PERFORMANCE ANALYSIS OF A KINEMATIC TERRESTRIAL LIDAR SCANNING SYSTEM

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ABSTRACT

Terrapoint has developed a novel kinematic terrestrial based laser scanning system that is deployed on a passenger vehicle. LIDAR, digital imagery and digital video is collected from the survey platform at speeds up to 100 km/h. The system is georeferenced using a GPS/INS system. Obtaining an accurate and reliable trajectory for the ground based platform is a much more difficult and challenging task than that of an airborne platform due primarily to frequent GPS signal outages caused by obstructions such as buildings, terrain and vegetation. However, the simultaneous collection of LIDAR data from the vehicle platform provides an accurate 3D reference that can be utilized to check the reliability, accuracy and consistency of the GPS/INS derived vehicle trajectory. Methods of utilizing the LIDAR data to validate and improve the GPS/INS trajectory will be presented. A comparison of tightly and loosely coupled GPS/INS trajectories and their respective impact on positioning accuracy will also be presented. Finally, overall absolute accuracy of survey results obtained with the kinematic terrestrial LIDAR system (when compared with dense DGPS ground control) will be presented and discussed.

INTRODUCTION

Commercial Airborne LIDAR remote sensing systems have been deployed for the better part of a decade, and the technology has been widely adopted by government and private industry as a fast and effective way for capturing detailed topographic information. The accuracy of the final 3D LIDAR point cloud is directly affected by the accuracy of the underlying GPS/INS trajectory utilized to georeference the LIDAR measurements. A precise trajectory is normally obtained by paying close attention to the GPS solution during the flight. With airborne LIDAR the environment is relatively benign (i.e. lack of significant cycle slips, no GPS signal shading, relatively low dynamics), and therefore a reliable GPS solution can be obtained by careful mission preplanning and attention to flight characteristics.

Ground based LIDAR systems however do not operate in the same benign GPS environment as the airborne systems. Frequently full GPS constellation coverage is masked due to obstructions such as building, trees and other vehicles. Therefore, more attention must be paid to precise GPS/INS processing to be able to obtain a reliable trajectory to precisely georeference LIDAR, video and digital imagery captured from a ground based platform. As a result, when developing, testing and using their Ground based LIDAR system, Terrapoint had to pay close attention to the proper methodology for processing the GPS/INS trajectory. Methodology was also developed to verify the trajectory using the LIDAR data captured during the survey missions.

TERRESTRIAL LIDAR BACKGROUND AND SYSTEM DESCRIPTION

The history of the kinematic terrestrial scanning system (called TITAN™) dates to early 2002 when Terrapoint (formerly Mosaic Mapping Systems) was developing their proprietary ALMIS-350 LIDAR system for use primarily on helicopters. During the development and testing of ALMIS, a cost-effective way to dynamically test the equipment was required. Obviously, chartering a helicopter for testing is fairly expensive, and therefore Terrapoint engineers developed a mounting mechanism to attach the ALMIS system to a truck for testing during design and development. Once the airborne system was operational, the truck mount was not developed further.

Figure 1. Prototype Mount of TITAN System, and TITAN on the Road in Afghanistan.

However, in mid 2003, Terrapoint was approached to perform a LIDAR survey of Highway 1 in Afghanistan between Herat and Kandahar. We quickly realized that an airborne approach had far too many safety concerns, and therefore the truck mounted system was resurrected. Details of the Afghanistan survey can be found in (Newby and Mrstik, 2005). Based on the success of the system in Afghanistan, Terrapoint decided to start offering TITAN as a commercial remote sensing solution.

