TIGHTLY COUPLED PRECISE POINT POSITIONING AND INERTIAL NAVIGATION SYSTEMS

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KEY WORDS: GNSS, INS, Precise Point Positioning

ABSTRACT:

In this paper we discuss Precise Point Positioning (PPP) as an aid for INS. We describe the integration using both loose and tight coupling, i.e. integration at either the position/velocity level, or at the observation level. The relative performance of these integration strategies are discussed in the context of PPP. We discuss operational aspects of PPP/INS compared to other means of INS aiding. We present initial results from airborne and land-based surveys using the TerraPOS software, developed by TerraTec AS, Norway. The performance is validated using NavLab, an independently developed INS software by the Norwegian Defence Research Establishment.

1 INTRODUCTION

Precise Point Positioning (PPP) requires only a single Global Navigation Satellite System (GNSS) receiver for accurate positioning, based on undifferenced code phase, carrier phase and Doppler observations together with precise ephemerides and satellite clock corrections (e.g. Zumberge et al., 1997; Kouba and Heroux, 2001).

The global nature of precise ephemerides and satellite clock corrections means that the PPP technique itself is also global. It will have homogeneous accuracy, and does not suffer from any of the distance-dependent limitations inherent in differential GNSS systems. The independence of ground infrastructure may pose huge logistical and operational benefits.

An Inertial Navigation System (INS) is a self-contained system consisting of an Inertial Measurement Unit (IMU) and a navigation computer (Jekeli, 2001). Usually equipped with accelerometer and gyro triads, the IMU gives precise measurements of accelerations and angular rates. By integrating these measurements, an INS provides position, velocity and attitude of the platform. The combination of any uncompensated sensor biases and integration represents highly unfavorable error propagation conditions, yielding poor stand-alone long-term performance. By aiding the INS with external measurements related to one or several of the system states, INS errors can be estimated and corrected for, e.g. by using a Kalman filter. The aiding measurements can be processed in a separate filter and included in the INS filter in the form of e.g. position and velocity observations, so-called “loosely coupled” integration. Alternatively, aiding measurements, e.g. GNSS range observations, may be included directly into the INS filter, so-called “tightly coupled” integration.

In airborne photogrammetry, and other kinds of remote sensing, three dimensional position and attitude of the sensor must be determined in order to correctly place the sensed objects in a reference frame. When this is achieved without any prior knowledge of the sensed objects locations, e.g. no ground control points etc., this process is often referred to as “direct georeferencing”.

For more than a decade, differential GNSS aided INS has been the working horse for applications demanding direct georeferencing. During the last few years also PPP coupled with INS has been utilized for this purpose. Contrary to differential GNSS, PPP shares the autonomous nature of INS, and integrated PPP/INS thus provides a competitive means for accurate, self-contained direct georeferencing.

It has been shown (e.g. Petovello, 2003) both theoretically and empirically that tightly coupled differential GNSS/INS has superior integrity and error detection capabilities compared to loosely coupled differential GNSS/INS. It is expected that tightly coupled PPP/INS will share this property. Compared to tightly coupled differential GNSS/INS, tightly coupled PPP/INS will have no limitations in coverage imposed by the need for ground stations, and compared to loosely coupled PPP/INS, the vulnerability to signal outages should be reduced.

In this paper we discuss tight and loose GNSS/INS integration in the context of PPP. Two different data sets and dynamic environments are used for validation and an initial assessment of the TerraPOS software. We present results from a typical airborne mission, with reasonably good GNSS conditions. We also assess the performance for accurate car navigation, in an environment where significant GNSS outages and signal degradation were experienced.

2 PRECISE POINT POSITIONING

Zumberge et al. (1997) demonstrated sub-centimeter accuracy for static PPP. Since then, a large number of kinematic applications have been investigated, e.g. precise orbit determination (e.g. Jäggi et al., 2007), airborne positioning (Zhang and Forsberg, 2007) and marine positioning (e.g Kjørsvik et al., 2006), all with decimeter accuracy or better.

The use of undifferenced GNSS range observations means that a large number of error sources must be taken into consideration. Many of these error sources have only negligible impact when using differential processing techniques. Some relevant geophysical effects include e.g. solid earth tide and loading displacements and atmospheric effects. In addition, a large number of hardware-related effects must also be considered, e.g. satellite and receiver hardware biases and receiver and satellite antenna phase center variations. In order to properly apply corrections for satellite antenna effects and the polarization of the signal, the satellite attitude must also be carefully modeled.

