Benefits of Using a Tactical-Grade IMU for High-Accuracy Positioning

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ABSTRACT: *Integration of GPS with inertial sensors can provide many benefits for navigation, from improved accuracy to increased reliability. The extent of such benefits, however, is typically a function of the quality of the inertial system used. Traditionally, high-cost, navigation-grade inertial measurement units (IMUs) have been used to obtain the highest position and velocity accuracies. However, the work documented in this paper uses a Honeywell HG-1700 IMU (1 deg/h) to assess the benefits of a tactical-grade IMU in aiding GPS for high-accuracy (centimeter-level) applications. To this end, the position and velocity accuracy of the integrated system during complete and partial GPS data outages is investigated. The benefit of using inertial data to improve the ambiguity resolution process after such data outages is also addressed in detail. Centralized and decentralized filtering strategies are compared in terms of system performance.*

INTRODUCTION

The integration of GPS receivers with inertial navigation systems (INS) has been well investigated in the past. The advantages of integrated systems relative to GPS-only are reported to be a full 6 degrees of freedom navigation solution, improved accuracy, smoother trajectories, and reduced susceptibility to jamming and interference [1]. Other studies have examined the benefit of using the inertial solution to improve ambiguity resolution performance [2–4].

The extent to which the above advantages hold is well known to be dependent on the quality of the inertial measurement unit (IMU) used in the integration. With this in mind, it is not surprising that past investigations have typically looked only at using high-end, navigation-grade inertial systems for high-accuracy (centimeter-level) applications. Unfortunately, the cost of these inertial units can be prohibitive for many applications and/or agencies. With the decreasing cost of tactical-grade inertial sensors, however, their use in integrated navigation systems is desirable. Yet the question arises of whether these lower-cost units will still be of benefit for applications demanding the highest accuracies. From a different standpoint, could the cost of a tactical-grade IMU be justified by the resulting improvements in the integrated solution relative to the GPS-only case?

This paper aims to quantify the benefits of using a tactical-grade IMU in high-accuracy navigation systems compared with using GPS alone. This work is novel in light of previous investigations that have used primarily navigation-grade units to obtain the highest navigation accuracy. In particular, the following performance parameters are investigated:

- Position accuracy during complete and partial GPS data outages. Results of this investigation determine the operational conditions under which the system can be used to maintain a given level of performance. Positioning performance is assessed for the situation in which L1 or widelane carrier-phase ambiguities are available. Velocity accuracy is also investigated for applications to which this parameter is most relevant.
- The time needed to determine the integer ambiguities after complete and partial GPS data outages. The veracity of the ambiguity fix is also considered. Again, the investigation addresses applications requiring L1 or widelane ambiguities.

The above parameters are investigated by simulating GPS data outages during postmission processing of real field data. A reference trajectory obtained using all available data is used for comparison purposes to assess system accuracy during the data outages. After the simulated data outages, the time required for the system to recover the fixed ambiguities is measured, as is the accuracy of the ambiguity fix.

In addition, by cross-referencing the ambiguity resolution performance with the positioning accuracy

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results, a more generic assessment of the benefit of using an inertial system for ambiguity resolution is obtained. This work contrasts with previous efforts that have focused on either navigation accuracy or ambiguity resolution without trying to link the two. Furthermore, GPS-only and GPS/INS ambiguity resolution performance under operational conditions is compared—something often overlooked in other studies.

A tactical-grade Honeywell HG-1700 IMU (1 deg/h) is used with a dual-frequency NovAtel OEM4 GPS receiver to assess the above parameters. Both loose and tight data integration strategies are investigated as appropriate for the parameter of interest. Initial assessments are obtained by simulating data outages in real GPS data.

The paper begins with a brief discussion of the relevant methodology, including a review of the integration strategies used, and the ambiguity resolution process and its relationship to position accuracy. The field tests used for quantifying improvements are then described, along with the analysis methodology itself. Finally, results are presented for each of the above performance parameters.

METHODOLOGY

This section reviews the GPS/INS integration approaches implemented herein, the GPS and INS setup, and the role of position accuracy in the ambiguity resolution process. For more details on these topics, the reader is referred to the cited references.

GPS/INS Integration Strategies

At the core of any integrated navigation system is a means by which the information is combined to produce a preferably optimal output. For GPS and INS integration, there are basically four levels of integration, based on how much information is shared. These four levels, listed in order of increasing complexity, are [3, 5]:

- Uncoupled integration
- Loose integration
- Tight integration
- Deep integration

The uncoupled approach is crude and will simply not be of much use in a high-accuracy system. Deep integration, although well suited to the problem at hand, requires access to GPS receiver hardware or at least tracking loop information, both of which are normally unavailable to most users. For these reasons, those integration strategies are not used herein.

The loose and tight integration strategies are those used most commonly in the literature. For convenience, the terms "loosely coupled" and "tightly coupled" are also used to represent the loose and tight integration strategies, respectively. In both cases, the GPS receiver and IMU are essentially working independently, with the difference between the integration strategies being the type of information that is shared. In loose integration, separate GPS and INS filters are implemented, and the position and/or velocity of the GPS filter are used as observations in the INS filter. With tight integration, only one filter is used to estimate all relevant GPS and INS states. Figures 1 and 2, respectively, depict these two integration strategies.

All things being equal, the two approaches yield identical results, assuming that the proper covariance information is shared between filters in the loose integration. Unfortunately, this equality is rarely realized because in a loose integration strategy, process noise must be added to both the GPS and INS filters. The increased process noise relative to the process noise added to the GPS/INS filter in the tight integration strategy (see below for details) will introduce some small discrepancies. A comparison of the two approaches has shown these discrepancies to be on the order of a few millimeters under good satellite coverage [6]. A comparison of the two approaches in the absence of good satellite coverage is investigated herein.

