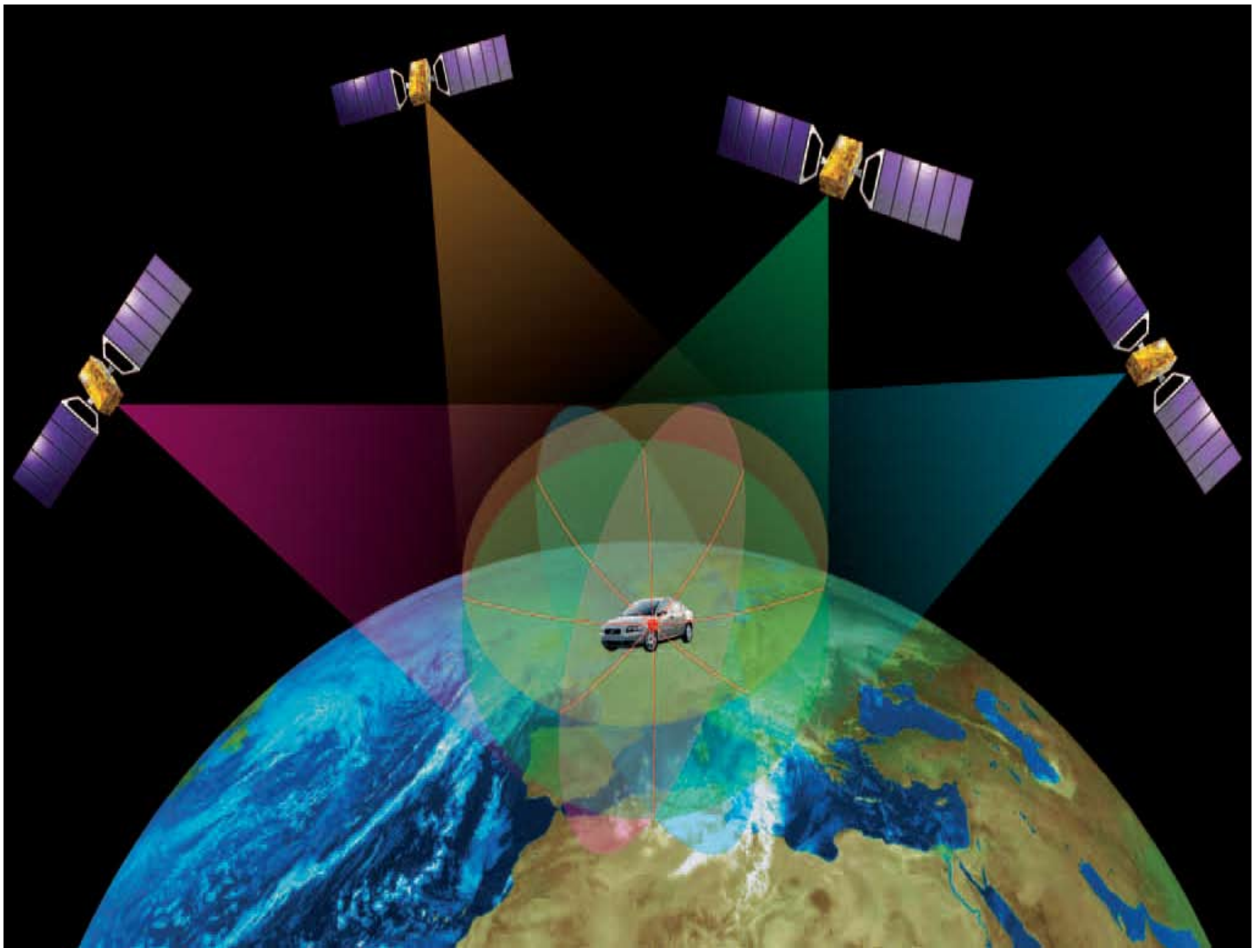
U.S. Department of Transportation

Federal Railroad Administration

Office of Research, Development and Technology
Washington, DC 20590

Positional Solution Comparative Analysis Technical Memorandum



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14. ABSTRACT (Maximum 200 words)

In support of the Rail-Crossing Violation Warning (RCVW) prototype funded by Federal Railroad Administration (FRA), this memorandum details the research and testing done to analyze a position solution with satellite-based correction against real-time kinematics. The conclusions and recommendations in this document should be taken into consideration for the RCVW prototype architecture.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0	1	2	3	4	5

Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

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Executive Summary

In support of the Rail-Crossing Violation Warning (RCVW) prototype funded by Federal Railroad Administration (FRA), this memorandum details the research and testing done to analyze a position solution with satellite-based correction against real-time kinematics. The conclusions and recommendations in this document should be taken into consideration for the RCVW prototype architecture.

1. Introduction

The US Department of Transportation (US DOT) is committed to the research and development of new technologies intended on making travel safer. Specifically, the Connected Vehicle (CV) initiative seeks to create applications and prototypes that rely on the exchange of safety-critical information from vehicle to vehicle (V2V) and between vehicle and infrastructure (V2I) using Dedicated Short-Range Communications (DSRC) radios. Beginning in 2015, the Federal Railroad Administration (FRA) and its subcontractors have been effective in producing a CV prototype called the Rail-Crossing Violation Warning (RCVW), which is designed to notify approaching drivers of an active rail crossing and warn them of a potential collision.

1.1 Background

The RCVW high-level architecture shown in Figure 1 includes some road-side based system (RBS) hardware interconnected to the grade crossing equipment at a highway-rail intersection (HRI) that receives and digitizes an HRI active signal, then broadcasts that signal over DSRC to the vehicle-based system (VBS) in an approaching vehicle.

