DGPS High Accuracy Velocity Determination Using Doppler Measurements

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BIOGRAPHIES

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ABSTRACT

This paper describes the results of a series of differential GPS tests conducted for the purpose of high accuracy aircraft velocity determination. Velocities were determined through the use of Doppler measurements obtained either through the raw receiver output or the application of carrier phase-derived Doppler measurements. Static and kinematic tests were performed using two sets of GPS receivers, specifically two NovAtel MiLLennium™ dual frequency receivers and two NovAtel single frequency PowerPack OEM2 with special high accuracy velocity software. The first static test was a short baseline test (< 10 m) in a moderate to high multipath environment and served as the best case scenario for velocity determination. The second static test was conducted during an aircraft static initialization with inter-antenna distance of about 1 km. The kinematic test was a flight conducted for the purpose of collecting gravity data. Inter-antenna distances of up to 90 km were obtained. Receiver performance for each test was assessed by differencing epoch-by-epoch between receiver raw Doppler and carrier phase derived velocities.

INTRODUCTION

Accurate velocities are required for a number of applications, including military aircraft test and evaluation analysis, GPS/Inertial Navigation System (INS) integration, gravity field determination, geophysical exploration, etc. GPS is a cost-effective means to obtain reliable and highly accurate velocities by exploiting the receiver Doppler and carrier phase measurements. This paper describes the results of a series of tests conducted to evaluate the accuracy of velocity estimates using two sets of GPS receivers: the NovAtel MiLLennium™ 24 channel dual frequency receiver and NovAtel PowerPack OEM2 12 channel single frequency receiver with special precise velocity firmware. Velocities obtained with raw receiver Doppler measurements were assessed and compared with carrier phase derived velocities.

Previous studies in the area of GPS velocities have been conducted. Fenton and Townsend [1994] conducted measurement domain analysis of curve-fitted statistically independent carrier phase measurements of the NovAtel GPSCard™ from which the phase (Φ), phase velocity and phase accelerations were derived. The authors reported zero baseline and 7 km static baseline phase velocity RMS values of 0.007 mm/s and 0.28 mm/s respectively for a 5 s curve fit of over 250 samples.

An in-depth analysis of GPS velocities obtained in a simulation environment was conducted by Cannon *et al.* [1997]. The Ashtech Z-12™ receivers were compared with the NovAtel MiLLennium™ receivers for performance in both low dynamics (accelerations < 0.5 g) and high dynamics (accelerations up to 5 g). It was determined that the best velocity results for low dynamics were obtained by applying a first-order central difference approximation to the carrier phase measurements and using these values as the carrier phase-derived Doppler for velocity determination. 3D velocity RMS values of 2.9 mm/s and 2.1 mm/s for the Z-12™ and MiLLennium™ were reported based on this technique.

TEST EQUIPMENT AND SOFTWARE

Two sets of GPS receivers were used for each of the tests conducted: the NovAtel MiLLennium™ and NovAtel PowerPack OEM2 with precise velocity firmware S65-3.20. Each receiver is a high performance Narrow Correlator™ receiver capable of outputting raw code and carrier phase measurements. Each receiver utilizes a 3rd-order Phase Lock Loop (PLL) which performs well under highly dynamic conditions (e.g. Cannon *et al*.. [1997]).

The NovAtel MiLLennium™ is a 24 channel dual frequency receiver with L1 C/A code, L2 P/Y code, L1 and L2 carrier phase measurements. The Doppler measurement of the MiLLennium™ is updated from the PLL at 100 Hz and is averaged over 50 - 100 ms. There is as much as a 10 ms time lag between the Doppler measurement and the measurement strobe which may affect the accuracy of the velocity estimates in high dynamics.

The NovAtel PowerPack OEM2 unit is based on the GPSCard™ series and is a 12 channel single frequency receiver. For the purpose of the velocity analysis for these tests, special Precise Velocity (PV) firmware S65-3.20 was used. The main feature of this firmware revision is the 50 Hz phase measurement 3rd-order curve fitting process providing more precise carrier phase, Doppler and phase acceleration measurements at 1 Hz. The curve fit is done over the ±0.5 s from the data point. The result is highly accurate measurements output with just over a 0.5 s latency.