The advantage of a loose integration strategy, in general, is that the dimension of the state vector is reduced relative to the tight integration case. This allows for computationally more efficient programs because of the reduced number of floating-point operations needed in the Kalman filtering algorithm. A second potential advantage is that the output from

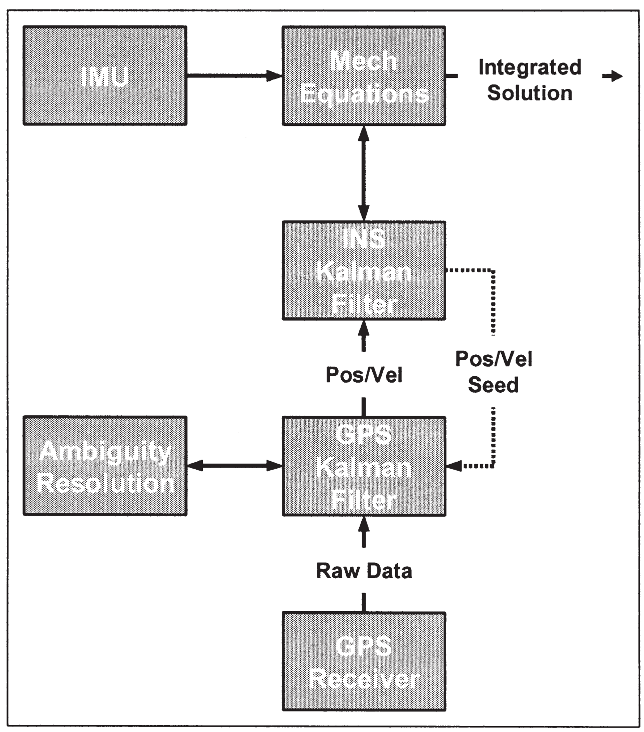

Fig. 1–GPS/INS Information Flow Diagram Using Loose Integration Strategy

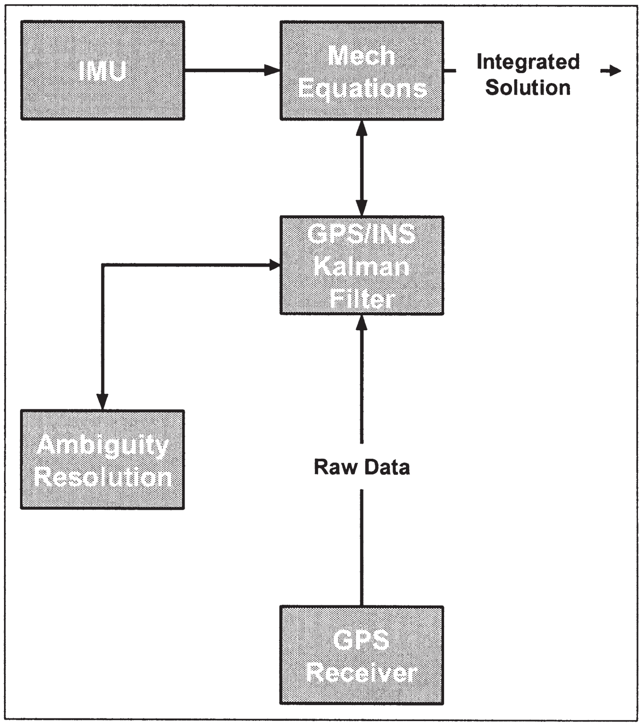

Fig. 2–GPS/INS Information Flow Diagram Using Tight Integration Strategy

a GPS receiver or existing software program can be used directly to update the INS filter, instead of having to compute a solution internally in the navigation software; the result is further computational savings and reduced development time.

The disadvantage of a loose integration strategy is that the GPS filter essentially operates independently of the rest of the system. While this poses no considerable problem under ideal conditions, if a full filter reset is required (e.g., because of loss of lock), the GPS-only filter is subject to the same shortcomings as a GPS-only system. To help circumvent this problem, Figure 1 shows a dotted line from the INS filter to the GPS filter. When a full GPS reset is required, the inertial position and velocity can be used to initialize, or seed, the GPS filter. In the process, the GPS filter can benefit from the additional information provided by the INS. For clarity, the use of seeding is always stated explicitly, as in "seeding the GPS filter" or "loose integration with INS seeding." This is done to avoid confusion with the more basic terms "loose integration" or "loosely coupled," in which seeding is not necessarily used. It is acknowledged that it may be difficult in practice to determine when to seed the GPS filter. This having been said, the objective here is to investigate the benefits of using such an approach, not to determine how or when it should be implemented.

The advantage of a tight integration strategy is that all information is contained within a single filter. This provides essentially three benefits. First, it allows a statistically rigorous sharing of information (to the extent that the input statistics are correct). Second, because process noise is added to only one filter, the ability to filter GPS observations is increased (i.e., the filter is better able to remove high-frequency effects). The final advantage is that programming a single Kalman filter can simplify software development, an important practical consideration.

The disadvantage of tight integration is that the INS state vector must be augmented by the GPS float-ambiguity states when they need to be estimated. This makes the filtering algorithm slower as a result of the increased number of floating-point operations. However, when the ambiguities are resolved as integers and are therefore not estimated in the filter, the tight integration strategy is actually more efficient than the loose integration strategy because the GPS/INS filter reduces to the INS-only filter without the need for a GPS-only filter.

With the integration strategies having been identified, the characteristics of the individual filters are discussed in the next section.

GPS, INS, and GPS/INS Filter Setup

The GPS filter used in the loosely coupled approach can theoretically estimate any state observable using GPS data. Typically, these observables will include position, velocity, and possibly acceleration errors, but may also include attitude parameters if multiple receivers are available. For the application considered here, the filter is assumed to estimate only position and velocity errors, with the latter being modeled as random-walk processes. Ambiguity states are also estimated as needed.

The inertial equations are mechanized in the earth-centered, earth-fixed (ECEF) frame. This frame was chosen for its relative ease of implementation relative to the local-level implementation. The ECEF mechanization is also more efficient than the local-level equivalent algorithm [7]. The inertial system error states are estimated in a Kalman filter using one of the previously discussed integration strategies. The following INS error states are estimated:

- Position errors (3)
- Velocity errors (3)
- Attitude misalignments (3)
- Gyro biases (3)
- Accelerometer biases (3)

The dynamic models for the above parameters can be written as a series of first-order differential equations, as follows (see [6] for more details):

$$
\begin{aligned}
\delta\dot{\mathbf{p}}^e &= \delta\mathbf{v}^e \\
\delta\dot{\mathbf{v}}^e &= -\mathbf{F}^e\boldsymbol{\varepsilon}^e + \mathbf{N}^e\delta\mathbf{p}^e - 2\boldsymbol{\Omega}^e_{ie}\delta\mathbf{v}^e + \mathbf{R}^e_b(\mathbf{b}^b + \mathbf{w}_1) \\
\dot{\boldsymbol{\varepsilon}}^e &= -\boldsymbol{\Omega}^e_{ie}\boldsymbol{\varepsilon}^e + \mathbf{R}^e_b(\mathbf{d}^b + \mathbf{w}_2) \\
\dot{\mathbf{b}}^b &= -\boldsymbol{\alpha}\mathbf{b}^b + \mathbf{w}_3 \\
\dot{\mathbf{d}}^b &= -\boldsymbol{\beta}\mathbf{d}^b + \mathbf{w}_4
\end{aligned}
\tag{1}
$$

Dots denote time derivatives, and the superscripts "e" and "b" denote parameters in the ECEF and body frames, respectively. The symbols are interpreted as follows:

$\delta\mathbf{p}$ is the 3-vector of position errors
$\delta\mathbf{v}$ is the 3-vector of velocity errors
$\mathbf{F}$ is the skew-symmetric matrix of the specific force vector
$\boldsymbol{\varepsilon}$ is the 3-vector of attitude errors (misalignments)
$\mathbf{N}$ is the tensor of gravity gradients
$\boldsymbol{\Omega}_{ie}$ is the skew-symmetric matrix of the rotation rate of the earth relative to inertial space
$\mathbf{R}_b^e$ is the rotation matrix from the body frame to the ECEF frame
$\mathbf{b}$ is the 3-vector of accelerometer biases
$\mathbf{d}$ is the 3-vector of gyro biases
$\boldsymbol{\alpha},\boldsymbol{\beta}$ are parameters for modeling the bias terms as first-order Gauss-Markov processes
$\mathbf{w}_i$ is a noise term

As implied by equation (1), velocity and attitude errors are modeled as random-walk states, whose process noise is derived from the measurement noise of the accelerometers and gyros, respectively. It should also be noted that the bias states could be modeled as any appropriate noise process. The simple model used here was selected to minimize computations by limiting the size of the state vector. Furthermore, since the data processed herein were collected in a land vehicle, the effect of sensor scale-factor errors should not be significant.

For the tightly coupled integration, the GPS position and velocity error states coincide with the INS position and velocity errors. In this way, the tightly coupled filter is identical to that of the INS-only filter discussed above, augmented by GPS ambiguity states when necessary.

The process noise parameters are summarized in Table 1. A range of values is specified for the gyro and accelerometer bias parameters since these were obtained on a sensor-by-sensor basis. The parameters apply to both integration strategies unless stated otherwise. Of particular interest is the amount of process noise added to the GPS filter in the loose integration strategy to account for vehicle dynamics (especially compared with the IMU sensor values). This relatively large value is later shown to play an important role in system performance.

Ambiguity Resolution and Position Accuracy

The ambiguity resolution process is what allows the highest possible accuracy to be obtained in a reasonable time period. By exploiting the integer nature of the carrier-phase ambiguities, the number of unknowns can be reduced, thus increasing the number of degrees of freedom for the entire system. This, in turn, translates into higher-accuracy position estimates.

Some ambiguity resolution algorithms are based in the position domain. These include the least-squares ambiguity search technique (LSAST) [8] and the ambiguity function method (AFM) [9]. For these algorithms, the relationship between the position estimate and the estimated ambiguities is obvious. However, ambiguity resolution methods in the ambiguity domain, such as the fast ambiguity search filter (FASF) [10] and the least-squares ambiguity decorrelation adjustment (LAMBDA) [11], are still reliant on knowledge of the receiver's position. It follows, therefore, that if the position estimate can be improved, the ambiguity resolution process can be expedited.

To show the desired relationship, the following equation representing the updated ambiguity covariance matrix after a reset of the ambiguity states is taken from [12]:

$$\mathbf{P}_a^+ = \mathbf{P}_a^- - \mathbf{P}_a^- [\mathbf{D}^T \mathbf{A}\, \mathbf{P}_{\delta p}^- \mathbf{A}^T \mathbf{D} + \mathbf{P}_a^- + \mathbf{R}_\phi]^{-1} \mathbf{P}_a^- \quad (2)$$

The superscript "−" denotes a quantity before update, and the superscript "+" denotes a quantity after update. The remaining terms are as follows:

$\mathbf{P}_a$ is the covariance matrix of the ambiguity states
$\mathbf{D}$ is the double-difference operator
$\mathbf{A}$ is the single-difference design matrix of the observations
$\mathbf{P}_{\delta p}$ is the covariance matrix of the position errors
$\mathbf{R}_\phi$ is the covariance matrix of the phase observations

It should be noted that this equation assumes the filter is updated only with carrier-phase measure-

Table 1 — Kalman Filter Process Noise Parameters

Parameter	Value
Gyro bias time constant	55 to 100 min
Gyro bias temporal variance	0.34 to 0.47 deg^2/h^2
Gyro noise spectral density	30.25 deg^2/h^2/Hz
Accelerometer bias time constant	68 to 170 min
Accelerometer bias temporal variance	8.0e^{-8} to 4.8e^{-7} m^2/s^4
Accelerometer noise spectral density	1.681e^{-3} m^2/s^4/Hz
GPS velocity spectral density (loose integration)	1.0 m^2/s^2/Hz

ments. If more observations are added, such as pseudorange (code) or Doppler measurements, the equation will change slightly, with the effect being a further-reduced ambiguity covariance matrix. Regardless, the usefulness of equation (2) is in showing that the covariance matrix of the ambiguities decreases with a smaller a priori covariance matrix of the position errors. In the context of GPS/INS integration, the inertial data can be used to reduce the a priori covariance matrix of the position errors. Specifically, in a loose integration with INS seeding, the quality of the INS position used to initialize the GPS filter after a data outage directly impacts the accuracy of the estimated ambiguity states. Similarly, for a tight integration, the position covariance during a GPS data outage is determined primarily by the quality of the IMU. In both integration strategies, therefore, if the inertial position uncertainty after the data outage is small, the result will be a reduced covariance estimate of the ambiguity states. Conversely, as the inertial position covariance increases over time during a data outage, the benefit to the ambiguity covariance matrix will decrease accordingly, with the limit being the GPS-only case.

Finally, the ambiguity search space is the volume of the hyperellipsoid defined by the ambiguity covariance matrix, and can be used to quantify the benefit of using an INS to aid the ambiguity resolution process by means of equation (2). In fact, theoretical investigations have been conducted in this regard using a quantity defined as the ambiguity dilution of precision (ADOP) [2–4]. While these investigations serve to illustrate the potential benefits of an INS in terms of ambiguity resolution, they are somewhat limited in a practical sense since ADOP is a purely statistical parameter. It is one of the objectives of this paper, therefore, to identify a more practical relationship between the INS position accuracy and the ambiguity resolution process.

ANALYSIS PROCEDURE

This section describes the equipment used, the field test performed, and the processing methods used for analyzing the data presented in subsequent sections.

Equipment

The GPS base station receiver is a NovAtel OEM4 dual-frequency receiver. This is a high-quality GPS receiver, capable of generating low noise code, Doppler, and carrier-phase measurements. The remote station (i.e., vehicle) equipment consisted of the NovAtel Black Diamond System (BDS). The BDS integrates a Honeywell HG-1700 AG11 IMU and a NovAtel OEM4 GPS receiver into a single unit. The IMU data are received and time tagged by the GPS receiver before being output through one of the receiver's serial ports. This eliminates any significant timing errors between the GPS and IMU data. Both the base and remote receivers use NovAtel 600 antennas.

