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Positional accuracy of the Wide Area Augmentation System in consumer-grade GPS units
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ABSTRACT

Global Positioning System devices are increasingly being used for data collection in many fields. Consumer-grade GPS units without differential correction have a published horizontal positional accuracy of approximately 10–15 m (average positional accuracy). An attractive option for differential correction for these GPS units is the Wide Area Augmentation System (WAAS). Most consumer-grade GPS units on the market are WAAS capable. According to the Federal Aviation Authority (FAA), the WAAS broadcast message provides integrity information about the GPS signal as well as accuracy improvements, which are reported to improve accuracy to 3–5 m. Limited empirical evidence has been published on the accuracy of WAAS-enabled GPS compared to autonomous GPS. An empirical study was conducted comparing the horizontal and vertical accuracy of WAAS-corrected GPS and autonomous GPS under ideal conditions using consumer-grade receivers. Data were collected for 30-min time spans over accurately surveyed control points. Metrics of median, 68th and 95th percentile, Root Mean Squared Error (RMSE), and average positional accuracy in the horizontal and vertical dimensions were computed and statistically compared. No statistically significant difference was found between WAAS and autonomous position fixes when using two different consumer-grade units. When using WAAS, a third unit type exhibited a statistically significant improvement in positional accuracy. Analysis of data collected for a 27-h time span indicates that while WAAS is altering the estimated position of a point compared to an autonomous position estimate, WAAS augmentation actually appears to decrease the positional accuracy.

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1. Introduction

Use of the Global Positioning System (GPS) is increasing as a means for data collection and data analysis in many fields. GPS is employed in environmental studies, biological and biomechanical studies, social sciences, meteorology, military applications, archaeology, navigation, mapping, surveying, and more (Witte and Wilson, 2004; Dauwalter et al., 2005; Shoval and Isaacson, 2006; Frenzel, 2007). An attractive option for differential correction for these GPS applications is the Wide Area Augmentation System (WAAS). WAAS provides real-time correction free of charge, and does not require extra hardware or software for use of the correction signal. This study evaluates the benefits of WAAS in three different GPS units: the Garmin 60cx, the Timble Juno ST, and the DeLorme Earthmate PN-20.

1.1. GPS positional accuracy

The positional accuracy of GPS position fixes is impacted by a number of factors including the satellite, the receiver, and signal propagation errors. The total typical positional accuracy for a GPS receiver without correction is in the order of 10 m. Sources that impact positional accuracy include ephemeris error, satellite and receiver clock error, multipath error, receiver measurement noise, satellite geometry measures, tropospheric delay, and most significantly, ionospheric delay (Klobuchar, 1996; El-Rabbany, 2006).

1.2. Differential correction

GPS positional accuracy can be improved by using differential correction. Differential correction uses information from a stationary receiver at a known location to enhance the quality of location data used by GPS receivers (Chivers, 2003; Bolstad et al., 2005). Differential correction can be applied in real time in the field, or through postprocessing after data are collected. Regardless of the technique, all differential GPS (dGPS) methods use the same underlying concept. dGPS requires the use of a base station, a GPS receiver at an accurately known location. The base station...
compares its known location to its location as calculated based on GPS satellite signal. This calculated difference in location is then applied to the roving GPS receiver as differential correction on the premise that any two receivers relatively near each other will experience similar errors (Chivers, 2003). The source of correction for dGPS is always a base reference station, but the medium to transmit the correction varies. Corrections can be accessed via radios, beacons, satellites, or the internet.

Of the factors that affect GPS positional accuracy, dGPS primarily reduces errors due to ionospheric and tropospheric delay. Ephemeris error and satellite clock error can also be reduced with dGPS; however, dGPS cannot correct for or reduce error from receiver noise, multipath error, or poor satellite measurement geometry (El-Rabbany, 2006).

2. WAAS

This study is concerned with the United States-based differential correction system known as WAAS. WAAS is a Satellite Based Augmentation System (SBAS) and was designed to augment and enhance GPS positional accuracy and integrity for use as a navigation aid for civilian aviation (Bolstad et al., 2005). The WAAS system reached full operational status in July of 2003 (FAA, 2005). The Federal Aviation Authority (FAA) manages WAAS and publishes quarterly performance analysis reports. The FAA reports that WAAS will provide 7 m accuracy—a 3 m improvement on the 10 m accuracy usually specified for most recreational receivers gathering data autonomously. FAA testing shows that WAAS accuracy is typically better than 7 m accuracy, with tests from the first quarter of 2008 indicating “the 95% horizontal and vertical accuracy at all evaluated sites are less than 2 m for both WAAS operational service levels” (FAA, 2008).