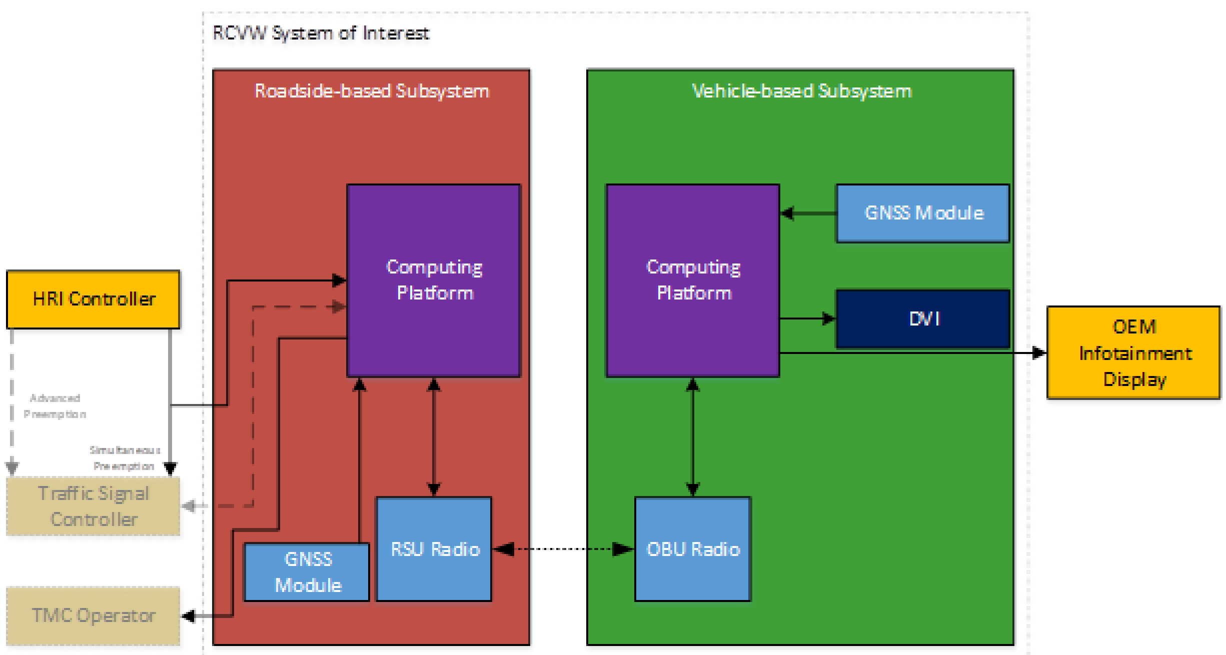

Figure 1: RCVW High-Level Architecture

1.2 GNSS Positioning

The two most ubiquitous GNSS solutions include the Global Positioning System (GPS) based in the US, and the Russian Global Navigation Satellite System (GLONASS). Both of the positioning solutions use a strictly configured constellation of satellites in orbit above the Earth in order to triangulate the location of the receiver that is listening to their signals. Such effectiveness depends on a number of factors, including perfectly synchronized clocks, but in practice a number of things degrade transmission performance and introduce clock skew. .

Therefore, typical commercial GPS receivers achieve closer to 4-5 meter accuracy (National Coordination Office for Space-Based Positioning, Navigation, and Timing (PNT), 2018). If the vehicle approaching speed is around 45 mph (20 mps), then the GNSS inaccuracies (E_P) alone may be responsible for warnings of up to 4 seconds early, which can be an unnecessary nuisance, or worse – 4 seconds late, which would be a major safety failure in the system. Instead the RCVW requirements insist that E_P must be within 1.5 m for 95% of the time. This study compares two readily available augmentation systems that attempt to correct the positional errors by sending localized corrections. The first attempts to do so using additional satellite transmissions, while the other shares the correction using other terrestrial communications means.

1.2.1 Satellite-Based Augmentation System (SBAS)

The SBAS system was developed for civil aviation use across wide areas through the use of satellites. The architecture is depicted in Figure 2 (European Space Agency, 2011).

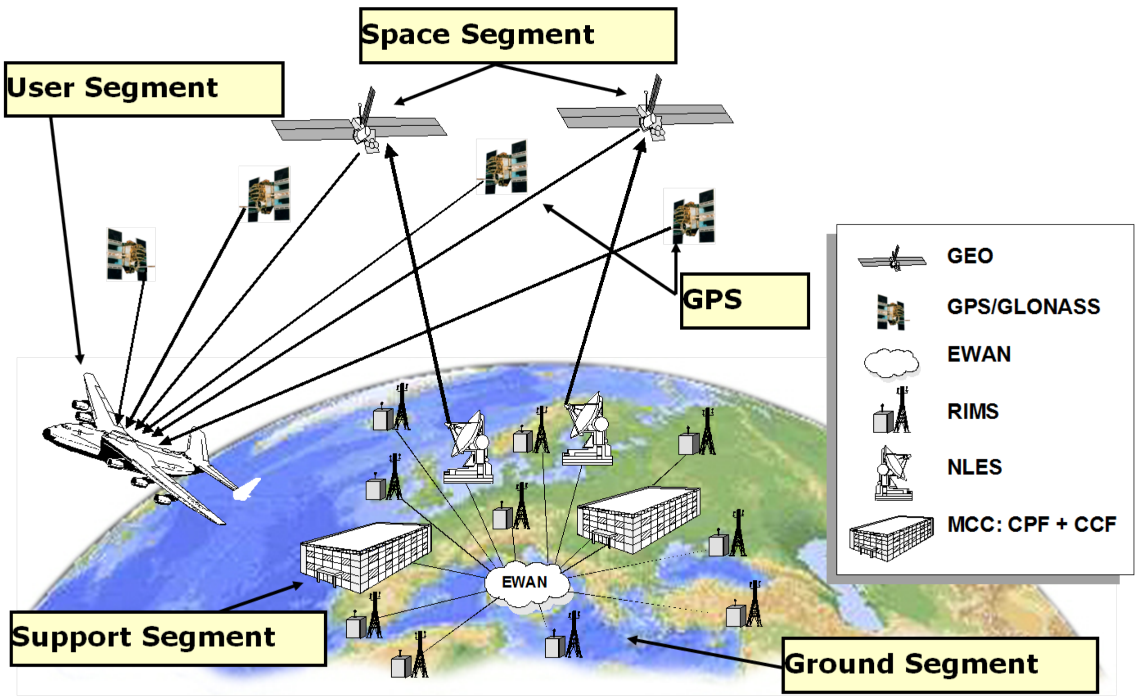

Figure 2: SBAS Architecture

The most common US based SBAS system is the Wide Area Augmentation System (WAAS) run by the Federal Aviation Administration (FAA). The primary benefit is the significantly large coverage area required for air travel, but some GNSS receivers use the WAAS correction because it is freely available, and the signals are similar to those emitted by the positioning satellites. The WAAS Performance Analysis report has detailed sub-meter horizontal positional accuracy for 95% of the time within the continental United States (NSTB/WAAS T&E Team, 2020).

1.2.2 Real-time Kinematics (RTK)

Differential GNSS (DGNSS) systems are those that utilize separate receivers in conjunction. The base station is one fixed to a known location, and the rover is the receiver whose position is changing while it moves. Assuming the two are in relatively close proximity, typically under 20 km, both the base station and the rover are essentially receiving the same GNSS signal, including the same errors and clock skew. However, because the base station is at a known point, it is easy to determine those errors and generate a set of corrections for each visible satellite that can then be used on the rover (European Space Agency, 2018).

RTK is a DGNSS system that looks for errors in the carrier wave signal, which is a high-frequency modulation and therefore can produce high precision position solutions once ambiguities in the wave are resolved. The algorithm relies on repeated application of fixed integers until the solution presents itself, which is known as *fixed* mode. An RTK receiver initially applies floating point numbers to obtain a solution, which is known as *float* mode. Although both are capable of providing sub-meter horizontal accuracies, the fixed mode is typically in the cm range while float mode is more in the dm, or tens of cm, range (European Space Agency, 2018).

1.3 Organization of the Report

This report first illustrates the setup of the tests used to gather the input data. Then, there is an overview of how the data was analyzed, before presenting conclusions and recommendations.

2. Test Design

2.1 Courses

There are two courses mapped out at the Transportation Research Center (TRC) that are used for RCVW testing. Using these specific courses for the GNSS accuracy testing provides added benefit when compared to driving around in random areas. First, some precise reference points have already been scoped out, namely the beginning and end of the RCVW approach lane, the stop bar, and the HRI hazard zone. These provide a good location for stationary testing. Additionally, as previously stated, the iterations may be repeated through simulation. Since both courses are already mapped out for use in the actual RCVW prototype field test, this simulation can be used to precisely measure performance of the application as a whole well in advance to running the fully instrumented vehicle through the same course.

2.1.1 Flat Course

This course is built within the TRC infield near the Smart Center. The approach lane 21, running from south to north, is around 1500 feet long. The vehicle was at test speed at or near the start of the lane and continued driving through the HRI location. The fixed points to use for stationary testing are the east edge of either stop bar line.