Some of the more relevant performance specifications for the Honeywell HG-1700 AG11 IMU are shown in Table 2 [13]. Also shown are the corresponding values for two different navigation-grade IMUs, as have typically been used for high-accuracy integrated systems [14]. A quick comparison shows that the HG-1700 has considerably lower performance characteristics and therefore represents a good candidate for assessing the benefits of tactical-grade sensors for high-accuracy applications.

Field Test

A field test was conducted, and the data collected were analyzed as described in the following section. The test was conducted just west of Calgary, Alberta, Canada, where there is good GPS satellite visibility, as this was critical to system analysis.

In the area are accessible pillars with known coordinates, one of which was used as a base station. The base station receiver was powered by a gas generator, as was the corresponding logging computer. The IMU was rigidly mounted to the floor pins of one of the test van's captain's chairs, and the GPS antenna was mounted on the roof of the van. The lever arm between the IMU and the GPS antenna was accurately measured to the millimeter level.

Two data collection runs were performed. Each run began with a static initialization period of about 12 min followed by about 20 min of driving. Vehicle

Table 2 — Specifications for Honeywell HG-1700 AG11 IMU and Two Navigation-Grade IMUs

Parameter		Honeywell HG-1700 AG11	Litton LTN90-100	Honeywell LRF-III
Gyro	Bias (1σ)	1.0 deg/h	0.01 deg/h	0.003 deg/h
	Scale-factor accuracy (1σ)	150 ppm	5 ppm	1 ppm
	Misalignment	500 μrad	10 μrad	10 μrad
Accelerometer	Bias (1σ)	1 milli-G	0.5 milli-G	0.25 milli-G
	Scale-factor accuracy (1σ)	300 ppm	50 ppm	50 ppm
	Misalignment (1σ)	500 μrad	24 μrad	24 μrad

speeds varied from stationary to 120 km/h. Vehicle dynamics were somewhat limited, with most of the data being collected at constant velocity. Although this represents a fairly ideal case, the INS filter should be able to handle more aggressive (ground) vehicle dynamics with little difficultly. Furthermore, the analysis procedure used (see below) considers not only the benign dynamic environments, but also periods with higher vehicle dynamics. The distance from the test vehicle to the base station ranged from a few meters during the initialization to up to 5 and 8 km during runs one and two, respectively.

Processing Strategy

The data were processed using the University of Calgary's Satellite and Inertial Navigation Technology (SAINT™) software. SAINT™ is based on the University of Calgary's Navigation Development Library (NDL™), a suite of C++ classes written to facilitate the development of navigation algorithms and software by relieving the user of many significant programming details. GPS processing was done using L1 or widelane carrier-phase data, as well as L1 C/A-code and L1 Doppler measurements. All observations were processed using the double-difference technique. Resolution of the GPS integer ambiguities was performed using the LAMBDA method.

The first processing step involved the determination of truth information. Specifically, generation of a reference trajectory and ambiguity values was desired. This was accomplished by processing all of the data together using the tight integration strategy. In both runs, the L1 and widelane carrier-phase ambiguities were fixed during the static alignment. For the first test, these ambiguity values were maintained throughout the run. For the second test, all but three of the ambiguities were lost after passing under a highway sign. The integer ambiguities were recovered a short time later and were maintained until the end of the dataset. An analysis of the measurement residuals and the static position at the end of the run confirmed that the ambiguities had indeed been resolved correctly. To be certain, however, the times during which the ambiguities were being resolved and a short time thereafter were avoided in the following analysis.

Given the above procedure, the reference trajectory is considered to be accurate to better than 3 cm, and the integer ambiguities are considered errorless. A comparison of trajectories obtained using L1-only and widelane carrier-phase measurements showed centimeter-level differences, which are to be expected if the ambiguities are fixed correctly. Furthermore, a comparison of the L1 truth solution with the solution obtained from the University of Calgary's FLYKIN+™ software was performed. The position differences in this case were also at the 1–2 cm level. Finally, the velocity accuracy is expected to be approximately 5 mm/s, based on an analysis of the corrections to the velocity error states when GPS updates are processed.

The second processing step was to simulate GPS data outages (also referred to as gaps). This was done by artificially raising the satellite cutoff elevation angle from the 10 deg default. For complete data outages, the elevation mask was raised to 90 deg. For partial data gaps, the elevation mask was selected on a run-by-run basis. Specifically, the elevation mask was set to 44.5 deg and 58.0 deg for the first and second runs, respectively. In each case, the number of visible satellites remaining was either two or three, implying that a stand-alone GPS solution was not possible. There were 6 data outages simulated in each run, for a total of 12 outages. The data gaps were selected to encompass a wide range of vehicle dynamics, from constant velocity to relatively large longitudinal and lateral accelerations. In this way, the benefit of the INS under a wider variety of operational conditions could be evaluated. Figures 3a and 3b show the trajectories of the first and second runs, respectively, along with the location of the different data outages.

Finally, solutions obtained during the simulated data outages were compared with the reference solution. Position and velocity accuracy during the data outages was assessed through the difference between the two solutions. Since the reference solution was accurate to the centimeter level in position and the millimeter-per-second level in velocity, the differences between the two solutions were due almost entirely to errors in the INS in the absence of GPS updates. When the GPS data were reintroduced at the end of the data outage, the necessary GPS ambiguities had to be re-estimated. Once these