2.1. WAAS history

WAAS was originally developed by the FAA in partnership with the United States Department of Transportation (DoT). The FAA first issued a request for proposals to build the WAAS network in 1994. The initial program was scheduled for 6 years and an estimated $400–500 million (Phillips, 1994, 1995). It was hoped that the system would reach initial operational capability in 1997. In August, 1995 the FAA awarded a $475 million contract to Wilcox Electric, teamed with Hughes Aircraft and TRW. This contract called for development and placement of approximately 35 ground stations to be located at air traffic control sites across the United States. Wilcox Electric failed to meet the FAA’s expectations for WAAS development, and the contract was terminated and quickly awarded to Hughes Aircraft in 1996 (Nordwall, 1996). In 1998 Raytheon purchased Hughes Aircraft’s Defense Electronics business, and took over the WAAS contract from the FAA. Testing and building of the WAAS network continued and after several delays it was certified for aviation use in July 2003 and reached full operational service.

The WAAS network continues to expand. In 2006–2007, 13 new reference stations were added. In 2006 a third master control station was added, and in 2007 the two geostationary satellites were upgraded. The current operational service area is shown below (Fig. 1) (FAA, 2010). LPV, localizer precision with vertical guidance, is an FAA term for an operational service level with a horizontal alert limit of 40 m and a vertical alert limit of 35 m. LNAV is a representation of lateral navigation area and VNAV is a representation of a vertical navigation area.

2.2. WAAS network

The WAAS network is composed of 38 WAAS reference stations (WRS) located across the continental United States, Alaska, Puerto Rico, Hawaii, Canada, and Mexico. It includes three

Fig. 1. WAAS service area.
master control stations, two geostationary Earth orbit (GEO) satellites, and four ground uplink stations (GUS) (Fig. 2) (FAA website, 2007; Eldridge, 2008). The WRSs are spaced widely and collect data from all visible GPS satellites as well as the WAAS GEO satellites. Each WRS is equipped with a high quality clock and multiple GPS receivers (Kee, 1996). The collected data are then sent to the master control stations. The master control stations process these data to determine satellite integrity, differential corrections, residual errors, and ionospheric delay (Eng and Van Dierendonck, 1996). The correction information is uploaded to the two GEO satellites that transmit the correction at the GPS L1 frequency. The GEO satellites also broadcast an L5 signal, which is used by GUS to calculate ionospheric delay (Schempp, 2008). The correction message consists of two components: the location-independent parameters of ephemeris and clock error, and area-specific ionospheric errors transmitted in a latitude–longitude grid (El-Rabbany, 2006; Schempp, 2008). Because the correction message is transmitted on the GPS L1 frequency, it can be received by all WAAS-enabled receivers at no cost, with no extra hardware or software.

2.3. WAAS reference stations

In 2006–2007, 13 new WRS were added to the WAAS network. Stations were added in Alaska, Mexico, and Canada. This significantly increased performance in North America. All WRS were upgraded to use a new GPS receiver that provides detailed information about GPS signal quality to be used in an improved signal-quality monitoring algorithm (Schempp, 2008). The third WAAS master control station was added to the network in June 2006. Three such stations ensure that the WAAS network will have at least two operational master control stations even when one is down for maintenance or upgrades (Schempp, 2008).

2.4. GEO satellites

In July 2007 the WAAS legacy GEO satellites were replaced with upgraded satellites that provide superior ranging capabilities. One of the GEO satellites is located at 133 W. It is identified by the pseudorandom noise code (PRN) 135. This is the Galaxy 15 PANAMSAT and is operated by Intelsat. The second GEO satellite is located at 107.3 W, PRN 138. This is the Anik F1R satellite operated by Telesat. These new GEO satellites ensure dual GEO coverage for all WAAS users (Schempp, 2008). The GEO satellites are located 36,000 km above the Earth’s equator.

