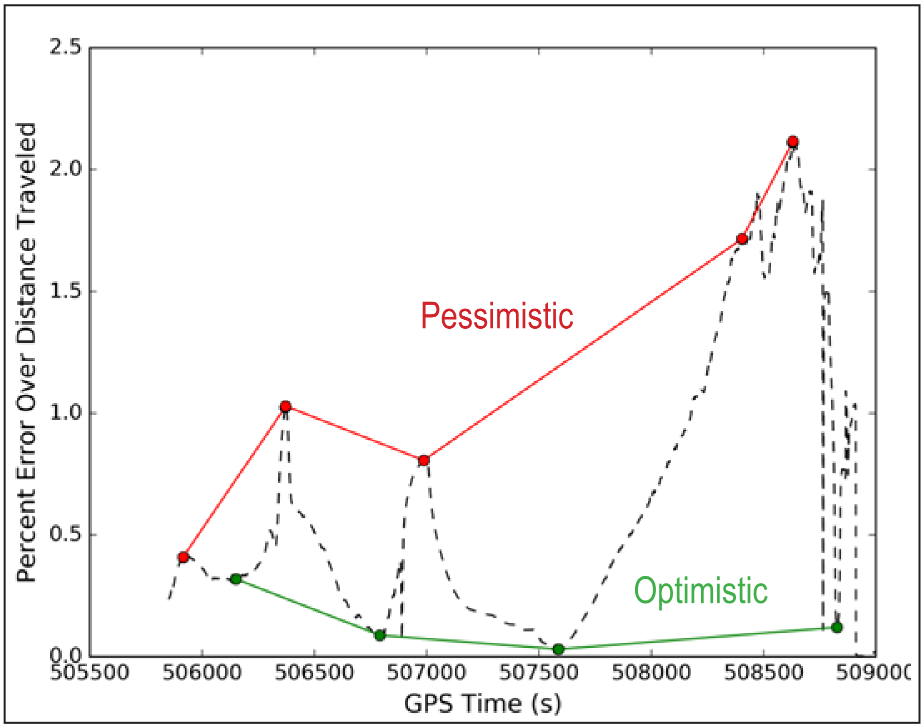
A typical method of representing the EDT statistic is producing an error table over specific outage or distance measurements. Table 1 is a sample table of outage duration performance.

The sample outage table shows a limited view of how well the system might perform, however it does not really convey the true performance of the system. This is especially true as the outage durations increase. By picking specific points to output the error, there is an opportunity to report heavily optimistic or pessimistic results. Figure 1 shows an example EDT plot of the IMU showing the entire outage as an example.

Table 1: Sample Outage Performance

Check Point	Outage Duration (s)	Distance Travelled	Error (m)	EDT (%)
1	400	10.8	34.4	0.32
2	1040	30.1	26.6	0.09
3	1835	54.6	16.4	0.03
4	3076	90.5	108.7	0.12