The first generation TITAN system, in use in Afghanistan, and used in the testing contained herein consisted of the following components:

- Riegl Q-140-60 laser scanner. Scans at 10 kHz with 20 mm resolution and a 60 degree field of view.
- Novatel DL-4 dual frequency GPS receiver.
- Honeywell HG1700 Ring Laser Gyro IMU (specifications in Table 1)
- Sony High Resolution Digital Video Camera
- Optional 11 Mpixel Digital Frame Camera

Table 1. HG1700 IMU Specifications, Novatel (2005)

Gyro Input Range	±1000 deg/s
Gyro Rate Bias	1.0 deg/hr
Gyro Rate Scale Factor	150 ppm
Angular Random Walk	0.125 deg/hr
Accelerometer Range	±50 g
Accelerometer Linearity	500 ppm
Accelerometer Scale Factor	300 ppm
Accelerometer Bias	1.0 mg

A block diagram which details system components and interactions is given in Figure 2. All data from the TITAN system is stored and processed post mission. The dotted blocks indicate subsystems that have been integrated into the second generation TITAN system scheduled for production release in October of 2006.

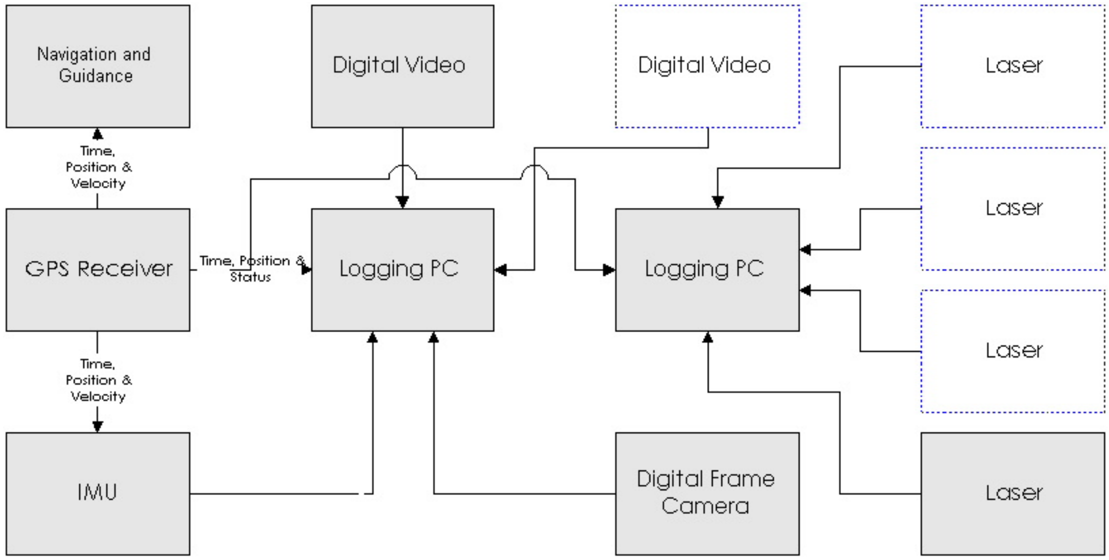

Figure 2. Block Diagram of TITAN System.

TRAJECTORY ESTIMATION AND VALIDATION

Obviously, the accuracy of the estimated trajectory from the combined GPS/INS system will have a direct effect on the overall accuracy of the LIDAR point cloud derived from TITAN. Therefore, an examination of GPS/INS integration strategies is an important step in analyzing the accuracy and reliability of a ground based scanning system. The most common strategies employed in the literature are normally referred to as loose and tight integration. These are the two main strategies implemented in Terrapoints proprietary GPS/INS integration software. An overview of each approach is given in the following sections. For a more detailed discussion, the reader is directed towards (Jekeli, 2000), (Petovello, 2003) or (Schwarz et. al., 1994).

Loose Integration

In a loose integration strategy, the raw measurements from GPS and the IMU are processed in separate Kalman Filters. The results from the DGPS filter (normally position, velocity and their respective variance and co-variance) are used as inputs into the INS Kalman filter. In addition, if the GPS and INS Kalman filters are run in parallel the INS predicted position and velocity can be fed into the GPS Kalman filter when there are GPS data gaps or loss of signal lock. A conceptual block diagram of the loose integration strategy is shown in Figure 3.

