ANALYSIS OF A TIGHTLY-COUPLED MEMS IMU BASED GNSS/INS WITH AN EXTERNAL ODOMETER

Joshua Houghton* and Sandy Kennedy†

NovAtel® has implemented a small form-factor MEMS technology IMU into SPAN® (Synchronized Position Attitude Navigation), its GNSS/INS solution. Selected to match the needs of autonomous, low latency, precision applications, the Analog Devices ADIS16488 iSensor® IMU integrates a triad each of MEMS gyroscopes and accelerometers, and a pressure sensor. This commercially-available IMU features a high acceleration range, small size, and factory calibration.

The absolute positioning solution computed by the GNSS provides updates to the relative INS solution generated from IMU measurements. SPAN takes advantage of the computed inertial solution to aid in the tracking of GNSS signals. Additionally, the tightly-coupled architecture allows corrections to the inertial solution with fewer than the four visible GNSS satellites required to compute a position. The real-time position, velocity, and attitude solution is computed by the OEM615™ GNSS card. An MIC (MEMS Interface Card) board stacked with OEM615 provides an interface to the ADIS16488 as well as with an external odometer.

This paper explores the performance improvement of the inertial solution due to GNSS aiding with fewer than four satellite ranges versus the aiding provided by an external odometer. The analysis uses real-world, ground vehicle data, processed through an offline implementation of the NovAtel SPAN engine. The offline approach enables total control over GNSS signal availability. Results focus on the effect each form of solution aiding has on the position solution accuracy during periods of reduced GNSS availability. Solution performance with additional, external equipment, versus a self-contained technique to mitigate solution drift is presented. Conclusions are drawn about the performance gain due to an external odometer versus tightly-coupled architecture. Factors addressed include the additional effort to implement an odometer, as well as operational environment advantages for each technique.

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* Geomatics Engineer, GNSS+, NovAtel Inc., 1120 58 Ave NE, Calgary, AB, Canada, T2E8S5.
† Chief Engineer, GNSS Core Cards & SAASM, NovAtel Inc., 1120 58 Ave NE, Calgary, AB, Canada, T2E8S5.

INTRODUCTION

Low latency, self-contained position, velocity and attitude solutions are essential to autonomous navigation. The objective of this analysis is to provide insight in the relative costs and benefits of adding an odometer to a land-based Global Navigation Satellite System/Inertial Navigation System (GNSS/INS), and determine if tightly-coupled system architecture is a suitable alternative, providing similar benefits. Solution performance in ideal and real-world situations is presented for consideration.

POSITIONING SYSTEM DESCRIPTION

Source Measurements

The platform for this analysis is based on NovAtel's Synchronized Position Attitude Navigation (SPAN) inertial navigation solution. This tightly-coupled system integrates motion information from an inertial measurement unit (IMU) with GNSS observations from a NovAtel high precision global positioning receiver and velocity information from an external odometer.

Inertial navigation systems use information about linear and rotational accelerations. These accelerations are measured, with respect to an inertial frame of reference, by a triad of mutually orthogonal accelerometers and gyroscopes. The summation of these measurements provides velocity and change in angle for the three axes. A second summation results in position and attitude. The result of this integration is relative to a starting point, which is the first advantage of combining GNSS with INS. The initial position (and with some additional assumptions, attitude) of the GNSS solution provides a starting point for the relative INS solution.

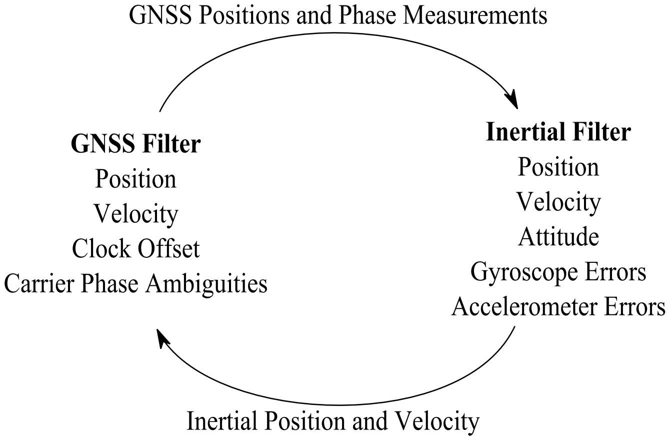

Figure 1. GNSS/INS Data Flow[1]

