Tightly Coupled Processing of Precise Point Position (PPP) and INS Data

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BIOGRAPHIES

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ABSTRACT

This paper looks at the implementation and results from processing un-differenced GPS data (PPP) with Inertial Measurement Unit (IMU) data using a tightly coupled filter in an airborne environment.

With the use of precise orbit and clock products, PPP has matured from a research topic to a practical GPS processing methodology. The major advantage of PPP GPS processing is that decimeter level accuracy can be achieved globally without any base station. The major drawback of PPP lies in the fact that the solution is slow to converge compared to conventional differential GPS. This can be a serious disadvantage for airborne missions with intermittent losses of lock or poor satellite geometry associated with turns. In fact, one of the principal time and cost constraints in conventional GPS-based airborne mapping lies in the necessity to maintain shallow bank angles on turns, typically less than 30 degrees. With a tightly coupled PPP/INS filter, results can significantly improve during periods of poor satellite geometry or after losses of lock. For this investigation, a tightly coupled PPP/INS filter was implemented in NovAtel's Inertial Explorer post processing software package and results from a variety of airborne missions are presented.

Using this methodology, multiple data sets from an airborne environment were examined. Bank angles of 45 and 70 degrees were implemented on every turn within actual airborne surveys by removing (in software) lower elevation satellites during the turns. The results are then compared to a reference trajectory and the position and attitude degradation examined.

INTRODUCTION

GrafNav is NovAtel's GNSS post-processing software package. Data can be processed forward and reverse in time. Base station data can be input from local base stations or downloaded from publicly available conventional or VRS reference sites. Precise clock and orbit data used for PPP can also be downloaded directly through the software. GrafNav supports data from most commercial GNSS receiver manufacturers and is available as a fully installed software package or as a DLL for system integrators. Inertial Explorer builds upon the GrafNav package to offer tightly-coupled GNSS/INS processing. Features like a boresighting module and forward/reverse solution combining and smoothing make the package particularly attractive to airborne-survey applications.

Unlike traditional differential GPS, precise point positioning requires no base station and no measurement differencing is performed. Instead, precise satellite orbit and clock information is used along with corrections for effects such as solid earth tides, satellite phase windup, tropospheric delay, ionospheric delay and satellite antenna offsets (Kouba et al. 2001). After filter convergence, decimeter to sub decimeter level accuracy can be achieved without the cost and complexity of local base station setup or consideration of solution degradation with baseline length. Waypoint Products Group has considerable experience in precise point positioning and its implementation of PPP is currently being used in production work for airborne and marine surveys.

A drawback of PPP is the convergence time of the filter. For surveys four hours in length or longer, this convergence problem is largely overcome when the forward and reverse trajectories are combined through inverse variance weighting. However, for surveys of less than four hours in length, forward and reverse trajectory weighting does not always resolve this issue. To mitigate this, multipass processing has been introduced. Multipass has shown significant improvements for data sets that have previously not had adequate convergence time. This paper will also look at the implementation and results of multipass methodology for a PPP/INS tightly coupled filter. In addition to the benefits of improved position convergence, a tightly coupled multipass approach can aid in the robustness of the inertial alignment procedure.

PPP works well if the environment provides good satellite availability with very infrequent losses of lock. However, with a complete loss of lock, the carrier phase ambiguity values have to be re-solved and a precise solution will be contingent on ambiguity re-convergence. Given the potentially long convergence times, PPP is not well suited to kinematic terrestrial surveys unless they are in a completely open sky environment.

Solution convergence issues are most evident in loosely coupled PPP/INS implementations where the PPP solution is computed first using only the GPS data and then combined with the IMU data in a secondary process. This processing method does not allow the INS data to aid the PPP computation. Furthermore, when less than 5 satellites are visible, a solution is not possible with PPP and the IMU solution will be processed in free-inertial mode with no GPS position or velocity updates to constrain the inertial drift.