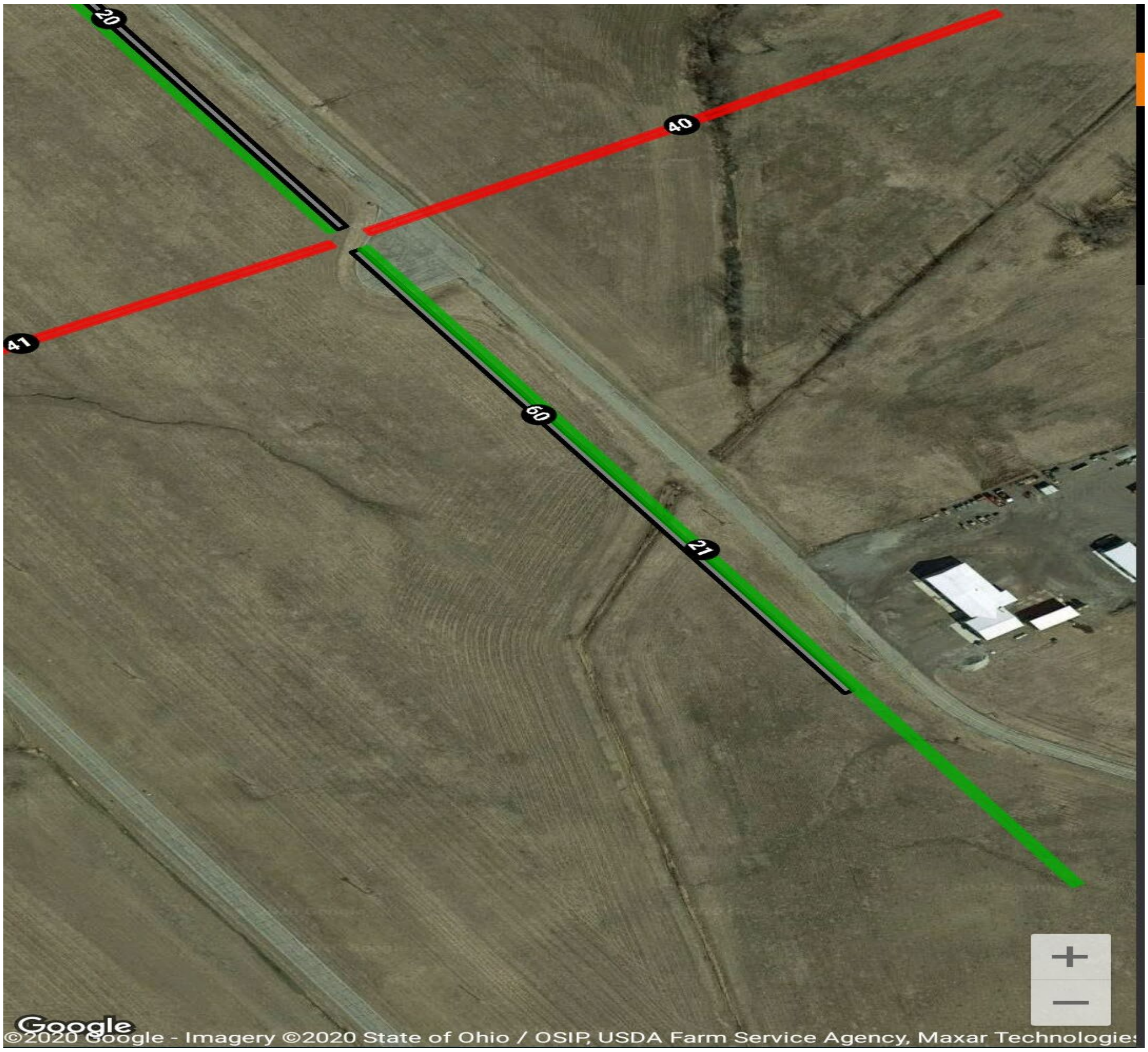

Figure 3: TRC Flat Course

2.1.2 Graded Course

The graded course is located off property from the main TRC facility. The approach lane 21 heads downhill from south to north is also intended to be around 1500 feet long. According to TRC, portions of this course are explicitly 10% grade, however since the lane extends beyond that portion, and thus upwards of 500 ft. are flatter that the expected 10%, the overall grade from top to bottom of lane 21 is 7%. No specific survey point was used for stationary testing, so only the accuracy relative to the ground truth is measurable.

Figure 4: TRC Graded Course

2.2 Equipment

2.2.1 Vehicle

TRC supplied a 2018 Honda Insight for testing in these two days. Some consideration was given to whether or not a Volvo heavy truck would be used as well. However, in order to maintain consistency across the entire suite of testing, the Honda Insight was exclusively used for the official iteration testing.

Figure 5: TRC Test Vehicle

2.2.2 GNSS Devices

The SBAS and the RTK GNSS systems in comparison are both manufactured by the Swiss semiconductor company uBlox. This is primarily due to existing relationships with the company and prior expertise with the hardware. One benefit to the uBlox receivers is the performance level achievable within a relatively low-cost device. Data collection for these devices were done using a laptop with the uBlox uCenter software. The software recorded the entire set of iterations together, but they were split up into separate KML files for later replay.

The uBlox units were placed into the trunk of the car, along with a single laptop running uCenter driving each via a USB port. The laptop charger was powered by a 300 Watt DC to AC inverter inside the vehicle running off of the cigarette lighter adapter.

Figure 6: uCenter Setup

uBlox NEO-M8U

The target platform used for the RCVW prototype is the uBlox M8U with SBAS augmentation and untethered Dead Reckoning (DR). The EVK-M8U module was bolted to a metal plate to maintain stability for the embedded DR sensors. This unit professes a 50% Circular Error Probable (CEP) horizontal accuracy of 2.5 m using the combined GPS and GLONASS satellites. However, that improves to 1.5 m when augmented with SBAS (uBlox.com, n.d.). Although not documented clearly in the uBlox data sheets, the company's engineers suggest that adding antenna to IMU "level arm" measurements can optimize performance. This was not known at the time of testing, however, thus is not taken into account.

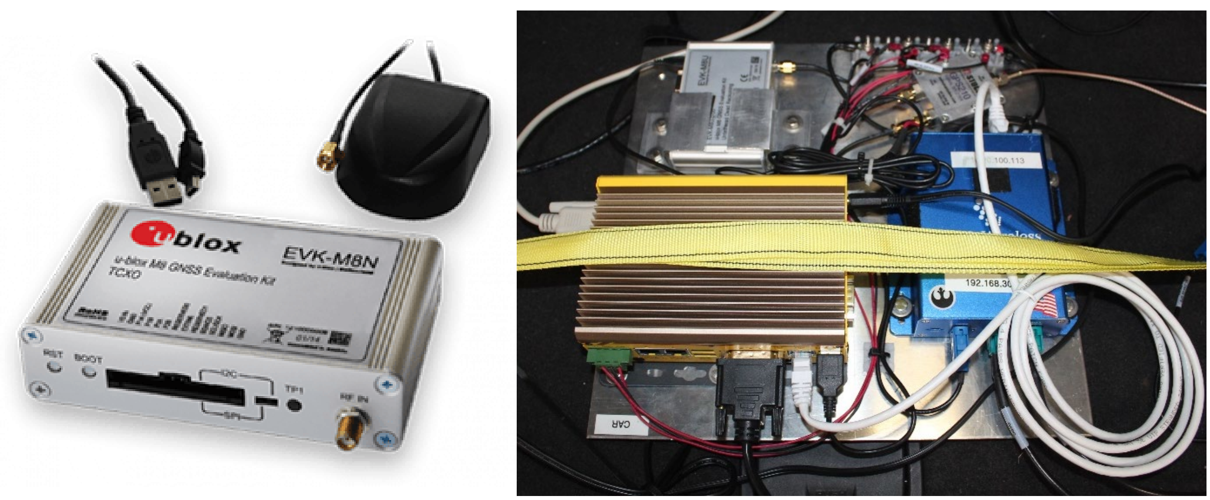

Figure 7: uBlox EVK-M8U Standalone and On Plate

uBlox ZED-F9P

The ZED-F9P module is a low-cost RTK solution that can function either as a rover or a base station. This module was contained within the C099-F9P breakout board. Horizontal accuracy is stated to be 1.5 m for 50% CEP without RTK and 0.01 m with, although it does not state if that is fixed mode only (ublox.com, n.d.).