Using an Extended Kalman Filter (EKF) to fuse the information from GNSS with the INS solution provides an estimate of the errors in the observations. Shown in Figure 1, a tightly-coupled GNSS/INS refers to the ability to correct for error in both the IMU measurements and the GNSS measurements, leading to a better overall solution than a loosely-coupled system. A loosely-coupled system can only make use of the resulting GNSS position and not the raw measurements[2].

Odometers, or DMIs (Distance Measurement Instruments), are a well-known source of independent velocity (or change in distance) in sensor fusion navigation solutions. Odometers measure distance by counting the revolutions (or partial revolutions) of a wheel. Precise odometers can provide change in distance on the order of millimetres, dependent on the wheel circumference. With respect to time, this distance becomes a velocity. The independent nature of the odometer, not relying on an external system like GNSS, is an obvious advantage. Estimated velocity derived in this way will be un-correlated with the remaining observations in the system, and can be implemented with relatively little effort because the SPAN architecture includes support for this type of information. However, there are costs associated with adding an odometer, including financial cost, vehicle design changes, and maintenance for moving components. The assumptions made when using an odometer require that the vehicle be ground-based and wheeled. Tracked based vehicles require dual DMIs to account for differential steering, a technique not considered in this analysis.

Tightly-coupled GNSS/INS

Two significant benefits gained by having access to the measurements (and signal tracking loops) of a GNSS receiver include improvements to signal reacquisition following loss of signal, and the use of range (and Doppler) measurements, even when there are not enough observations to compute a position. With a correctly designed filter, even a reduced observation set will help estimate and control the inertial errors and improve the resulting solutions stability and accuracy.

When attempting to acquire a signal, a GNSS receiver must search across both code shifts and Doppler frequency to find the objective signal. With a priori information about receiver and satellite position and velocity, the search space for the signals is focused, allowing for quicker reacquisition of signals. Information about the satellite is derived from broadcast almanac and ephemerides, while information about the antenna position can come from the inertial solution. This feedback of information from the INS to the GNSS receiver ultimately results in longer total signal lock-time and more observations in areas where GNSS observations are routinely blocked.

Phase Updates

Access to the raw GNSS range measurements allows the positioning filter to make use of any available information, even when there are not enough observations to compute an absolute position. Positioning by satellite ranges requires a minimum of four signals to compute a position, one for each dimension (x,y,z) and one for time. A reduced set of observations, less than four signals, can be used as an update in a fully integrated GNSS/INS filter.

In a loosely-coupled GNSS/INS, the only available information from the GNSS receiver is a computed position. In this case, when only two of three satellites are available, assumptions are required to compute a position to use as an inertial update. In a tightly-coupled solution, when two or more GNSS observations are available, a phase update is possible[3]. Patented by NovAtel, the use of GNSS phase measurements to aid INS in an underdetermined situation (less than 4 satellites) is especially useful in urban canyons or locations where heavy foliage cause signal attenuation. Two or three satellite ranges translate into one or two phase updates, respectively. While a full position update is very powerful, this relative, smooth and precise update is a significant advantage in a GNSS denied environment.

TEST METHODOLOGY

This analysis focusses on the performance of the system for ground-based systems. To provide meaningful results, the data presented here was collected in real-world conditions. A circuit of roads located in Calgary, Alberta, with four straights of approximately 1.6 km, served as the test route. The relative proximity to the NovAtel office, combined with minimal sky obstructions, and no underpasses make this route ideal for collecting all-in-view GNSS data. With full signal coverage in the collected data, various levels of GNSS aiding of the INS can be tested.

