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Accuracy of Speed Measurements using GNSS in Challenging Environments

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ABSTRACT— ***Global Navigation Satellite System (GNSS) receivers are now widely used for navigation and speed measurements. General public and companies which use GNSS rely not only on positional accuracy but also on speed accuracy. Manufacturers of GNSS receivers supply speed accuracy parameters in the relevant data sheets. However, little information is provided regarding specific conditions when the specified speed accuracy of GNSS receivers might be met. Also, little research was conducted to reveal the practical speed accuracy parameters of GNSS receivers in a variety of conditions focusing on challenging GNSS environments. Finally, no activities was conducted to understand if adding more constellations to GPS, for example, GLONASS provides any value in speed accuracy reporting. This research firstly aims to analyse and practically estimate the performance of high end, mid-range and low grade GNSS receivers for measuring speed in challenging environments and determine if practical differences in their speed accuracies are observed. Secondly, the research also aims to determine if adding GLONASS to GPS in the GNSS receiver's computations provides any value in speed accuracy determination. Lastly, the research aims to derive a simple quality indicator which might be used to filter potentially unreliable GNSS speed records. After designing and calibrating the accurate non-GPS based test vehicle and analysing its uncertainty of measurements, a number of GNSS receivers were tested. Test results demonstrate that high end, mid-range and low grade GNSS receivers perform differently when measuring speed and caution should be exercised when relying on GNSS speed in challenging environments, specifically if such speed records are considered to be used in the court of law. It was also determined that for a specific receiver adding GLONASS does not improve the performance in speed accuracy. Finally, Horizontal Dilution of Precision (HDOP) parameter derived from GNSS receivers might be considered as a simple statistical quality indicator to assess whether specific speed records can be relied upon but cannot be used as an integrity indicator for individual speed records. The research recommends that every receiver shall be individually tested in a variety of environments to reveal its true errors in speed measurements.***

Keywords— GNSS, Speed, GPS, Accuracy

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1. INTRODUCTION

A lot of companies and individuals are currently using Global Navigation Satellite System (GNSS) devices for positional and speed information. GNSS produced speed is used in a variety of applications, such as individual users monitoring their driving speed, telematics industry, unmanned aerial vehicles, speed monitoring of drivers who committed a number of driving offences, Intelligent Transport Systems (ITS) and many others. The level of integration of GNSS technology is rapidly increasing and GNSS speed records are already used in the court of law, for example, when people try to challenge their speeding fines using the data from their own GPS receivers or loggers. However, not a lot of information is published in terms of how accurate GNSS receivers are when it comes to practical speed measurements in challenging environments. It has become a general consumer expectation that GNSS receivers are always accurate and can be relied upon when measuring speed in any circumstances. Such information is regularly published in newspapers when general consumers tried to use their GPS receivers or loggers to challenge their speeding fines in the court of law with help of speed records obtained from their equipment [1], [2]. However, little research supports GNSS speed accuracy when it comes to driving around such structures as overpasses or tree canopies where multipath influences the measurement outcome. Also, no actual research exists confirming the behavior of GNSS receivers if they have any additional constellations enabled, say GLONASS in addition to GPS.

The Victorian Court of Appeal in Australia in 1990 decided (Kearon v. Grant) that speeding offences are the type of offences for which a defence of honest and reasonable mistake does not exist. All Magistrate Courts are obliged to follow this decision and apply it in practice [3]. This means a belief of a particular individual as to how fast a vehicle with this individual was driven cannot offer any assistance in defending a speeding charge in any court. More and more often this belief is based on GPS speed records as people use GPS more and more in their vehicles. In this instance the court may not accept evidence based on uncertified GPS devices, which were not independently verified with traceability of their speed measurements to national standards. In fact, there is also very limited number of accredited laboratories in the world which can issue official certificates to confirm the speed accuracy of the particular GNSS receivers with traceability to national standards.

As permanent speed cameras based on radar technology are often located on overpasses or gantries above the road, GNSS receivers used by people to challenge speed camera measurements in such situations may produce incorrect reading around such structures. This highlights the need of independent testing of each type of GNSS receiver to ensure how it might be relied upon in such challenging environments and such testing shall be traceable to national standards in its metrological aspects. In court, the prosecution can prove that the speed camera was calibrated and periodically tested to be compliant to the specific accuracy requirements, whereas an individual relying on speed records from uncertified GNSS has to prove that his/her GNSS receiver can produce accurate results. In this instance the court may not rely on data sheets of GNSS devices but rather seek an independent evidence of testing, including in the specific circumstances, such as speed accuracy around overpasses, road gantries, tree canopies, etc. Also, the court may request evidence that the GPS speed measurements were not compromised by ionospheric disturbances, weather conditions or electromagnetic interference or seek an advice from expert witnesses. This again highlights how important is to investigate speed accuracy parameters of individual GNSS receivers.

2. PRIOR PRACTICAL RESEARCH OVERVIEW AND RESEARCH OBJECTIVES

A number of experiments were conducted by the researchers to estimate speed accuracy of GNSS receivers when they are stationary, for example the research [4]. However, those experiments were conducted in open sky conditions and GNSS receivers speed was very close to zero because they did not work under challenge or driven through a variety of environments. Also, a few research activities were performed in kinematic mode when GNSS receivers were driven along a specific route and their speed was compared to specific speed references. At the same time, in almost all investigations conducted in this manner it was seen that

a/ no data was provided in regards to whether a test vehicle was calibrated and to what accuracy and how this calibration is traceable to national standards;

b/ little investigation was conducted with the focus on specific situations when a receiver operates around high rise buildings, tree canopies or overpasses, i.e. structures creating a multipath for GPS signals;

c/ such research did not focus on formulating specific simple quality indicators when speed records can be relied upon;

d/ there was no focus on a variety of different types of GNSS receivers based on their grade or any other form of classification and how such receivers perform in relation to each other in challenging environments.