The software used to derive velocity estimates for the analysis was C^3NAV™ [Cannon, *et al*., 1995]. C^3NAV™ was developed at The University of Calgary and utilizes a combined code and carrier phase processor (carrier-smoothed code generation) for navigation purposes. It provides an epoch-by-epoch single difference solution where rover velocities are based solely on Doppler measurements.

In addition to utilizing the receiver raw Doppler measurements in the analysis, carrier phase-derived Doppler measurements were obtained by applying a Taylor Series expansion on the carrier phase which yields an estimate of the derivative (i.e. the Doppler). A full description of this technique is given in Hebert [1997]. Care was taken to ensure that cycle slips were accounted for, thus, a dual frequency (if available) or single frequency phase velocity trend cycle slip detection algorithm was applied.

TEST DESCRIPTION AND ANALYSIS CONDUCTED

Three main tests were conducted: static short (< 10 m) baseline test, aircraft static initialization and a kinematic test. The static short baseline test was conducted on the roof of the Engineering building at The University of Calgary. The tests were conducted at different times and were used as the basis for comparative analysis by providing the best case scenario for velocity estimates. The roof is a moderate to high multipath environment. Data was collected for 1/2 hour at 1 Hz data rate.

The aircraft static initialization was performed on March 3, 1997, using a Cessna T310-IIR twin-prop aircraft with engines running. Thus, there was a considerable amount of vibration and multipath. A dual frequency antenna was mounted on the fuselage and the signal was split between the MiLLennium™ and PV receivers. The LNA jumper was removed from the PV receiver so antenna power was fully supplied by the MiLLennium™. The monitor station similarly used a dual frequency antenna with chokering and the signal was split between MiLLennium™ and PV receivers. The inter-antenna distance between rover and monitor stations was about 1 km. 15 minutes of data was collected at 2 Hz and 1 Hz for the MiLLennium™ and PV receivers respectively.

The kinematic test took place immediately after completion of the 15 minute static initialization. The purpose of the flight was to collect gravity data, hence a grid pattern was flown with gentle flying and limited banked turns to avoid cycle slips. Figure 1 shows the trajectory of the aircraft in relation to the fixed reference station with the 8 east/west and 2 north/south sections with constant velocity highlighted. Inter-antenna distance of up to 90 km were experienced during the flight test which lasted about 3 hours.

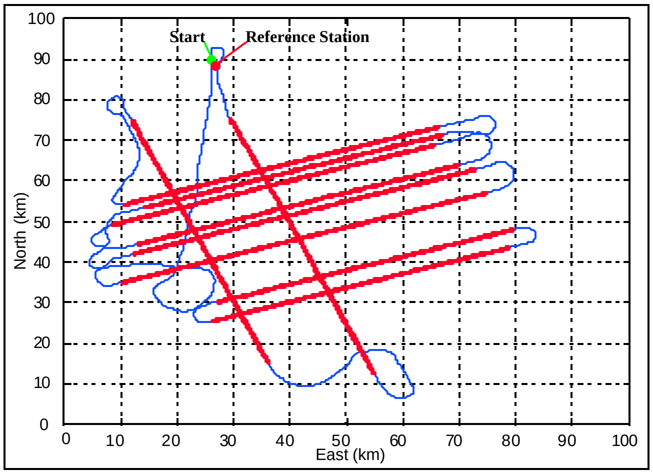

Fig. 1 - Kinematic test flight path.

The kinematic test reference trajectory components are shown in Figure 2. During the flight, the altitude remained fixed at 1800 m ASL with some noticeable excursions occurring during some of the turns.