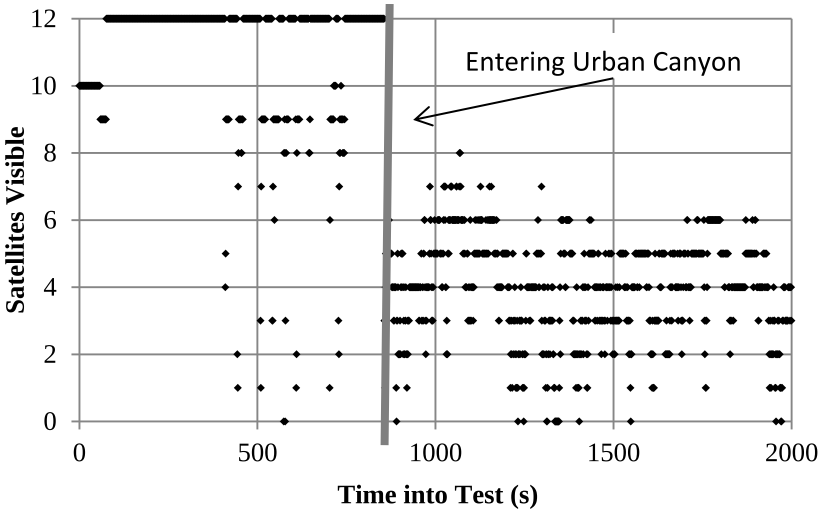

Figure 2: Satellites Visible in an Urban Canyon

To further understand the impact of different aspects of GNSS aiding, real-world data was collected in a challenging GNSS environment. The urban centre of Calgary, Alberta presents a significant test for GNSS. Shown in Figure 2, the numbers of satellites that are visible in an urban setting are significantly fewer than in open sky conditions. With highly-reflective surfaces, deep urban canyons and numerous pedestrian overpasses between buildings, the test route selected had frequent periods where a complete (four satellite) GNSS update was impossible.

GNSS/INS Receiver

Figure 3. SPAN-IGM-A1 Enclosure.

The GNSS/INS receiver under test was the NovAtel SPAN-IGM-A1. Shown in Figure 3, the system is composed of an enclosed OEM615 GNSS card, an MIC (power and interface card), and the Analog Devices ADIS16488 iSensor IMU. A GPS-702-GGL antenna was chosen for both the rover and base station. The base station was used to improve the control solution quality by using a differential GNSS positioning technique as part of the post-processing.

Table 1: ADIS16488 Specifications[*]

Parameter	Value	Unit
Gyroscope Input Range	±450	deg/sec
Gyroscope Initial Bias Error	±0.2	deg/sec
Gyroscope In-Run Bias	6.25	deg/hr
Angular Random Walk	0.3	deg/√hr
Accelerometer Input Range	±18	*g*
Accelerometer Initial Bias Error	±16	m*g*
Accelerometer In-Run Bias Stability	0.1	m*g*
Velocity Random Walk	0.029	m/sec/√hr

The manufacturer specifications for the ADIS16488 are given in Table 1. With high input thresholds for both attitude and acceleration, the IMU is suitable for operation in high dynamic situations, while remaining commercially exportable, and non-ITAR controlled.

As a source of reference to determine the error in the system, control data from a navigation-grade IMU was collected at the same time. The Honeywell HG2100 μIRS (Micro Inertial Reference System) is a high accuracy ring laser gyroscope (RLG) IMU, with very stable biases. The quality of this IMU, post-processed using NovAtel Waypoint® Inertial Explorer® (which take advantage of a Rauch-Tung-Striebel (RTS) smoother), results in a highly accurate reference solution. The ability to process both forward and backwards in time provides a strong confidence in the resulting control solution.