In a tightly coupled PPP/INS implementation, the IMU and GPS measurement data are processed together to compute a solution. When the satellite count drops below the minimum necessary to compute a PPP solution, the measurement data can still be used in the inertial filter to provide a precise constraint on the inertial drift. When the satellites are re-acquired, the IMU measurement data can assist in re-initializing the PPP solution computation process. While tightly coupling PPP and INS data will not necessarily allow PPP processing to work optimally in an urban or other harsh signal environment, it can help bridge periods where the number of satellites drops to less than 5 or where short, infrequent complete losses of lock are encountered. This is possible in an airborne survey where steeply banked turns can obstruct satellites.

PPP BACKGROUND

Precise orbit (SP3 files) and clock information required for PPP processing are available from a variety of services over the Internet in as little as one day after the survey. These files can be downloaded directly through the GrafNav and Inertial Explorer software packages. The accuracies for precise satellite orbits and clocks have significantly improved over the past 15 years. Currently the RMSE of the rapid orbit and clock information is less than 3 cm (Griffiths et al. 2008). In addition, some services now provide satellite clock information at a higher data rate of 5 seconds versus the 30-second or 5-minute file formats previously output. Higher rate clock files aid in reducing noise within the solution. It is important to note that when processing older data sets with PPP, the solution noise will likely be increased as the precise satellite orbit and clock information will contain more noise.

The main observation equations used in precise point positioning are formed with the ionospheric free combination of dual frequency GPS pseudorange and carrier phase. With the ionospheric free combination, the impact of the ionosphere is mitigated at the cost of increased signal noise from combining the observations. Also it should be noted that the carrier phase ambiguities are non-integer values.

Unlike the ionosphere, the troposphere is a non dispersive medium for radio waves. This means that the impact of the troposphere can not be removed from combining signals with different frequencies. However, because PPP does not do any signal differencing, it does a very good job of stochastically observing the tropospheric zenith path delay. The ability of PPP to observe the tropospheric delay is one of the attributes that makes it very well suited to an airborne environment as compared to traditional differential processing where the base station and rover can have a large vertical separation and hence very dissimilar tropospheric characteristics.

PPP does not treat the carrier phase ambiguities as integer values that can be resolved per conventional differential surveys. The ambiguity values are left as floating point numbers that require continuous phase tracking to converge to the "correct" value. The time required for solution convergence depends on the quality of the pseudo range observation, the number of available satellites and the geometric strength of the satellites observed. In post processing, the data can be processed in forward and reverse directions. This largely eliminates convergence issues provided there are few complete signal outages.

Table 1 shows the expected kinematic accuracies for NovAtel's PPP-only processing module. It is important to note that these accuracies assume open sky conditions with a high quality dual frequency receiver and two hours or more of continuous data.

Table 1: PPP Kinematic position accuracy

Component	RMS (cm)
Horizontal	2 to 12
Vertical	3 to 15

Table 2 provides the accuracies that are typically obtainable with PPP for static point surveying. This can be useful in determining and verifying base station coordinates.

Table 2: PPP Static position accuracy over time

Data Processing Length	Horizontal RMS (cm)	Vertical RMS (cm)
1 Hour	6.5	6.3
2 Hour	3.4	3.2
3 Hours	2.2	2.9
6 Hours	1.3	2.4
12 Hours	0.9	2.0
24 Hours	0.7	1.6

PPP and INS TIGHTLY COUPLED

Stand-alone PPP requires a minimum of 5 satellite observations to compute a solution. Five observations are used to solve the 3 position unknowns, receiver clock bias and the tropospheric zenith path delay. If fewer than 5 satellites are present, cycle slip detection will be performed on the remaining satellites and the epoch will be skipped with no solution output. However, with a tightly coupled PPP and INS filter approach, GPS measurement data can still be used in the filter computation when less than 5 satellites are present. It is important to note that when less than 4 satellites are observed, the GPS receiver clock bias can not be solved for directly and must be handled appropriately. Nevertheless, the observed phase measurements on the remaining satellites can greatly aid in reducing the position error growth during periods when PPP position computation is impossible.

To avoid this situation in aerial mapping, flight paths are designed to include wide flat turns so that satellite visibility is more or less completely maintained. This ensures that there is little danger of any unacceptable degradation in the GPS/INS solution due to signal blockage during the turn – at a potentially significant cost increase in flying time. In a tightly coupled scenario, the remaining satellites can still be used within the overall solution and significantly aid in reducing the error growth which is likely to occur during partial signal outages. Cost-wise, accurate bridging through partial GPS outages could be highly beneficial in these applications.