Precise ephemerides and satellite clock corrections are a prerequisite for achieving centimeter accuracy, but are fortunately freely available from e.g. the International GNSS Service (IGS) for post-processing purposes (Dow et al., 2005).

Ionospheric effects can be virtually eliminated by forming proper linear combinations of dual-frequency observations. Due to the presence of uncalibrated hardware biases in both satellites and receivers, initial phases etc., reliable ambiguity resolution for kinematic PPP is currently not feasible.

The simultaneous estimation of receiver clock biases, residual tropospheric delay and carrier phase biases leads to a system that may require 10–20 minutes of fairly continuous data for reasonable convergence. Frequent partial or total signal outages with corresponding re-initialization of the carrier phase bias estimates may thus lead to reduced performance.

From a user perspective, the huge benefit compared to differential techniques is the autonomous nature of PPP. This flexibility allows operations to be executed without considering the coverage of ground infrastructure such as base stations or reference services. On the other hand, PPP used for high accuracy applications demands long, more or less uninterrupted series of carrier phase observations. This might give rise to a need for special arrangements, e.g. ensuring reliable power supply to the equipment. It may also place limitations on the operation, e.g avoiding large aircraft bank angles, or for land and sea applications, keeping clear of areas where frequent signal blockage must be expected.

3 AIDED INERTIAL NAVIGATION

The INS Kalman filter can be formulated as a complementary filter, where the aiding sensors observe the errors of the INS. The INS error dynamics can be approximated by a set of differential equations (Jekeli, 2001). The error dynamics and the functional relation between aiding measurements and system error states together form the basis of the Kalman filter and smoother (e.g. Gelb, 1974).

GNSS positions used as an INS aid contain stochastic signals that are the complex result of a plethora of underlying errors. Designing a near-optimal model to be used in the Kalman filter can be very challenging. In the case of GNSS position aiding, no aiding will be available if the number of satellites drops below 4. In practical life a minimum of 6–7 satellites is desired.

Tightly coupled systems demand a more complex software design, with the potential of having a very high number of system states. The advantage is that even a single GNSS satellite will provide valuable aiding to the system. Observation errors can be modeled per satellite and observable in the range-domain. These models are more easily implemented, and have a sounder theoretical foundation based on the actual physical processes being observed.

In the case of frequent partial or total satellite outages, proper convergence of a pure GNSS system might not be reached. This problem is most prominent for PPP due to the weaker observability, but also poses great challenges for reliable ambiguity resolution in differential GNSS applications. A tightly coupled GNSS/INS (either PPP or differential) may enhance the convergence of the GNSS-parameters by bridging the GNSS outages.

The introduction of tightly coupled PPP/INS could enable the use of PPP in applications now deemed unfavorable, such as aerial operations with extreme bank-angles, or land operations in areas where signal blockage must be expected.

4 SOFTWARE

4.1 TerraPOS

The TerraPOS software (e.g. Kjørsvik et al., 2009) is developed by TerraTec AS, Norway. The PPP-module has been commercially available since 2006, and has been successfully applied in virtually all parts of the world. Applications range from e.g. snow-cat missions in the Antarctic, via seabed mapping, to airborne LIDAR surveys.

The development version of TerraPOS may be run in one of three modes:

- GNSS mode, Precise Point Positioning,
- GNSS/INS mode, tightly coupled PPP mode,
- INS mode, loosely coupled mode.

The latter is a generic mode in which any position and velocity source may be used to aid the INS, e.g. a PPP trajectory from TerraPOS, or a differential GNSS solution from a 3rd party software.

TerraPOS uses state-of-the-art models to correct for all relevant geophysical and hardware-related effects. The software implements the conventions and recommendations of the International Earth Rotation and Reference Systems Service (IERS) and IGS, thereby making full use of the accuracy of the clock and ephemeris products of the IGS. In essence, this provides the user with access to the globally available high-quality and long-term stable reference frames of the IERS, the International Terrestrial Reference Frame (ITRF).

TerraPOS uses an optimal Kalman filter and smoother combination for estimation of the navigation and sensor bias states.

4.2 NavLab

NavLab (Navigation Laboratory) is developed by the Norwegian Defence Research Establishment and is a versatile tool intended for navigation system research and development (Gade, 2004). The main emphasis during the development has been a solid theoretical foundation with a stringent mathematical representation, to ensure that statistical optimality is maintained throughout the entire system.