For example, such research as [5], [6], [7], [8], [9] and [10] are all falling under this category.

Research activities were also conducted with calibrated GPS simulators and in real world environments with calibrated vehicles [11], [12]. Both [11] and [12] research publish the results of testing with GPS simulators but such testing does not provide any real world challenge to the receivers under test. Therefore, testing for speed with simulators has relatively minor value and can only discover issues when the receivers have bugs in their speed measurement algorithms. In [11] a test was also described with the calibrated real test vehicle; however, the focus was on only one specific GPS receiver and it appears that testing was conducted on a highway with relatively good GNSS visibility. This caused a receiver to perform really well all along the journey. Also, the research [11] focuses on GPS receiver only and no combined solution, say GPS and GLONASS, was tested in one receiver. Research [12] also focuses on GPS only receivers and the receivers under test are of the same scale. Therefore, it is unclear if a consumer can extrapolate the conclusions of such research on high end, mid-range or low grade receivers. Finally, the research [12] does not specifically focus on challenging GNSS environments.

GNSS chipsets or receivers manufacturers are not generally willing to provide evidence of their own testing when it comes to speed accuracy. Usually chipset data sheets contain speed accuracy parameters but it is unclear whether such parameters were tested with GNSS simulators or in static or kinematic modes, including in conditions with multipath. For example, in [13] the datasheet states that an accuracy of velocity determination is 0.1 m/s with a note that this parameter corresponds to good GPS conditions, whereas it is not specified what the good conditions might mean and what happens if bad conditions are applied. In [14] the technical specifications section states that velocity accuracy is 0.01 m/s without specifying when this parameter is guaranteed. As a result, such datasheets do not contain any specific conditions when speed records might fall outside the compliance limits and a general user or even more advanced customer may assume that such speed accuracies are always guaranteed. General consumers or even researchers can rely on such datasheets without realizing that the accuracies described might be guaranteed in ideal open sky conditions only.

Therefore, it is paramount to practically investigate the following areas:

a/ what the accuracy of GNSS receivers might be when they conduct speed measurements in the real world challenging environments, such as generation of speed records around such structures as bridges, overpasses, road gantries, roads with tree canopies, etc. Such information would be valuable in understanding whether the receivers can be trusted and their speed records might be used for evidentiary purposes;

b/ if there is any difference in speed accuracy parameter between high end, mid-range and low grade GNSS receivers;

c/ if adding GLONASS to GPS in speed computations provides any value in terms of speed accuracy improvement;

d/ If there is a simple quality indicator used in many GNSS receiver to be able to filter potentially unreliable GNSS speed records.

Note 1. In further discussion GNSS receivers would mean not only the devices showing GNSS data on their display but also the devices capable of logging this data either on SD-cards or via any output ports. Such devices are widely available to general public and researchers.

Note 2. In this practical research GNSS receivers are treated as black boxes as long as they use the same fundamental speed measurement algorithm to determine and report speed records, i.e. Doppler derived methodology. The approach of treating GNSS receivers as black boxes is in line with the performance based specifications for GNSS equipment.

3. TEST METHOD AND CHALLENGES OF TESTING GNSS RECEIVERS FOR SPEED ACCURACY

3.1 How GPS/GNSS Receivers Measure Speed

When the first GPS receivers were implemented, they mainly used distance over time based methodologies for speed determination. As distance between neighbouring two position records can be calculated by the receiver and time between such records is known, it is possible to calculate speed. This method is inaccurate simply because it depends on positional accuracy. At low speed inaccurate positional determination may cause large speed errors. Also, in this method measurements shall be done faster to provide higher accuracy, otherwise zig-zag movements would influence an error.

The next generation of GNSS receivers uses so called Doppler derived methodologies for speed determination. They are the so called raw Doppler method and method based on Carrier Phase observations.

In the raw Doppler method since each satellite emits a steady frequency, the different frequencies measured by the GNSS receiver are due to the motion of this receiver, subject to speed and vectors of movement of satellites are well known. Hence, the receiver is able to determine its instant speed based on measured frequencies of satellite signals. The frequency experienced by the receiver can be represented as [15]

$$Fr = (1 + Vrad/Vprop) * Ft \quad \text{if moving toward}$$

and

$$Fr = (1 - Vrad/Vprop) * Ft \quad \text{if moving from the receiver,}$$

where

- Fr and Ft are the received and transmitted frequencies respectively;
- Vprop is the propagation speed of the waves which is equal the speed of light in vacuum in this context;
- Vrad is the relative radial velocity between the satellite and the receiver in the line of sight direction.

Through re-writing the formulas, the Doppler shift might be presented as

$$\Delta Fr = (Fr\text{-}Ft) = \pm\,(Vradial/C) * Ft = \pm\,(Vradial\,/\,\lambda ft),$$

where

- λft is the nominal/transmitted frequency wavelength;
- C is the speed of light.

The main sources of errors in speed determination are the following [16]:

- Satellite atomic clock errors which define variations in frequency;
- Signal propagation errors;
- Multipath errors, when the reflected signal travels a longer distance than the direct signal.

Signals from low satellite elevations manifest greater multipath errors. A simple mitigation method to raise the allowable cut-off angle in practice may not work well;

- Receiver dependent errors. Subject to the grade of manufacturing, a GNSS receiver clock is normally made from a quart crystal oscillator which drifts in frequency. Unlike satellite clocks, the receiver clock information is usually not available and may significantly influence the speed accuracy [16].

Based on the above theoretical model of speed determination, it is clear that the main sources of errors might be divided into two categories: sources which might be well estimated and understood, such as atomic clock and signal propagation errors, and sources which are more random, such as surrounding structures causing multipath and clock errors of the specific receiver. The last component may well depend on the receivers complexity and cost as shown in [16].