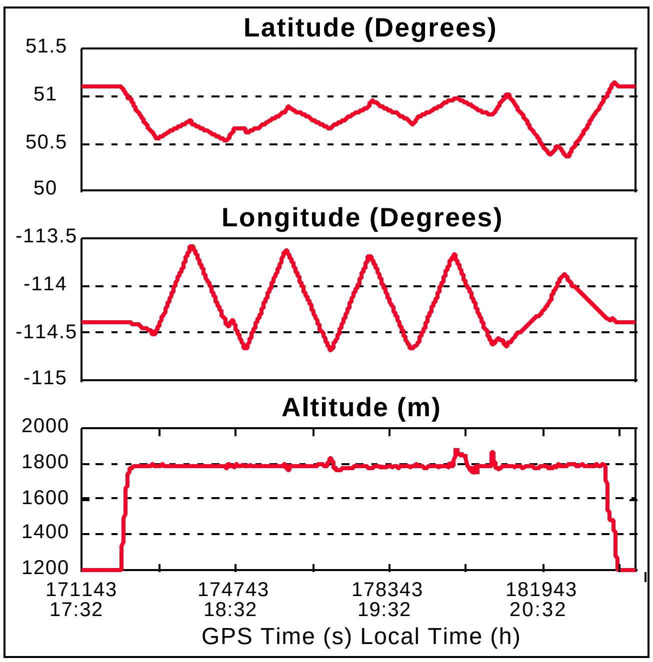

Fig. 2 - Kinematic test trajectory components.

During the 80 m/s constant velocity sections of the test flight from which the velocity analysis were conducted, the dynamics remained low with accelerations averaging < 0.5 m/s^2 and jerk averaging < 0.5 m/s^3. During the turns, accelerations up to 5.5 m/s^2 were experienced. Figure 3 shows the dynamics experienced during the entire kinematic test.

In order to assess the accuracy of the velocity estimates for each receiver pair, a number of analyses were conducted using raw Doppler measurements of both

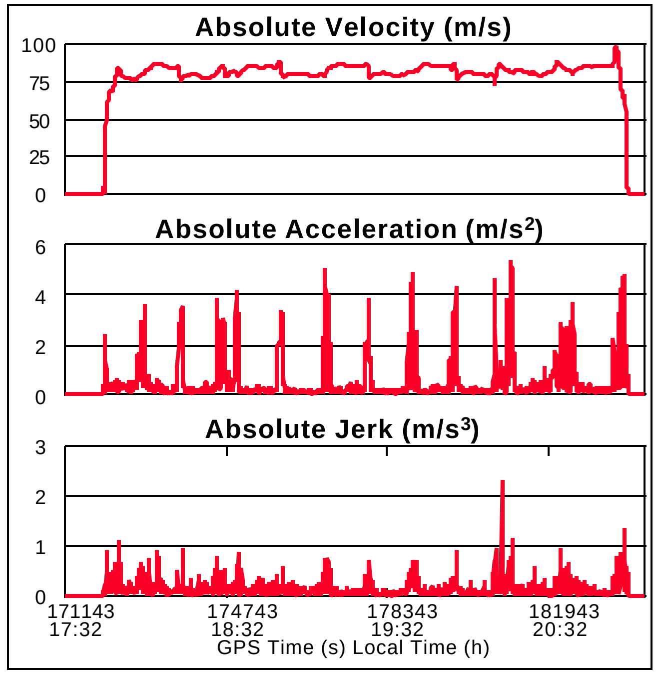

Fig. 3 - Kinematic test dynamics.

receiver pairs as well as the 1st-order central difference approximation of the MiLLennium™ carrier phase measurements.

For the static baseline test, velocity estimates were compared with the zero velocity truth. This analysis gives a good indication as to the best independent results possible in a benign and controlled environment affected by multipath.

For the aircraft static initialization, velocity estimates were also compared with the zero velocity truth yielding best possible independent results in a static but more realistic (i.e. aircraft vibration, high multipath, long baseline) environment. In addition to comparison against zero velocity truth and in order to support the statistical inferences made for the kinematic analysis, differencing epoch-by-epoch between receiver raw Doppler and carrier phase derived velocities was performed. In each case, differencing was done with the MiLLennium™ 1st order carrier phase derived velocities since it has been previously established [Cannon *et al.*, 1997] that 3D velocities of the order of 2 mm/s can be expected for low dynamic conditions.

For the kinematic test, raw Doppler velocity estimates were assessed by differencing epoch-by-epoch between receiver raw Doppler and carrier phase derived velocities since it has been previous established that high accuracy velocity estimates can be obtained using carrier phase derived Doppler measurements under similarly low dynamic conditions [Cannon *et al.*, 1997].

TEST RESULTS

This section presents the results of the three main tests conducted.