Distance Measurement Instrument

The DMI used in this test is an optical Kistler Wheel Pulse Transducer (CWPTA511), providing a resolution of 2000 counts per revolution. Assuming a wheel circumference of 2.0 m, this translates to a resolution of 1.0 mm per count. The WPT provides a pulse train to the SPAN-IGM-A1, where the interface card generates a cumulative sum of wheel events at a 1.0 Hz frequency, referenced to precise GPS time.

When DMI data is part of the available sensor inputs, an additional state of wheel size is added to the inertial filter. Pneumatic tires are susceptible to changes in dimension as they heat under friction, resulting in an increase in volume, and a larger circumference. This state allows for estimation of wheel size, and changes to the wheel size during the test, providing a stronger observation.

Determination of velocity or distance travelled from a DMI must account for the physical properties of the vehicle. In this test, the DMI is located at a different location than the IMU. Because of the offset from the IMU to the DMI (lever arm), the DMI will have a different velocity vector while the vehicle is turning. To account for this, and simplify the system, the filter does not use wheel velocity observations while the vehicle is turning. Additionally, the issue of wheel

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[*] http://www.analog.com/static/imported-files/data_sheets/ADIS16488.pdf

slippage can be mitigated by ensuring that observations are taken with respect to a non-drive wheel, thus the majority of the wheel rotation is due to actual vehicle motion.

Controlled GNSS Outages

To ensure that the comparison between the effect of phase updates and the effect of DMI updates is valid, an offline implementation of the SPAN inertial engine is used to process the same dataset with different update configurations. The offline version is an exact recreation of the real-time firmware which runs on the NovAtel GNSS receiver cards, and uses collected observations, in the form of data logs as input.

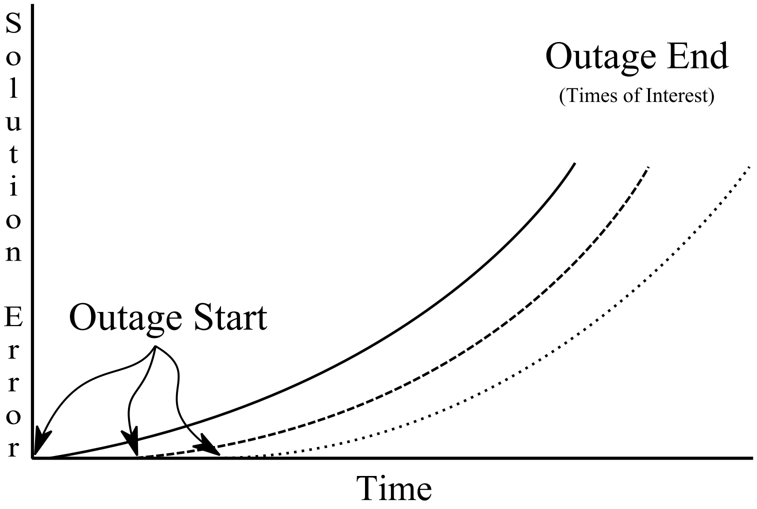

Figure 5. Outage Error Growth and Time of Interest.

The key performance of concern in this paper is the drift over time of the inertial solution with various forms of filter updates or corrections. To measure this, the offline implementation has the ability to remove GNSS observations for a period of time. Illustrated in Figure 5, GNSS is removed from the solution updates for a period of time, allowing the inertial solution to drift. It is then captured at the end of the outage and compared to a solution where there was no outage. Statistical significance is gained by applying an outage which begins at every epoch in the dataset, thus yielding statistics for all vehicle dynamics and over thousands of outages. By using all the epochs available in the data; bias due to selected dynamics, such as long stationary periods or particular driving technique, are removed.

ANALYSIS

Data Collection

The source data for the first part of this analysis was collected in an area with excellent GNSS availability. The location was selected for testing to ensure that the reference in the analysis was of high quality, minimizing the error in the resulting statistics as well as ensuring that there would be sufficient observations to remove during controlled outage testing. Data was collected with both the SPAN-IGM-A1 and the reference system (Honeywell µIRS), yielding in a dataset slightly longer than one hour in length.