An example of an aircraft banking a steep turn of 70 degrees is provided below. Figure 1 shows the number of satellites available before, during and after the banking event. During the turn, all but 3 satellites were removed from the actual data for a period of 60 seconds and the data re-processed with the reduced satellite configuration. Figure 2 illustrates the error growth of the loosely coupled filter compared to the truth trajectory in the forward direction before smoothing. In the loosely coupled approach, the PPP solution is created first independent of the INS data. No GPS data is available to aid the INS solution during the partial outage, so the INS filter is operating in free-inertial mode and, as such, the position drift during the turn is significantly larger.

Figure 3 illustrates the error growth of the tightly coupled filter compared to the truth trajectory. It is seen that using only 3 satellites introduces very little error during this turn. It should be noted that with less than 5 satellites, the error growth depends on the geometric strength of the remaining satellites and the quality of the IMU. For example, if only three satellites were visible and all satellites were on the horizon, there would be very little vertical constraint to the solution and more vertical error growth would be expected.

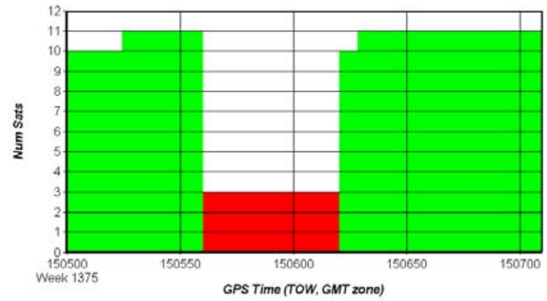

Figure 1: Number of satellites

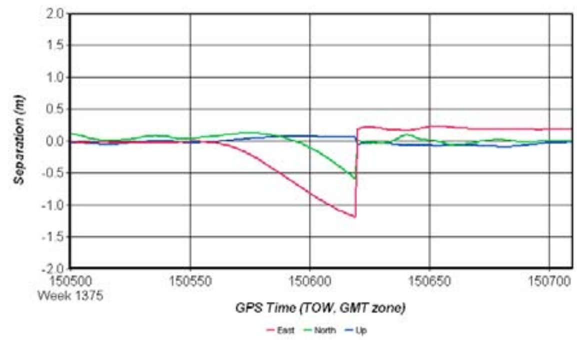

Figure 2: Forward direction error with loosely coupled processing

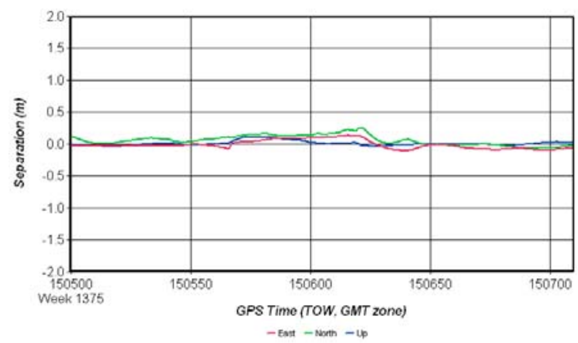

Figure 3: Forward direction error with tightly coupled processing

MULTIPASS PROCESSING

Given short data sets of less than four hours, the long convergence times typical of PPP can degrade the overall solution. Multipass was developed to obtain a better trajectory solution in these situations.

Using multipass, the data is processed three times sequentially: forwards, reverse and then forward again. After each run, the converged Kalman Filter states (position, velocity, tropospheric delay, attitude, carrier phase ambiguities etc.) are preserved. Multipass processing can provide a 20% to 40% position improvement for aerial surveys of 4 hours or less in duration.

This level of improvement is achievable on typical aerial flights collected with an unobstructed view of the sky, low multipath, good satellite geometry, and minimal loss of GPS signal lock. The level of improvement on surveys greater than 4 hours is less significant.