Static Short Baseline Test

Analysis of the two receiver pairs using receiver raw Doppler measurements in a benign and controlled static environment (see Figure 4) shows that there is a significant increase in accuracy in velocity estimates as a function of how the Doppler is internally computed. Recall that the MiLLennium™ raw Doppler is updated from the PLL at 100 Hz and is averaged over 50 - 100 ms resulting in a much more noisy signal compared with the PV receiver raw Doppler, which curve fits phase measurements over ±0.5 s.

Figure 5 shows the MiLLennium™ velocity estimates based on the carrier phase derived Doppler compared with the PV unit. It is clear that the magnitude of the velocity errors are more or less equivalent, the MiLLennium™ 1st-order velocities slightly outperforming the PV unit raw Doppler velocities.

Table 1 summarizes the static baseline test north, east up and 3D velocity statistics for the MiLLennium™ raw Doppler, MiLLennium™ 1st-order Φ, and PV receiver raw Doppler.

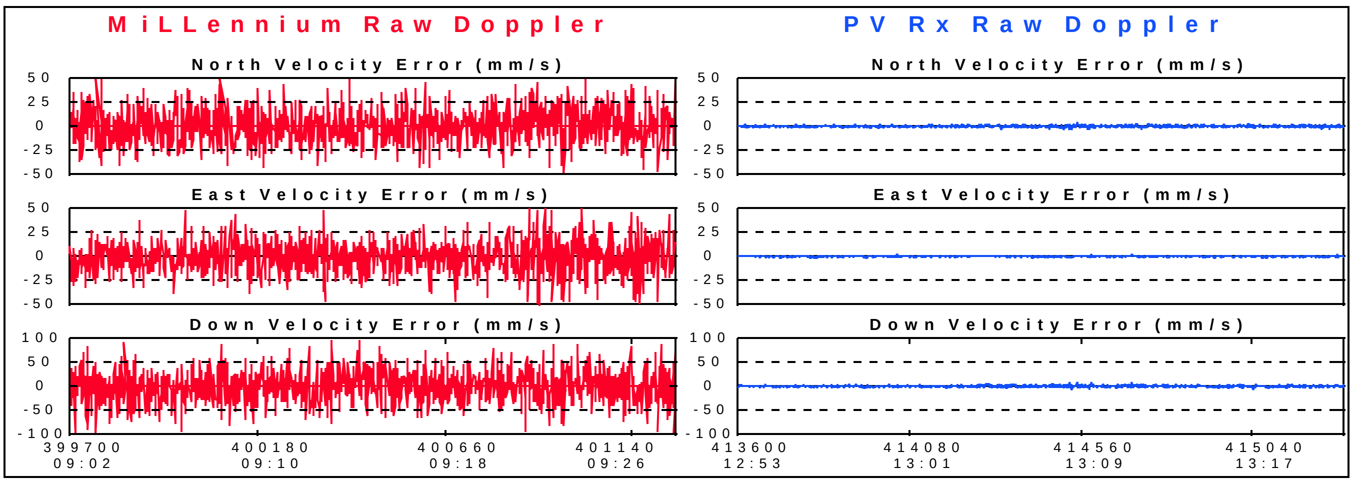

Fig. 4 - MiLLennium™ raw Doppler vs. PV Rx raw Doppler (static baseline).