Figure 6. Southbound Portion of Urban Canyon Test.

The second component of this test involved the downtown core of Calgary. A typical pedestrian overpass in this environment is shown in Figure 6, under which satellite lock is lost. A repeatable route was selected and driven for a period of one hour. The purpose of the repeatable route was for the ability to visually observe deviations in the pass-to-pass trajectory. Both the SPAN-IGM-A1 and the reference system were collected, providing an opportunity to characterize the solution in terms of approximate absolute error. Using the same offline implementation as in the controlled outages allows for a comparison of the solution with and without the addition of a DMI.

Analytic Technique

To estimate system performance once the solution has converged, or reached *steady state*, the solution collected on the test unit was compared to the control system. This was done in both ideal and urban situations. To accomplish this, the offsets from the control to test units were precisely measured, with an estimated error of less than 0.01 m in each direction. The resulting control solution was translated to the location of the test unit, and through iterative rotation, the attitude offset was removed.

GNSS outage analysis was conducted by using the controlled GNSS outage technique, run with a limited amount of update types, for each length of outage. To illustrate the impact of each update type, a baseline performance test was performed, where no updates were permitted during the GNSS outage. Each type of update configuration was also tested, including adding DMI information, adding 2, 3, or 4 satellites to the solution (partial GNSS outages).

RESULTS

The presented results are the root-mean squared (RMS) error (either absolute, or relative depending on the test). This approximates one standard deviation of error (1σ confidence).

Results of Steady State Analysis

Table 2: Solution Error with Full GNSS (Single Point)

Updates Used	2D Position Error (m)	Height Error (m)	2D Velocity Error (m/s)	Up Velocity Error (m/s)	Pitch Error (deg)	Roll Error (deg)	Heading Error (deg)
GNSS	0.896	0.800	0.015	0.018	0.020	0.020	0.119
GNSS + DMI	0.898	0.802	0.013	0.015	0.020	0.020	0.118

Analysis of the system performance when GNSS is fully available and in terms of absolute error is presented in Table 2. This shows the performance of the system when using every observation possible and can be considered *ideal* conditions. The solution error is computed by translating the reference solution from the µIRS to the location of the system under test. The mean offsets of the attitude are removed and considered to be a constant offset caused by misalignment in the mounting of the IMUs.

Table 3: Solution Error while in Urban Canyon (Single Point)

Updates Used	2D Position Error (m)	Height Error (m)	2D Velocity Error (m/s)	Up Velocity Error (m/s)	Pitch Error (deg)	Roll Error (deg)	Heading Error (deg)
GNSS	1.335	1.288	0.050	0.018	0.031	0.028	0.123
GNSS + DMI	1.568	1.135	0.037	0.016	0.030	0.025	0.119

Given in Table 3, the absolute error of the system with and without DMI information is given relative to a control system. These values represent the performance of the system during a difficult real-world scenario. The plot in Figure 2 shows an excerpt of the satellites available during a portion of this test.