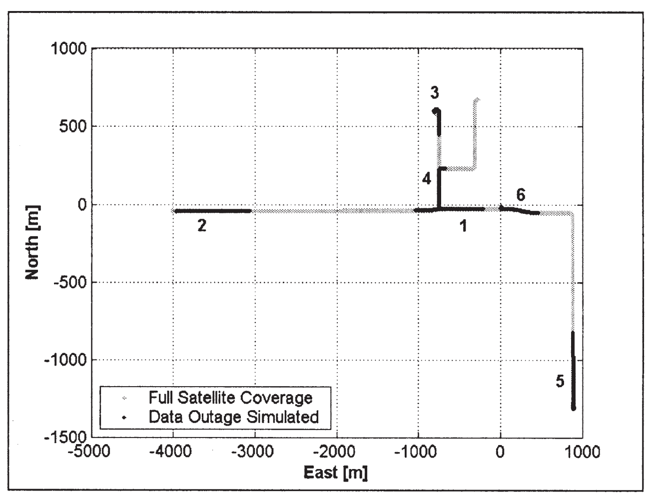

Fig. 3a – Trajectory and Data Outages Relative to Base Station for Run #1

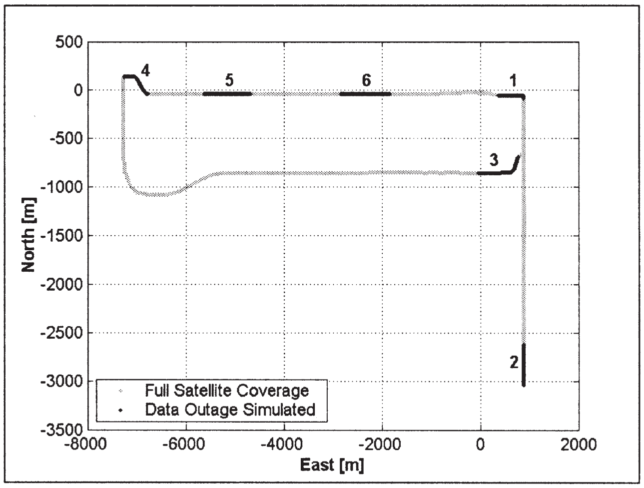

Fig. 3b–Trajectory and Data Outages Relative to Base Station for Run #2

ambiguities had been resolved to their integer values, they were compared with the reference ambiguity values to ensure their veracity. Also of interest in this regard is the time required for the ambiguities to be resolved to their (hopefully correct) integer value.

The above processing strategy was repeated for each of the different integration strategies discussed above using L1 and widelane carrier-phase data. The duration of the simulated data gaps was varied from 2 to 40 s to help determine the length of time over which the INS would provide significant improvements over the GPS-only solution.

RESULTS

Results are presented below in the two categories previously discussed. The position and velocity results are presented first, followed by an assessment of the ambiguity resolution performance.

Position Accuracy

To assess the positioning capability of the integrated system during data outages, the north, east, and up position errors were computed as a function of the time since the last GPS update for each simulated outage. The root mean square (RMS) error across all simulated data gaps was computed and is assumed to be a good estimate of the inertial system's ability to bridge data outages. Figure 4 shows the RMS position error of the tightly integrated solution obtained using L1 data during complete GPS outages. As can be seen, the position accuracy degrades to about 1.2 m after 30 s. However, if one considers that a differential code solution will provide a similar accuracy (i.e., 1 to 1.5 m), the benefit of the inertial system becomes apparent. Specifically, the inertial system can provide RMS position accuracies as good as, or better than, those provided by differential GPS for data outages of up to about 30 s. This improved position accuracy has two main advantages. First, it initializes the navigation filter to a considerably better value than one would obtain if the inertial system were absent; this in turn should provide faster filter convergence. Second, the enhanced position estimate allows for improved ambiguity resolution performance, as per equation (2). This point is revisited in the next section. It should also be noted that the estimated position standard deviations from the Kalman filter closely match the results shown in Figure 4.

The three-dimensional position accuracies obtained using L1 and widelane carrier-phase observations are compared in Figure 5. The loose integration solutions using the two observables closely follow the results of the tight integration approach (within a couple of

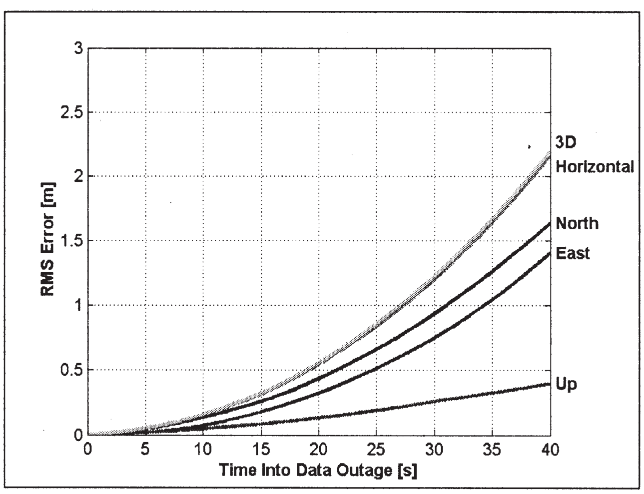

Fig. 4–RMS Position Error across All Complete Data Outages Using L1 Carrier-Phase Data

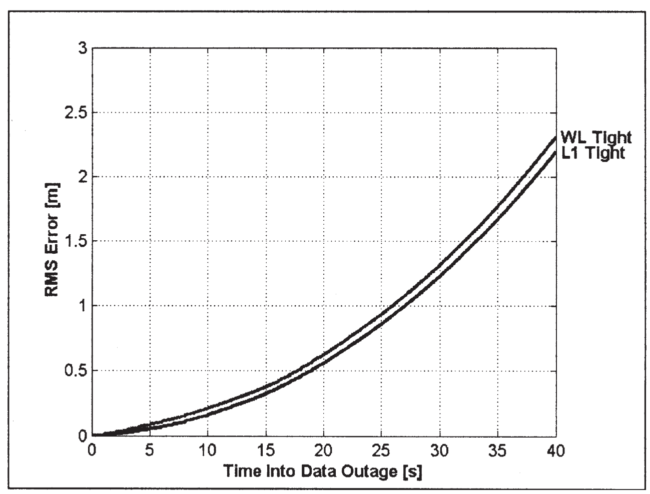

Fig. 5–Comparison of Three-Dimensional RMS Position Error during All Complete Data Outages Using Different Processing Strategies

centimeters) and are therefore not shown. As can be seen, widelane carrier-phase observations are not as useful for bridging data outages as are the corresponding L1 measurements. The reason is that the reduced accuracy of the widelane observable limits its usefulness for calibrating the inertial errors, thus causing more rapid error accumulation during data outages.

Figure 6 shows the integrated system's RMS three-dimensional position error during partial GPS outages, using L1 and widelane carrier-phase data for the loose and tight integration strategies. The graph is shown on the same scale as that of Figure 5 to facilitate comparison. As can be seen, the RMS position error is considerably better than during complete data outages. As with the full data outages, L1 data are better than widelane data because of the former's greater accuracy. In this case, however, the tight integration significantly outperforms the loose integration. The primary reason for this difference is the estimated accuracy of the GPS-only solution (for the loose integration approach) during the data outages. To illustrate, Figure 7 shows that the estimated standard deviation of the GPS-only position estimate during partial data outages grows very rapidly over time. This rapid increase is due to the relatively large amount of process noise that is required in the GPS filter to account for vehicle dynamics (see Table 1), and the fact that only two or three satellites remain visible during a simulated partial data outage. These large standard deviations imply that very little useful position information is being provided to the INS-only filter (from the GPS filter) in the loose integration approach. Therefore, during partial data outages, the loosely integrated solution tends to the situation where no GPS data are available at all. In contrast, the tight integration approach does not require the additional (GPS-only) process noise and is thus better able to extract the useful information contained in