The major advantage to the loose integration strategy is its simple implementation. Because the GPS and INS filters are run separately a stand-alone COTS GPS processing package can be utilized to generate the input position and velocity information for the INS filter. As a result, the data user would only have to implement the INS Kalman filter equations which are significantly less complicated.

The largest disadvantage of the loose integration strategy is that the GPS filter is run essentially independently of the final integrated solution estimation. This doesn't normally cause a problem with good GPS data (i.e. short baselines with minimal loss of lock or obstructions), however, with total loss of lock the GPS filter would need to be reset and wouldn't take advantage of the additional inertial information. This problem can be circumvented if the GPS and INS Kalman filters are run in parallel. In this instance, when GPS filter resets occur the position and velocity of the INS filter can be used to seed or initialize the GPS Kalman filter (dotted line in block diagram). The independent GPS filter is also a concern when less than four satellites are tracked. In this case, no solution is available from the GPS filter and as a result no updates are available for the INS Kalman filter.

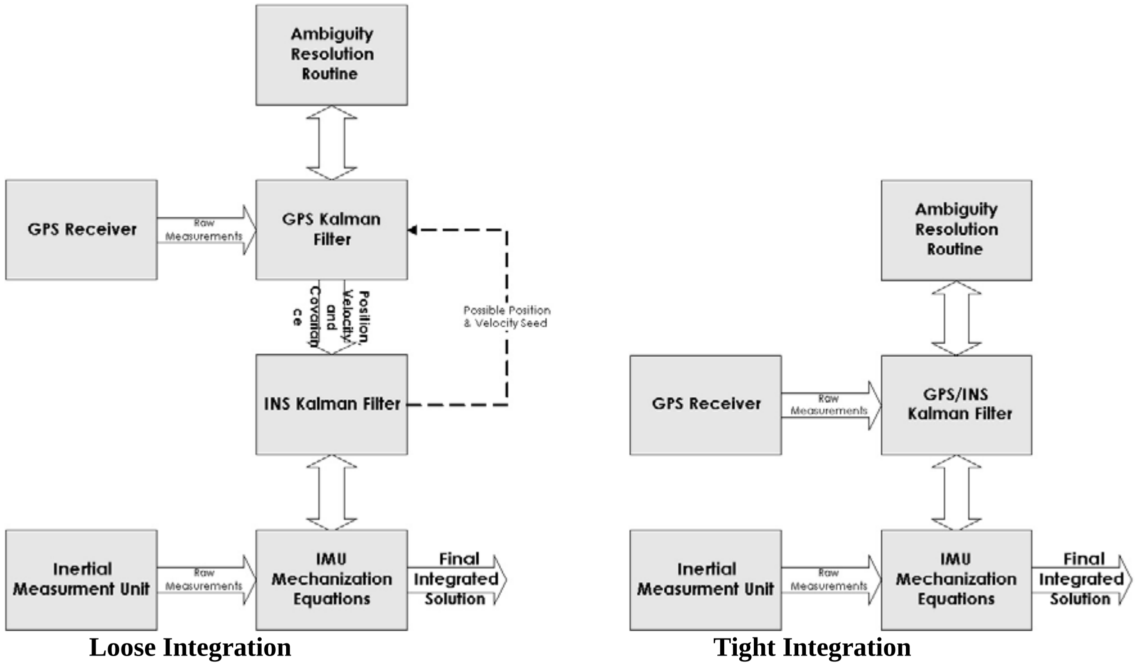

Figure 3. Block Diagrams Detailing Process Flow for Loose and Tight Integration Strategies.

Tight Integration

In a tight integration strategy, the raw GPS and IMU measurements are processed together in one centralized Kalman filter. A conceptual block diagram of the tight integration strategy is given in Figure 3.

This approach has several attractive advantages, especially when the GPS data is not collected under ideal conditions (i.e. lots of cycle slips, loss of lock and obstructions). First off all, because the raw measurements are all processed together it normally provides a more statistically rigorous model that can more effectively reject blunders or noisy measurements and therefore provide a higher reliability solution. In addition, for epochs when there are less than four satellites, the GPS measurements can still be included in the estimation process, giving a higher degree of reliability during partial GPS outages.