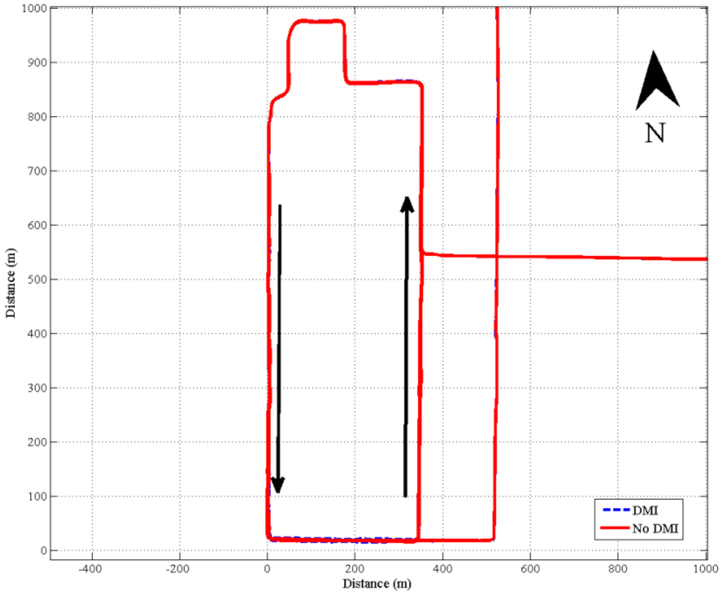

Figure 7. Position Solution in Urban Canyon

Shown in Figure 7 above, is the trajectory of the test during four passes over the same route. The difference between the solution with additional DMI information and the solution without the DMI aiding is negligible in most cases, and the pass-to-pass repeatability is consistent between both systems.

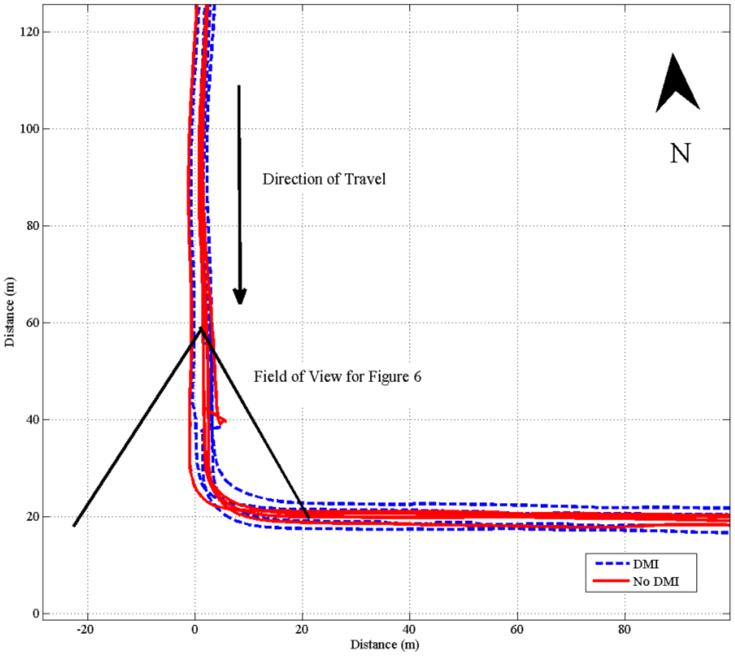

Figure 8. Close View of Position Solution in Urban Canyon

Enlarged to provide detail, Figure 8 shows the performance of both the DMI and non-DMI aided solution in an area of extremely poor GNSS quality. The image in Figure 6 was obtained along the test route and illustrates the south portion of the sky.

Results of Controlled GNSS Outage Analysis

Table 4: Solution Error Growth during 10 Second GNSS Outage

Updates Used	2D Position Error (m)	Height Error (m)	2D Velocity Error (m/s)	Up Velocity Error (m/s)	Pitch Error (deg)	Roll Error (deg)	Heading Error (deg)
None	0.312	0.064	0.061	0.006	0.025	0.021	0.060
DMI	0.258	0.063	0.051	0.006	0.025	0.016	0.054
1 Phase *2 Satellites*	0.290	0.065	0.056	0.006	0.024	0.020	0.057
2 Phases *3 Satellites*	0.255	0.065	0.050	0.006	0.021	0.018	0.047
3 Phases *4 Satellites*	0.215	0.063	0.041	0.006	0.018	0.016	0.036

Table 5: Solution Error Growth during 60 Second GNSS Outage

Updates Used	2D Position Error (m)	Height Error (m)	2D Velocity Error (m/s)	Up Velocity Error (m/s)	Pitch Error (deg)	Roll Error (deg)	Heading Error (deg)
None	16.116	1.131	0.705	0.040	0.094	0.079	0.261
DMI	9.342	0.978	0.442	0.034	0.088	0.030	0.217
1 Phase *2 Satellites*	14.380	1.034	0.634	0.036	0.085	0.066	0.237
2 Phases *3 Satellites*	11.814	1.000	0.520	0.034	0.070	0.057	0.159
3 Phases *4 Satellites*	5.779	0.954	0.231	0.031	0.038	0.032	0.109