In this practical research the GPS/GNSS speed outliers would be investigated, which are generated in their vast majority not because of atomic clock, signal propagation or receiver dependent clock errors but mainly because of multipath related errors. All receivers under test would use the raw Doppler algorithm for speed determination, which was confirmed through manufacturers datasheets or correspondence with manufacturers for some receivers and for more complex receivers the raw Doppler algorithm was put through software settings prior to testing.

The method of GNSS speed determination based on Carrier Phase observations is outside of scope of this research because none of the receivers under test used it.

3.2 Calibration of the Test Vehicle

The modern GNSS chipsets which represent an integral part of GNSS receivers usually have a minimum sampling and processing rate of at least 1 Hz or higher. While the majority of GNSS chipset manufacturers claim that measured speed accuracy is about 0.1-0.4 km/h or even better, the first metrological challenge is to have a test vehicle which would be capable to have a similar speed accuracy parameter or even better within the whole range of speeds. As the speed of a test vehicle represents a reference speed to compare against, the reference speed inaccuracies must be well understood and estimated via proper uncertainty of measurements (UOM) techniques. Also, a test vehicle shall be calibrated with traceability to national standards and preferably driven with all GNSS receivers on a specific day just after calibration and then its calibration shall be checked again after the test on the same day to ensure that calibration is still maintained.

Secondly, speed records produced by the test vehicle shall be time synchronized with all GNSS speed records produced by the receivers under test during the whole test.

To address the second challenge the test vehicle gets synchronization from the Universal Coordinated Time (UTC) using NMEA data strings produced by the high end geodetic quality GNSS receiver. Figure 1 below represents a structure of the speed measurement system of the test vehicle working in speed measurement mode in this instance.

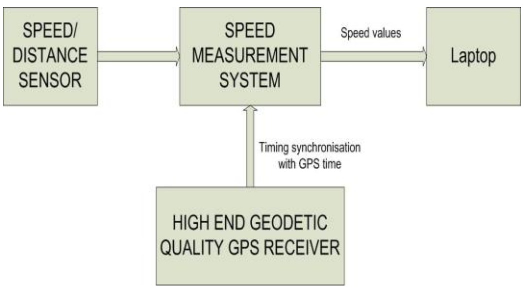

Figure 1: Speed Measurement System Operating in Speed Mode

The above approach enables synchronization of the speed measurement system with NMEA records produced by GNSS receivers. If GPS is totally unavailable, NMEA messages from the high end geodetic quality GPS receiver would be generated to the timing accuracy reliant on the internal clock of this receiver. In any case, the microcontroller of the speed measurement system gets a string of NMEA data every second, subsequently starting completing the previous speed measurement and immediately starting the next logging interval. Within the logging interval the speed measurement system counts pulses from a speed / distance sensor installed on a wheel. In the experiments described below the sensor represents an industrial encoder WDG 58H manufactured by German company Wachendorff Automation GMBH & Co. The encoder produces 2048 pulses per revolution of the wheel and allows the whole speed measurement system to be accurate in distance measurements as distance calibration is conducted with high degree of accuracy. Installation of the sensor is shown on Figure 2 where the speed / distance sensor is visible; however, before the test the sensor itself is covered to protect it from the direct sunlight and rain.

Figure 2: Speed / Distance Sensor Installation

The speed measurement system is based on microcontroller and uses an internal calibration coefficient to convert the number of pulses from the speed / distance sensor into speed records, produced every second in synchronization with GPS time. Effectively, the logged speed records of the test vehicle look like shown on Figure 3, where time is shown in UTC. As the GNSS receivers under test also report speed records in synchronization with UTC and one of them, i.e, the high end receiver, is used to synchronize the measurements in terms of timing, the speed records of the test vehicle and all GNSS receivers would match in time.

TIME 211213.0 SPEED 92.0 km/h

TIME 211214.0 SPEED 91.1 km/h

TIME 211215.0 SPEED 90.2 km/h

TIME 211216.0 SPEED 89.8 km/h

TIME 211217.0 SPEED 90.0 km/h

TIME 211218.0 SPEED 90.2 km/h

Figure 3: Speed Records of the Test Vehicle

Therefore, the speed measurement system based on microcontroller has a sampling rate of 1 Hz and logs the speed data of the test vehicle with this sampling rate. The GNSS receivers under test have the same sampling rate and therefore are fully synchronized with the test vehicle. This approach addresses the issue of synchronizing the speed records between the test asset and GNSS receivers under test.

The second challenge which relates to the expected accuracy of the test vehicle, is addressed through separate calibration of distance and time measuring diagrams of the test vehicle, when such diagrams represent the integral parts of the speed measurement system, on a specific test date before and after the test. Also, a thorough UOM analysis was conducted to assess the magnitude of inaccuracies attributed to the test vehicle.

Speed is calculated as distance covered by the test vehicle over a specific time and if both distance and timing diagrams are properly calibrated, the UOM might be estimated and taken on board when analyzing GNSS speed records.

Calibration of the distance measurement diagram is always conducted on a specific test date before and after the test to ensure that the test vehicle stays within the prescribed limits during the test. Calibration site represents a straight section of the side road with the surveyed part of 361.3 m shown on Figure 4. This site was surveyed with the use of electronic distance measurement methodology to the accuracy better than 0.01 m, which is achieved by the use of optical survey equipment. This section of the road is located in Noble Park area in Melbourne, Australia and is actually going in parallel to Princess Hwy but with almost no traffic as it represents a side road. During distance calibrations the test vehicle is driven from A to B with the speed measurement system working in calibration mode.

Figure 4: Distance Calibration Site

A diagram reflecting the calibration mode for distance measurements is shown on Figure 5.