Figure 1: How EDT Is Misrepresented in Real-Time Data



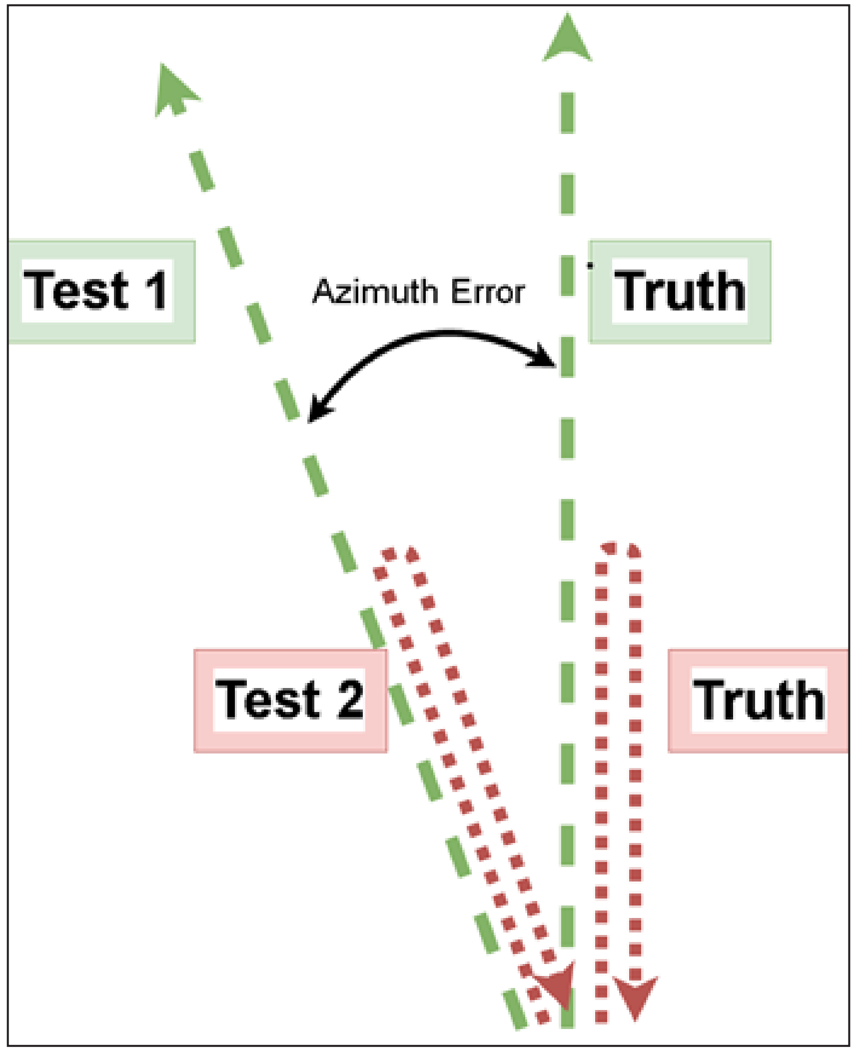
Note that the EDT can be quite variable throughout the outage. This is certainly not the behavior the outage table infers and the limitations of such an outage table are immediately apparent.

The changes in EDT over the course of an outage correlate to zero velocity updates and changes in the direction travelled. Figure 2 illustrates how azimuth plays a role in EDT calculations. Two simplified test cases are given in which EDT is calculated. In both cases we assume no velocity error and a constant azimuth error. In Test 1 the test unit is driven 100 km in a straight line. In Test 2, the unit is driven 50 km in a straight line and then turned around 180 degrees and driven back 50 km. Both these test cases amount to the same distance traveled, but the second case will finish with zero EDT while the first will not. Two important topics regarding EDT are now clear.

1. Many data points for each outage duration are needed to ensure statistical validity
2. Trajectory dynamics play a major role in EDT numbers, all dynamics must be included in the calculation of EDT

With an error budget in mind, it would be prudent to make a decision based on many datasets. Repeatability of results in varying environments and dynamics is needed to quantify the performance. This information is relevant to the IMU choice required for a specific application. As with everything, a higher performance IMU will heavily influence the error performance achievable during an extended outage.