The GEO satellites broadcast a signal at the earth with a footprint defined by the curvature of the Earth. The signal cannot bend around the Earth; the footprint is circular in shape. Once projected, the footprint appears oval in shape. While the GEO satellite signal covers a large area, the service area as shown in Fig. 1 is only the area where reference and master stations are in place to work with the GEO satellites.

2.5. WAAS architecture

WAAS is based on the WADGPS model, and is specifically a state-space-domain WADGPS (El-Rabbany, 2006). Instead of providing a scalar range error correction for each satellite as is done in dGPS, WADGPS calculates a vector of error corrections. WADGPS is nearly constant in the monitored region, and degrades smoothly on the perimeter. Computation of the error correction vector is the key component of WADGPS. The correction accounts for three-dimensional ephemeris clock error and clock bias for each visible GPS satellite, plus ionospheric delay (Kee, 1996).

Communication between WAAS components is handled by a terrestrial communication network (TCN). Redundancy is built into the network to increase system integrity. Each WRS is equipped with three reference equipment units; data are used from two of the units while the third is a backup. The TCN is divided into two separate networks, each of which utilizes a T1 backbone. Each master control station is equipped with two correction processors and two safety processors. If an error is detected in the safety processors, another correction and validation device automatically takes over. Each GUS receives a message from each master control station. Should the GUS fail to receive a message from a master control station, a different master control station is used in its place. A pair of GUS sites is assigned to each GEO satellite; should one of the GUS sites fail the other automatically takes over. Most users in North America have dual GEO satellite coverage. Should one of the GEO satellites fail, the users’ receiver will automatically switch to the other satellite.

2.6. Other SBAS networks

The United States is not the only country with a SBAS in place. Japan, Europe, India, and China have or are implementing similar augmentation systems. These SBAS networks are similar in design and functionality to the United States’s WAAS. Japan’s augmentation system known as the Multifunction Satellite-based Augmentation System (MSAS) became operational in 2007 and was developed by the Japanese Civil Aviation Bureau (Gakstatter, 2008). Europe’s SBAS is the European Geostationary Navigation Overlay Service (EGNOS), which is being developed by the European Commission (ESA) and EUROCONTROL (European Organization for the Safety of Air Navigation) (Wilson, 2008). The Geo-Aided GPS Augmented Navigation system (GAGAN) is currently under development in India, with plans to be operational by 2012–2014. GAGAN is a joint partnership between Airports Authority of India and the Indian Space Research (Matthews, 2007; Kibe, 2006). China is implementing an SBAS known as the Satellite Navigation Augmentation System (SNAS) (Wilson, 2008). Information on SNAS is incomplete. Eleven reference stations have been installed around Beijing (Grewal et al., 2007).

2.7. Accuracy determination

In order to utilize the WAAS signal, the GPS signal must first be available. In theory, GPS and WAAS signals are always available; in practice, GPS and WAAS signals can be equally affected by obstructions. The availability of the signals can be affected by line of sight problems. Line of sight between the receiver and either the GPS or the WAAS satellite can be obstructed by tall buildings, mountains, or thick tree canopies. Additionally, GPS and WAAS signals are generally not available indoors. A study conducted by...
Bolstad et al. (2005) evaluated the availability of the WAAS signal. It was found that in the open the WAAS signal was available 98% of the time. Under a forest canopy the WAAS signal was available 23–33% of the time while stationary, and only 7–22% while moving. This study also compared data that were corrected via postprocessing, WAAS, and autonomous and concluded that in a higher end unit the difference between these three methods was minimal. It was concluded that differences in lower end units were caused by other outside influences and not the type of correction used.

A study by Wing et al. (2005) tested the accuracy of six different consumer-grade units in a variety of landscape settings. Differential correction of any kind was not explicitly applied in this study. Data were collected at known locations in three different landscape settings: an open sky landscape, a young forest landscape with 40–50% closed canopy, and a 100% closed canopy landscape. Mission planning software was used to schedule collection times around particularly strong satellite geometry (low PDOP). In order to maintain consistency during collection, wooden staffs were built to hold each GPS receiver 1.2 m above the ground. Twenty-five observations were taken at each known location, approximately 4 s apart to allow for averaging. Positional accuracy was determined based on the straight line distance between the averaged coordinate and the known coordinate. Positional accuracy ranged from 1.4 to 19.6 m in all landscape settings and all unit types. Positional accuracy in the top performing units was approximately 5 m in an open sky landscape, 7 m in young forest landscape, and 10 m in closed canopy landscape.