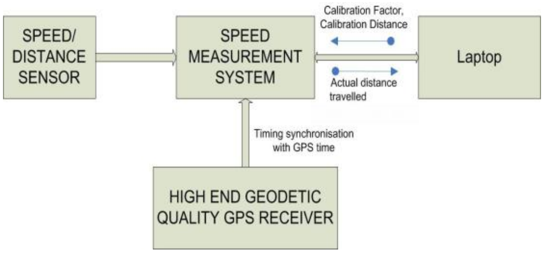

Figure 5: Distance Calibration Mode

In distance calibration mode the test vehicle was driven from A to B covering a known distance of 361.3 m and the speed measurement system was loaded with an expected calibration coefficient from the laptop before the calibration. Laptop working as a distance data logger in this mode of operation shows the distance measured by the test vehicle rather than speed. In case of this distance was different by 0.1 m from the actual surveyed distance, a new calibration coefficient was calculated and then loaded with the subsequent drive from A to B again. When a measured distance differed from the surveyed one by less than 0.1 m, distance calibration was complete and the corresponding calibration coefficient loaded on to speed measurement system from the laptop and is kept in the microcontroller of the speed measurement system until the next recalibration.

Timing calibration (verification) is conducted with the use of a specific diagram shown on Figure 6.

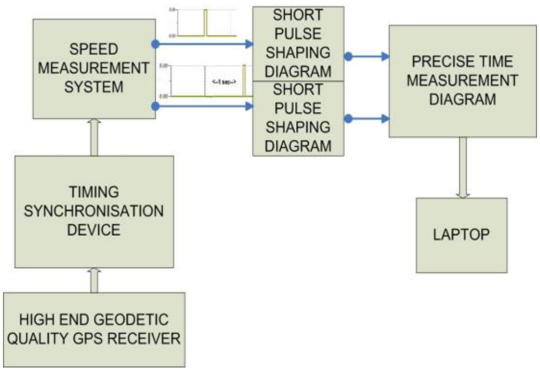

Figure 6: Time Calibration Diagram

Speed measurement system in any mode, including calibration mode, outputs short pulses from the microcontroller, when such pulses constitute the beginning of the new measurement (top output, see Figure 6) and the end of the current measurement (bottom output, see Figure 6). The short pulse corresponding to the beginning of a new speed measurement is generated shortly after every relevant NMEA string of data is produced by the geodetic quality GPS receiver and the microcontroller gets it through a Timing Synchronization Device, which is an integral part of the microcontroller. In this instance the microcontroller completes a speed calculation for a previous measurement, puts the speed value to the output and starts the new measurement. The short pulse at the bottom output is generated when the next NMEA string in 1 sec comes in. Therefore, the timing interval between the pulses at the top and bottom outputs of the speed measurement system should be close to 1 sec with a deduction of microcontroller's time to complete a measurement and output it. This timing interval between the two short pulses should be measured to ensure it sits within certain limits, as it determines the time used by the speed measurement system to count pulses from the speed / distance sensor. A specific microchip called Universal Frequency to Digital Converter (UFDC-1) was selected to conduct this measurement because of the microchip's high accuracy in different modes of operation, including in time measurement mode [18]. This microchip interacts with a laptop via RS232 while the laptop uses the Terminal software to log such timing intervals in microseconds.

Timing calibration is achieved here simply via verification that 1 sec timing intervals of speed measurement which is determined by timing between two NMEA data strings, is sitting within the prescribed limit to maintain the proper UOM. Usually the measurement time sits within 0.999996 sec and 0.999998 sec as some little time is lost when the microcontroller interrupts the measurement upon the NMEA data string coming, outputs the result of the previous cycle and starts the new cycle of speed measurement.

Calibration of the test vehicle to specific distance and time values provides an assurance that the test vehicle is accurate enough. Calibration also provides a basis to assess the UOM of the test vehicle to ensure it is capable to test GNSS systems for speed.

Uncertainty of measurements calculations were conducted as per methodology described in [19] to determine how accurate the test vehicle is. The following factors were taken into consideration when UOM was assessed:

- Number of pulses produced by the speed / distance sensor per revolution of a wheel;
- Changes in tires pressure and subsequent circumference when a vehicle was driven at higher speeds due to warm tires;
- UOM of calibration;
- Resolution of the speed measurement system;
- Randomness of pulses coming from the speed / distance sensor in relation to 1 sec measurement timestamps;
- Performance noise of the receiver under test (GPS speed noise);
- Variations in timing intervals used as timestamps to measure speed as distance over time

and some other factors which are less significant than the above mentioned.

The end result was calculated and it was determined that the UOM for the test vehicle equals to 0.4 km/h. This means that 95% of speed records produced by the test vehicle are located within 0.4 km/h from the true speed with the normal distribution of an error. Such UOM effectively allowed conducting testing of GNSS receivers for speed as it is comparable to the performance of GNSS considering not only the number of datasheets for various GNSS receivers but, more importantly, their practical performance in speed measurements when the receivers are stationary.

3.3 Test Route and Equipment Setup

Four GNSS receivers were tested to address four research tasks mentioned in the Prior Research Overview section. The first test was conducted on 21 February 2015 on a specific route consisted of freeways with a number of overpasses, suburban areas and countryside roads where tree canopies covered some sections of the roads alongside with open sky longer sections. Figure 7 represents a drive within the suburban area, covering M1 and M3 freeways in Melbourne with a number of overpasses, whereas Figure 8 represents a part of the drive where the test vehicle left Melbourne and was driven to the countryside.