NavLab consists of a simulator part and an estimator part. Simulations are carried out by specifying a trajectory for the vehicle, and the available types of sensors. The output is a set of simulated sensor measurements. The estimator part is a flexible aided inertial navigation system, which makes optimal Kalman filtered and smoothed estimates based on the available set of measurements. The measurements can be either from the Simulator or from real sensors of a vehicle. This structure makes NavLab useful for a wide range of navigation applications, including research and development, analysis and post-processing of real data.

Since the development started in 1998, NavLab has been used extensively by research groups, universities, commercial companies, and the military. High accuracy has been proven for a variety of applications. Vehicles navigated include AUVs, ROVs, ships, aircraft, helicopters and cars. Commercially, NavLab has provided the positioning for more than 30 000 billed survey hours.

5 RESULTS

In order to validate the implementation and performance of TerraPOS, two different test cases were investigated.

5.1 Instrumentation

The IMU specifications are listed in table 1. The specifications are based on experience with the particular sensors and corresponds to the settings used in the processing. The numerical values may deviate from those provided by the respective manufacturers.

	LN200	**HG9900**
Manufacturer	Northrop Grumman	Honeywell
Gyro technology	Fiber optic	Ring laser
Acc. technology	MEMS pendulous	Pendulous
Gyro noise	$0.1°/\sqrt{h}$	$0.006°/\sqrt{h}$
Gyro bias repeatability	$0.5°/h$	$0.003°/h$
Gyro bias variation	$0.3°/h$	$0.01°/h$
Gyro bias time constant	30 s	600 s
Gyro scale factor rep.	30 ppm	5 ppm
Acc. noise	$100\ \mu g/\sqrt{Hz}$	$15\ \mu g/\sqrt{Hz}$
Acc. bias repeatability	$1000\ \mu g$	$100\ \mu g$
Acc. bias variation	$200\ \mu g$	$100\ \mu g$
Acc. bias time constant	1800 s	1200 s
Acc. scale factor rep.	500 ppm	100 ppm

Table 1: IMU specifications.

The LN200 represents a typical sensor used in many direct georeferencing applications, with a reasonable cost/performance trade-off. The HG9900 is a high-end sensor.

5.2 Case A: Airborne platform

An airborne mission over southern Sweden is used in this case. The aircraft was fitted with two different GNSS receivers sharing the same antenna, and an LN200 IMU (cf. table 1). The total duration of this flight was 5 h 15 min. The entire flight was be used for the PPP processing, while only the part in the vicinity of the reference stations was used for the differential processing. Comparisons will hence be limited to this part of the flight, lasting 1 h in total. Figure 1 shows the trajectory, with attitude in figure 2. The altitude was fairly constant at approximately 600 m during the period analyzed.

5.2.1 Differential GNSS processing. A differential GNSS trajectory was established using one of the airborne receivers, local reference stations from the SWEPOS network and a commercial software for GNSS post-processing.

5.2.2 PPP processing. In order to verify the PPP solution, a GNSS trajectory was computed by TerraPOS in PPP-mode. To ensure some independence of the differential solution, the second GNSS receiver was used. Differences between the PPP solution and the differential GNSS solution are shown in figure 3, and summarized in table 2.

5.2.3 TerraPOS INS validation. In order to validate the TerraPOS INS implementation, data from the LN200 and the differential trajectory were processed using both TerraPOS and NavLab, with settings as identical as possible. The position differences are shown in figure 4, the attitude differences are shown in figure 5, and all results are summarized in table 3.

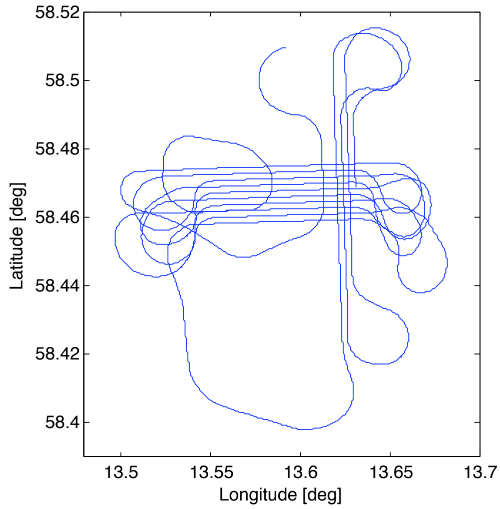

Figure 1: Trajectory of the airborne test data.