An example of the benefits of multipass processing is provided. A relatively short one hour airborne data set was collected. For this test a nearby base station was present and a high quality differential reference trajectory was created using Inertial Explorer. The error on this reference trajectory is expected to be within 5cm. The usual tightly coupled single pass PPP/INS solution was first computed. Multipass processing was also performed. Figure 4 shows the difference between the combined PPP/INS solution and the reference solution. Figure 5 shows the difference between a multipass PPP/INS tightly coupled solution and the reference GPS/INS differential solution.

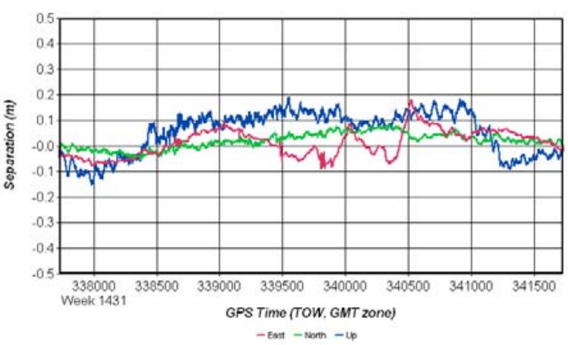

Figure 4: Position error without multipass processing

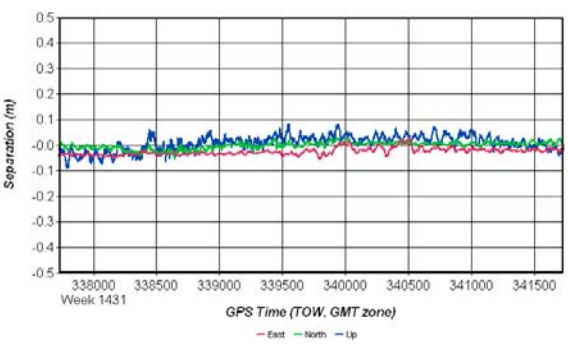

Figure 5: Position error with multipass processing

Multipass processing works optimally with data sets that have at least 90 minutes of continuous data. Occasionally, 60 minutes of data will not provide enough data for the filter to completely converge.

TEST DESCRIPTION

To test the PPP/INS tightly coupled processing method, a sample of seven airborne data sets were examined. For each data set, a reference trajectory was created using differential GPS / INS processing within Inertial Explorer. In these data sets the typical maximum bank angle flown varies between 15 and 25 degrees. To test the effectiveness of the tightly coupled solution, the bank angle needs to be increased. To achieve this, satellites were removed from the data sets in order to artificially increase the bank angle during turns. Bank angles of 45 and 70 degrees were tested, although it is acknowledged that a 70 degree bank is likely an exaggeration for aerial survey applications. For both the 45 and 70 degree bank angle tests the PPP/INS tightly coupled solution were computed and the position and attitude compared against the reference trajectory.

A typical data set is described in detail below. Following that a summary of the results from a collection of data sets is provided. The data sets are from various locations and aerial mission types together with different IMU types.

FLIGHT 01

Duration:	4 hours
Flying Height:	3000m
IMU Used:	LN200 (tactical-grade)
GNSS Receiver:	NovAtel OEM V
Original Bank Angle:	15 degrees

Figure 6 shows an outline of the flight. Figure 7 illustrates the number of available satellites with a simulated 70 degree bank angle. The average turn length was approximately 60 – 90 seconds for this project. In four of the turns the number of satellites dropped to four. Figure 8 plots the difference between the PPP tightly coupled trajectory with 15 degree bank angles and the reference differential trajectory.

Figure 9 shows the PPP tightly coupled trajectory with simulated 70 degree banked turns versus the reference trajectory. In this flight the position RMS remained below 10cm for both the 45 and 70 degree bank turn simulations. Table 3 outlines the position RMS versus the differential reference trajectory for the default 15 degree and 45 and 70 degree bank angle cases. The RMS values displayed in all cases are for the entire flight, including the turns. Table 4 shows the attitude RMS for the various bank angles versus the reference trajectory. The attitude variation is within the acceptable noise level of an LN200 IMU.