Validation with LIDAR

The use of a scanning laser system on a kinematic platform affords a novel and effective way to measure the performance of an integrated INS/GPS system. Because the LIDAR units makes measurements of objects away from the moving platform, it is able to directly measure coordinates of static control points placed along the path the vehicle travels. This allows a quantifiable measurement of overall system accuracy, instead of simply measuring trajectory differences relative to one another. In addition, because the LIDAR measurements behave like a long lever-arm (with length proportional to the scan range), they have a tendency to magnify small angular and positional errors in the GPS/INS solution. Therefore, using LIDAR, it is much easier to notice small differences in results from the GPS/INS data processing.

In addition to direct comparison with ground control, the LIDAR data can also be used in another indirect way to check the internal precision of a trajectory solution. Often in a LIDAR survey, a road or other item to be surveyed is driven and data is captured in more than one direction at different epochs of time. The overlap of the opposing passes can be compared and examined for inconsistencies.

TEST DESCRIPTION

During the testing of the first generation TITAN system a test range was set up along two stretches of highway near Terrapoint Canada's Ottawa office. Figure 4 gives a road map overview of the test site, and Figure 5 shows a current aerial image of the test ground.

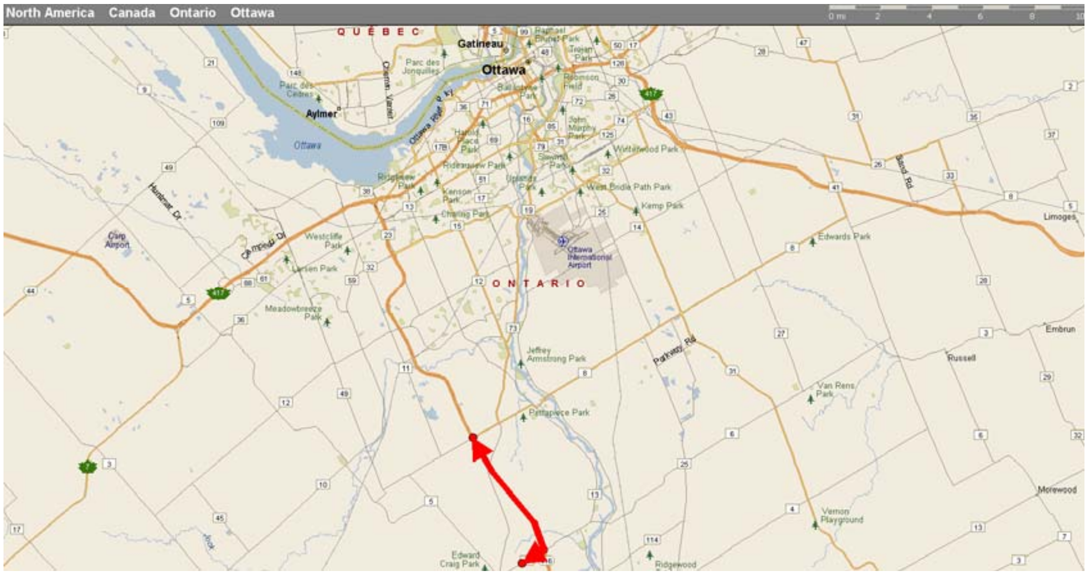

Figure 4. North Gower Test Range Location.

Figure 5. Aerial Image of Test Range Location (Arrow Denotes Location of Ground Truthing).

The route chosen is relatively clear of aerial obstructions (e.g. building or trees) except for two locations obstructed by overpasses. A permanent network of 1st order control points were installed along the test range. In addition dense ground truthing information was acquired along the test roads. The ground truthing consisted of fast static and kinematic DGPS points, along with total station cross-sections of the road bed and ditches.