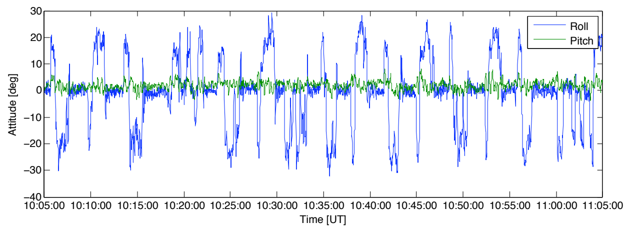

Figure 2: Attitude of the airborne test data.

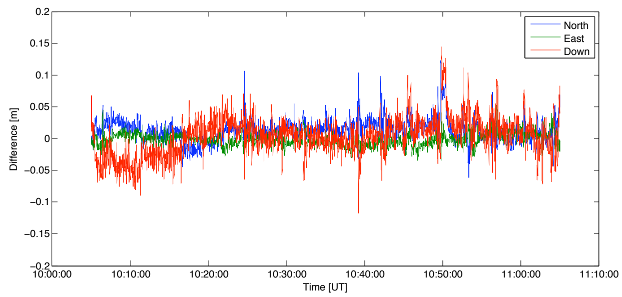

Figure 3: Position differences between PPP and the differential GNSS solution for the airborne test data.

	Mean	**Std. dev.**
Latitude	0.013 m	0.017 m
Longitude	-0.001 m	0.010 m
Height	0.003 m	0.027 m
North velocity	-0.001 m/s	0.042 m/s
East velocity	0.001 m/s	0.035 m/s
Vertical velocity	0.002 m/s	0.129 m/s

Table 2: Statistics of differences between PPP and the differential GNSS solution for the airborne test data.

5.2.4 PPP/INS in tightly vs. loosely coupled mode. The final test for the airborne data assesses the performance of tight vs. loosely coupled PPP/INS using TerraPOS. The differences between the solutions are shown in figure 6 and table 4.

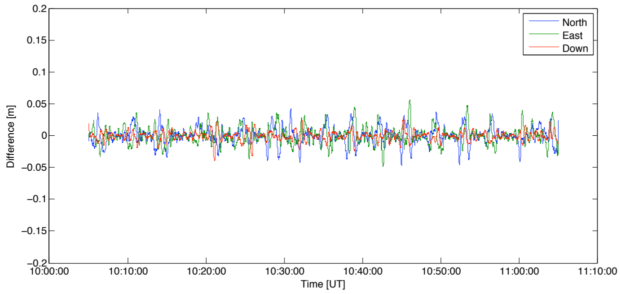

Figure 4: Position differences between TerraPOS vs. NavLab in loosely coupled GNSS/INS mode for the airborne test data.

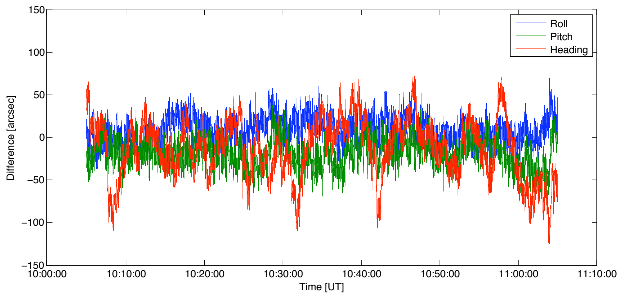

Figure 5: Attitude differences between TerraPOS vs. NavLab in loosely coupled GNSS/INS mode for the airborne test data.

	Mean	Std. dev.
Latitude	0.000 m	0.013 m
Longitude	0.000 m	0.014 m
Height	-0.001 m	0.007 m
North velocity	0.000 m/s	0.002 m/s
East velocity	0.000 m/s	0.002 m/s
Vertical velocity	0.000 m/s	0.001 m/s
Roll	8 ″	15 ″
Pitch	-19 ″	16 ″
Heading	-13 ″	34 ″

Table 3: Statistics of differences between TerraPOS and NavLab using loosely coupled GNSS/INS for the airborne test data.