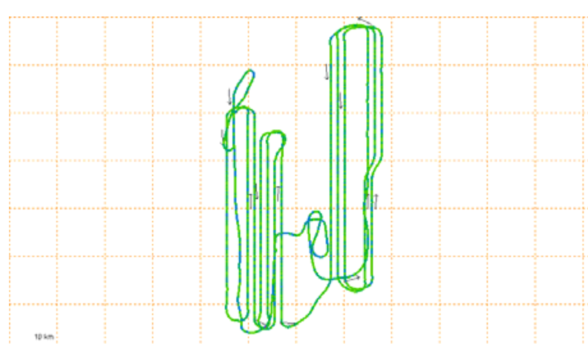

Figure 6: Map of flight 01 flight lines

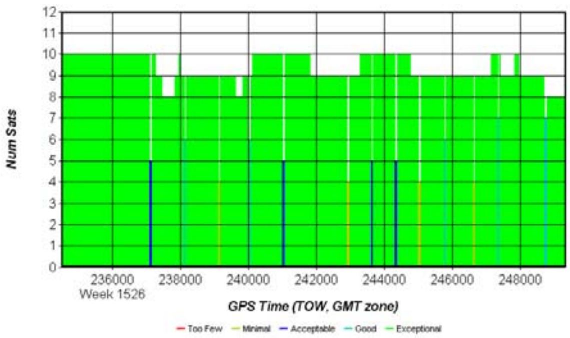

Figure 7: Flight 01 number of satellites with 70° banked turns

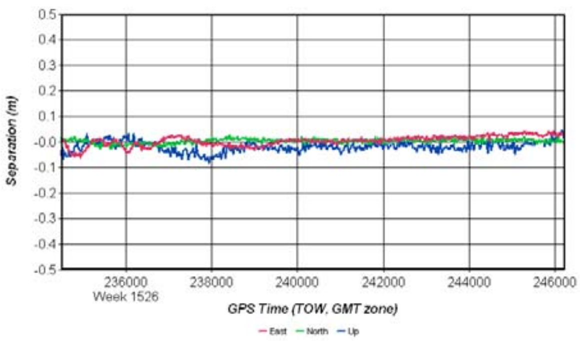

Figure 8: Flight 01 Position Difference - PPP Tightly coupled versus reference trajectory – 15° bank

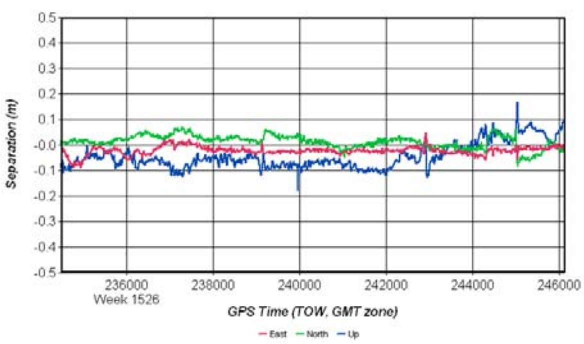

Figure 9: Flight 01 Position Difference - PPP Tightly coupled versus reference trajectory - 70° bank

Table 3: Flight 01 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
25°	0.029	0.010	0.046
45°	0.026	0.028	0.062
70°	0.027	0.028	0.067

Table 4: Flight 01 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
25°	0.029	0.027	0.187
45°	0.033	0.031	0.207
70°	0.035	0.032	0.227

FLIGHT 02

Duration:	6 hours
Flying Height:	9000m
IMU Used:	Honeywell Micro IRS (navigation-grade)
GNSS Receiver:	NovAtel OEM 4
Original Bank Angle:	25 degrees

Table 5 shows the position RMS of the PPP tightly coupled solution versus the differential reference trajectory for the various bank angles. Table 5 shows that even with a 70 degree bank angle, the horizontal and vertical RMS are each within 10cm. Table 6 shows how the attitude agrees with the reference trajectory attitude. The attitude variation is within the acceptable noise level for a Micro IRS solution.