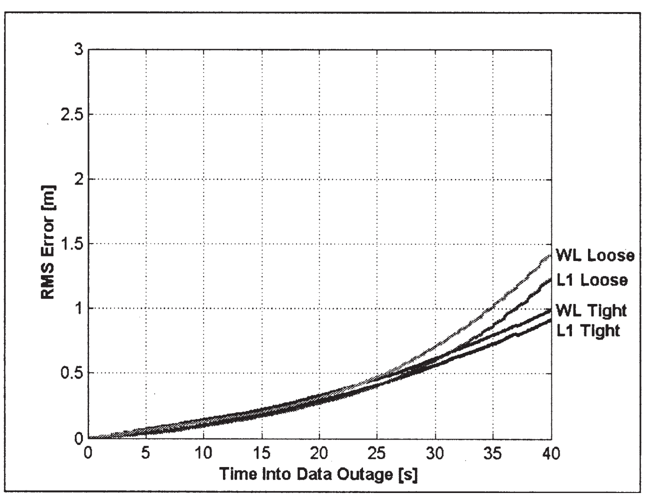

Fig. 6–RMS Three-Dimensional Position Error across All Partial Data Outages Using Different Processing Strategies

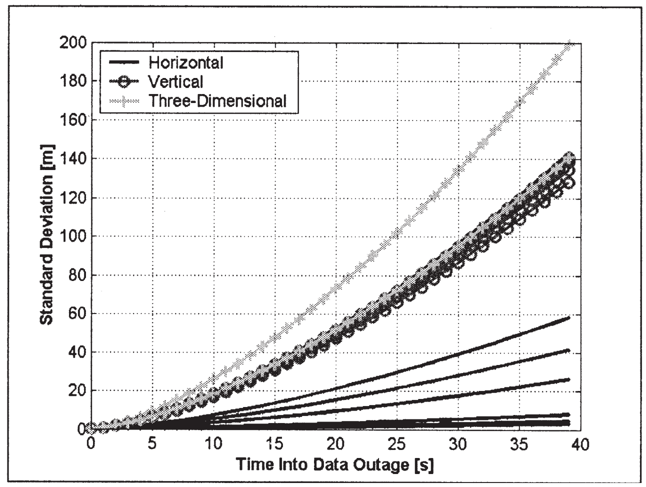

Fig. 7–Estimated GPS-Only Standard Deviations during All Partial Data Outages Using L1 Carrier-Phase Data

the measurements from the remaining GPS satellites. The result is a significant improvement in system position accuracy.

The above results show that the different integration strategies provide similar performance in terms of position accuracy during complete data outages. For partial data outages, however, the integration strategy plays a much more important role, with distinct advantages being observed for the tight integration approach for data outages lasting 25 s or longer. For both integration strategies and for both types of GPS data outages, the L1 carrier-phase solution performs better than the corresponding widelane solution.

A direct comparison of the above results with those obtained using a navigation-grade IMU would illustrate the difference between the two systems. Unfortunately, a navigation-grade IMU was not available for this purpose. However, the position error behavior for a navigation-grade unit will be similar to that shown above, though the error will accumulate at a slower rate. This implies that, as a rough approximation, the time scale on the above plots can essentially be expanded or contracted depending on the quality of the IMU under consideration. For example, for a navigation-grade IMU, the time scales on the above plots could span 0–80 s (instead of 0–40 s).

Velocity Accuracy

For applications in which velocity is the most important parameter, Figure 8 shows the RMS three-dimensional velocity error during complete and partial data outages when using L1 data and a tight integration approach. The velocity error increases approximately linearly with time for both types of outages. For complete data outages, the three-dimensional velocity error reaches approximately

11 cm/s after 40 s. In contrast, errors during partial data outages reach about 4 cm/s over the same time interval. The results for other integration strategies are not included, as they can be inferred from the corresponding positioning accuracy plots shown above.

Ambiguity Resolution

The ability of the integrated system to recover from complete and partial GPS outages and return to a correctly fixed integer ambiguity solution is extremely important. Since it is the exploitation of the integer nature of the ambiguities that allows for high-accuracy position estimates in a timely manner, it follows that the ambiguity resolution process is vital to achieving the integrated system's objectives. In this context, two parameters are of interest. First, how long does it take the ambiguity resolution process to resolve the ambiguities as integers? Second, are the selected integer ambiguities correct? While the time to fix is important for achieving the highest accuracy in a timely manner, it is crucial that the ambiguities be resolved correctly. A wrong fix of one cycle on a single satellite is capable of producing position errors that far exceed the navigation system's estimated accuracy for that position, thus presenting serious integrity problems.

Figure 9 shows the time required to fix the L1 ambiguities as integers for each complete data outage for the first run. It is noted that in this case, all ambiguities were resolved correctly, so the focus of the analysis is the time needed to fix. The graph shows that using the inertial system allows for considerable reductions in the time required to fix the ambiguities, regardless of the integration strategy. In particular, it is noted that the largest reductions in the time to fix occur for data outages lasting less

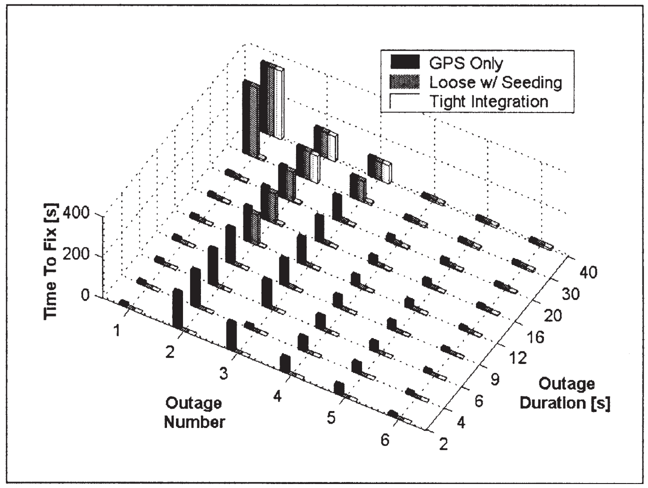

Fig. 9–Time to Fix L1 Ambiguities after Each Complete Data Outage (Run #1)

than about 30 s (most noticeable for data gaps 1 and 3). This corresponds to the amount of time for which the integrated system can match or exceed differential GPS position accuracy, as discussed previously. For longer data outages, the inertial system is unable to provide sufficient information to improve the ambiguity resolution process relative to the GPS-only case. Stated differently, if the inertial system can bridge a data outage with an accuracy as good as or better than that provided by differential GPS (about 30 s in this case), the improvement in the time needed to resolve the ambiguities is likely to be significant.