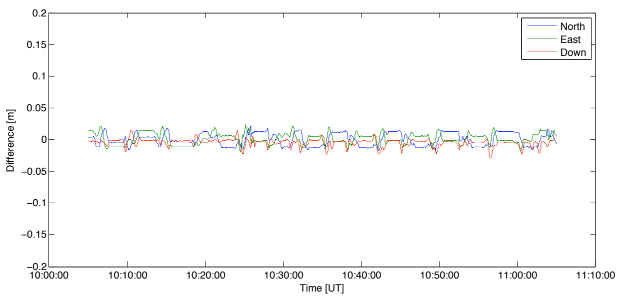

Figure 6: Position differences between loosely coupled PPP/INS and tightly coupled PPP/INS for the airborne test data.

5.3 Case B: Car navigation

The IMUs and GNSS antenna were mounted on a rigid steel frame. The body-frame coordinates of the sensors were established by close-range photogrammetry. The frame was mounted on a car driving along the approximately 1 km x 1 km route shown in figure 7. The height varied only a few meters along the route.

	Mean	Std. dev.
Latitude	0.000 m	0.010 m
Longitude	0.002 m	0.009 m
Height	-0.005 m	0.006 m
North velocity	0.000 m/s	0.001 m/s
East velocity	0.000 m/s	0.001 m/s
Vertical velocity	0.000 m/s	0.001 m/s
Roll	1 ″	4 ″
Pitch	1 ″	5 ″
Heading	9 ″	10 ″

Table 4: Statistics of differences between the loosely and tightly coupled PPP/INS for the airborne data.

Only modest roll and pitch were experienced during the test.

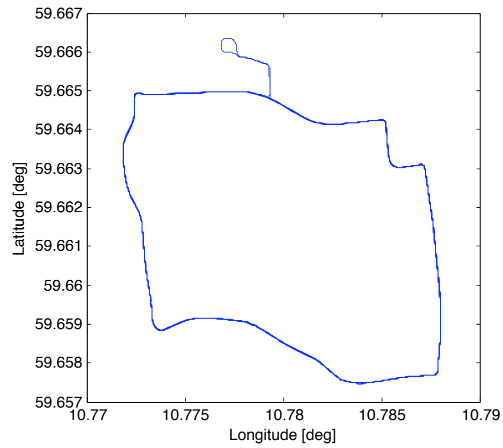

Figure 7: Car trajectory, covering approximately 1 km x 1 km.

The PPP processing utilized the first 2 h of the data to allow for some convergence, with results from the first hour being used to compute the performance metrics. The environment is a mixture of open fields, some nearby building as well as lots of vegetation and large trees in residential areas.

5.3.1 TerraPOS INS validation. The first test is a validation of the TerraPOS INS implementation. A differential GNSS solution was computed by the use of a local reference station in the middle of the test area and a commercially available software. Only epochs with reliably fixed carrier phase ambiguities were retained for further use. Data from the LN200 and the differential trajectory were processed using both TerraPOS and NavLab, with settings as identical as possible. The position differences are shown in figure 8, the attitude differences are shown in figure 9, and all results are summarized in table 5.

5.3.2 Reference trajectory. The resulting positions were used to aid the HG9900 IMU in a loosely coupled processing in NavLab. Due to the superiority of the HG9900 over the LN200, this reference trajectory is considered suitable both for a validation of the TerraPOS implementation, and to give indications of the PPP solution quality.

5.3.3 PPP solution. TerraPOS was used to compute a PPP solution. Results from comparison with the reference trajectory are shown in figure 10 and table 6.

5.3.4 Loosely coupled PPP/INS. TerraPOS was used to compute a loosely coupled PPP/INS solution using the LN200 and the

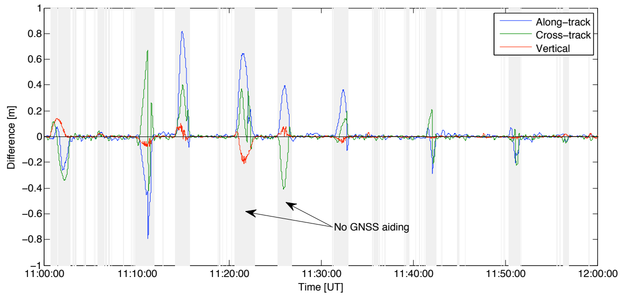

Figure 8: Position differences between TerraPOS with differential GNSS aiding and the corresponding trajectory computed with NavLab. Shaded areas denote periods without GNSS aiding.