Figure 2: Azimuth's Contribution to EDT

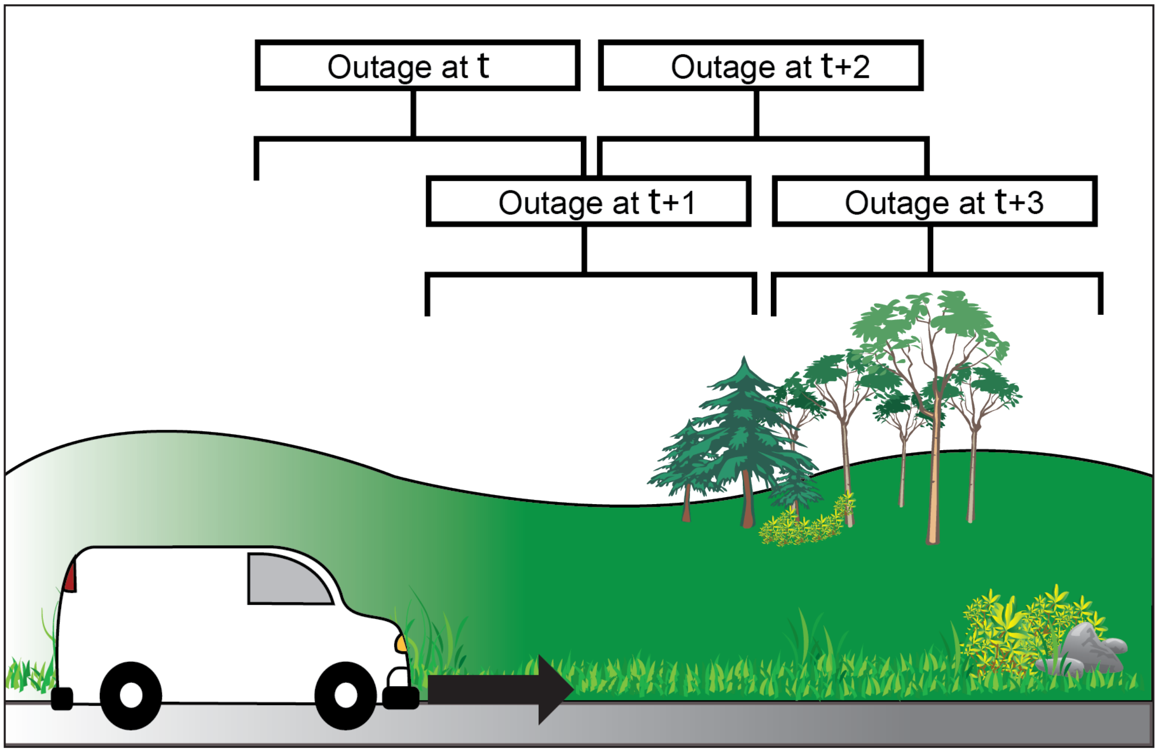


Emulation

The more practical way to get data for multisensory dead reckoning systems performance is with a GNSS outage applied on a raw measurement dataset in emulation. In this method, GNSS measurements are intentionally removed to induce an outage. A dataset consisting of raw inertial and GNSS measurements is first collected. Those measurements observed in a real environment are input into the algorithm engine as if they were seen by the receiver in real time, but instead in a PC emulating the receiver.

In emulation, a GNSS outage is applied to the dataset at different times and durations throughout the dataset. This creates a moving outage window, indirectly randomizing directional and motion changes for each outage. Different outage durations are also applied across the same dataset.

Figure 3: Different Outages Across the Same Dataset



The emulated outage trajectory is compared against the truth trajectory to compute error. Error statistics are then compiled for each of the outage durations. Emulated outages both increase the number of data points included in the EDT calculations, as well as provide coverage of all the dynamics within a test route.

Data Collection

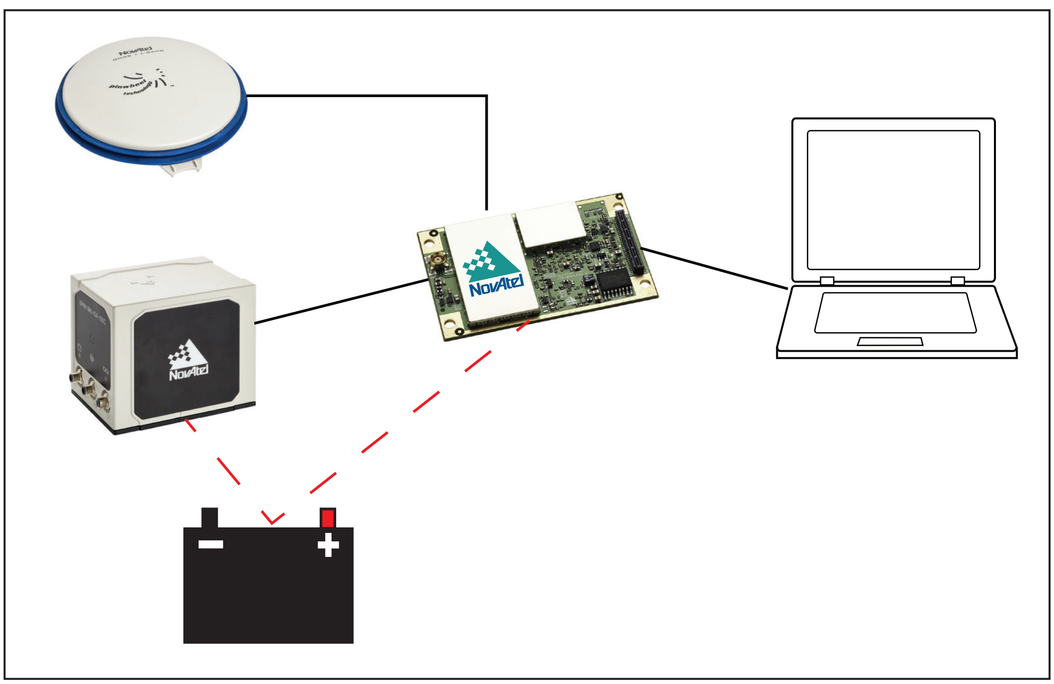
For the Land Vehicle performance tests, data was collected with three grades of IMU. Each IMU's performance is summarized in Table 2. Each IMU was mounted in a test vehicle and attached to a separate OEM7700 GNSS receiver. A GNSS antenna was attached to the receiver. The receivers were then connected to a PC for data logging. Figure 4 demonstrates the setup for one of the three IMUs.