These results show a practical correlation between position accuracy and ambiguity resolution performance for an integrated GPS/INS system. While equation (2) suggests that there should be an improvement regardless of the position accuracy after the data outage (i.e., regardless of how large $P_{\delta p}$ becomes), the above results show that this improvement is limited in a practical sense. This finding could possibly be used to better identify potential IMUs for a given application. Specifically, as discussed above, the time scale on the position accuracy plots (Figures 4 to 6) could be expanded or contracted depending on the quality of the IMU under consideration. For example, if the time scale on the position accuracy plots could be scaled up by a factor of 2 for a particular navigation-grade IMU (i.e., data outage times of 0–80 s), such an IMU could presumably provide significant benefits in ambiguity resolution time for outages lasting up to approximately 60 s (instead of 30 s with the unit tested in the work documented herein).

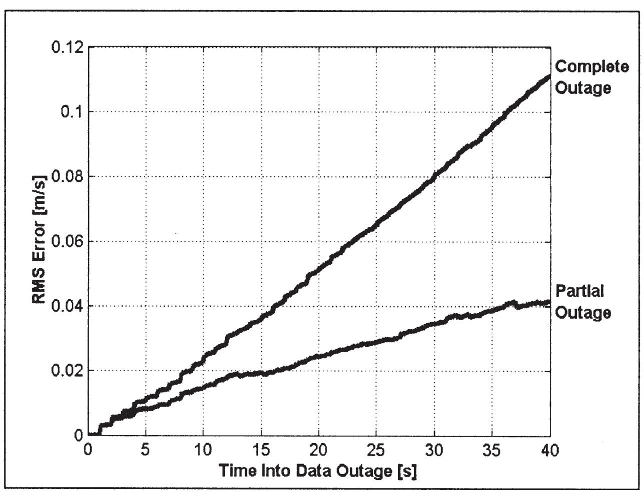

Fig. 8–RMS Three-Dimensional Velocity Error during All Complete and Partial Data Outages Using L1 Carrier-Phase Updates and a Tight Integration

In addition to the above analysis, Figure 9 shows that the tightly coupled approach is better able to improve the ambiguity resolution process than the loose integration with seeding. This superior performance is attributable to the reduction in process noise with the tightly coupled approach, which in turn allows the tightly coupled Kalman filter to better estimate both the position and ambiguity states—hence the improved ambiguity resolution performance.

The time to fix the L1 ambiguities after a complete data outage for the second run is shown in Figure 10. In this case, the GPS-only solution appears to have resolved faster without the inertial system in several cases. However, if one considers that every time the GPS-only time to fix is less than the corresponding value using the inertial system (using either the loose integration with INS seeding or the tight integration), the results become clear. In total, there were nine incorrect ambiguity fixes using GPS alone and none using either of the integrated approaches. Also of note is that on several occasions the ambiguities could not be resolved before the end of the dataset. While this is not an ideal situation, it is certainly better than fixing incorrectly.

Table 3 summarizes the number of times the ambiguities were fixed incorrectly or could not be resolved. It should be noted that all of these problems occurred during data gaps 4 and 5. These represent the longest baselines over which the ambiguities had to be resolved, suggesting that the differential errors were playing a role in the results obtained. Further investigation, however, revealed that differential code errors (due to multipath) were the most likely reason for the incorrect fixes. This being the case, it can be concluded that the integrated system not only reduces the time needed to fix the ambiguities, but is also more robust to code errors than is GPS alone. For applications in which code multipath could be significant, this is important.

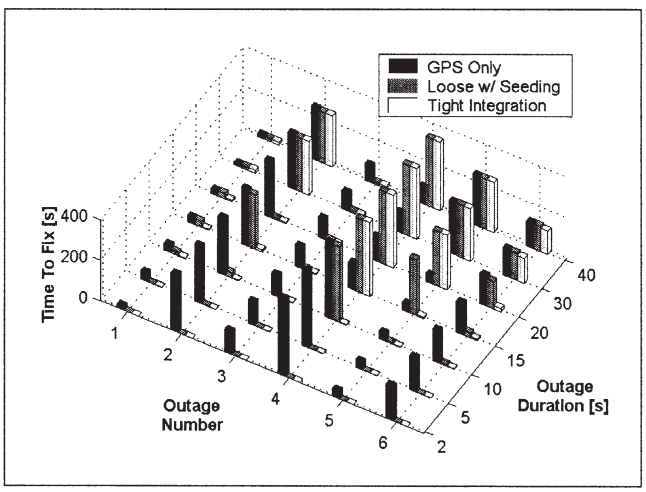

Fig. 10–Time to Fix L1 Ambiguities after Each Complete Data Outage (Run #2)

Table 3—Number of Times Each Integration Strategy Fixed Incorrectly or Could Not Fix

	Integration Strategy		
Error/Problem	GPS-Only	Seeding	Tight
Wrong fix	9	0	0
Could not fix	5	9	8

When widelane ambiguities are employed, the use of the inertial system is not as significant because of the relative ease with which the widelane ambiguities can be resolved using GPS alone. For example, the first run shows that the GPS-only filter can resolve the ambiguities within 1 s after every data outage. In contrast, both integrated approaches show instantaneous ambiguity resolution. This represents only a modest improvement. For the second run, however, results indicate that under some circumstances, the benefit of the inertial system can be significant, as shown in Figure 11. As above, the differential code errors significantly limited the ability of the GPS-only filter to resolve the widelane ambiguities as integers, despite their increased wavelength. However, both integrated approaches show near-instantaneous ambiguity resolution. Again, the ambiguities were resolved correctly in all cases.

Ambiguity resolution after partial data outages shows results that parallel those just discussed. However, it should be noted that in this context, loosely coupled integration with INS seeding has no real meaning since the INS seeding was intended for use only after complete data outages. With this in mind, the times needed to fix the L1 ambiguities after each partial data gap are shown in Figures 12 and 13 for the first and second runs, respectively. Again, considerable improvements are seen with use of the inertial system.

When trying to resolve widelane ambiguities after partial data outages, the GPS-only filter was able to determine the correct ambiguity set instantaneously for every data outage simulated in the first run, so no plot is shown. Results for the second run are shown

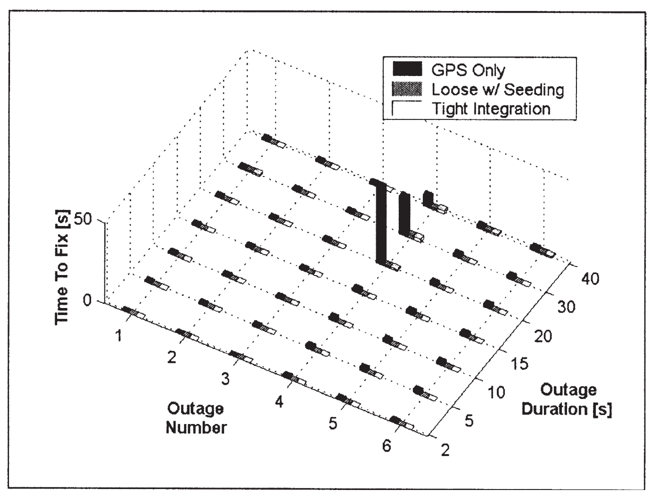

Fig. 11–Time to Fix Widelane Ambiguities after Each Complete Data Outage (Run #2)