Table 4 and Table 5 present the results of the inertial solution error growth during periods of outage and reduced observations. Prior to every removal of GNSS, the inertial filter was given 200 seconds of observations and vehicle dynamics to allow the inertial solution to converge to known values. This ensures the outage begins from a converged system state and the error growth reflects the true error growth of the system. To determine error growth, the result at the end of an outage is compared to the solution if there had been no outage at all.

DISCUSSION

In an operational environment, every possible source of information helps to constrain error growth during GNSS outages. During periods where full GNSS is available, the position error is dominated by the error in GNSS. When an outage occurs, the errors accumulated from the IMU measurements become the dominant factor in solution accuracy. Therefore, the ability to use all available measurements is critical to improving solution accuracy. The analysis presented above illustrates the benefit of using phase updates. When two phase updates are available, the growth in position, velocity and attitude error is constrained in a similar degree as if a DMI was used.

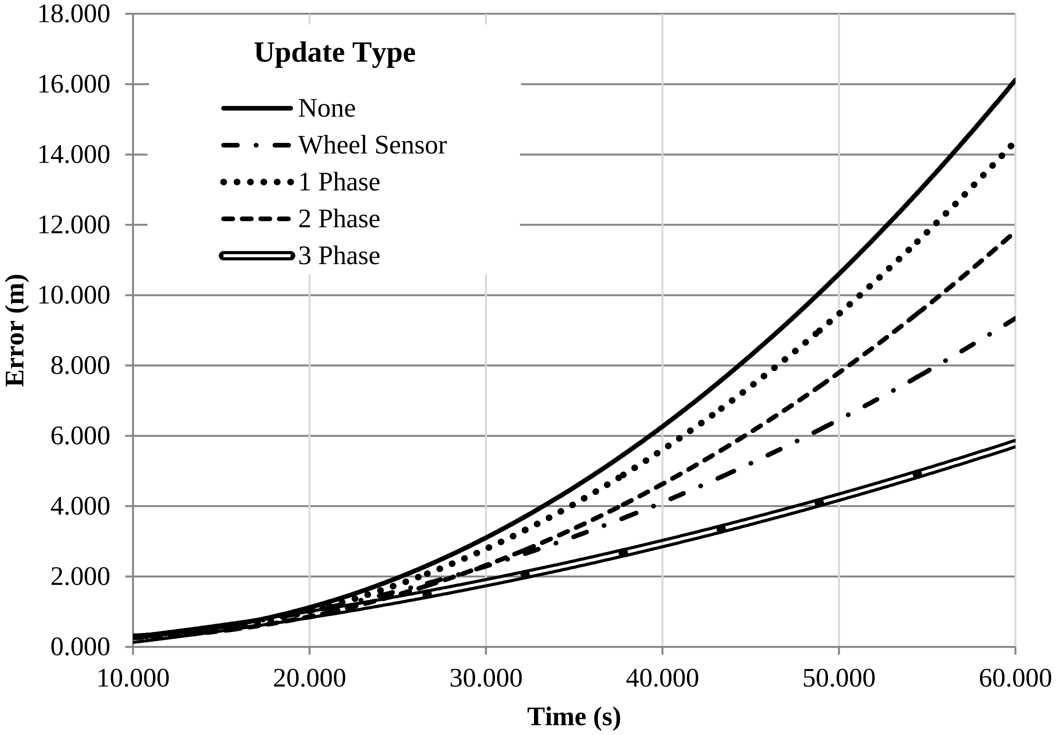

Figure 9: 2D Position Error During GNSS Outage

Shown in Figure 9, adding a single phase update during a 60 second GNSS outage reduces the position error growth by 18% from 21.05 m to 17.20 m. The value of a phase update is even stronger in heading, where the error growth is reduced by 31% from 0.342 degrees to 0.237 degrees.