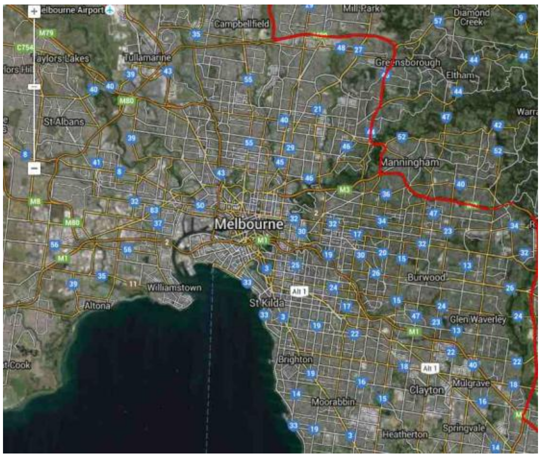

Figure 7: Test Route in Suburban Areas

Figure 8: Test Route in the Countryside

The test drive started on Monash Fwy (M1) from Berwick area, then driving to Dandenong where a vehicle exited from M1 and entered M3 EastLink then was driven along M3 Eastren Fwy. The above freeways have a number of overpasses and little bridges above the road, including for pedestrians, as well as road gantries, therefore the data collected might be used to determine the speed outliers generated by GNSS receivers in case of passing such structures. Then a vehicle was driven through a number of Melbourne suburbs with the subsequent driving to Echuca, which is located on the border between Victoria and New South Wales. The goal of driving through this section was to collect both the open sky data and data related to situations when a vehicle is driven along the roads with tree canopies. Also, both sections of the test aimed to determine if adding GLONASS to GPS provides any value for GNSS speed measurements. The day was having Australian typical conditions, i.e. it was generally sunny, the temperature was about 27 degrees and no rain. The distance between South-Eastern suburbs of Melbourne where the test started and Echuca was approximately 240 km. To eliminate any potential causes of random errors which might be experienced by all receivers on the day the following measures were put in place:

a/ space weather warnings were analyzed to ensure that during the test day there are no geomagnetic storms or any other events which could potentially affect all receivers under test. The closest warnings were issued for the 27th of January and the 25th of February 2015 and the test date sits outside of problematic dates;

b/ GPS operational advisory Notice Advisory to NAVSTAR Users (NANU) Reports were analyzed to ensure that nothing serious happened with GPS constellation, including for satellites around Australia, on the day in question. It was found that only PRN8 satellite was unavailable but this satellite was not in use for a number of months before and after the test date;

c/ GNSS planning software was used to review if any outages could be expected due to poor satellite availability around Victoria when such outages could provide systemic problems for GNSS receivers under test. GPS and GLONASS satellites availability and Dilution of Precision (DOP), including HDOP plots were put in place to prove an absence of systemic problems. These plots are shown below.

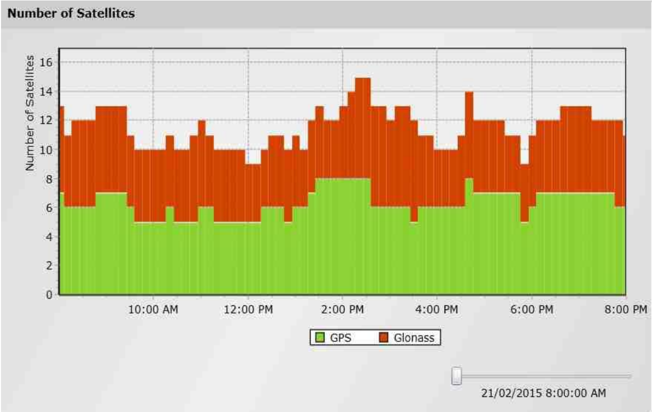

Figure 9: GPS and GLONASS Satellites Availability in Victoria on 21 Feb 2015

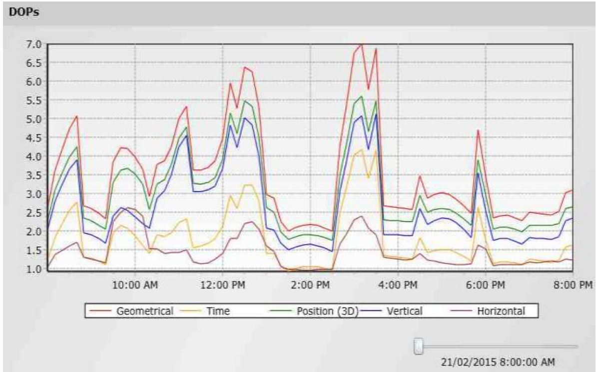

Figure 10: GPS DOP predicted Availability in Victoria on 21 Feb 2015

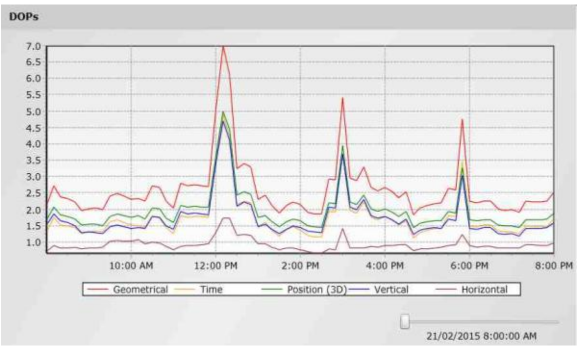

Figure 11: GPS + GLONASS DOP predicted Availability in Victoria on 21 Feb 2015

It is visible that for GPS only receivers the number of satellites during the test day ideally varies from five to eight and for GPS +GLONASS receivers from nine to 15 in open sky conditions. Also, HDOP for GPS only receivers is no more than 2.5 and for GPS+GLONASS receivers is no more than 1.75 in open sky conditions. All the above demonstrates that systemic causes of errors related to GNSS availability in the area are eliminated.

Equipment under test included the following GNSS receivers:

- geodetic quality GPS receiver with only GPS enabled (Receiver A);
- geodetic quality GNSS receiver which had GPS and GLONASS enabled (Receiver B);
- Mid-range GPS receiver (Receiver C);
- Low grade recreational GPS receiver (Receiver D).