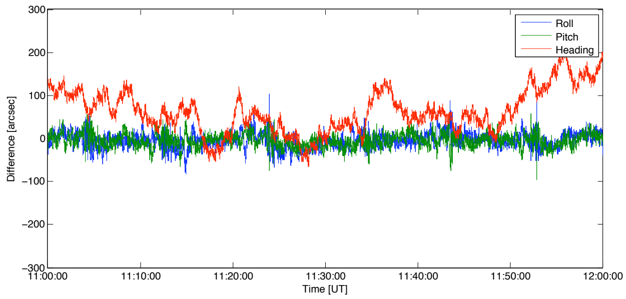

Figure 9: Attitude differences between TerraPOS with differential GNSS aiding and the corresponding attitude computed with NavLab.

	Mean	Std. dev.
Along track	0.020 m	0.139 m
Cross track	0.003 m	0.096 m
Vertical	-0.002 m	0.030 m
Along track velocity	0.000 m/s	0.005 m/s
Cross track velocity	0.000 m/s	0.005 m/s
Vertical velocity	0.000 m/s	0.001 m/s
Roll	-5 $''$	16 $''$
Pitch	-4 $''$	15 $''$
Heading	64 $''$	51 $''$

Table 5: Statistics of differences between TerraPOS and NavLab in loosely coupled GNSS/INS mode for the car test.

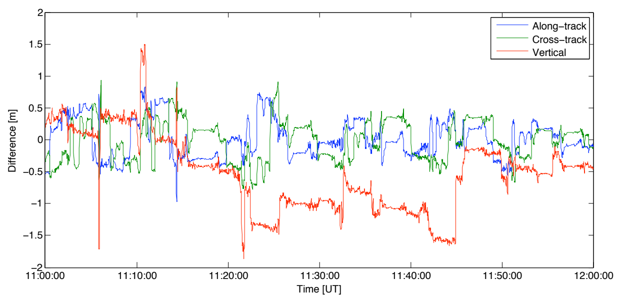

Figure 10: Position differences between PPP and the reference trajectory for the car test.

PPP solution described above. Results from comparison with the reference trajectory are shown in figures 11–12 and table 7.

5.3.5 Tightly coupled PPP/INS. In the final run, a tightly coupled PPP/INS solution was computed using TerraPOS and the

	Mean	Std. dev.
Along track	0.012 m	0.299 m
Cross track	-0.003 m	0.313 m
Vertical	-0.520 m	0.590 m
Along track velocity	0.008 m/s	0.063 m/s
Cross track velocity	0.000 m/s	0.045 m/s
Vertical velocity	-0.003 m/s	0.067 m/s

Table 6: Statistics of differences between PPP and the reference trajectory for the car test.

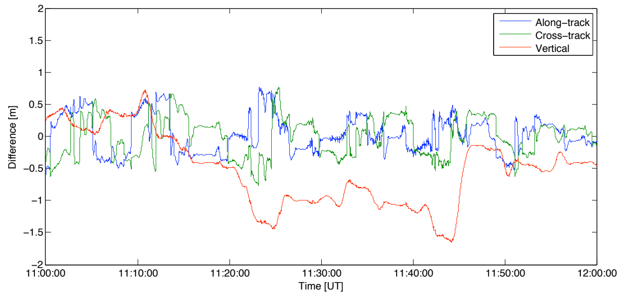

Figure 11: Position differences between loosely coupled PPP/INS and the reference trajectory for the car test.

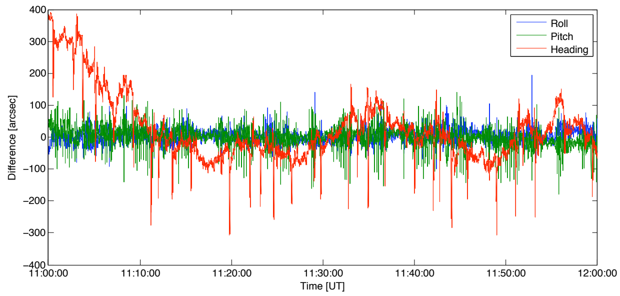

Figure 12: Attitude differences between loosely coupled PPP/INS and the reference trajectory for the car test.