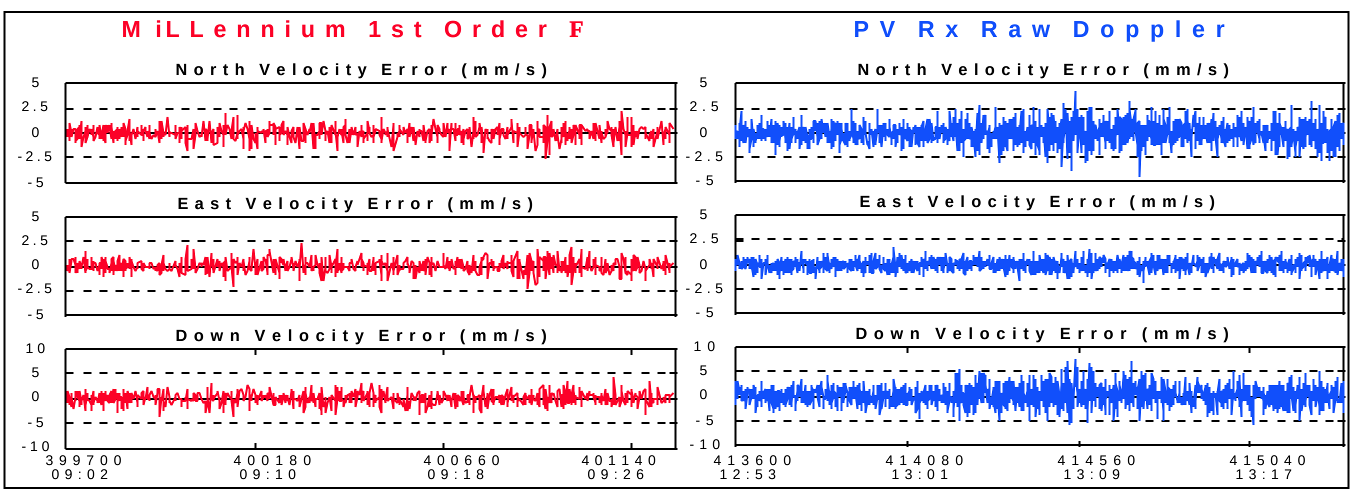

Fig. 5 - MiLLennium™ 1st order derived Doppler vs. PV Rx raw Doppler (static baseline).

TABLE 1
Summary of Statistics
Static Short Baseline Velocities

	68 Percentile Velocity Error (mm/s)			
	N	E	U	3D
MiLL Raw	16.9	15.1	31.6	41.0
MiLL 1st Order	0.6	0.6	0.7	1.4
PV Raw	0.9	0.5	1.7	2.1

From Table 1, it is evident that 3D velocity accuracies in a benign controlled environment are at best 1.4 mm/s when using the carrier phase derived Doppler measurements. The difference in the accuracy between the MiLLennium™ 1st order and PV raw Doppler derived velocities may likely be due to the interval over which the Doppler is computed (averaged over 2 s for the MiLLennium™ 1st order vs. curve fit over 1 s for the PV receiver raw Doppler). Since the tests were conducted at different times, there will be small variations in accuracy due to satellite geometry and availability.

Aircraft Static Initialization

The longer baseline (> 1 km) together with utilizing the same antennas (hence signal) for each receiver pair during the aircraft static initialization will yield results which can be compared directly. Similar to the previous analysis, each receiver pair was assessed on its own in terms of velocity estimates.

Figure 6 shows the comparison of the velocity estimates using receiver raw Doppler measurements. The magnitude of the estimates are similar to those shown in Figure 4, the MiLLennium™ yielding 3D velocity accuracies of 43.2 mm/s compared with the PV receiver which yields accuracies of the 3D velocity estimates better than 2 mm/s.

Applying the first order central difference approximation to the MiLLennium™ carrier phase results in improved velocity estimates for static conditions to the level of 3.5 mm/s (refer to Figure 7). In this case, however, the accuracy of the velocity estimates is not as good as the PV receiver raw Doppler velocities, which yielded velocity accuracies 1.7 mm/s. The vibration of the running aircraft is likely the cause of this difference in accuracies and illustrates that the curve fitting algorithm applied by the PV receiver performs well under these conditions.

Figure 8 shows the comparison of the epoch-by-epoch between receiver raw and carrier phase derived velocity differences. Again, both the MiLLennium™ raw Doppler and PV receiver raw Doppler results were differenced with the MiLLennium™ 1st order derived Doppler velocities. It is clear that the noise of the velocity estimates is dominated by the MiLLennium™ raw Doppler velocities, yielding differences on the order of 44 mm/s.

Similarly for the differencing between the MiLLennium™ 1st order velocities and the PV receiver raw Doppler, the level of noise of the velocity estimates increased to 3.6 mm/s, which is comparable to the independent results for the MiLLennium™ 1st order derived velocities (3.5 mm/s).

