Oral Presentation

An Overview of GNSS and GPS based Velocity Measurement in Comparison to Other Techniques

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Abstract

GNSS-based speed sensing have some advantages over other methods with no moving parts, not affected by tire properties, dust, ground ruggedness, tall vegetation, suitability for measuring human speed, etc. However, GNSS receiver manufacturers do not provide detailed data on the accuracy of their products in velocity measurement under different conditions. Hence, studies are conducted to assess the speed accuracy of the GNSS receivers. This paper overviewed studies on the accuracy of GNSS receivers for speed measurement and basic knowledge on other methods was also included. Studies revealed key findings: GNSS units determine the speed based on three methods (travel distance/time, Doppler shift and time-differenced carrier phase, TDCP) and the TDCP method can offer better accuracy than the other two methods. GNSS receivers with higher update frequencies give more accurate speed data as compared to the lower ones, especially in varying speed conditions (acceleration and deceleration). High correlation exists between GPS velocity error and acceleration and deceleration (R^2>0.70) in variable speeds meaning that the error rises in higher acceleration and decelerations. GPS units underestimate the speed as compared to the actual speeds. The accuracy of speed with DGPS was improved as compared to non-differential GPS. Adding GLONASS to GPS does not improve the performance considerably. HDOP might be used as a quality indicator for speed data reliability. Also, caution should be exercised for GNSS speed measurement under challenging environments (overpass, forest, urban area, etc.).

Keywords: GNSS, GPS, Speed, Velocity, Measurement, Sensor, Accuracy

Introduction

Speed refers to how fast an object is moving while velocity defines the speed and direction in which an object is moving relative to true north (Novatel, 2018). Measurement of ground speed is needed on various platforms including road vehicles, off-road vehicles, trains, bikes, humans, ships, aircrafts, etc. The aim of the speed measurement may vary according to the application (Table 1) (Richardson et al., 1982; Grevis James and Bloome, 1982; Clark and Adsit, 1985; Summers et al., 1986; Tompkins, 1988; Khalilian et al., 1989; Self, 1990; Ess and Morgan, 2003; Vishwanathan et al., 2005; Keskin and Say, 2006; Dogan et al., 2010; Mullenix et al., 2010; Freda et al., 2015; Keskin et al., 2017; Novatel, 2018).

Table 1. Speed measurement applications on various platforms

Speed Measurement Application	Platform
- Monitoring and controlling speed limit for safety purpose	- All vehicles
- Calculating power (Power=Force*Speed)	- Off-road vehicles, farm tractors
- Computing field work capacity (ha/h)	- Off-road vehicles, farm machinery
- Assessing slippage and draft efficiency	- Off-road vehicles, farm tractors
- Calculating and mapping instantaneous yield (tons/ha)	- Harvesting machinery
- Variable-rate application of agricultural inputs (fertilizers, pesticides, seeds, etc.)	- Farm machinery
- Evaluating driver and vehicle performance (speed, fuel efficiency, work efficiency, energy efficiency, etc.)	- Road vehicles, off-road vehicles, farm tractors, farm machinery
- Efficiency of different routes in logistics	- Road vehicles, ships, aircrafts
- Assessing mobility of people with cardiovascular diseases	- Humans
- Evaluation of mobility of tourists and visitors	- Humans
- Relation between human speed and socioeconomic activity	- Humans
- Studying performances of persons of sports activity	- Humans, bikes, motorcycles, cars
- Monitoring speed and distance for safe operation	- Road and railroad vehicles, ships, aircrafts
- Observing position and velocity of vehicles for real-time traffic management	- Road vehicles
- Auto guidance applications, auto steer systems	- Road vehicles, farm tractors
- Control of unmanned aerial vehicles (UAV)	- Unmanned aerial vehicles
- Vehicle testing	- On-road vehicles