1. OEM7700 and OEM7720 Cards
2. IMU (see Table 2)
3. GPS-702-GGL Dual Frequency Antenna

Table 2: IMU Specifications

	IMUs		
	Epson G320N (7700)	Litef µIMU-IC (7720)	Litef ISA-100C (7720)
PHYSICAL CHARACTERISTICS			
Size (mm)	24 x 24 x 10	85 d x 60 h	180 x 150 x 137
Power (W)	0.1	8	18
GYROSCOPES			
Bias Repeatability (°/hr)	1800	10	0.5
Bias Repeatability (°/hr)	3.5	6	0.5
ARW (°/hr)	0.1	0.3	0.012
ACCELEROMETERS			
Bias (mg)	15	3	1.25
Bias Instability (mg)	0.1	0.05	0.01

Figure 4: IMU Receiver Setup



Test Environments and Results

IMU evaluation happens under different test environments in order to cover the different dynamics for land vehicles. Error over Distance Traveled (EDT) and azimuth error are used to evaluate the performance of a particular combination of IMU and profile. EDT is presented as a percent of the horizontal error divided by the distance traveled. EDT is only statistically relevant with sufficient data points and therefore cannot be used as a reproducible metric in real-time testing (where only one real data point is available per duration). While real-time testing is critical in confirming system performance, emulated outages are better used for statistical data as they gather enough data-points to confidently determine a reproducible EDT. Note that EDT is a less stable statistic at shorter duration outages where the outage duration does not yet cover all the dynamics of the route. Azimuth error is represented as a 1 sigma standard deviation. The error envelopes produced in the plots in Figure 6 are 1 sigma from the mean.

Open Sky Test Route

The Open Sky route contains a mixture of freeway and city driving with no overhead obstructions. The mixed environment has an average speed of 65 km/hr and incorporates a moderate amount of dynamics. Performance is evaluated after initial system convergence. Regarding EDT, this test route includes a wide amount of dynamics. The route includes a moderate number of turns and speed variations while not having an over optimistic speed to build the distance traveled denominator. Emulated outages are used to evaluate performance on this route. Figure 5 shows the trajectory of the Open Sky route.

Table 3 shows the improvements seen when applying Land Vehcile to the SPAN solution. Azimuth error is seen to increase by a slight amount while the EDT measure is dramatically reduced. This is a trade off in error mitigation for the dynamics in the open sky route.

A comparison of profiles is presented in Figure 6. Additional improvements achieved by adding a Distance Measurement unit (DMI) to the SPAN solution are also reported. A high accuracy DMI (1000 ticks/revolution) was used in the DMI Profile, in addition to having Land Vehicle enabled.