PERFORMANCE RESULTS

Terrapoint has validated the TITAN system on the North Gower test track on a number of different occasions over the last four years, and has used a majority of these datasets to arrive at optimal post-processing procedures to generate the “best” GPS/INS trajectory. Methods of examining overlap between different drive-bys and missions have also been developed to identify and fix problems in the post-processed GPS/INS trajectory. The results given below are for one of these test datasets, but should be considered representative of Terrapoint’s experience with kinematic ground based LIDAR scanning and GPS/INS trajectory determination.

As a first step in the analysis of the results, overlapping passes of LIDAR data are examined for uniformity and consistency, especially in the time period immediately proceeding and following a known loss of lock with one or more GPS satellites. In general, for the ground based LIDAR system in its current configuration the data analyst is looking for a smooth RMS agreement in the overlap of somewhere between 3 and 5 cm.

Once the internal consistency of the dataset is verified, it can then be compared to the independent ground truthing along the test track right of way. Table 2 details the comparison statistics between the LIDAR data and the ground control.

Table 2. Comparison of TITAN Data With DGPS Ground Control and Total Station Cross-Sections .

LIDAR v.Ground Truth	Value (meters)
Average	-0.016
Maximum	0.101
Minimum	-0.105
Standard Deviation	0.058
RMS	0.059

The results above show an RMS agreement at the level of 6cm with the ground control. Analysis has shown that this level of agreement is at or near the expected noise level of the first generation TITAN system, (Glennie, 2006).

In order to validate and compare the different GPS/INS trajectory solutions, the smoothed optimal GPS/INS solution which was used to generate the statistics above will be used as a reference to compare other GPS/INS solutions to. The reference trajectory was obtained using a tight integration strategy, and there was no GPS loss-of-lock within or immediately before or after the location of the ground control data.

As a simple first comparison of integration strategies, the GPS/INS data along the reference trajectory was reprocessed using both a tight and loose integration strategy, but with a simulated complete GPS data gap of 5, 10, 20 and 30 seconds inserted into the processing. The loose integration strategy was performed without GPS filter seeding, i.e. the results would be similar to using separate a separate software package to compute the GPS trajectory before feeding it into the INS Kalman filter. A comparison of the LIDAR for the 5 second gap trajectories with the reference LIDAR data is given in Figure 6. The yellow shaded area in the graph (and in subsequent graphs) highlights the area of simulated GPS gaps.

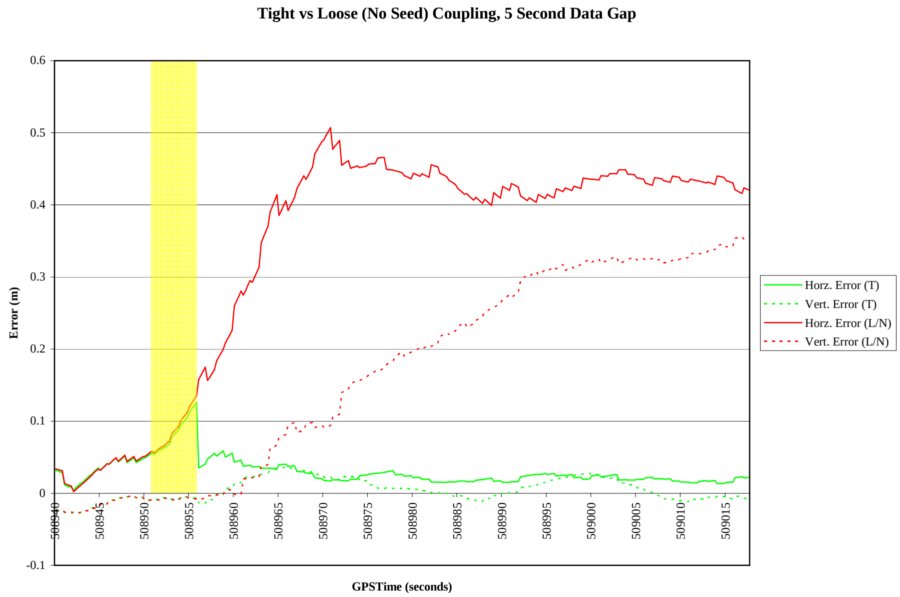

Figure 6. Tight vs. Loose (No GPS Filter Seeding – L/N) Coupling, with 5 second GPS Data Gap (in yellow)