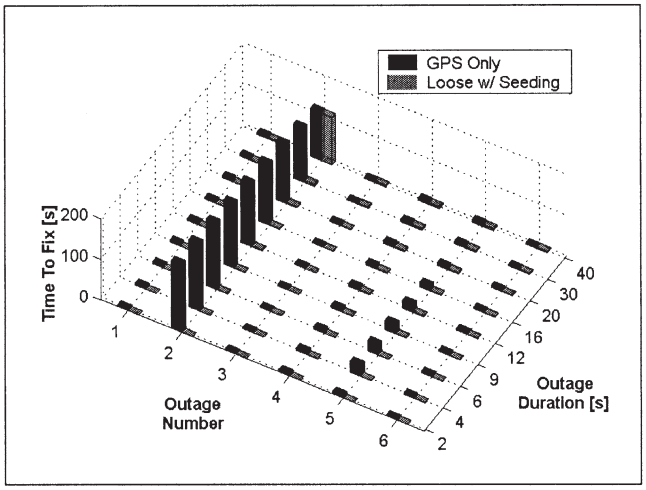

Fig. 12–Time to Fix L1 Ambiguities after Each Partial Data Outage (Run #1)

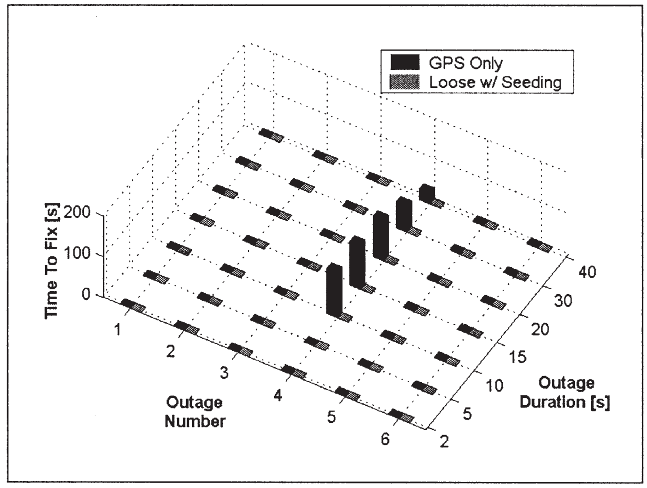

Fig. 14–Time to Fix Widelane Ambiguities after Each Partial Data Outage (Run #2)

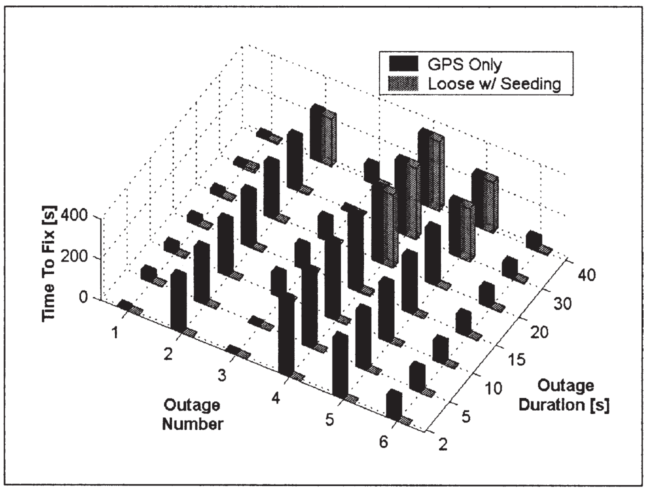

Fig. 13–Time to Fix L1 Ambiguities after Each Partial Data Outage (Run #2)

in Figure 14. As with the complete data outages, the advantage of the inertial system is most obvious for the fourth baseline because of the increased code errors. Otherwise, the longer widelane wavelength is sufficient to provide instantaneous ambiguity resolution even for the GPS-only case.

From the above analysis, it can be concluded that the introduction of an inertial system can yield significant improvements in the ambiguity resolution process after data outages relative to the GPS-only case. In particular, both the loose integration with seeding and tight integration approaches showed the ability to dramatically reduce the time needed to resolve the ambiguities relative to the GPS-only case. Also, and perhaps more important, using the inertial information allows for more robust ambiguity resolution, while the GPS-only approach may produce incorrect fixes.

Comparing the loose integration approach with the INS seeding and tight integration strategies shows that the tightly coupled approach does offer some advantages. While these advantages are not necessarily significant in all applications, they may need to be taken into consideration under some circumstances.

CONCLUSIONS

This paper has investigated the benefits of using a tactical-grade INS to augment GPS for high-accuracy applications. Simulation of partial and complete GPS data outages was used to assess position and velocity accuracy during data outages, as well as to investigate ambiguity resolution performance once the GPS data became available again. Two different integration strategies were used for this purpose—loose integration with seeding and tight integration. Results obtained using L1 or widelane carrier-phase data were compared.

During complete data outages, the inertial system is capable of providing half-meter accuracy for periods lasting up to about 20 s (RMS). The error degrades to the level of differential GPS (i.e., 1 to 1.5 m) after about 30 s. Slight differences (about 10 cm over 40 s) were seen depending on the carrier-phase observations used, with L1 outperforming widelane.

For partial data outages, position accuracies for the tight integration case were reduced to less than 1 m for data outages lasting 40 s. Again, L1 was better than widelane; however, the tight integration strategy significantly outperformed the loose integration strategy and is therefore considered to be the better integration approach.

Velocity accuracy was shown to be bounded to 11 cm/s and 4 cm/s (RMS) for complete and partial data outages, respectively.

In terms of ambiguity resolution, results show that using a loose integration with INS seeding of the GPS filter or a tight integration significantly reduces the time needed to fix ambiguities after a data outage, primarily with L1 ambiguities. In some cases, L1 ambiguity resolution times were reduced by 100 percent; that is, instantaneous ambiguity resolution was possible. Widelane ambiguities could be resolved instantaneously much of the time; however, the improvements over GPS alone were not as significant as with L1. Yet perhaps more important than the ambiguity resolution time, the reliability of the ambiguity fixes was shown to be considerably higher with the integrated system. Results from one test showed that nine incorrect fixes with GPS-only were eliminated when using the information from the inertial system.

By correlating the position accuracy during data outages with the ambiguity resolution performance, it was shown that once the inertial position has degraded to the level of differential (code) GPS, there is little if any benefit to the ambiguity resolution process relative to the GPS-only case.

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