On most platforms, especially on road vehicles, velocity is measured and monitored not to exceed the speed limits for safer operation of the vehicle while speed data is necessary to calculate power (Power=Force*Speed) on off-road vehicles and farm tractors. Drivers can be evaluated based on the speed data along with other parameters such as fuel efficiency, travel time, etc. on road and off-road vehicles. In logistics, vehicle speed is an important parameter in the evaluation of different transport routes along with location and fuel level tracking (against fuel theft), fuel efficiency and exhaust emissions (Senthilkumar et al., 2017; Kan et al., 2018). Another use of the velocity is in health studies in which the walking speed and distance of the patients with some diseases particularly with cardiovascular diseases are evaluated (Le Faucheur et al., 2007). Speed of humans is used to evaluate the social and economic activities (Kawahata et al., 2017). In some sports activities such as car racing, horse racing, cycling, etc., speed is an key variable in the evaluation of the racers and the vehicles (Schutz and Herren, 2000; Witte and Wilson, 2004; Beato et al., 2016). In tourism studies, touristic places where visitors have tendency to move slower and stay longer can be studied using GPS (Global Positioning System) data loggers or recorders (Bauder, 2015). In addition, GPS based data are used for positioning and velocity measurement in real-time traffic management (Zhao et al., 2014).

In agriculture, ground speed data is necessary to compute, monitor and map crop yield in yield monitoring and mapping systems in precision agriculture applications (Keskin et al., 1999; Ess and Morgan, 2003; Keskin et al., 2009; Say et al., 2017). It is also required to properly change the application rate of the agricultural inputs including seeds, pesticides, and fertilizers in variable rate application systems (Richardson et al., 1982; Vishwanathan et al., 2005; Mullenix et al., 2010; Novatel, 2018). Velocity data is also used in tractor auto steer systems (Novatel, 2018) and to assess wheel slip, traction (draft) efficiency and energy consumption of agricultural tractors (Richardson et al., 1982; Khalilian et al., 1989; Lackas et al., 1991; Zhixiong et al., 2013). Another use of speed data is to compute field work capacity (ha/h) which is the amount of area (hectar) processed in unit time (hour). So, a ground speed sensor is one of the main components in modern farm machinery.

In recent years, GNSS (**G**lobal **N**avigation **S**atellite **S**ystem) receivers are used in an increasing amount in speed measurement along with positioning, navigation, and timing. However, GNSS receiver manufacturers do not provide enough information on speed accuracy of their products under different conditions (Dyukov, 2016). Thus, researches conduct studies to assess the speed measurement accuracy of the GNSS receivers. In this paper, working principles, advantages, and disadvantages of each velocity measurement method along with the GNSS and GPS-based method were presented and related research studies were summarized. Particularly, current studies carried out to test the accuracy of GNSS and GPS receivers for speed measurement were included.

Material and Method

In this study, literature was searched, collected and reviewed on the velocity measurement methods used on different platforms. Related scientific articles, reports, books and relevant internet pages obtained after the review process were studied and information related to the subject was compiled. The essential findings were summarized in tables to make the data more readable and comparable. Particularly, advantages, disadvantages and accuracy of each of the velocity measurement methods including GNSS / GPS based method reported by different researchers were included in the article.

Research Findings and Discussion

a) Ground Speed Measurement Methods

In the past, researchers studied, evaluated and compared different measurement methods to assess velocity which includes magnetic shaft encoders, optical shaft encoders, RADAR sensors, ultrasonic sensors, Laser / LIDAR sensors, image processing and GNSS / GPS receivers (Richardson et al., 1982; Grevis James and Bloome, 1982; Clark and Adsit, 1985; Summers et al., 1986; Tompkins, 1988; Khalilian et al., 1989; Self, 1990; Ess and Morgan, 2003; Vishwanathan et al., 2005; Keskin and Say, 2006; Dogan et al., 2010; Mullenix et al., 2010; Keskin et al., 2017). The velocity measurement methods, advantages and disadvantages of each method can be classified as given in Table 2.