Classification of the receivers was conducted based on their complexities, cost, possibility of the user to change GNSS settings via the software, used frequencies and some other parameters. For example, receivers A and B were of the same brand and priced approximately $6,000 each. The receiver A was a 72-channels receiver capable to operate with L1 and L2 GPS+GLONASS frequencies but was configured to use L1 GPS only. Also, the receiver is capable to use SBAS and DGPS but these functionalities were also switched off simply because SBAS is not available in Australia and its use may provide errors rather than benefit and DGPS would disadvantage the other receivers under test. The GPS receiver B is similar to the receiver A but is capable to use L1 frequency only. Both receivers A and B had very complex software manuals providing a capability for the user to use several hundred commands to configure a receiver via changes in GNSS settings. Each receiver A and B outputted an instantaneous speed every second with several digits after the decimal point via RS232 ports and had an external GNSS antenna mounted on the roof of the test vehicle. The manufacturer's datasheets for these receivers claimed that they can measure speed with the accuracy of 0.11 km/h Root-Mean-Square (RMS), while their practical performance in prior experiments with the stationary mode and open sky demonstrated that the speed may vary from zero up to 0.3 km/h. Mask angle for both receivers A and B was established at the level of 15 degrees.

The Receiver C was a $500 priced GPS logger recording speed every 10 milliseconds on its own SD card with a number of digits after the decimal point and with an internal GPS antenna. This receiver belongs to mid-range in our classification because it does not allow the user to change any GPS settings and configure the receiver in a way the user wants and does not have a capability to output NMEA data and therefore there was no option to understand the satellites used by this receiver and signal to noise ratio (SNR) of these satellites. At the same time the receiver is capable to work with IPhone via Bluetooth where a performance test application might be used on smart phone to work with the data. Also, the receiver is flexible in the use of either the internal or external GPS antenna and it uses a 20 Hz GPS engine. The Receiver C was located on the dashboard of the test vehicle. The manufacturer's datasheets for this receiver claimed that the receiver can measure speed with the accuracy of 0.1 km/h without specifying the environmental GPS related conditions when such accuracy can be achieved. Mask angle for the receiver C was hardcoded by the manufacturer at the level of 7 degrees.

The receiver D represented a low grade GPS receiver in our classification because of multiple factors, such us: no ability to change configuration settings by the user, no ability to use an external GPS antenna and very limited logging availability in terms of GPS parameters. This GPS logger's cost was $70 and it logged GPS speed every second with integer speed values on its own SD card using CSV file rather than NMEA. Therefore, for this receiver it was not possible to derive which satellites were used at any specific times, their SNR and many other parameters available through NMEA data. It also had an internal antenna and was also mounted on the dashboard of the test asset. For this receiver the manufacturer did not specify the speed accuracy parameter.

All receivers under test used Doppler based algorithm for speed computations conducted in the receivers internally rather than calculating speed through position records. For the receivers A and B the use of raw Doppler algorithm was enabled via the software and for the receivers C and D the use of Doppler algorithm was confirmed through the datasheet and by the manufacturer respectively. The test vehicle represented a vehicle Mazda 3 hatchback manufactured in 2004.

4. RESULTS

4.1 Number of Speed outliers

For the entire test the speed measurement system of the test vehicle was operational. Before the test and after the test the speed measurement system was checked for the correctness of distance and time measurements and such checks proved the accuracy of the system. Also, for the entire test run a good match was generally observed between speed records of the test vehicle and high end geodetic GPS receivers. Figure 12 shows a speed difference distribution for the GPS Receiver A, i.e. the number of records of the GPS Receiver A corresponding to the specific speed errors, when such errors were measured as differences between the calibrated test vehicle and the GPS Receiver A. Statistical analysis of the differences is provided in Table 1.

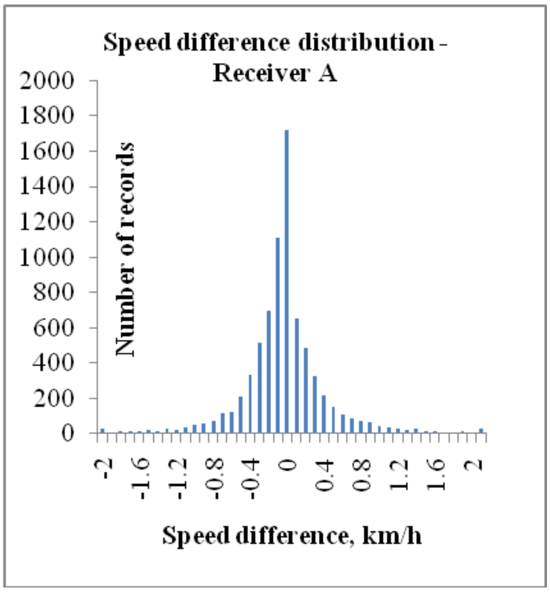

Figure 12: Speed Difference Distribution for GPS Receiver A

Table 1: Statistical performance of GPS Receiver A

Parameter	Value
Mean, km/h	-0.08
Standard error, km/h	0.006
Standard deviation, km/h	0.52
Number of measurements	7644

It is evident that there is a very good match between the test vehicle and the GPS Receiver A, considering the UOM of the test vehicle as 0.4 km/h and the manufacturer's datasheet stating that the Receiver's A speed accuracy equals to 0.11 km/h RMS, while prior practical experiments of the Receiver A in stationary mode demonstrated that its actual speed measurement accuracy in ideal conditions is around 0.3 km/h. This match allowed investigating further and focusing on instances how all GNSS receivers under test behaved in challenging environments, such as overpasses and roads with tree canopies.

Once all speed records from the receivers were aligned and processed, the amount of records for the entire run was obtained from each receiver for further analysis. This amount is represented in Table 2. After that certain filtering of records was applied, such as

- GNSS speed records were filtered out for situations when a test vehicle was stationary. The goal of this step was to filter out static records for further use of dynamic records only;
- only those GNSS speed records were used where a test vehicle was not accelerating or braking in such a way when speed between the neighbouring records of the test vehicle exceeded 0.4 km/h. In this way only those GNSS records were analysed which corresponded to the smooth movements of the test vehicle, taking into consideration that the UOM of it equals to 0.4 km/h.