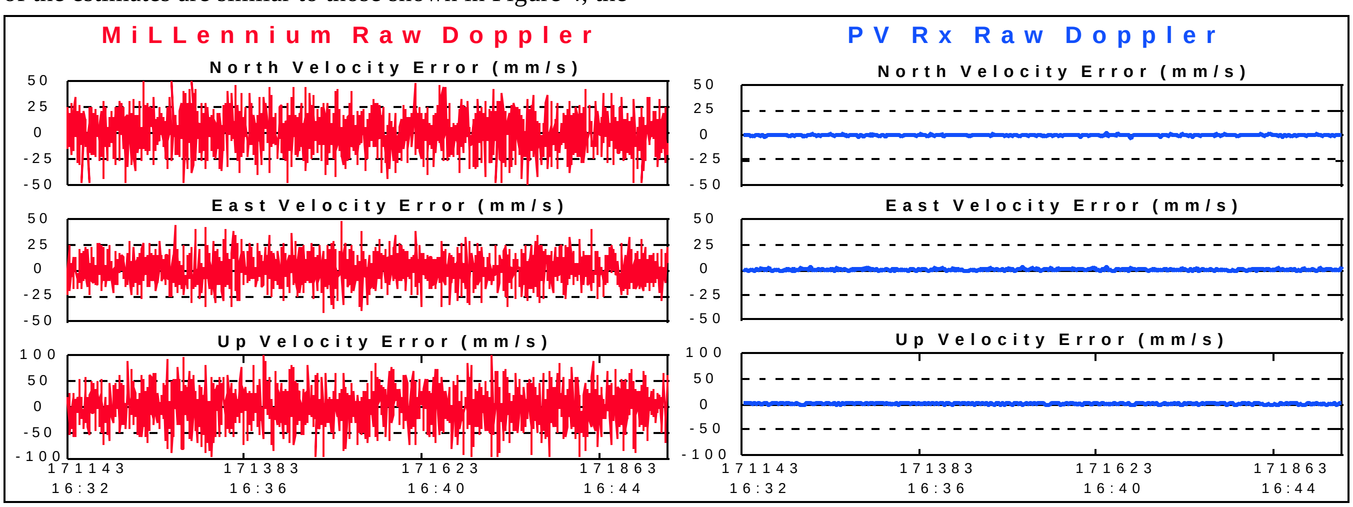

Fig. 6 - MiLLennium™ raw Doppler vs. PV Rx raw Doppler (aircraft static initialization).

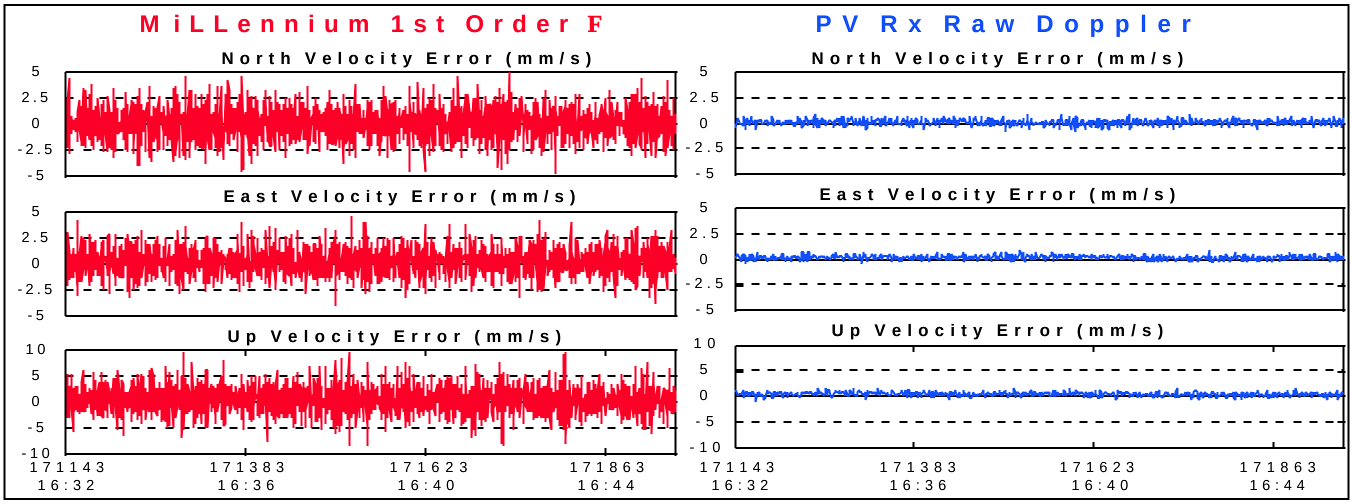

Fig. 7 - MiLLennium™ 1st order Doppler vs. PV receiver raw Doppler (aircraft static initialization).