Time and Distance method: This method is used to calculate the average speed by dividing a specific distance by the time required to travel that distance. Time is usually measured by a stopwatch. Even if the method is easy and simple, it gives only average speed not instantaneous speed. This method is generally used to calibrate speed sensors. In addition, this method is employed on toll highways to monitor speed limit violations. In this case, the plate number, entrance time and exit time of the vehicle is recorded by an automated system with RFID or similar technology on a section of the highway. The travel time is calculated by taking the difference of the entrance and exit times and the average speed (km/h) is calculated by dividing the length (km) of the highway section by the travel time (h).

Table 2. Speed measurement methods with their advantages and disadvantages

Methods	**Advantages (A) and Disadvantages (D)**
Time and distance	**A**: Easy and simple **D**: Gives only average speed, not instantaneous speed
Magnetic shaft encoder	**A**: Inexpensive **D**: Affected negatively by wheel slippage, tire pressure changes, age of the tire and ground surface type
Optical shaft encoder	**A**: Relatively inexpensive and precise **D**: Affected negatively by wheel slippage, tire pressure changes, age of the tire and ground surface type
RADAR	**A**: Not affected by wheel slippage **D**: Relatively expensive and complex, negatively affected by ground ruggedness, tall vegetation, dust, wind, vehicle movement (pitch, yaw, roll). Low accuracy in low speed and backward movement. Signal interference.
Ultrasonic	**A**: Not affected by wheel slippage **D**: Relatively expensive and complex, negatively affected by ground ruggedness, tall vegetation, dust, wind, vehicle movement (pitch, yaw, roll). Low accuracy in low speed and backward movement. Ultrasonic waves are affected by air temperature changes (need compensation).
LASER / LIDAR	**A**: Less complex and more accurate compared to the radar systems. **D**: Hand-held only, difficult to focus on a target.
Image processing	**A**: Relatively inexpensive **D**: Affected negatively by dust and changes in illumination.
GNSS / GPS-based	**A**: No moving parts. Not affected by tire slippage, dust, ground ruggedness and tall vegetation. Suitable for measuring human speed. **D**: Not accurate enough in increasing and decreasing speed conditions. Low signal quality or acquisition under closed areas such as tunnels, overpasses forests, deep valleys, urban areas, etc.

Magnetic Shaft Encoders: These sensors are mostly used on road and off-road vehicles to measure the ground speed. The velocity is calculated from the number of wheel revolutions per unit time (rpm) and the wheel circumference. The speed is computed by multiplying the number of wheel revolution per unit time and the travel distance per one wheel revolution. The sensor consists of at least one magnet and magnetic pickup pair (Figure 1). The sensor pair could be more than one to increase the accuracy and precision of the speed measurement. The sensor can be mounted on the front or rear wheel as well as on an auxiliary wheel; but, mounting the sensor on front wheel is not appropriate since the travel distance is affected in turns, also, its use on draft wheel is not suitable as the accuracy is affected by wheel slippage. Even if these sensors are inexpensive, they were reported to be affected by wheel slip and tire pressure changes and they require different calibration equations for different surfaces (Tompkins et al., 1988; Vishwanathan et al., 2005; Mullenix et al., 2010).

Optical Shaft Encoders: Similar to the magnetic shaft encoders, optic shaft encoders are generally used on road and off-road vehicles to measure the ground speed (Figure 1). The speed is calculated based on the number of wheel revolution per unit time (rpm) and the wheel circumference. The optic shaft encoders produce pulse signals from several pulses to hundreds even thousands pulses per one wheel revolution. Thus, unlike the magnetic shaft encoders, these sensors could be more precise and accurate. They have similar advantages and disadvantages with the magnetic shaft encoders explained above.