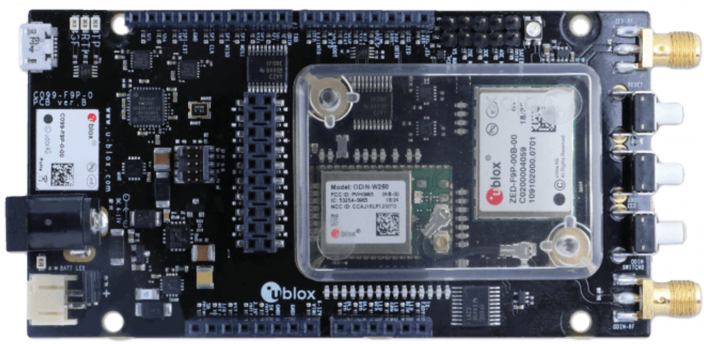

Figure 8: uBlox C099-F9P Breakout Board

OxTS RT3000

The OxTS RT3000 v3 is a high performance, professional grade RTK system that was used for ground truth measurements. It has a stated accuracy of 1 cm and maximum data rate of 250 Hz. The ground truth system is intentionally set for a higher position, velocity, and time (PVT) update rate that the uBlox units (oxts.com, n.d.).

Figure 9: OxTS RT3000 v3

2.3 Antenna

2.3.1 GNSS Antenna

uBlox ANN-MB-01

The default antenna for the ZED-F9P is listed for high-precision use and supports both the L1 and L2 GPS and GLONASS frequency bands, which is a requirement for proper RTK use. The L1 gain is listed as 3.5 dBic (uBlox.com, n.d.). For consistency, this same antenna was used in each of the positions.

Figure 10: uBlox ANN-MB-01 Antenna

2.3.2 Positioning

Half of the iterations were run in the nominal rooftop antenna position, representative of the best signal strength and quality. The other half were executed using other antenna positions, including center of the hood, which is about a meter lower than the roof, and inside the car on the driver-side backseat, representing a very low signal case. See Figure 11 for approximate locations. The antennae were fixed with a metal ground plane, which for the hood and backseat position were taped to the vehicle, and pre-wired at each position prior to starting testing (see Figure 12 and Figure 13 below). Therefore, only the disconnect of one wire and reconnect to the next was needed to reconfigure while testing was in progress. In addition, the weather conditions for the tests were less than ideal for good GPS reception due to cloudy, overcast skies and frequent rain.

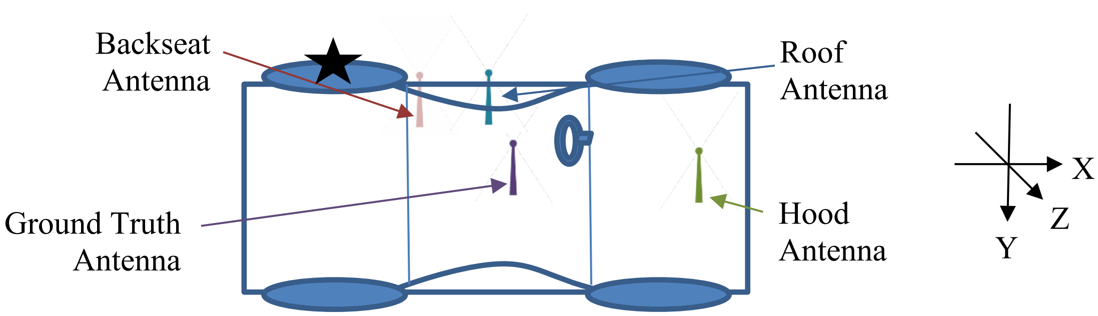

Figure 11: Antenna Positions

Since each antenna is in a different location, the position readings must be translated into a common point of reference on the vehicle, which is on the driver-side rear wheel as depicted in Figure 11. Those exact offsets are given below in Table 1.

Position	X Offset (in)	Y Offset (in)	Z Offset (in)
RT	41	36	-31
Roof	38	20	-55
Hood	118	35.5	-35
Backseat	19.5	21.5	-20.5

Table 1: Antenna Offsets

Figure 12: Rooftop Antenna Position and RT Antenna

Figure 13: Hood and Backset Antenna Position

2.4 Test Iterations

The design was to run 20 iterations of each course at each of the 5 test speeds – 15, 25, 35, 45 and 50 mph – for a total of 100 iterations per course. Half of the iterations at each speed utilized the rooftop antenna position, while the remaining iterations were split across the hood and the backseat positions. Table 2 summarizes the number of flat course iterations.

Position	15	25	35	45	50
Roof	10	10	10	10	10
Hood	5	5	5	5	5
Backseat	5	5	5	5	5

Table 2: Test Iterations on Flat Course

However, due to the wet pavement on the day of testing, as well as the overall precarious conditions involving the run up to and the decent down the 10% grade, it was deemed to risky to traverse the graded course at either 45 or 50 mph. Therefore, those tests were omitted. The graded course test iteration summary is in Table 3.

Position	15	25	35	45	50
Roof	10	10	10	DNA	DNA
Hood	5	5	5	DNA	DNA
Backseat	5	5	5	DNA	DNA

Table 3: Test Iterations on Graded Course

For schedule practicality, the test iterations for each antenna position was performed in entirety across each speed, in other words across the rows, prior to switching positions.

In addition to the moving iterations, some 20 minutes of stationary testing was attempted on each course. Those times were broken up into chunks of time at each antenna position. These stationary tests were done at the end of the moving iterations on each course.

Position	0 (min)
Backseat	5
Hood	5
Roof	10

Table 4: Stationary Test Times on Each Course

3. Data Analysis

The PVT data from both uBlox devices and from the ground truth device were dumped to a CSV file by iteration. Each iteration for the specific course and speed was combined together into a single spreadsheet. The most precise measurement in the data is the timestamp of the value because every device reported the time at which the measurement was taken. For the RT3000, this time was "GPS time", while for the uBlox devices it was UTC time. Since GPS time does not count leap seconds, the RT timestamp was 18 seconds ahead of the UTC time (GPS Clock, 2020), so the matching of the ground truth timestamp to the uBlox data required subtracting 18 seconds. This offset was confirmed visually in the data by seeing first movement from a stopped position.