Table 2: Amount of speed records processed for the entire run

	GPS Receiver A	GNSS Receiver B	GPS Receiver C	GPS Receiver D
Number of valid speed records for the entire test	7644	12036	10235	13236
Number of valid speed records after filtering static records and sharp movements of the test vehicle	3283	4937	5439	3328

Note. The number of speed records used for processing was different for each Receiver due to a variety of factors, such as the use of GPS for the Receivers A, C and D and GPS + GLONASS for the Receiver B, non-generation of records by the Receiver C when stationary due to having an internal independent movement sensor preventing records going to the output when a vehicle is stationary, higher masking angle for the Receivers A and B in comparison to the Receivers C and D, more conservative practical behaviour of Receivers A and B in comparison to C and D, etc.

Further, all valid speed records from the bottom line of Table 2 were analysed with a specific focus on driving across overpasses and roads with tree canopies. It was revealed that the receivers performed completely differently facing such environments and records with speed difference higher than 2.5 km/h were observed for all of them, although at a different scale.

Table 3 below summarises the number of such problematic records, i.e. outliers, for the entire test run.

Table 3: Average speed spikes for overpasses and the number of spikes during the test

	GPS Receiver A	GNSS Receiver B	GPS Receiver C	GPS Receiver D
Average speed difference between the test vehicle and the receiver under test for outliers produced by all receivers around overpasses, km/h	5.35	4.74	10.7	10.5
Number of outliers (speed spikes)	7	10	30	23

Figures 13-16 below demonstrate Google views of some environments where the outliers were generated by the specific receiver.

Figure 13: Examples of Environments where the GPS Receiver A generated Speed Spikes

Figure 14: Examples of Environments where the GPS Receiver B generated Speed Spikes

Figure 15: Examples of Environments where the GPS Receiver C generated Speed Spikes

Figure 16: Examples of Environments where the GPS Receiver D generated Speed Spikes

Several conclusions were derived from the processed records as follows:

- It is evident that despite the fact that all receivers use an embedded Doppler based algorithms to determine speed, the performance of high end professional receivers in speed measurements is considerably better than mid-range and low range receivers in terms of the number of outliers and their corresponding magnitude. In the majority of instances around overpasses the Receivers A and B produced either a good record or produced blank records indicating unreliability of speed measurement with only several outliers, i.e. seven and 10 respectively for the Receivers A and B. At the same time, the Receivers C and D produced more outliers with the reported good GPS quality indicators looking at number of satellites and Horizontal Dilution of Precision (HDOP) in the relevant speed records;

- The use of GLONASS in the Receiver B did not significantly improve the performance in terms of both speed accuracy and the number of outliers but rather increased the number of valid speed records in general.

- Low range GPS receivers may not necessarily perform worse than the mid-range ones, looking at the performance of the GPS Receiver D versus GPS Receiver C.

- Looking at each problematic record it was noticed that the GPS Receiver C produced speed spikes not only around considerable number of overpasses but also around a little bridge crossing the road above it. Also, the GNSS Receiver B produced one spike around a gantry staying above the road capturing the number plates of passing vehicles.

Finally, the receiver C unlike the others generated more 122 outliers in the countryside on those sections of the road where tree canopies were in place. The average magnitude of such outliers was equal to 3.8 km/h. It is important to highlight that this behaviour was not observed for geodetic quality receivers A and B and low range receiver D.

4.2 HDOP as a Quality Indicator for Speed Records

In this research HDOP was selected as one of possible quality indicators for speed records to look at. The goal in here was to determine, if any, a certain HDOP threshold when it might be possible to say that individual speed records are potentially unreliable. In other words, the task is to determine what the practical HDOP value might be when the user can rely on speed records either individually or statistically. Some other parameters might be used for this purpose also; however, HDOP is the most widely used parameter outputted by GNSS receivers at the moment and some receivers tested during this research do not use any others like Positional Dilution of Precision (PDOP) or Speed Dilution of Precision (SDOP). More importantly, within the framework of practical applications of GPS based telematics devices in industry HDOP is already used as a parameter to quantify the reliance on speed records. Finally, HDOP is used as a parameter in guidance documents describing the performance parameters of GPS.

Each speed outlier produced by geodetic quality Receivers A and B was analyzed to take an indication if the number of satellites or HDOP parameters might be helpful to indicate a problem. Tables 4 and 5 below represent each individual outlier with GPS parameters derived from NMEA data.

Table 4: GPS parameters for speed outliers produced by GPS Receiver A

UTC Time	HDOP	Number of Satellites	Speed Difference, km/h
210424	9.3	4	-6.02
212004	26.3	4	7.60
212019	4.8	4	6.14
212036	7.4	4	4.38
212658	2.1	6	5.41
215446	2.2	6	2.57
220249	1.6	7	5.33

Table 5: GPS parameters for speed outliers produced by GPS Receiver B

UTC Time	HDOP	Number of Satellites	Speed Difference, km/h	Notes
210921	1.6	7	-2.74	
211025	1.1	11	2.75	
211429	0.9	12	2.51	
211944	7.2	6	3.85	
212808	9.2	6	5.87	
213932	1.2	8	-2.92	Road gantry
215153	1.2	11	9.6	
220249	1.1	12	6.07	

It is seen from the above tables that speed records with high values of HDOP might be used as a reasonable indication of a problem in speed measurement, however, for some records HDOP values are not indicating a problem in speed measurements, whereas the speed spikes are present. This means that it is highly likely that the receivers report HDOP incorrectly due to multipath related issues.

An analysis was also conducted with neighboring to outliers records for both GPS Receiver A and GNSS Receiver B to assess the magnitude of problems around overpasses and timing recovery of GPS Receiver A versus GNSS Receiver B. It was found that both Receivers A and B had some issues with neighboring records close to speed spikes but the magnitude of issues was similar for both and adding GLONASS did not provide a noticeable improvement.