Figure 1. A schematic view of a magnetic shaft encoder speed sensor (left), an optical shaft encoder on auxiliary wheel of a farm tractor (right)

RADAR Speed Sensors: RADAR is an acronym for "**Ra**dio **D**etection **a**nd **R**anging". Radar speed sensors use microwave which is sent to the ground with a specific angle and the reflected signal is received back. Depending on the velocity of the vehicle, a difference exists between the frequencies of the signals sent and received. This frequency difference is called "Doppler shift". Although radar speed sensors are not affected by wheel slippage, they are relatively expensive and complex, negatively affected by ground ruggedness, tall vegetation, dust, wind and vehicle movement (pitch, yaw, roll); also, their accuracy is reduced in low speed conditions and backward movement (Khalilian et al., 1989; Imou et al., 2001; Mullenix et al., 2010). Also, they require filtering and averaging and have problems of obstruction by dust, crop motion, and wind (Richardson et al., 1982) and prone to signal interference (Singh et al., 2014). These sensors are widely used on farm tractors to measure speed; but, with the progress of the GNSS technologies, GPS speed sensors are offered to replace the radar speed sensors. The replacement GPS speed sensors send the speed data in pulse signals similar to the radar speed sensors (Mullenix et al., 2010). Radar speed sensors are used on trains on railroads (Schubert et al., 1995; Akita et al. 2015) and also by law enforcement officers to monitor speed violations. A vehicle's speed on which it has a radar speed sensor is calculated based on the equation presented below (Schubert et al., 1995; Williams, 1999):

$$Fd = F_0 \,.\, (2V / c) \,.\, \cos\alpha \rightarrow V = (Fd \,.\, c) / (2.\, F_0 \,.\, \cos\alpha)$$

where;

Fd: Doppler frequency shift (Hz)

F_0: Frequency of the microwave (Hz)

V: Velocity of the vehicle (m/s)

c: Velocity of the microwave (speed of light)

α: Angle between microwave direction towards surface and the horizontal plane.

Ultrasonic Speed Sensors: This type of speed sensors is very similar to the radar speed sensors with several differences. Firstly, they use ultrasonic waves instead of microwaves. Since the ultrasonic waves are affected by the air temperature, these sensors require temperature compensation. The working principle, advantages and disadvantages of these sensors are similar to those of the radar speed sensors explained above.

LASER / LIDAR Speed Sensors: LASER or LIDAR (**Li**ght **D**etection **a**nd **R**anging) based systems are based on sending a narrow light beam (generally infrared) to a moving subject and receiving the reflected light while keeping the time between sending and receiving the beam (Singh et al., 2014). The distance is calculated by using the time and the speed of light (Distance=Time x Speed of Light). Then, the speed is calculated by dividing the distance by time (Speed=Distance/Time). Laser / Lidar speed sensors are mostly used by law enforcement officers to monitor speed violations (Singh et al., 2014). These systems are less complex and more accurate compared to the similar radar systems while they are used hand-held only and difficult to focus on a target (Singh et al., 2014).

Image-Based Speed Measurement: Some researchers used video camera and image processing to estimate real time speed of moving vehicles from the images (Stone and Kranzler, 1992; Nishiwaki et al., 2002; Czajewski and Iwanowski, 2010; Dogan et al., 2010). For off road vehicles like farm tractors, the camera is mounted under the vehicle or in front of the vehicle. The travel distance, travel time and the instantaneous speed is calculated from two consecutive images taken by the camera using an appropriate image processing algorithm. A modified version of this method is also utilized on toll highways to monitor speed limit violations. In this case, the plate number, entrance time and exit time of the vehicle is recorded by two cameras, one positioned at the beginning and the other at the end of a section of the toll highway. The travel time is calculated by taking the difference of the entrance and exit times and the average speed (km/h) is calculated by dividing the length (km) of the highway section by the travel time (h).

GNSS and GPS based speed sensors: A GNSS / GPS receiver is capable of computing speed as well as location (latitude, longitude, altitude) (Jeffrey, 2010). Various countries possess satellite-based GNSS systems. The most popular one is the GPS (Global Positioning System) operated by the US. Russia has also a GNSS system similar to the GPS called GLONASS. The European Union and China are working on similar systems of their own named Galileo and Beidou/Compass, respectively. GNSS / GPS receiver technologies have been gaining importance in recent years for all sectors. One of the application of the GPS receivers is speed measurement. GNSS receivers determine the speed with three different methods (Zhang et al., 2004; Chalko, 2007; Freda et al., 2015; Gaglione, 2015):

a) In the first method, the speed is calculated from the travel distance divided by the time required to take that distance (speed=distance/time) (Chalko, 2007). This calculation is based the equation given below (Gaglione, 2015):

$$V_u = dR_u / dt = (V_{xu}, V_{yu}, V_{zu}) = (R_u(t_2) - R_u(t_1)) / (t_2 - t_1)$$

where;
V_u = Speed of the user (receiver) (m/s)
dR_u = Distance travelled (m)
dt = Elapsed time to take the distance (s).