Figure 5: Open Sky Test Route

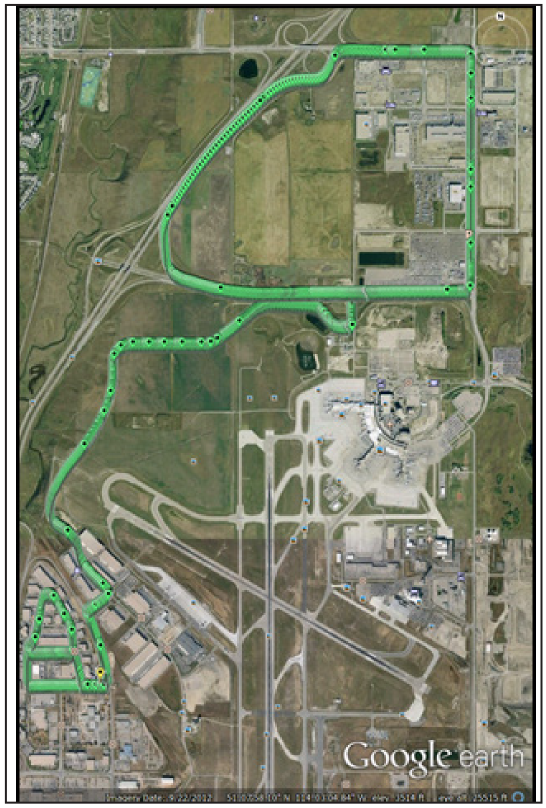
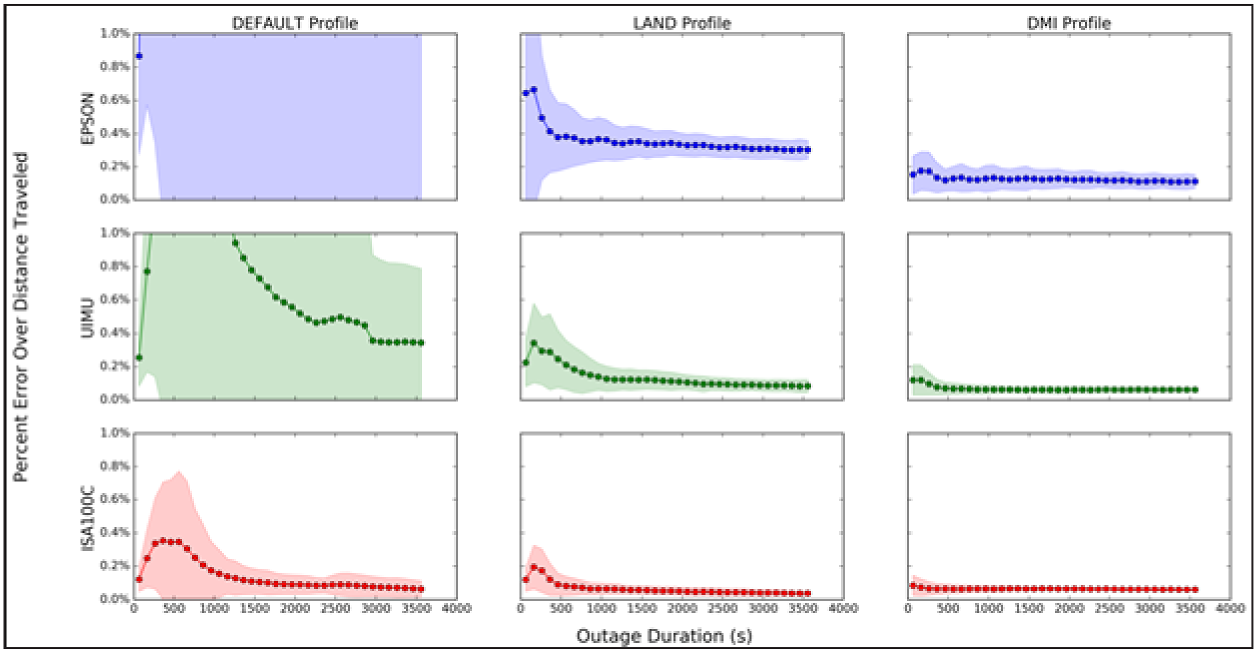


Table 3: Open Sky Test Route Results (1 hour outages)

IMU	EDT Default Profile (%)	EDT Land Profile (%)	Azimuth Default Profile	Azimuth Land Profile
EPSON G320N	111.7	0.31	1.08	1.74
Micro IMU	0.6	0.09	0.14	0.16
ISA100C	0.08	0.04	0.06	0.12

Figure 6: DMI and Land Vehicle Comparison Error Over Distance (Open Sky Route)



Straight Highway Test Route

The highway straight road test route was collected on a freeway connecting Calgary to Edmonton, which is approximately 260 kilometres long. The average speed of the route is 110 km/hr. The route has little change in azimuth, making it a challenging route for inertial systems during a GNSS outage. Regarding EDT, any azimuth error causes position error growth in one direction. EDT is therefore expected to be worse than in the case of the Open Sky route. Emulated outages are used to evaluate the performance of Land Vehicle on this route. Figure 7 shows the route's trajectory.