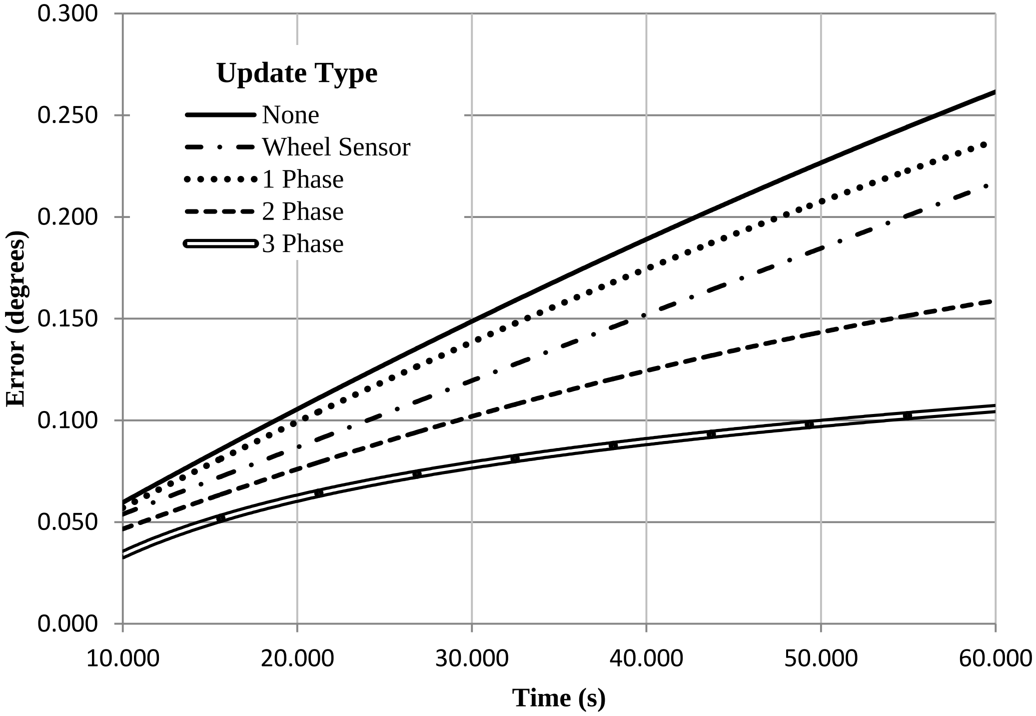

Figure 10: Heading Error During GNSS Outage

The benefit to the heading, illustrated in Figure 10 is more significant for phase updates than DMI updates. This is due to the additional information regarding directionality that is incorporated in phase updates. Compared to the sharp adjustment of a full position update following an outage, the continuous, precise phase update constrains solution drift and reduces the required correction to the inertial solution.

CONCLUSIONS

The experimental results show that the tight-coupling of GNSS and INS has the powerful advantage of constraining error growth during periods of reduced GNSS availability. The addition of a DMI to the solution provides a similar level of performance improvement as adding three visible satellites (two phase updates).

Wheel sensors have an obvious benefit in the control of error growth during total GNSS outages, but are only useful in ground-based applications. Restricted to land vehicles, DMIs are an additional piece of equipment to purchase, install, and maintain. The additional benefit of phase updates is gained without the need for additional equipment. Precise odometers are also comparatively expensive; significantly increasing the price for MEMS-based GNSS/INS. During periods of three or four visible GNSS satellites, the advantage of DMI information is overshadowed by the strength of phase based updates.

In a challenging urban environment, the benefit of a DMI is similar to the advantage of tightly-coupling the GNSS and INS components of the system, and using phase updates. For optimal performance in a real-time positioning system, all possible observations should be considered. However, given constraints on budget, considerations to operating environment and maintainability; the addition of phase information to the navigation filter is an excellent match to the benefit derived from an external odometer.

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