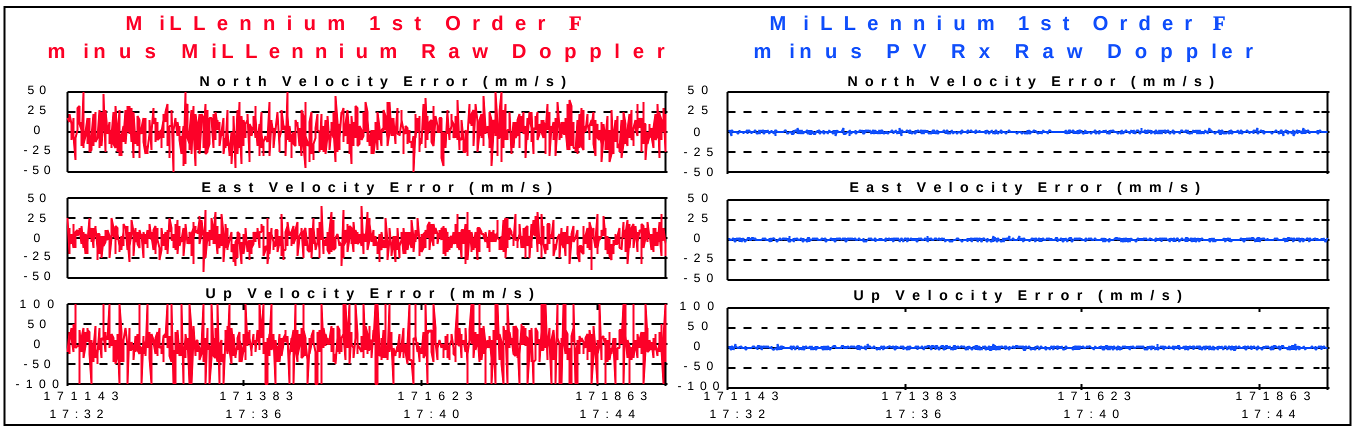

Fig. 8 - MiLLennium™ raw Doppler vs. PV receiver raw Doppler differences (aircraft static initialization).

Table 2 summarizes the statistics for the results of the aircraft static initialization discussed above.

TABLE 2
Summary of Statistics
Aircraft Static Initialization Velocities

	68 Percentile Velocity Error (mm/s)			
	N	E	U	3D
MiLL Raw	18.4	13.6	34.8	43.2
MiLL 1st Order	1.5	1.3	2.7	3.5
PV Raw	0.7	0.7	1.2	1.7
MiLL 1st - MiLL Raw	20	14	34	44
MiLL 1st - PV Raw	1.5	1.2	2.7	3.6

It is evident by referring to the results of the differencing listed in Table 2 that the PV receiver raw Doppler velocity results for static long baselines under aircraft vibrations are at least as good, if not better than those of the MiLLennium™ 1st order carrier phase derived velocities.

Kinematic Test

Figure 9 shows the results of the epoch-by-epoch between receiver raw Doppler and carrier phase derived velocities differenced with the MiLLennium™ 1st order derived velocities for the constant velocity sections of the kinematic test. It is evident that the accuracy of the velocity estimates are on the same order of magnitude as those of the aircraft static initialization. Again, the dominant error is from the MiLLennium™ raw Doppler results, differences yielding 46 mm/s.