b) In the second method, the velocity is determined from the Doppler frequency shift. The relative motion between the GPS satellite and the GPS receiver results in a frequency difference (Doppler shift) which is the difference between the frequency of the signal sent by the GPS satellite and the frequency of the signal acquired by the receiver (Zhang et al., 2004). Signals from at least four GNSS / GPS satellites are needed to determine the speed. However, the accuracy of the speed determination is affected by some factors (signal delay in ionosphere and troposphere, satellite clock error, satellite orbit error, signal multipath receive error, receiver error, etc.) (Zhang et al., 2004). The speed calculation based on Doppler shift was reported to be more accurate than the first method (Chalko, 2007; Townshend et al., 2007; Chalko, 2009; Sathyamorthy et al., 2015). If the error factors are compensated, the accuracy of the speed was reported to be in the order of cm/s (Zhang et al., 2004). The calculation is based the equation given below (Gaglione, 2015):

$$D = Fr - Ft = - Ft / c \left[(Vs-Vu) * (R - Ru) / \| R - Ru \| \right]$$

where;
D = Doppler frequency shift (Hz)
Fr = Frequency of signal received (Hz)
Ft = Frequency of signal sent by the satellite (Hz)
c = Speed of light (speed of GPS satellite signal) (m/s)
Vs = Speed of the satellite (m/s)
Vu = Speed of the receiver (user) (m/s)
R = Position of the satellite (m)
Ru = Position of the receiver (user) (m).

c) The third method, called time-differenced carrier phase (TDCP) technique involve in time difference of successive carrier phases to the same satellite at small sampling intervals (<1Hz) and as a result, most error sources are eliminated including constant integer ambiguities, most common errors such as satellite clock bias, ephemeris error, tropospheric error, and ionospheric error yielding more accurate velocity data (Freda et al., 2015).

Regarding the accuracies of these three methods, the first method is inaccurate (in order of m/s), the second method (Doppler shift) has an accuracy of cm/s and the third one (TDCP) can offer best accuracy in the order of mm/s (Freda et al., 2015; Gaglione, 2015).

There are some commercially-available low-cost GPS-based speed sensors that send the speed data in pulse signal similar to the radar speed sensor developed particularly for the agricultural sector (Mullenix et al., 2010). Their price is in the order of several hundreds US dollars. A GPS speed sensor consists of an antenna, a microprocessor to calculate the speed, a monitor to show the speed data and a connector cable (Figure 2).

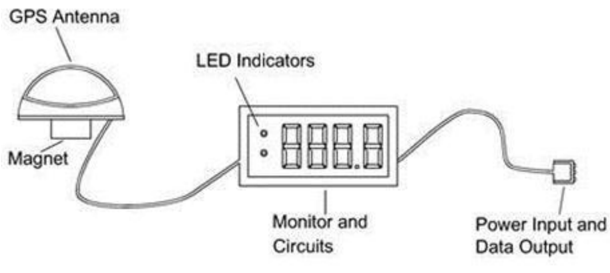

Figure 2. A schematic view of a commercially available GPS speed sensor

b) Performance of GPS based speed measurement systems

A number of studies have been reported on the performance of GPS receivers for velocity measurement on different platforms. The key findings are summarized in Table 3.