Only a select set of points that happen between the lane entry and the stop bar, which is a distance around 1500 feet or 457 m, are analyzed. This was determined by comparing the measured lat/long on the ground truth to the fixed position of the approach lane entry point on the test map. Only after the position is known to be "inside" those points, thus inside the approach lane, would that record be considered for analysis. Likewise, any point that goes beyond the stop bar is excluded. Although the vehicle was expected to be at test speed during this section, it cannot be guaranteed due to the lack of cruise control function at the lower speed of 15 mph and for the inability for the accelerator to remain fixed on the graded course.

3.1 Position

The most critical aspect of this study is to determine the accuracy of the vehicle position. All the devices return a latitude and longitude reading. The RCVW system itself calculates 2D distances geodesic vectors on a spherical Earth, also known as great-circle distance, with a mean earth radius of 6371 km. Therefore, this mathematics used for these calculations were broken down into its portions for spreadsheet use. The positional error results were grouped together in varying combinations of speed and antenna position, then sorted highest to lowest and plotted into an Excel radar chart, to visualize how frequently the results stray outside the 1.5 m tolerance. Because the data is pre-sorted, each positional accuracy chart represents the 0% to 100% CEP error value reading counterclockwise. Additionally, the median and 95th percentile value was calculated to specifically obtain a value for the 50% and 95% CEP.

3.1.1 Horizontal Error

The first position vector calculated is for the latitude and longitude produced by the RT3000, which would be the precise location of the antenna. Therefore, using the offsets from Table 1, this measured location is first moved backwards in the X direction, then left in the Y direction to obtain the location of the vehicle at the driver rear-wheel reference point. The same process is applied to the associated latitude and longitude value from each uBlox device. The calculated distance in meters between those two locations is the horizontal error.

3.1.2 Vertical Error

The variation in the altitude values are much simpler to calculate. The vertical error is the simple difference between the altitude from the ground truth measurement, minus the RT antenna offset in the Z direction, and the altitude measured at the uBlox antenna, minus its Z offset.

3.2 Velocity

The speed of the vehicle in RCVW is to be measured directly from the vehicle telemetry data obtained through the controller-area network (CAN). However, since the CAN messages are typically proprietary, it is feasible that the RCVW application may have to function without available speed data. The alternative, therefore, is to use velocity as calculated by the positioning solution, which would at least be consistent if the assumed positional and timing errors are consistent between locations. Therefore, this study considers how accurate the augmented GPS receiver is at determining velocity. The simple difference between the velocity recorded by the ground truth unit with the speed determined by the uBlox is considered the measured velocity error, in mps, which again is sorted highest to lowest and graphed in the radar chart for a 0% to 100% CEP visualization.

As a secondary comparison, the velocity measurement from the RT may itself be inaccurate, so there should also be a comparison to the (relatively) few runs at which cruise control was engaged to the proper value. The difference between that expected speed and the measured is considered an overall estimated velocity error, in mps. This value, however, is converted to a positional error by calculating the sight distance required for that change in speed. The distance error caused by the inaccuracy of this velocity must be less than 1.5 m for 95% of the time. For example, if the speed of the run is 50 mph (22.352 mps) case is measured by the GNSS system as 50.37 mph (22.517 mps), then the estimated velocity error is 0.37 mph (0.165 mps), which under the typical parameters, such as 2.5 s reaction time and 3.4 m/s^2 deceleration, results in a 0.43 m estimated velocity-incurred positional error. This data is plotted on a radar chart to visualize the 0 to 100% CEP of the velocity error, along with the calculation of specific 50% and 95% values.

3.3 Time

The positional accuracy checks are set up to only consider the dimensional space difference between two points. However, it is conceivable that even identical points are inaccurate, namely because they are measured at two different times. If the time lag is greater than the time it takes to move the 1.5 m tolerance, then it should be considered in violation of the requirement. For the worst case of 50 mph (22.352 m/s), that should be 1.5 m / 22.352 mps = 67 ms. Again, the ground-truth system is assumed to be most accurate clock.

In order to determine if there are time inaccuracies, one must first know what the actual location should have been at the given time. It is possible to do this by re-aligning the data by position. However, doing so would require two separate analysis sheets. Therefore, the time errors are estimated using the known distance to the fixed stop bar. The accepted distance from the driver-side rear wheel to the stop bar is given by the latitude and longitude readings of the RT unit, projected to the wheel using the antenna offsets. In a perfect world, that distance would be exactly the same as the measured position from the uBlox antenna, projected to the same spot, but minus the already known horizontal error. In other words, if both distances were from the same spot, then the only error incurred would be the error of the GNSS device. Practically, these values have discrepancies, albeit sometimes very small. For this study, these are presumed to come from a timing error, which also must be within the 1.5 m tolerance 95% of the time. Again, the positional error incurred due to incorrect timing is sorted highest to lowest and plotted on the radar chart, along with the median and 95th percentile calculations. Further, this error divided be the speed at that point in mps times 1000 is a decent estimate for the clock error in ms, which is also plotted for 0% to 100% CEP.

4. Results

The results drawn from the data analysis were sufficiently varied by the course they were executed, that it is worth separating each in the report. The graphs depict the performance (accuracy measures) of the units against the requirement of 1.5 m tolerance 95% of the time, as seen in the plot of the data points within the 1.5 m circle. Additionally, the same graph can denote the reliability of this performance across the entirety of the tests, shown as a near perfect circle. Whereas the accuracy is a key component of the overall performance, it is just as important for the application to trust that this level of performance is expected at any time during the use of the unit, especially under the variable conditions of a real deployment.

4.1 Positional Accuracy

Whereas much positional accuracy testing, particularly for horizontal accuracy, is done in the industry with stationary testing, this study is more focused on the specific RCVW application, which requires a moving vehicle. Therefore, the *nominal* case for comparison is considered only when moving. Likewise, only the two outdoor antenna positions are included for the nominal case, whereas the backseat position is used mainly to describe the units' behavior in the worst-case signal strength. It is not expected that RCVW function normally in such conditions, but from this data an algorithm may be constructed to detect poor signal conditions in which the system may be automatically disabled instead of producing suspect results.

The primary focus of this study was for horizontal accuracy, namely because the grade is calculated from the data points in the static map, which are assumed to be well-surveyed. Therefore, the vertical accuracy analysis was mostly academic, so only the graded course stationary measurements were considered.

4.1.1 uBlox NEO-M8U

Flat Course

According to the logs, SBAS corrections were applied the entirety of the flat course nominal runs, i.e. the hood and roof positions, at every speed. The horizontal accuracy of the unit under these conditions is excellent, with a median (50%) measure of 0.52 m, and a 95% measure of 1.46 m, which satisfies the requirement. Figure 14 shows that nearly 96% of the time the requirement is met, but the accuracy values are more scattered in that remaining 4%.