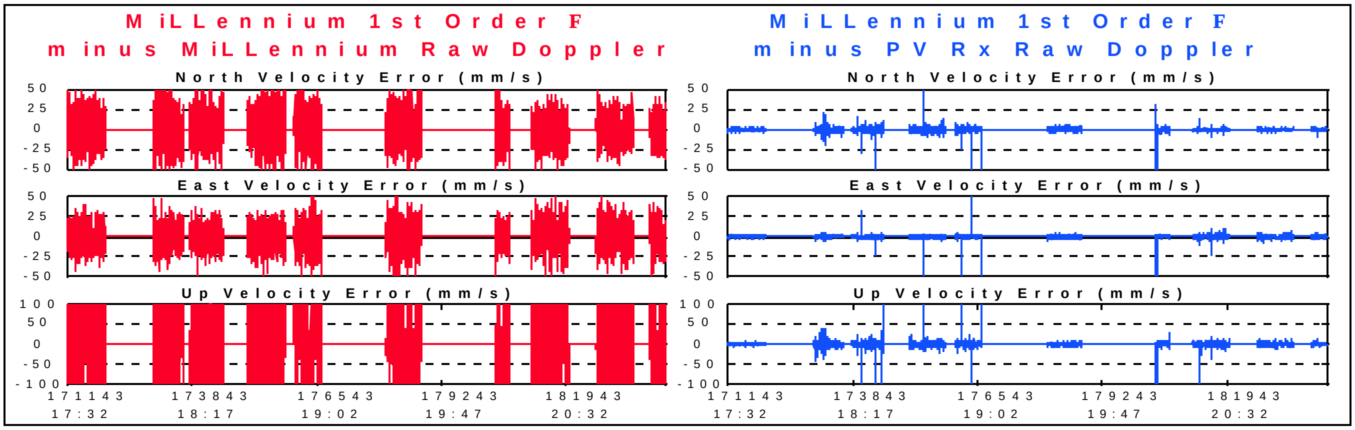

Fig. 9 - MiLLennium™ raw Doppler vs. PV receiver raw Doppler differences (kinematic test).

Table 3 summarizes the statistics for the kinematic test results. The table also compares the kinematic results with those of the aircraft static initialization and clearly illustrates that the accuracy of the velocity estimates are consistent between the two tests conducted. Although the dynamics experienced during the kinematic test were higher than those of the static initialization, this only caused a slight decrease in accuracy in velocity differences, from 3.6 mm/s down to 5.2 mm/s. It can be inferred from the statistics that, assuming best case the contribution of the MiLLennium™ 1st order derived velocity error remains at 3.5 mm/s (i.e. the level of accuracy obtained during static initialization), the PV receiver raw Doppler velocity results under dynamic conditions (constant velocity or accelerations < 0.5 m/s^2) are about as good as (certainly no worse than 3.8 mm/s) and likely better than those of the MiLLennium™ 1st order derived velocities.

TABLE 3
Summary of Statistics
Kinematic Velocities

	68 Percentile Velocity Error (mm/s)			
	N	E	U	3D
MiLL 1st - MiLL Raw (Kinematic)	**19**	**14**	**37**	**46**
MiLL 1st - PV Raw (Kinematic)	**1.9**	**1.5**	**4.3**	**5.2**
MiLL 1st - MiLL Raw (Static)	*20*	*14*	*34*	*44*
MiLL 1st - PV Raw (Static)	*1.5*	*1.2*	*2.7*	*3.6*

CONCLUSIONS

The accuracies of GPS derived velocities have been assessed for two sets of GPS receivers (the NovAtel MiLLennium™ and the NovAtel PowerPack OEM2 units) under a variety of static and kinematic conditions. Velocities were obtained by utilizing both raw and carrier phase derived Doppler measurements in order to assess the level of improvement obtained. Analysis of kinematic results were achieved by differencing epoch-by-epoch between receiver raw and carrier phase derived velocities.

From the results, it is evident that under constant velocity or low acceleration (< 0.5 m/s^2) conditions, the accuracy of the raw Doppler derived velocity estimates using the NovAtel PowerPack OEM2 with special precise velocity firmware S65-3.20 are at least as good, if not better than the velocity estimates of the MiLLennium™ using the 1st order central difference approximation of the carrier phase. Based on the statistics from the kinematic tests, the expected accuracy of the NovAtel PowerPack OEM2 with special precise velocity firmware S65-3.20 is at least at the level of 3.8 mm/s in a low dynamic aircraft environment.

Further research in the area of GPS velocities is being conducted in order to assess the level of performance of the precise velocity NovAtel PowerPack OEM2 for higher dynamics (accelerations up to 50 m/s^2) under controlled environments [Lachapelle *et al.*, 1997].

ACKNOWLEDGMENTS

The authors wish to acknowledge Canagrad Surveys Limited for collecting the GPS data for the kinematic test.

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