Table 5: Flight 02 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
25°	0.016	0.008	0.033
45°	0.037	0.031	0.063
70°	0.055	0.042	0.101

Table 6: Flight 02 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
25°	0.006	0.004	0.027
45°	0.006	0.005	0.041
70°	0.010	0.007	0.095

FLIGHT 03

Duration:	1.5 hours
Flying Height:	900m
IMU Used:	Honeywell HG1700 AG58 (tactical-grade)
GNSS Receiver:	NovAtel OEM V
Original Bank Angle:	15 degrees

Multipass processing is particularly interesting for this dataset because of the short flight length. Table 7 shows position RMS for the various bank angles and Table 8 shows the attitude RMS for the various bank angles. In this test flight, the multipass processing is shown to work well with the 45 degree and 70 degree banked turns.

Table 7: Flight 03 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
25°	0.051	0.027	0.038
45°	0.055	0.027	0.051
70°	0.062	0.032	0.071

Table 8: Flight 03 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
25°	0.070	0.072	0.280
45°	0.076	0.072	0.281
70°	0.082	0.075	0.339

FLIGHT 04

Duration:	2 hours
Flying Height:	9000m
IMU Used:	Honeywell Micro IRS (navigation-grade)
GNSS Receiver:	NovAtel OEM 4
Original Bank Angle:	25 degrees

Flight 4 is from a high altitude airborne data set. In this flight, the number of observed satellites always remains at 5 or more, even with a 70 degree bank angle. The position and attitude RMS agree very well for each of the bank angle scenarios. To process this data set multipass processing was used.

Table 9: Flight 04 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
25°	0.035	0.019	0.025
45°	0.037	0.022	0.045
70°	0.044	0.027	0.046

Table 10: Flight 04 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
25°	0.012	0.007	0.031
45°	0.014	0.009	0.042
70°	0.015	0.009	0.042

FLIGHT 05

Duration:	1 hour
Flying Height:	1000m
IMU Used:	LN200 (tactical-grade)
GNSS Receiver:	NovAtel OEM V
Original Bank Angle:	15 degrees

Flight 5 is a very short boresight calibration flight. Although PPP would not likely be used in a boresight calibration flight largely due to the short duration and very high accuracy requirements, this flight was used for testing the PPP tightly coupled processing as a matter of interest. Due to the short duration of the flight, multipass processing was enabled. The 15 degree bank angle PPP trajectory agrees very well with the differential reference trajectory. It should be noted that flights this short can occasionally have difficulty converging to a sub-decimeter level. Typically a minimum of 90 minutes of continuous data should be used for multipass processing.

The trajectory with the 45 degree banked turns shows significant error growth of some 15 – 20 cm in the horizontal component. During the turns the number of observed satellites drops to 4. One factor possibly causing this increased position degradation is that the flight lines are very short, typically only a couple of minutes in length. With short flight lines there is little time for the carrier phase ambiguities that have been lost during the turn to converge back to a reasonable solution before the next turn.

In the 70 degree bank angle scenario, the number of observed satellites occasionally drops down to only 2. In this flight although the position RMS is seen to degrade to a level of sub 20 cm during the higher bank angle turns, little impact is seen on the attitude RMS. Another factor likely degrading the 45 and 70 degree bank angle results is the brevity of the data set - only one hour in length. The processing was performed in multipass mode.

In the 15 degree bank angle case, there was a sufficient amount of data to allow the solution to converge. In the 45 and 70 degree bank angle cases, the easting has a consistent bias likely caused by the solution not completely converging within the first pass. The combination of short data times and short flight lines results in 10 – 15 cm position degradation for the 45 and 70 degree bank angle cases.

Table 11: Flight 05 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
15°	0.018	0.012	0.035
45°	0.104	0.072	0.053
70°	0.135	0.085	0.065

Table 12: Flight 05 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
15°	0.028	0.016	0.049
45°	0.030	0.016	0.054
70°	0.035	0.020	0.059

FLIGHT 06

Duration:	2 hours
Flying Height:	9000m
IMU Used:	Honeywell Micro IRS (navigation-grade)
GNSS Receiver:	NovAtel OEM 4
Original Bank Angle:	25 degrees

In Flight 6, multipass processing was selected. Table 13 details the position RMS for the various bank angles. The RMS associated with the 45 and 70 degree banked turns show greater degradation than the other flights analyzed. The 10 - 12 cm horizontal error present in this solution is probably a function of the satellite geometry during these turns. Table 14 shows the attitude RMS for the various bank angles. This is well within the acceptable noise level for a Micro IRS IMU.