By examining Figure 6, it is evident that the tight integration strategy (green lines) was able to instantly re-resolve the GPS ambiguities after the 5 second gap, and maintain the LIDAR data accuracy at the expected system level. However, the loose integration strategy was unable to instantaneously re-resolve the GPS ambiguities, and as a result the trajectory solution drifts to almost 50 cm horizontal and 40 cm in vertical. Although not shown, the results, for the simulated 10, 20 and 30 second gaps exhibit similar characteristics.

Next, to highlight the added benefit of GPS filter seeding after GPS data gaps to the loose integration strategy, the GPS/INS data was again processed with complete 5, 10 and 20 second GPS gaps. However, this time loose integration strategy was performed with GPS filter seeding enabled. The results of this comparison are given in Figure 7.

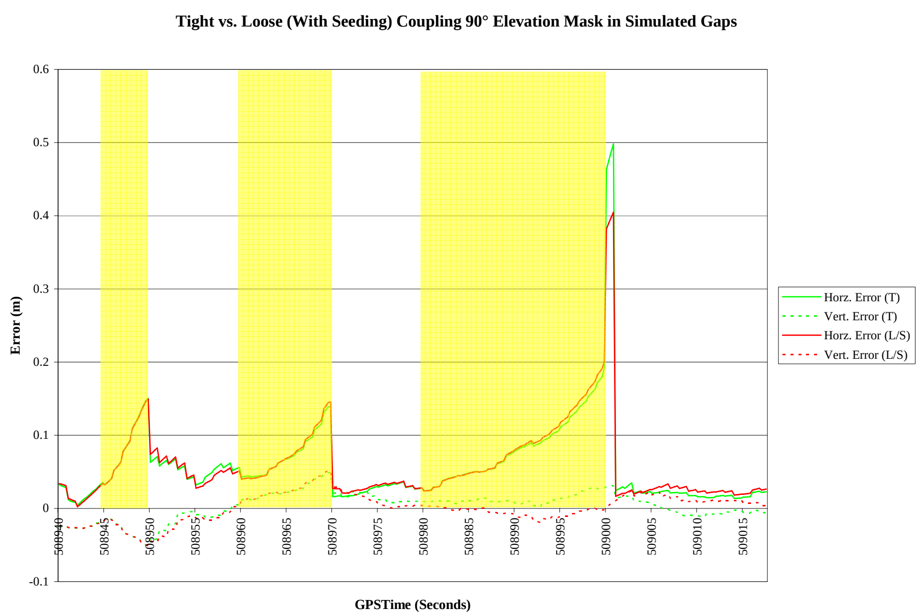

Figure 7. Tight Coupling vs. Loose Coupling (With Seeding – L/S), Simulated Full GPS Gaps (in yellow)

Figure 7 clearly shows that the loose and tight integration results are identical for datasets when there are total GPS data gaps and the GPS filter is seeded using the INS position and velocity immediately after the data gap.

However, in real world situations, the GPS data gaps almost never show a total loss of GPS satellite tracking. In urban canyons and in areas of dense vegetation there are at least a few (1 to 3) satellites that are still tracked in areas of high obstruction. It is this real world case that we are most interested in comparing the performance of the GPS/INS filtering strategies. Therefore, as a final test the dataset was processed with a series of 1, 2 and 5 second gaps. The gaps were not complete GPS outages however. For each gap, the GPS elevation mask was set to 70° which left two available GPS satellites in view. The data was processed in three ways: tight integration, loose integration with GPS filter seeding, and loose integration without GPS filter seeding. The results are presented in Figure 8.