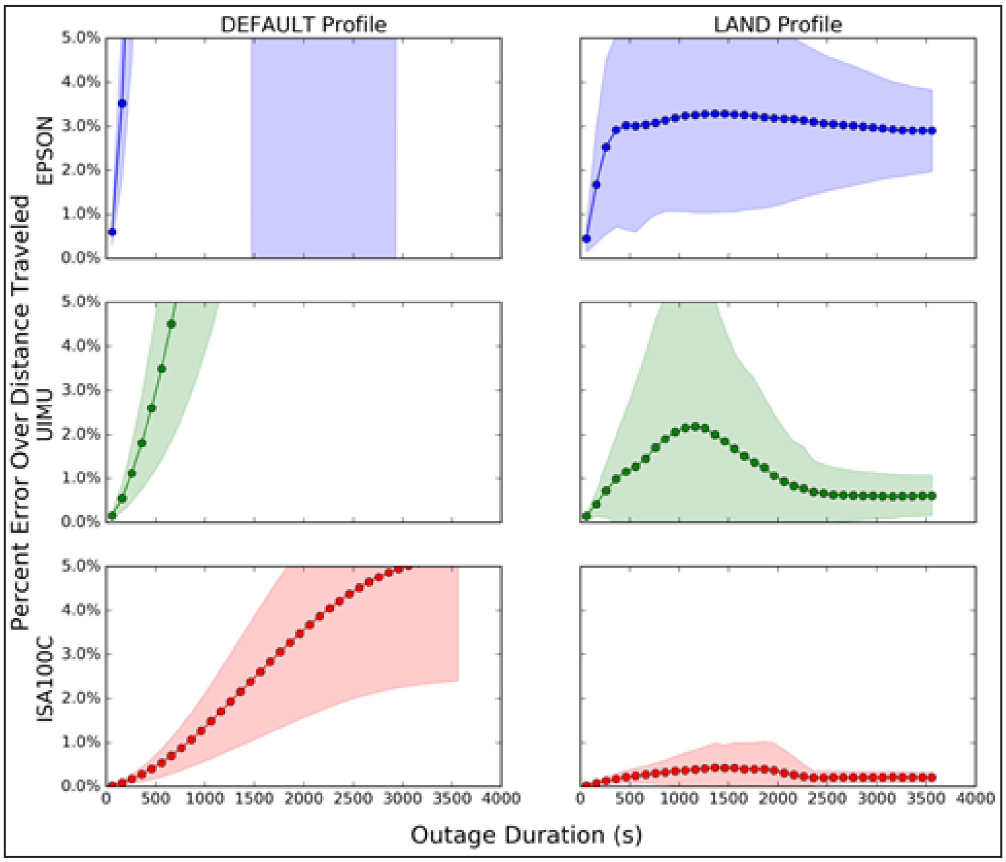
Figure 7: Highway Straight Road Test Route

Table 4 shows the improvements seen when applying Land Vehicle to the SPAN solution. Both EDT and azimuth error are dramatically mitigated by the effects of Land Vehicle. Figure 8 highlights the benefits seen when using Land Vehicle on the Highway Straight Road test route. Error growth, with a default profile, is as expected with the IMU driving the error growth exponentially. Land Vehicle mitigates this growth and ensures performance confidence at long duration outages.

Table 4: Open Sky Test Route Results (1 hour outages)

IMU	EDT Default Profile (%)	EDT Land Profile (%)	Azimuth Default Profile	Azimuth Land Profile
EPSON G320N	8226.0	3.00	17.37	0.81
Micro IMU	44.6	0.75	0.84	0.46
ISA100C	5.9	0.24	0.15	0.19

Figure 8: DMI and SPAN and Vehicle Comparison EDT (Highway Straight Road Route)



Conclusion

Proper weighting and application of land vehicle constraints are capable of dramatically reducing inertial error growth when GNSS is not available. The effects of this are far greater on lower cost sensors, though there is still a reliability and performance advantage to beginning with a more stable IMU sensor.

Metrics for performance over extended GNSS outages are difficult to quantify in a statistically relevant manner, and therefore provided specifications can be quite misleading. The method described herein should give confidence that this system and technology has been thoroughly tested and is presented with a high degree of confidence.

For more information on the NovAtel range of SPAN systems, please visit:

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

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