Table 13: Flight 06 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
25°	0.037	0.037	0.048
45°	0.096	0.041	0.098
70°	0.124	0.047	0.129

Table 14: Flight 06 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
25°	0.009	0.006	0.023
45°	0.010	0.007	0.049
70°	0.041	0.013	0.053

FLIGHT 07

Duration:	6 hours
Flying Height:	2000m
IMU Used:	LN200 (tactical-grade)
GNSS Receiver:	NovAtel OEM V
Original Bank Angle:	35-50 degrees

Flight 7 is interesting because the data was actually flown with steep turning angles in the range of 35 to 50 degrees. Therefore no 45 degree simulation was necessary. The results from this actual data set agree well with the reference trajectory and provide real confirmation of the accuracies observed in the simulated 45 degree bank angle data sets.

Table 15: Flight 07 Position RMS vs Reference Trajectory

	Easting RMS (m)	Northing RMS (m)	Height RMS (m)
35°-50°	0.058	0.039	0.064
70°	0.099	0.064	0.084

Table 16: Flight 07 Attitude RMS vs Reference Trajectory

	Roll (arcmin)	Pitch (arcmin)	Heading (arcmin)
35°-50°	0.035	0.029	0.251
70°	0.063	0.061	0.339

SUMMARY OF RESULTS

The results for the 7 flights are given below. Figure 10 provides a summary of the vertical RMS for the various flights and bank angles. Figure 11 summarizes the horizontal RMS. It is shown that even with 70 degree banked turns horizontal and vertical position error values lie within 15cm RMS on all flights. With 45 degree bank angles, only flight 5, the short boresight calibration had RMS values above 10 cm.

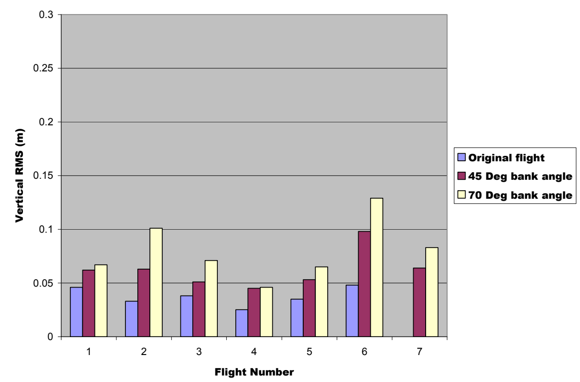

Figure 10: Vertical summary of flight results

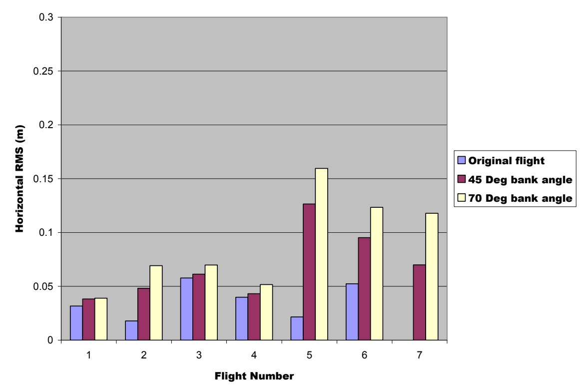

Figure 11: Horizontal summary of flight results

CONCLUSION

In this paper, a tightly coupled precise point and INS (PPP/INS) Kalman filter has been developed and results computed with a representative number of airborne data sets. The data sets were analyzed with 45 and 70 degree bank angles. These were shown to have a horizontal and vertical position RMS within 15cm of their associated differential reference trajectories. The attitude RMS in all cases is within the acceptable noise level for the given IMU in each flight.

The quality of the solution depends on the number of observed satellites, the satellite geometry, the length of the flight lines and the length of the data set. Flying with steeper bank angles is better suited to flights with longer flight lines and a longer data collection period.

The tightly coupled precise point and INS filter provides an improvement to the loosely coupled approach in the range of 5% to 30% after the trajectories have been smoothed and combined. With filtering only, the improvements are much more significant. In tightly coupled processing the workflow is also simplified as all processing can now be completed in a single processing step.

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