Table 3. Findings on the performance of GPS based speed measurement

Reference	Findings
Schutz and Herren, 2000	Speed data from a differential GPS receiver (DGPS) had a standard deviation of 0.08 km/h for walking and 0.11 km/h for running. There was a significant linear relation between actual and DGPS speed (R^2 = 0.99). Accuracy of speed from DGPS was improved by a factor of 10 as compared to non-differential GPS.
Witte and Wilson, 2004	The speed from a non-differential GPS receiver (REB 2100 GPS) was within ±0.2 ms^{-1} of the true speed for 45% of the values with a further 19% lying within ±0.4 ms^{-1}.
Al-Gaadi, 2005	The error in ground speed from a hand-held GPS receiver (Garmin eTrex Venture) was on average 1.27 km/h (less than %7). An error of up to -80.16% was obtained when the vehicle slowed down from 1.65 km/h to 11.19 km/h.
Vishwanathan et al., 2005	A GPS speed sensor (AgExpress GVS GPS) and two radar speed sensors were studied. GPS sensor had maximum error within 6.44 km/h during acceleration due to the latency.
Keskin and Say, 2006	Two hand-held GPS receivers (Magellan SporTrak, Garmin eTrex Vista) were tested. GPS receivers can be used for ground speed (R^2=0.99) under constant speed conditions.
Koc et al., 2006	A hand-held GPS receiver (Magellan-Explorist-300) gave on average 1.25 km/h lower speeds than the reference in constant speed conditions (3.0-7.0 km/h).
Mueller, 2007	The baud rate and update rate of a GPS receiver should be in accordance with each other; if not, time delay of up to 8 s could be observed resulting in inaccurate speed data.
Fulton, 2010	GPS based and radar based speed measurement methods were compared. Quick acceleration produced time lags in GPS based speeds compared to radar based system.
Supej and Cuk, 2014	Five GPS receivers with different frequencies (1 Hz, 20 Hz) were compared. Low-cost GNSS receivers with 1 Hz had high latency (up to 2.16 s) and are not suitable to track speed especially during dynamic movements.
Zhao et al., 2014	The velocities from a GPS tracking device (BT-338X) were quite accurate with a tendency of underestimation. The error between recorded and actual velocity increased with the speed. Accuracy under acceleration and deceleration was not studied.
Dyukov et al., 2015	Geodetic GPS and GPS+GLONASS receiver were better than mid and low-range receivers. Adding GLONASS did not improve the performance. HDOP might be used as a quality indicator to assess reliability of speed data. Caution should be exercised for GNSS speed in challenging environments (overpass, multipath, etc.).
Beato et al., 2016	The speed of male soccer players obtained from a 10 Hz GPS unit (StatSports) was lower than the reference speed obtained from video image analysis.
Keskin et al., 2017	Two low-cost hand-held GPS receivers (Magellan SporTrak Map, Garmin GPSMAP 60) were tested. GPS receivers sent the speed data with a time delay of 1.7-2.5 s and 3.6-5.2 s under variable speed conditions (Figure 3). GPS receivers show accurate speeds under constant speeds but inaccurate speeds under varying speed conditions.
Akkamis et al., 2018	High correlation existed between GPS velocity error and acceleration (R^2>0.70). Based on the maximum acceleration (up to 1.15 m/s^2), mean error was up to 46%, 16% and 12% for 1 Hz, 5 Hz and 7 Hz GPS speed sensors. Maximum mean speed error at constant speed was -%2.3, -%1.8 and -%1.4 for 1 Hz, 5 Hz and 7 Hz units.
Gloersen et al., 2018	Three GNSS receivers (Garmin Forerunner 920XT 1 Hz; Catapult Optimeye S5 10 Hz; ZXY-Go differential receiver 10 Hz) were tested for position, speed and timing. 10 Hz receivers gave better results (0.038-0.072 m/s) than 1 Hz receiver (0.660 m/s).