By examining Figure 8, it becomes very evident that the loose integration strategy without seeding is fairly poorly suited for the urban or obstructed environment that a terrestrial kinematic LIDAR unit is operated in. The separate processing of the GPS without using the INS seeding to help recover from filter resets, loss of lock and data gaps results in a noisy trajectory estimate that does not take full advantage of the redundant navigation information provided by the GPS and INS subsystems.

The loose integration strategy with GPS filter seeding shows much improved performance over the unseeded loose integration strategy, however, the accuracy of this trajectory during the partial GPS outages suffers because this approach cannot take advantage of the two visible satellites. Therefore, it represents an intermediate compromise, but still ignores some redundancy.

The tightly integrated solution, as expected has the best performance. It is able to seed the GPS ambiguity search and at the same time make use of the two visible satellites during the partial GPS outages to improve the trajectory accuracy.

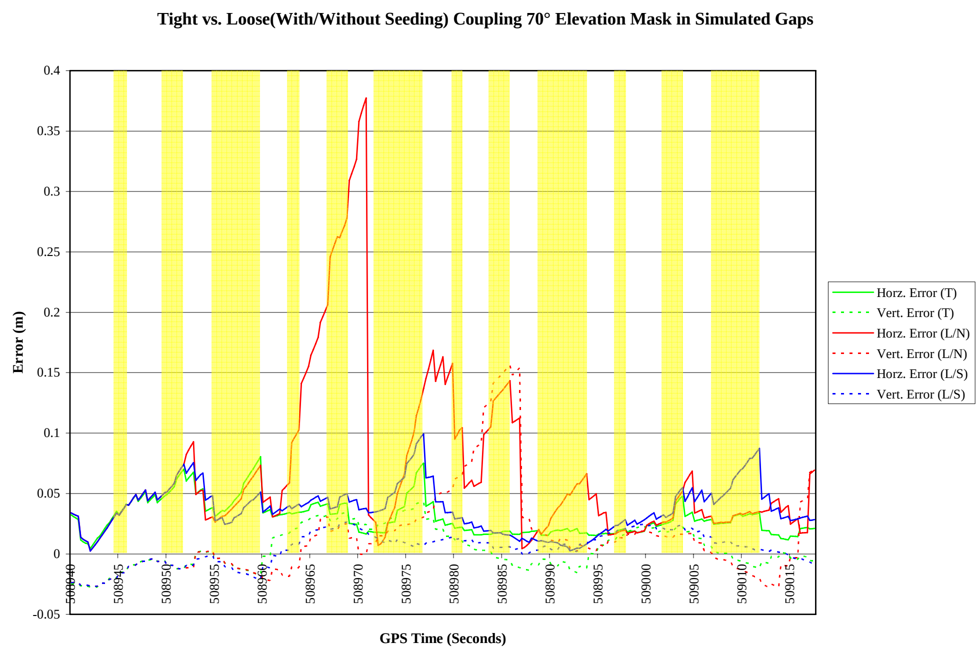

Figure 8. Tight Coupling vs. Loose Coupling (With(L/S)/Without(L/N) Seeding), Simulated Partial GPS Gaps (in yellow) with a 70° Elevation Mask.

CONCLUSIONS AND AREAS OF FUTURE WORK

Through comparison with ground control, the first generation TITAN system was shown to achieve a 5.9 cm RMS vertical accuracy for ground control points located along a roadway. The tight integration of GPS/INS data was also shown to clearly be the preferred method of trajectory estimation for ground based kinematic LIDAR surveys. The tight integration strategy is best at making use of all available navigation observations and provides the most uniform and accurate estimate of trajectory.

The second generation TITAN system is scheduled to be released in the fourth quarter of 2006. The new system has an upgraded IMU, to allow INS bridging of significantly longer GPS gaps than the current system allows. In addition, the new system contains an array of overlapping lasers to allow further trajectory verification and increased LIDAR coverage per vehicle pass. Further research is also currently being undertaken to automate the analysis of overlap between LIDAR passes to provide a means of automatic trajectory validation and repair.

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