3.2. Objectives

This study is designed to evaluate the potential benefit of WAAS and its positional accuracy relative to autonomous GPS as implemented in consumer-grade units. The primary objective is to determine horizontal and vertical positional accuracy of WAAS-corrected GPS and autonomous GPS through a comparison with surveyed control points under ideal conditions. The research hypothesis was that autonomous GPS data gathered under ideal conditions are statistically different from WAAS-corrected GPS data gathered under ideal conditions. In addition, variability in the autonomous accuracy between different receivers is assessed. While there are many dimensions and benefits of the WAAS system to civil aviation, its impact on positional accuracy is most relevant when looking at its use in consumer-grade units.

3. Data and methods

3.1. Control point determination

In order to evaluate positional accuracy, collected data must be compared to a known point. The location of known points is determined with a system of higher accuracy than the hand-held receivers being used in this test. The known point is the “true” location of the point in question, or the control point. Control points were selected from the National Geodetic Survey (NGS) and the Albuquerque Geodetic Reference System (AGRS). NGS points used were “high-accuracy” GPS control points. AGRS control points used were first-order horizontal and second-order vertical accuracy. These data are obtained from the NGS datasheet retrieval page (ngs.noaa.gov) and the City of Albuquerque web page (cabq.gov/gis/survey.html), respectively. A total of 10 control point locations were selected in Albuquerque, New Mexico, within relative proximity (20 km) of the WRS located in the northeast part of the city at approximately 35°10’19” N, 106°33’59” W. Two control points were set in each geographical location initially collected at 11:00 am daily, and then moved to anytime between 10:00 am and 3:00 pm after data on diurnal patterns were collected and analyzed. Three different types of consumer-grade units were used in data collection: Garmin 60cx, DeLorme Earthmate PN20, and Trimble Juno ST (Table 1). The Garmin and DeLorme units have external antennas, whereas the Trimble unit’s antenna is embedded in the ring of the unit.

Data collection was originally attempted by capturing the GPS NMEA string, which is the raw GPS data unaltered by the unit for presentation. However, there was no significant difference between the NMEA string and the data presented by the different receiver types in track or point files. To simplify logistics of data collection, the NMEA string was not gathered for data analysis. Data were collected at each of the 10 control points for 30-min intervals, on two unique visits, resulting in a sample of 20 data collection sets for each type of unit. Data were collected during the months of January to April 2009. The units were set to record a fix every second, resulting in 1800 data points collected at each control point.

For the purpose of comparing autonomous GPS with WAAS-corrected GPS, two identical receivers were mounted side by side on a tripod, which was placed directly over the control point. The height from the control point to the antenna was measured, and accounted for when calculating observed height. Units were on average 1.5 m above the control point. Receivers were positioned such that the antennas of each unit were as close over the control point as possible, within approximately 15 cm. One receiver was operating in autonomous mode, and the other in WAAS mode.

The last objective is to determine how WAAS correction benefits differ over a longer data collection period. Data were collected at a control point for a continuous 27 h. This test was conducted using only the pair of Garmin 60cx units. The track record was set to record one point every 10 s. This test was conducted on two separate occasions, first on January 12, 2009,

Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Chip set</th>
<th>High sensitivity</th>
<th>Channels</th>
<th>Published autonomous accuracy (%)</th>
<th>Published WAAS accuracy (95%) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garmin</td>
<td>SiRFstar III</td>
<td>Yes</td>
<td>12</td>
<td>&lt; 10 m</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Trimble</td>
<td>SiRFstar III</td>
<td>Yes</td>
<td>12</td>
<td>Not published</td>
<td>2–5</td>
</tr>
<tr>
<td>DeLorme</td>
<td>STMicroelectronics SiGE RF front end</td>
<td>Yes</td>
<td>12</td>
<td>&lt; 15 m</td>
<td>&lt; 3</td>
</tr>
</tbody>
</table>

Ideal conditions for this test are defined as an open area with minimal obstructions, within 20 km of the WRS. Data were initially collected at 11:00 am daily, and then moved to anytime between 10:00 am and 3:00 pm after data on diurnal patterns were collected and analyzed. Three different types of consumer-grade units were used in data collection: Garmin 60cx, DeLorme Earthmate PN20, and Trimble Juno ST (Table 1). The Garmin and DeLorme units have external antennas, whereas the Trimble unit’s antenna is embedded in the ring of the unit.