Considering that both the GPS Receiver A and GNSS Receiver B were configured with 15 degrees elevation mask, it is not possible to get any indication that the receivers are experiencing an issue while generating a speed record simply looking at HDOP and number of satellites values. Therefore, from the evidentiary point of view it is much safer to exclude such speed records around overpasses from the assessment rather than rely on them. The same results were observed for the GPS Receiver D where HDOP and number of satellites values around overpasses were mixed and could not provide a definitive indication of a problem.

GPS Receiver C does not have any DOP parameter logged with speed records and therefore it was not possible to assess each spike and understand why it was produced. However, looking at number of satellites for each speed spike it was again not possible to conclude that the Receiver experienced problems at specific epochs when spikes happened.

As a result, it was concluded that the number of satellites expressed in each speed record is not a definitive parameter to filter out potentially unreliable speed records. Also, it might be a challenge to always use HDOP as a 100% reliable measure to filter those speed records which might be suspected of being inaccurate. At the same time, speed records having high HDOP, including higher than two, in combination with an overpass might be a good indication of probable issues.

4.3 HDOP as a Statistical Measure of Reliability of Speed Records

The objective of this analysis was to also assess the statistical accuracy of GPS speed records depending on HDOP and subsequently determine whether HDOP still might be considered as a reasonable statistical measure to filter potentially unreliable speed records. To conduct such an analysis different tests were conducted with a focus on countryside roads with the significant areas of tree canopies, which provided much worse GNSS visibility in comparison to the previous test.

HDOP was picked up as a parameter to be looked at simply because this parameter is outputted by many GPS loggers in speed records. Some manufacturers of GNSS receivers provide the Speed Dilution of Precision (SDOP) as a quality indicator in speed records. However, the algorithms of calculating SDOP in such receivers are usually unknown and hence cannot be used in the court of law. Also, the number of GNSS receivers outputting SDOP with every speed record is very limited, while the majority of GNSS receivers output HDOP as one of the standard parameters, including in NMEA data. Therefore, there might be worthwhile to explore the use of HDOP as a statistical quality measure for speed records. It is worth to mention that none of the receivers tested used SDOP as a parameter to output and some used only HDOP.

For this specific test a second test drive was conducted which included driving in countryside roads with lots of tree canopies areas where HDOP would definitely vary within a broad range due to a variety of GNSS environments. Subsequently, examination of the data was conducted with filtering of speed records for different HDOP intervals and deriving statistical speed errors depending on HDOP values. Findings obtained from the test are as follows:

Table 6: Standard Deviation of the Speed Error for GPS Receiver A depending on HDOP

HDOP range value	Standard Deviation of Speed Error, km/h	Number of Records assessed
All range of HDOP	0.92	18982
HDOP<=1	0.24	2210
1.1 - 2	0.39	13370
2.1 – 3	0.82	1502
3.1 – 4	1.01	618
4.1 – 5	1.32	310
5.1 – 6	1.12	223
6.1 – 7	1.51	145
HDOP>7	4.27	604

Table 7: Standard Deviation of the Speed Error for GPS Receiver D depending on HDOP

HDOP range value	Standard Deviation of Speed Error, km/h	Number of Records assessed
HDOP<=1	0.7	18565
1.1 - 2	1.6	7332
2.1 – 3	6.4	24
HDOP>3	4.4	77

There is a clear dependency of the speed error of GPS receivers A and D on HDOP and considering the datasheet for this receiver A and the UOM of the test vehicle only speed records with HDOP up to 2 might be considered as reliable. For the GPS receiver D the situation with the HDOP threshold is even worse and only records with HDOP <=1 might be statistically considered as reliable. The remaining speed records from the statistical point of view are unreliable as their speed error sharply increases and stays beyond the manufacturer's speed accuracy parameter. Therefore, HDOP parameter derived from this GPS receiver might be considered as a reasonable statistical quality indicator to assess whether the specific speed records can be relied upon. However, this conclusion is a statistical one and individual GNSS environments shall be assessed to ensure that a receiver does not drive through overpasses or any other specific areas where multipath might be present. Also, for each receiver the specific HDOP threshold when speed records might be considered as reliable might be different, which highlights an importance of individual testing / type approval of each receiver. It is also visible that the receiver A performed considerably worse during this test with the same test vehicle because the receiver was driven through a different route where much more tree canopies represented a challenge for speed measurements.

5. CONCLUSION

It has been validated that the speed error of GNSS receivers might be relatively high around such structures as overpasses or any other structures were multipath may disturb the correctness of speed measurements. In this specific research while high end geodetic GPS and GNSS receivers performed generally better compared to mid-range and low range receivers, they still occasionally experienced speed spikes of up to several km per hour, including in instances when they are configured with relatively high elevation mask filtering. Mid-range and low grade GPS receivers may generate relatively substantial number of measurement outliers around overpasses with up to 10 km/h reported errors in speed measurements. This conclusion, however, should not be generalized and authors encourage conducting an independent testing of each receiver to reveal its true performance in the real world environments, particularly when/if such speed records might be used in the court of law.

Secondly, the benefit of enabling additional GNSS constellations to complement GPS in speed measurements in terms of improving speed accuracy is very marginal.

Lastly, HDOP parameter derived from GNSS receivers might be considered as a reasonable statistical quality indicator to assess whether specific speed records can potentially be relied upon. Based on results for high end and low range GPS receivers it was shown that statistically it is possible to rely on speed records with HDOP<2 for the high end and HDOP <=1 for low range specific receivers and filter all the others as potentially unreliable. This conclusion cannot be generalised for all receivers but it highlights an importance to test or type approve each receiver to derive its true behaviour. It is required to emphasise however, that statistical reliance is not equal to the reliance in specific circumstances. Therefore specific GNSS conditions, i.e. presence of overpasses, trees and other structures should be analysed when looking at a specific speed record. More research might be needed based on several GNSS receivers to confirm the conclusion related to the statistical use of HDOP for filtering potentially unreliable speed records.

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