	Mean	Std. dev.
Along track	0.025 m	0.292 m
Cross track	-0.002 m	0.304 m
Vertical	-0.516 m	0.562 m
Along track velocity	-0.001 m/s	0.013 m/s
Cross track velocity	0.000 m/s	0.006 m/s
Vertical velocity	0.001 m/s	0.006 m/s
Roll	3 $''$	17 $''$
Pitch	0 $''$	21 $''$
Heading	26 $''$	104 $''$

Table 7: Statistics of differences between loosely coupled PPP/INS and the reference trajectory for the car test.

LN200. The results from comparison with the reference trajectory are shown in figures 13–14 and table 8.

6 CONCLUSIONS AND FUTURE WORK

We have discussed loose and tight integration of PPP for INS aiding.

The INS implementation in TerraPOS has been verified by com-

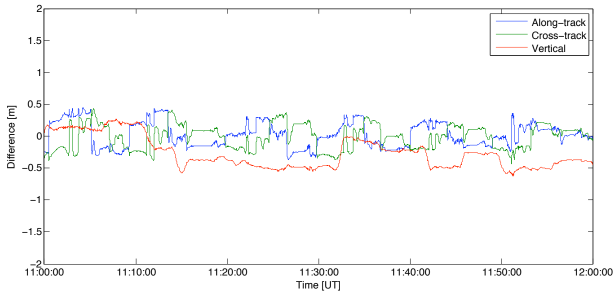

Figure 13: Position differences between tightly coupled PPP/INS and the reference trajectory for the car test.

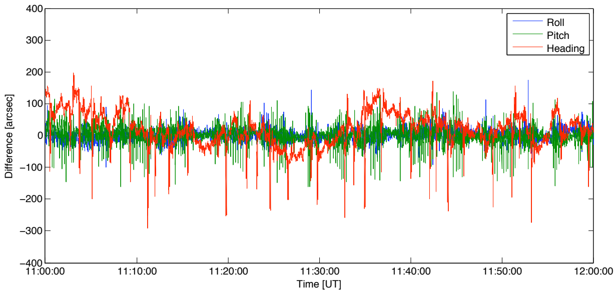

Figure 14: Attitude differences between tightly coupled PPP/INS and the reference trajectory for the car test.

	Mean	**Std. dev.**
Along track	0.022 m	0.195 m
Cross track	-0.012 m	0.192 m
Vertical	-0.268 m	0.243 m
Along track velocity	0.002 m/s	0.005 m/s
Cross track velocity	0.000 m/s	0.005 m/s
Vertical velocity	0.000 m/s	0.004 m/s
Roll	1 ″	15 ″
Pitch	0 ″	18 ″
Heading	19 ″	53 ″

Table 8: Statistics of differences between tightly coupled PPP/INS and the reference trajectory for the car test.

paring the results from two experiments to results from NavLab, an independently developed INS software with a proven record for both research and commercial applications.

The airborne experiment indicates that PPP/INS solutions have comparable accuracy to differential GNSS/INS solutions. No significant differences between loosely and tightly coupled PPP/INS can be found in the current test data (cf. figures 11–12 and table 7). PPP is likely very suited for many airborne direct georeferencing applications. Using a medium-accuracy IMU, like in this experiment, sub-decimeter accuracies can be expected.

The car experiment highlights the difficulties of PPP in environments with frequent GNSS outages. The outages prevent proper convergence of the carrier phase bias estimates, and inaccuracies of code phase observations greatly affects the INS navigation states. Loosely coupled PPP/INS yields no significant improvement over a pure PPP solution. Position accuracies of a few decimeters were demonstrated using a tightly coupled strategy, an improvement of 30–40%.

Despite the tight integration, PPP was insufficient as a sole navigation aid in the car navigation test. Further navigation aids should be considered in a future study, e.g. zero velocity updates, odometers, attitude aiding with multiple GNSS antennas etc.

Although not prominent in this airborne data set, the advantages of a tight coupling should be evident when analyzing more problematic data sets, e.g. with extreme banking.

Both experiments with medium-accuracy IMUs indicate accuracies at the level of 0.5 arc min for roll and pitch, and around 1 arc min for heading.

No GLONASS data was considered in this study, due to the current lack of high-rate clock corrections for GLONASS satellites. Additional satellites impact both the availability and precision of the GNSS solution, and will improve the PPP convergence.

ACKNOWLEDGEMENTS

The authors would like to thank the IGS for generously providing the clock and ephemeris products used in this research.

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