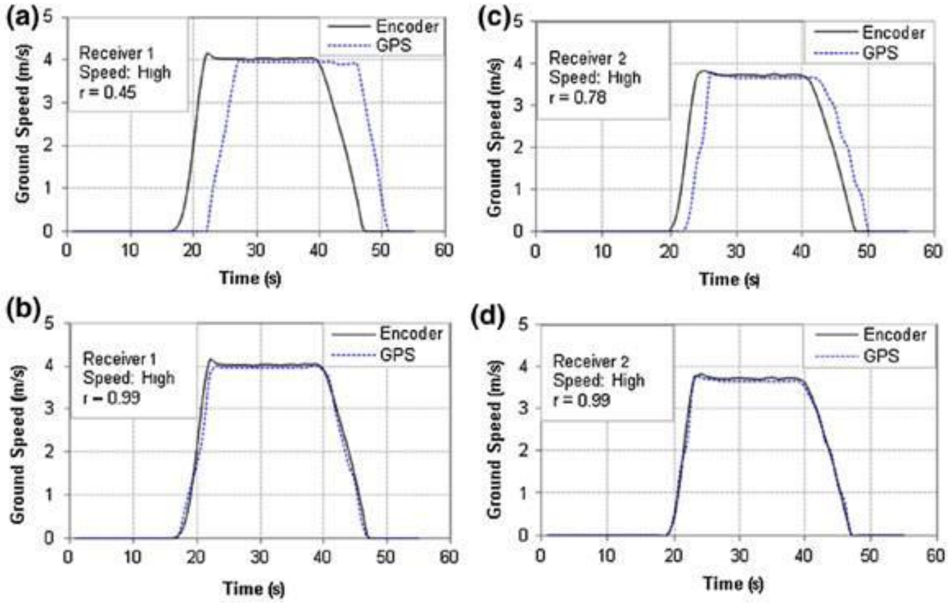

Figure 3. Ground speed over time for two GPS receivers a) Speed data from rotary encoder and Receiver 1 b) Data after correction for Receiver 1. c) Speed data from rotary encoder and Receiver 2 d) Data after correction for Receiver 2 (Keskin et al., 2017)

Results and Suggestions

Velocity data is used on various platforms including road vehicles, off-road vehicles, bikes, trains, humans, ships, aircrafts, etc. for various aims such as assessment of speed limit, energy consumption, fuel efficiency, driver performance, mobility of persons, sporter performance in sports activity and traffic management. With the advances of technology, new GNSS / GPS receivers, data loggers, trackers and speed sensors are available with smaller size, lower cost, multi-frequency, receiving signals from more than one GNSS and having higher data update frequencies. One of the crucial improvements is the higher data update frequencies up to 20 Hz which lowers the disadvantage of the latency.

In this paper, working principles, advantages and disadvantages of various velocity measurement methods in reference to GNSS-based method were presented and related research studies were summarized. Especially, current studies carried out to test the accuracy of GNSS receivers for speed measurement were included.

GNSS receivers have some advantages over other speed measurement methods with no moving parts, being not affected by tire slippage, dust, ground ruggedness and tall vegetation and being suitable for evaluating human speed. In contrast, they have some drawbacks such as inaccuracy in increasing and decreasing speed conditions, low signal quality or acquisition under closed areas such as tunnels, forests, overpasses, deep valleys, urban areas, etc.

Previous studies on speed measurement with GNSS receivers revealed important findings: GNSS units determine the speed based on three methods (travel distance/time, Doppler shift and time-differenced carrier phase, TDCP) and TDCP method can provide better accuracy then the other two methods. GNSS receivers with higher data update frequencies give more accurate speed data as compared to the lower frequency receivers, especially in varying speed conditions (acceleration and deceleration). High correlation existed between GPS velocity error and acceleration and deceleration (R^2>0.70) in increasing and decreasing speeds meaning that the error rises in higher acceleration and deceleration conditions. The accuracy of speed with DGPS was improved as compared to non-differential GPS. GPS units underestimate the speed as compared to the reference speeds. Adding GLONASS to GPS does not improve the performance significantly. HDOP might be used as a quality indicator to assess reliability of speed data. Also, caution should be exercised for GNSS speed measurement in challenging environments (overpass, signal multipath, etc.).

Disclaimer: The use of product or firm names in this paper is for descriptive purposes only and does not imply endorsement by the authors.

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