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and second on February 2, 2009. The same control point was used on each occasion.

3.3. Data processing

After data were collected, data points from the GPS receivers were downloaded to a computer. For the Garmin units this was done using either DNR Garmin software or MxGPS. Data from the DeLorme units were transferred to the computer using DeLorme’s TopoUSA 7.0 software. Data were transferred from the Trimble units using Trimble’s GPS Pathfinder Office software. For all unit types, data were set to transfer in geographic coordinate system WGS 1984 to avoid any automatic datum transformations. WGS is the native reference system used in GPS.

A shapefile was created for each set of points and loaded in ESRI ArcMap 9.2. For one control point there would be a shapefile for the control point location, the WAAS track for 30 min, and the autonomous track for 30 min. The coordinate system of the point data was modified from the GPS default of WGS 1984 GCS to NAD 83 New Mexico State Plane Central Zone using the ESRI transformation NAD_1983_to_WGS_1984_5. Details on this seven-parameter geographic datum transformation are as follows: code, 1515; method, Coordinate Frame; DX, −0.991; DY, 1.9072; DZ, 0.5129; rX, −0.02579; rY, −0.00665; rZ, −0.01166; ds, 0.

To ensure equal comparison of elevation information, whether a given unit recorded orthometric or ellipsoid height was noted and this information was used accordingly when computing vertical accuracy. The Garmin and DeLorme units recorded orthometric height. In investigating the cause behind large discrepancies in height, it was found that the Garmin and DeLorme units use a very coarse geoid model, resulting in unreliable elevation estimates. The geoid model is what is used to convert from ellipsoid height, which is inherent to the GPS signal, to orthometric height, which the Garmin and DeLorme units report. The Trimble units could be set to record either orthometric or ellipsoid height. The units were set to record ellipsoid height to avoid possible problems caused by the geoid model.

From the coordinates of each point in the 30-min span, the median, 68th percentile, 95th percentile, and Root Mean Squared Error (RMSE) are determined for horizontal (x,y) and vertical (z) dimensions. Additionally, the positional accuracy in averaged x,y,xy, and z is computed. The average positional accuracy for the x, y, and z dimensions for each position fix is determined using the mean formula: \( x = \frac{1}{n} \sum x_i \). The 68th and 95th percentile determines the k-th percentile of values in a range of n values. The formula used for RMSE is \( \text{RMSE} = \sqrt{\frac{1}{n} \sum (e_i^2) \} \), where \( e_i \) is the positional error in each unique GPS position fix (Devlin et al., 2007). These metrics were recorded for every data collection session and cataloged.

3.4. Testing average position for bias

For each set of data collected, the average positional accuracy in x, y, and z was tested against zero in a one-sample hypothesis test to determine if bias is present. A one-sample hypothesis test allows for the mean values to be tested against a known value to assess bias. For instance, after being tested for normality, the 20 values of average x positional accuracy in autonomous GPS using Garmin units were tested against zero, and then the 20 values of average x positional accuracy in WAAS were tested against zero. The test was repeated for each metric, and for each unit type. It is expected that these metrics will be near zero. A test of bias shows if the metric is statistically different from zero. Testing is conducted at the 0.05 \( \alpha \) level.

3.5. Test of means

For each set of data collected at a given control point, the median, 68th percentile, 95th percentile, and RMSE were calculated and compared to determine if WAAS and autonomous GPS data are statistically different. To test these data, a two-sample t test, a hypothesis test of means was conducted. A two-sample t test allows for the comparison of the mean responses of each metric between the WAAS sample and the autonomous sample. A table for each metric being tested was created showing the positional accuracy for WAAS and autonomous for each dataset. This sample was then tested for normality using an Anderson-Darling test in the statistical software package Minitab. Assuming that the data were normal, a two-sample t test is conducted at the 0.05 \( \alpha \) level to determine whether the WAAS population mean of each metric is statistically different from the autonomous population mean of each metric.