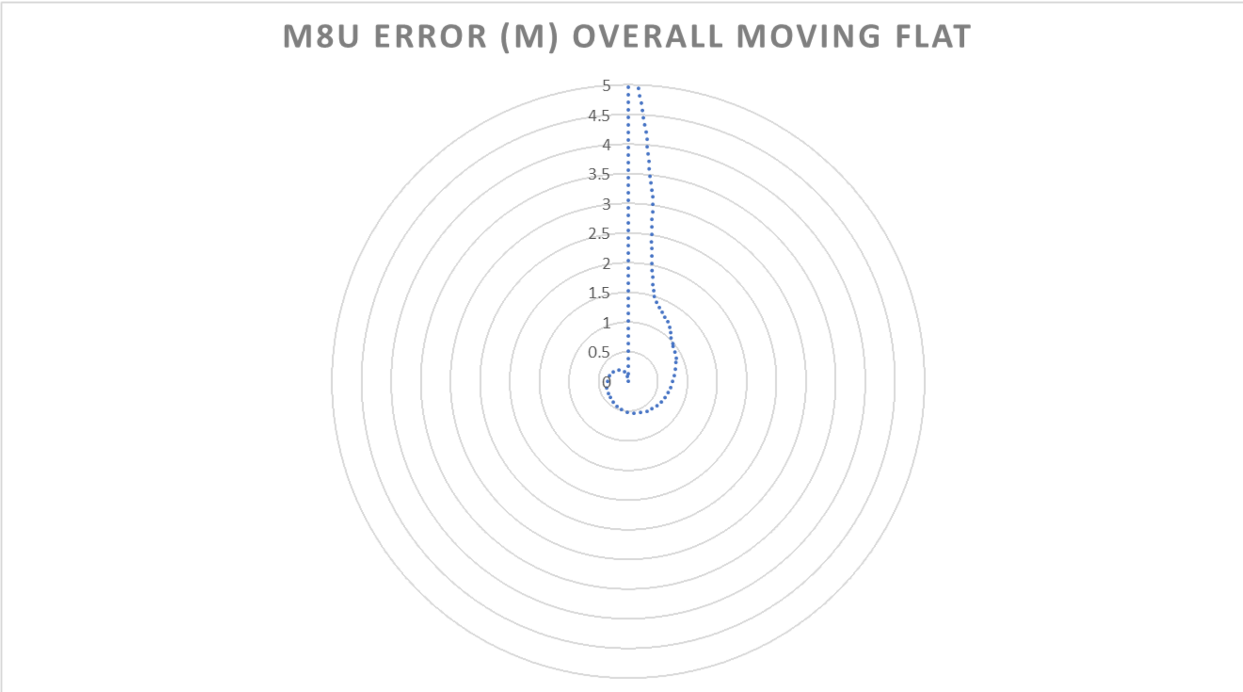

Figure 14: M8U Nominal Horizontal Accuracy on the Flat Course

Similarly, the stationary tests on the hood and roof positions performed sub-meter at around 0.54 m for the median, and 1.66 m for 95%. This is under the required amount, although not too significantly, because there is only a 6.7% violation of that requirement. Again, there is some instability in the remaining 3.3%, although not as dramatic as the moving results. Both the moving and stationary results seem to confirm the uBlox documented accuracy claim of around 1.5 m CEP (50%) with SBAS. In fact, it seems much more like 95%.

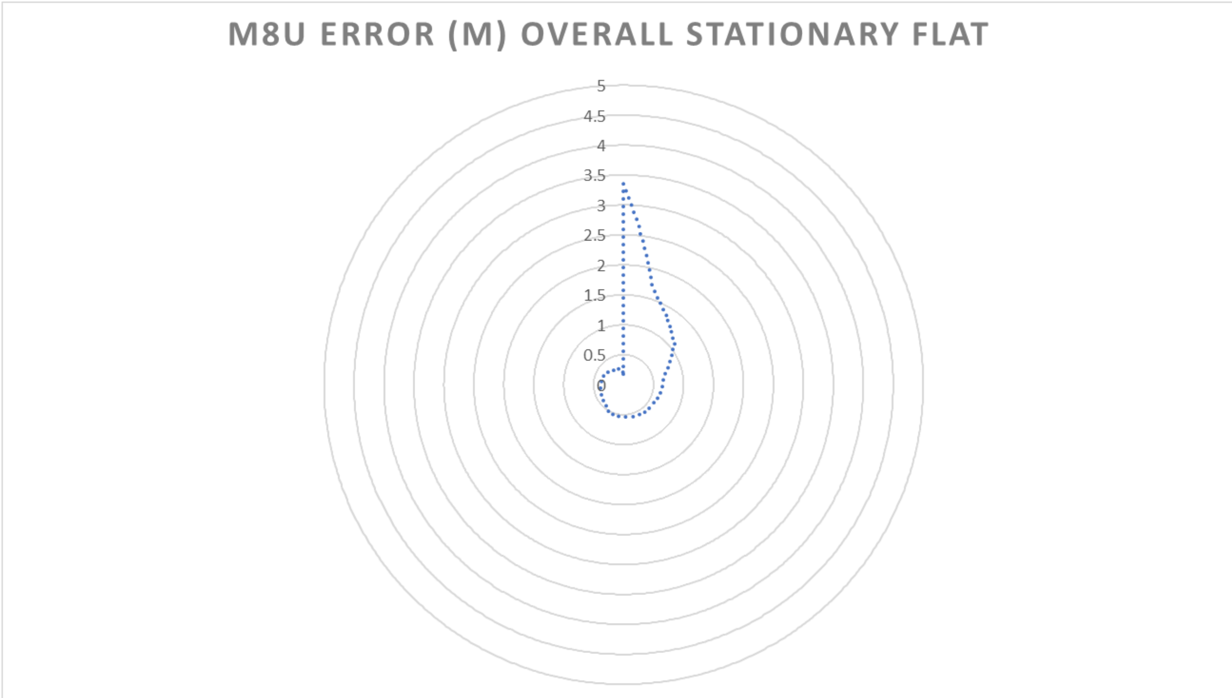

Figure 15: M8U Stationary Horizontal Accuracy for Flat Course

Unsurprisingly, the rooftop antenna position provided the most accurate results, with a 1.35 m 95th percentile, followed by the hood position (2.13 m), whereas the M8U performance clearly breaks down under the backseat position (39.33 m), as seen below in Figure 16, Figure 17 and Figure 18.