3.6. Accuracy variability in different receivers

The second objective is to determine variability in autonomous accuracy between different receivers. All units were tested under similar conditions and the data were processed in the same manner. To compare the different receiver types tested, two-sample t tests were conducted testing the autonomous median values of each unit type against each other to determine if the autonomous position fixes of the units were the same or different. While the median value, which represents the 50th percentile in positional accuracy, was used in this test, any of the statistical metrics could have been used.

4. Results and discussion

Scatter plot diagrams of each individual data collection session suggest that there is no statistically significant difference between the WAAS population and the autonomous population when using the Garmin or Trimble units under ideal conditions (Figs. 3 and 4). This suggestion is not supported when assessing data collection sessions using the DeLorme units (Fig. 5). It is further noted that wandering in the position fixes collected over a
The observations in the diagrams are supported by the results of the one-sample hypothesis test against zero. A $p$ value greater than 0.05 suggests that the mean of the given average metric is not statistically different than zero; conversely a $p$ value less than 0.05 suggests that the given metric is statistically different than zero (Table 2).

For metrics that are statistically different than zero, Garmin autonomous $x$, Garmin $z$ both WAAS and autonomous, Trimble $x$ both WAAS and autonomous, and Trimble autonomous $z$, it can be seen that the range of accuracy is close to zero for $x$ and $y$ metrics. A striking difference can be seen in the Garmin units regarding average $z$ accuracy. Whether with WAAS or without, the estimate of height was considerably different from zero. This is due to the coarse geoid model used in the Garmin units.

Interestingly, in the Trimble units, evidence suggests that while the $y$ average positional accuracy is not statistically different than zero, the $x$ average values are, for both WAAS and autonomous. In evaluating average $z$ accuracy, autonomous elevation accuracy estimates are closer to zero which would be expected, whereas WAAS elevation estimates are not near zero. This contradicts the assumption that WAAS improves positional accuracy.

In the DeLorme units, a wide range of positional accuracy was observed. Average $x$ and $y$ accuracy in the Trimble and Garmin units is typically 5 m or less, whereas the DeLorme units are closer to 10 m or less. Large positional accuracy variability in the average $z$ dimension was shown in the DeLorme units for both autonomous and WAAS.

After the test for bias was completed, the test of means between all WAAS and autonomous metrics was conducted. Using the resulting metrics from data processing, hypothesis tests were conducted for each metric, for each different unit. Absolute values of $x$, $y$, and $z$ average positional accuracy were used because directional accuracy was not being tested. The results of this testing show that based on the collected sample, there is no statistically significant difference in horizontal or vertical metrics between the autonomous GPS population and the WAAS-corrected GPS population when using the Garmin or Trimble units (Table 3). This result rejects the common belief and published manufacturer assertions that WAAS positional estimates are better than autonomous positional estimates.

In the DeLorme units there is a statistically significant difference between WAAS and autonomous locations in horizontal metrics. This result supports the assumption and published manufacturer specifications that a WAAS positional estimate is better than an autonomous positional estimate. However, a statistically significant difference was not found in the average vertical position.

A lower-tailed, one-sided, two-sample statistical test was completed for the DeLorme metrics, which showed a statistically significant difference between the WAAS population and the autonomous population. Resulting $p$ values suggest that for all horizontal metrics using the DeLorme units, the average positional accuracy is improved when using WAAS. As shown previously, there is no statistically significant difference in the average $z$ accuracy between WAAS and autonomous. This result could be tied to the unreliable height reported by the DeLorme units, which use a very coarse geoid model. $p$ values are presented in Table 4.

Diagrams of WAAS median versus autonomous median and WAAS RMSE versus autonomous RMSE were created to gain a better understanding of the effect of WAAS (Fig. 7). The diagrams show that no relationship is evident between WAAS and autonomous data. If there were no effect at all from WAAS, all points in the graphs in Fig. 7 would lie along a straight line. As can be seen, many points do not lie close to a straight line. The data presented

30-min time span as expected is not seen in the DeLorme data. Rather, the DeLorme scatter plots present data that are often in a straight line. The data points also appear to follow an obvious grid. The grid pattern is on the centimeter level and is therefore only visible when zoomed in very close on the data points. These two factors suggest that the DeLorme units could be averaging and truncating positional information. While the Garmin and Trimble data also appear to be gridded, the grid pattern is only evident at a large scale. This suggests that the Garmin and Trimble data are also truncated, but not to the extent that the DeLorme data are.

Average $x$, $y$, and $z$ metrics were first tested against zero in a one-sample $t$ test. It is expected that the values of these metrics will be near zero. These data are represented in Fig. 6, which shows box plots of the average $x$, $y$, and $z$ metrics for each unit type.
in the diagrams highlight the cases where WAAS has a large effect. If WAAS were making a large impact, it would be expected to see many points of the case where the autonomous positional error was high, and the WAAS positional accuracy was low. While there are a few cases of this scenario, there are also a few cases of the exact opposite, points where the WAAS positional error is high and the autonomous positional error is low. The graphs representing the DeLorme units show more cases where the autonomous error is high, and the WAAS error is low.

Based on FAA reports, WAAS will provide 7 m or better positional accuracy. The maximum median accuracy values for the Garmin and Trimble units are less than 7, 3.38, and 6.08 m, respectively. However, the maximum median accuracy value for the DeLorme unit is 12.48 m, above the 7 m threshold of what is expected when utilizing WAAS based on FAA publications. In FAA WAAS Performance Analysis Reports, WAAS accuracy is typically better than 7 m accuracy. Tests from the first quarter of 2008 indicate “the 95% horizontal and vertical accuracy at all evaluated sites are less than 2 m for both WAAS operational service levels” (FAA, 2008). It bears noting that system evaluations for WAAS
The primary objective of the current study was to evaluate the effects of WAAS on the positional accuracy of position fixes in consumer-grade units. Data were first evaluated to determine the presence of bias. No bias was found in horizontal positional accuracy using the Garmin units, but a slight bias was found for the Trimble units. Garmin units, on the other hand, provided biased estimates of heights that were consistently higher than the actual surveyed height. The DeLorme units showed bias in horizontal and vertical positional accuracy but the magnitude of the observed bias was quite small relative to the magnitude of positional error.

Statistically significant differences between the positional accuracy of WAAS and autonomous positioning were determined using a test of means. While the range of positional error appears to be lower for WAAS positioning compared to autonomous positioning, there is no statistically significant difference between the horizontal and the vertical positional accuracy of WAAS and autonomous positioning when using the Garmin or Trimble receivers. This supports the conclusion reached by other related studies which found no statistically significant difference among postprocessed differential, WAAS, and autonomous positioning using mapping-grade Trimble units (Bolstad et al., 2005). This study provides evidence that this conclusion also holds true when using recreational Garmin units. In testing the DeLorme receiver, however, the current study found a statistically significant improvement in the horizontal positional accuracy of WAAS positioning compared to autonomous positioning but no such difference was found for vertical positional accuracy.

Significant differences were observed in the autonomous accuracy of the three different receiver types. Garmin units were the most accurate (1.7 m average median error) followed by Trimble (3.0 m), and DeLorme (9.4 m). This conclusion supports the results of Wing et al. (2005), which reported a wide range of accuracy metrics among six different receiver types. Wing et al. (2005) determined positional accuracy on the basis of 25 position fixes recorded over approximately a minute and a half while the current study recorded 1800 position fixes over a 30-min time span.

The conclusions from the current study contribute empirical evidence regarding the positional accuracy of WAAS positioning compared to autonomous positioning in consumer-grade GPS receiver. Results show that the benefits of WAAS with respect to positional accuracy vary with the type of receiver, which has not previously been considered in the literature. Consumer-grade GPS units are increasingly being used for data collection in many different fields. The use of WAAS for differential correction is typically recommended by manufacturers and WAAS has become a standard feature on most current models. WAAS provides real-time differential correction that is both easily accessible and free to users of consumer-grade receivers. The current study has demonstrated that WAAS provides limited benefits in terms of positional accuracy on these types of receivers. Several of the other potential benefits of WAAS, in particular signal integrity monitoring for the commercial aviation community, are not available to users of consumer-grade receivers. As regional Satellite Based Augmentation Systems (SBAS) become more widely adopted (EGNOS in Europe, MSAS in Japan, GAGAN in India, and SNAS in China) the potential benefits and risks to users of consumer-grade GPS receivers warrant further investigation.