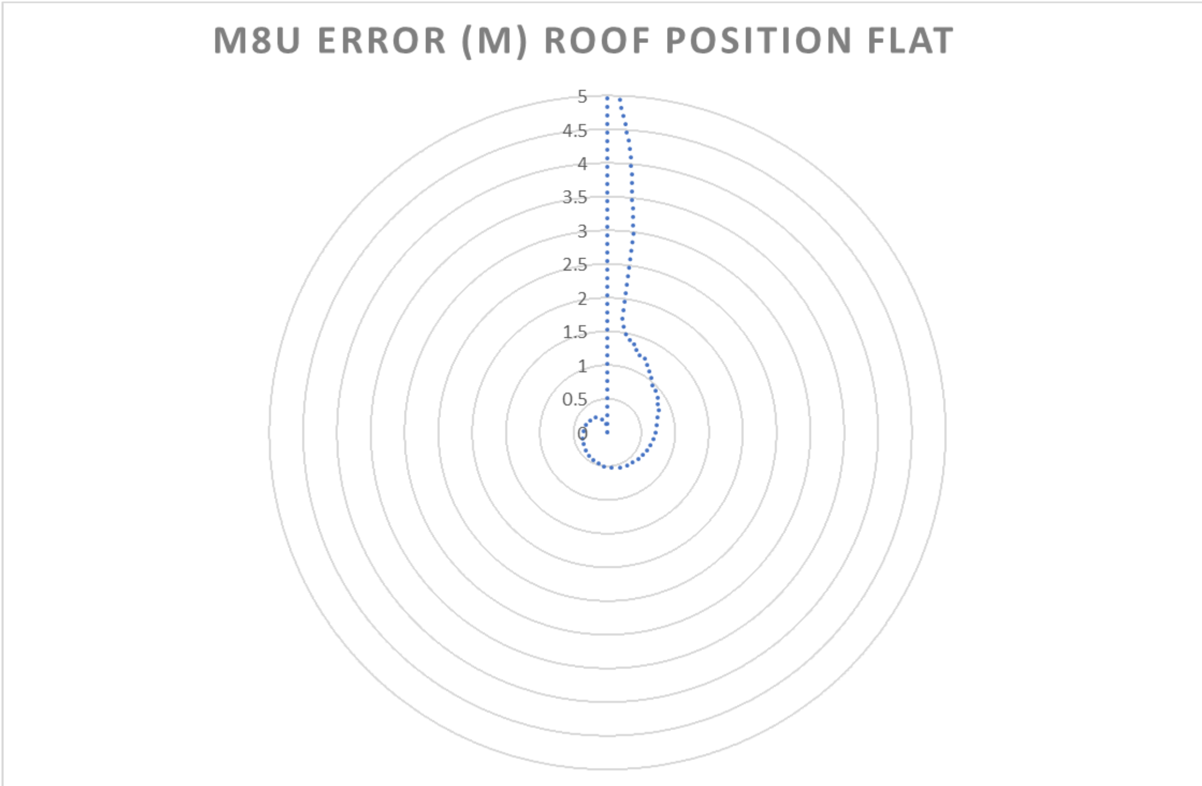

Figure 16: M8U Roof Position Horizontal Accuracy for Flat Course

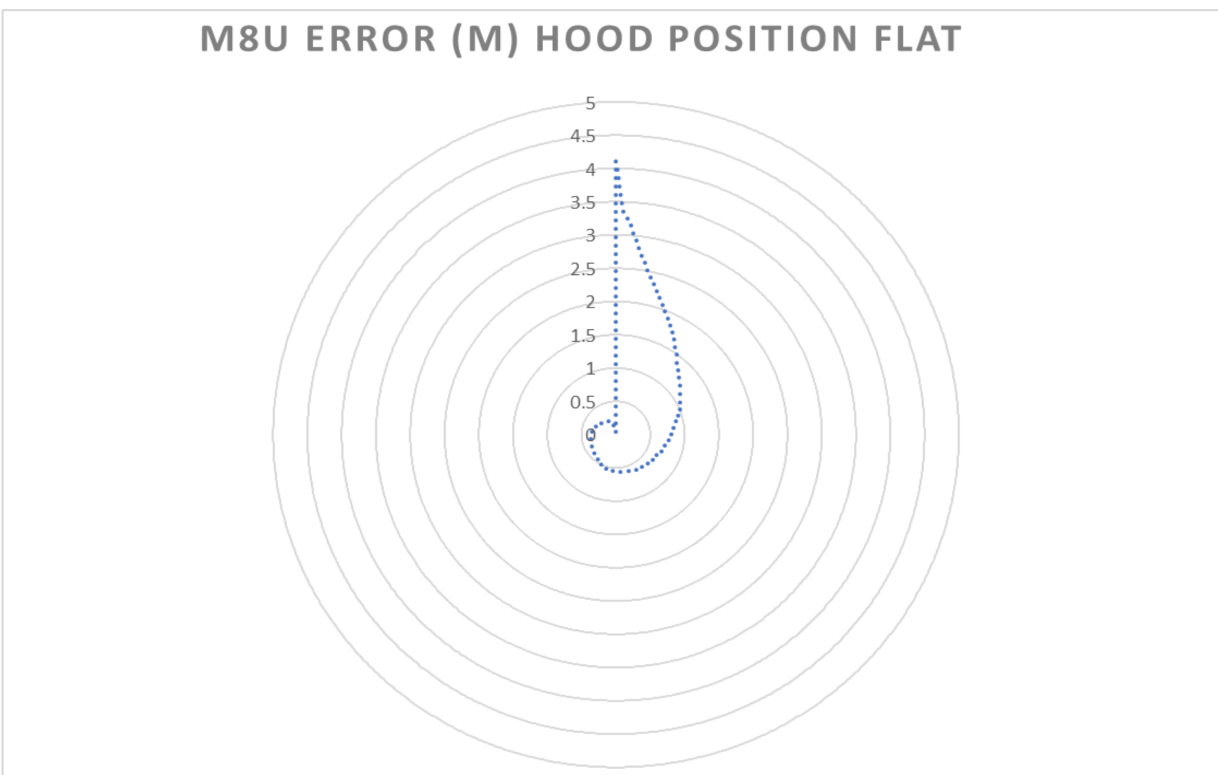

Figure 17: M8U Hood Position Horizontal Accuracy for Flat Course

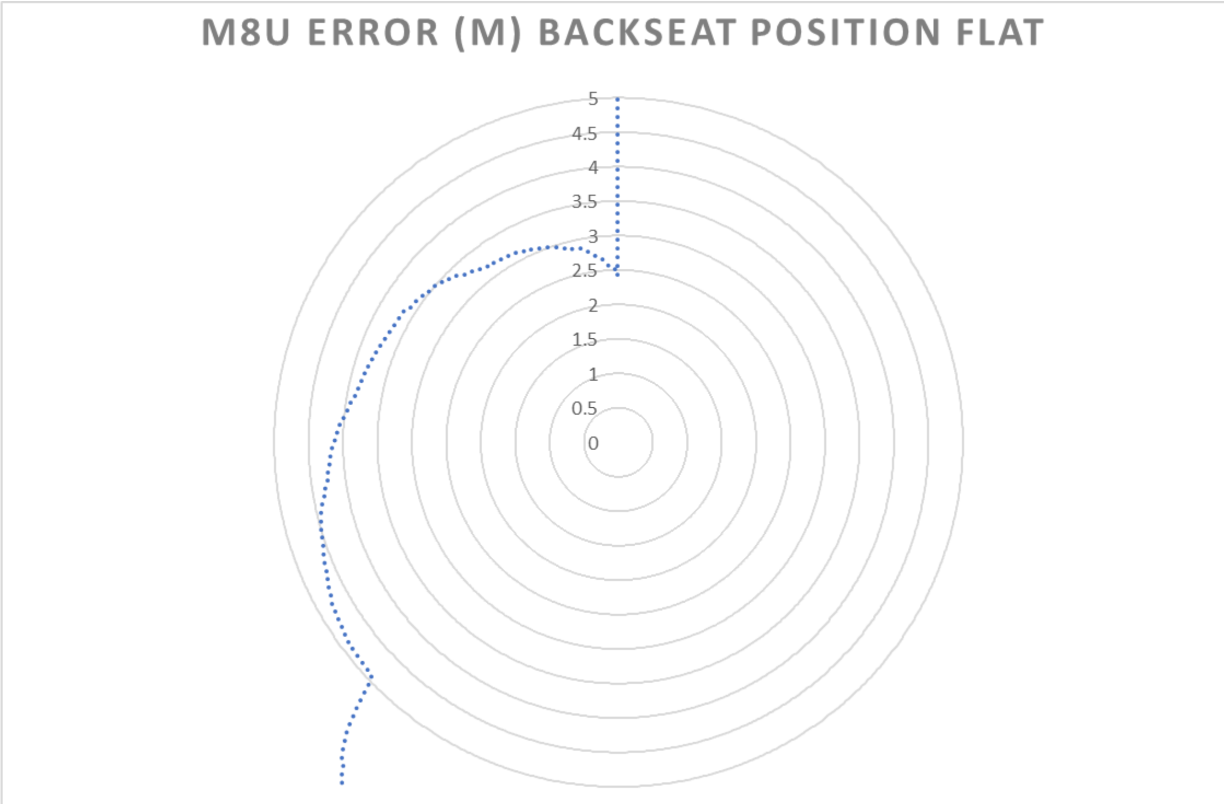

Figure 18: M8U Backseat Position Horizontal Accuracy for Flat Course

Graded Course

Overall, the graded course proves a difficult challenge for the SBAS corrective GNSS unit. Whereas over 99% of the time, SBAS was available in the rooftop and hood position, there is little to no corrections available for the backseat configuration. Even still, the nominal performance on the graded course is a very large drop off from the very strong accuracy seen in the flat course. With over 78% of the time failing to meet the 1.5 m tolerance, the median (50%) CEP is 1.81 m while the 95% CEP is 2.76 m. As seen in Figure 19, there is few sub-meter measurements, followed by a very large degrading of performance after about the 50% point. While still technically close to the uBlox specification of 1.5 m 50% CEP, this accuracy clearly falls short of the required specification.