5. Conclusions

5.1. Summary of results and significance

The primary objective of the current study was to evaluate the effects of WAAS on the positional accuracy of position fixes in consumer-grade units. Data were first evaluated to determine the presence of bias. No bias was found in horizontal positional accuracy using the Garmin units, but a slight bias was found for the Trimble units. Garmin units, on the other hand, provided biased estimates of heights that were consistently higher than the actual surveyed height. The DeLorme units showed bias in horizontal and vertical positional accuracy but the magnitude of the observed bias was quite small relative to the magnitude of positional error.

Statistically significant differences between the positional accuracy of WAAS and autonomous positioning were determined using a test of means. While the range of positional error appears to be lower for WAAS positioning compared to autonomous positioning, there is no statistically significant difference between the horizontal and the vertical positional accuracy of WAAS and autonomous positioning when using the Garmin or Trimble receivers. This supports the conclusion reached by other related studies which found no statistically significant difference among postprocessed differential, WAAS, and autonomous positioning using mapping-grade Trimble units (Bolstad et al., 2005). This study provides evidence that this conclusion also holds true when using recreational Garmin units. In testing the DeLorme receiver, however, the current study found a statistically significant improvement in the horizontal positional accuracy of WAAS positioning compared to autonomous positioning but no such difference was found for vertical positional accuracy.

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The conclusions from the current study contribute empirical evidence regarding the positional accuracy of WAAS positioning compared to autonomous positioning in consumer-grade GPS receiver. Results show that the benefits of WAAS with respect to positional accuracy vary with the type of receiver, which has not previously been considered in the literature. Consumer-grade GPS units are increasingly being used for data collection in many different fields. The use of WAAS for differential correction is typically recommended by manufacturers and WAAS has become a standard feature on most current models. WAAS provides real-time differential correction that is both easily accessible and free to users of consumer-grade receivers. The current study has demonstrated that WAAS provides limited benefits in terms of positional accuracy on these types of receivers. Several of the other potential benefits of WAAS, in particular signal integrity monitoring for the commercial aviation community, are not available to users of consumer-grade receivers. As regional Satellite Based Augmentation Systems (SBAS) become more widely adopted (EGNOS in Europe, MSAS in Japan, GAGAN in India, and SNAS in China) the potential benefits and risks to users of consumer-grade GPS receivers warrant further investigation.

5.2. Limitations and recommendations

The current study has several limitations. First, only three different types of receivers were employed. The Garmin and Trimble units have the same chipset and showed that WAAS was not statistically different from autonomous GPS. It would be worthwhile to determine if the same conclusion is reached when testing with other types of units that also employ the same chipset. The DeLorme unit has a different chipset, suggesting that...
Fig. 7. Median and RMSE scatter plots. (a) Garmin–Horizontal Mean, (b) Garmin–Horizontal RMSE, (c) Trimble–Horizontal Mean, (d) Trimble–Horizontal RMSE, (e) DeLorme–Horizontal Mean, (f) DeLorme–Horizontal RMSE.

Fig. 8. Control point scatter plot example, 27-h time span—Garmin.
the results in terms of positional accuracy could be explained by the chipset, but further testing of other types of units using the same chipset would be necessary to confirm this. In general, more types of units could be tested, using the same chipset as the one already tested as well as other chipsets. Differences in engine processing and software algorithms used by each unit type could potentially explain the performance of WAAS in the tested units. While these factors are worthy of further study, design specifications are proprietary information of the individual manufacturing companies and are not published.

The current study could also be improved by collecting data throughout the WAAS coverage area. Of particular interest would be testing at more northern latitudes where the WAAS satellites are lower on the horizon. Also of interest would be testing near the edge of the WAAS coverage area. The current study could also be improved by determining the effect of distance from WAAS reference stations using a receiver that has shown a statistically significant difference between WAAS and autonomous positioning. More data could also be gathered over an extended time period to enable a detailed evaluation of diurnal patterns in positional accuracy. Lastly, the performance of WAAS could be evaluated when the GPS receiver is in motion, which was not included in the current study. It could be expected that positional accuracy in general will be worse in dynamic mode as opposed to stationary mode which is a relevant component for GPS in navigation.

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