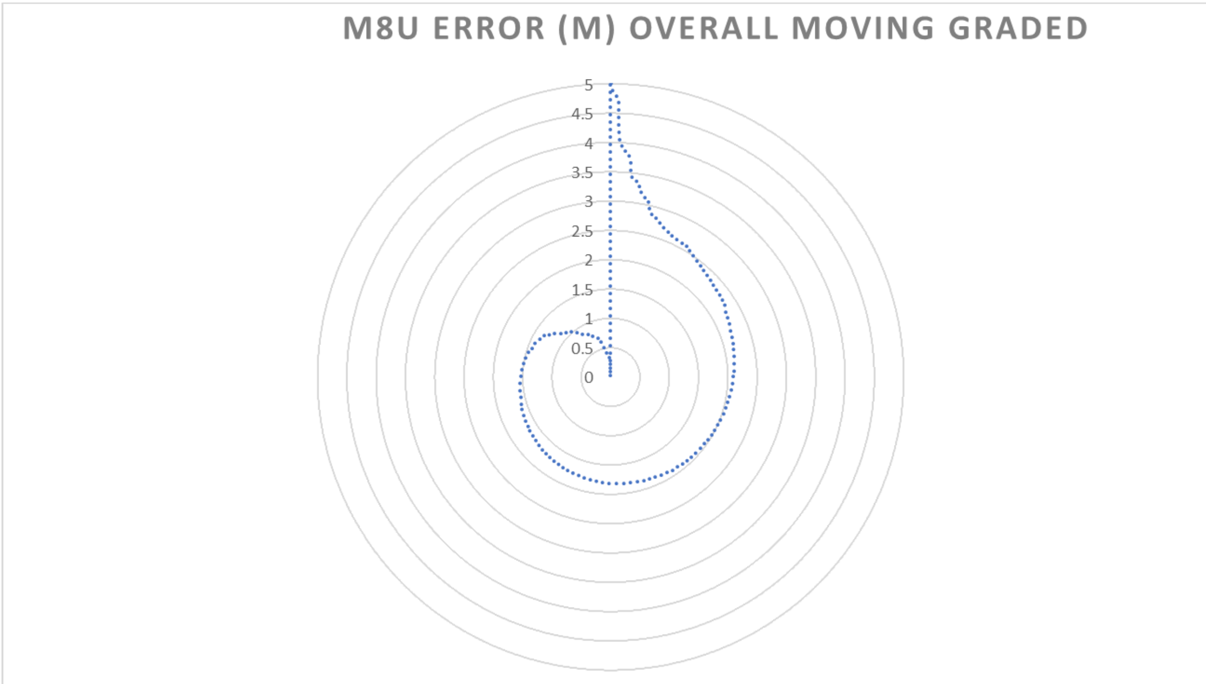

Figure 19: M8U Nominal Horizontal Accuracy on Graded Course

The stationary performance on the graded course never comes close to meeting the specification 1.5 m with a 50% CEP of 5.73 m and 95% CEP of 7.28 m. The jump in accuracy at about the 75% mark represents the transition from the rooftop antenna position to the hood. It would seem that the 20 inch drop in altitude at the bottom of the graded course constitutes a major source of error, possibly from more significant multipath problems.

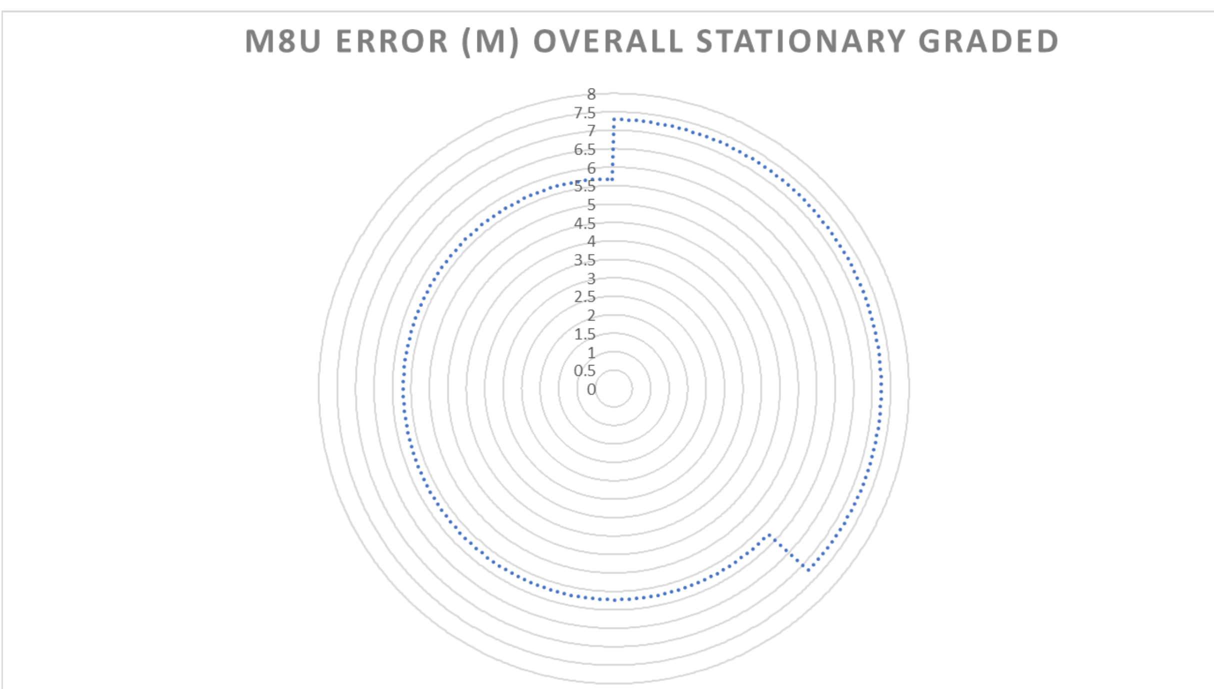

Figure 20: M8U Stationary Horizontal Accuracy for Graded Course

The poor performance of the stationary tests on the graded course impacts the graph of the horizontal accuracy based on the antenna position, making it difficult to draw a reasonable conclusion. However, it seems from the nominal case that much of the time the accuracy is still under the required 1.5 m.

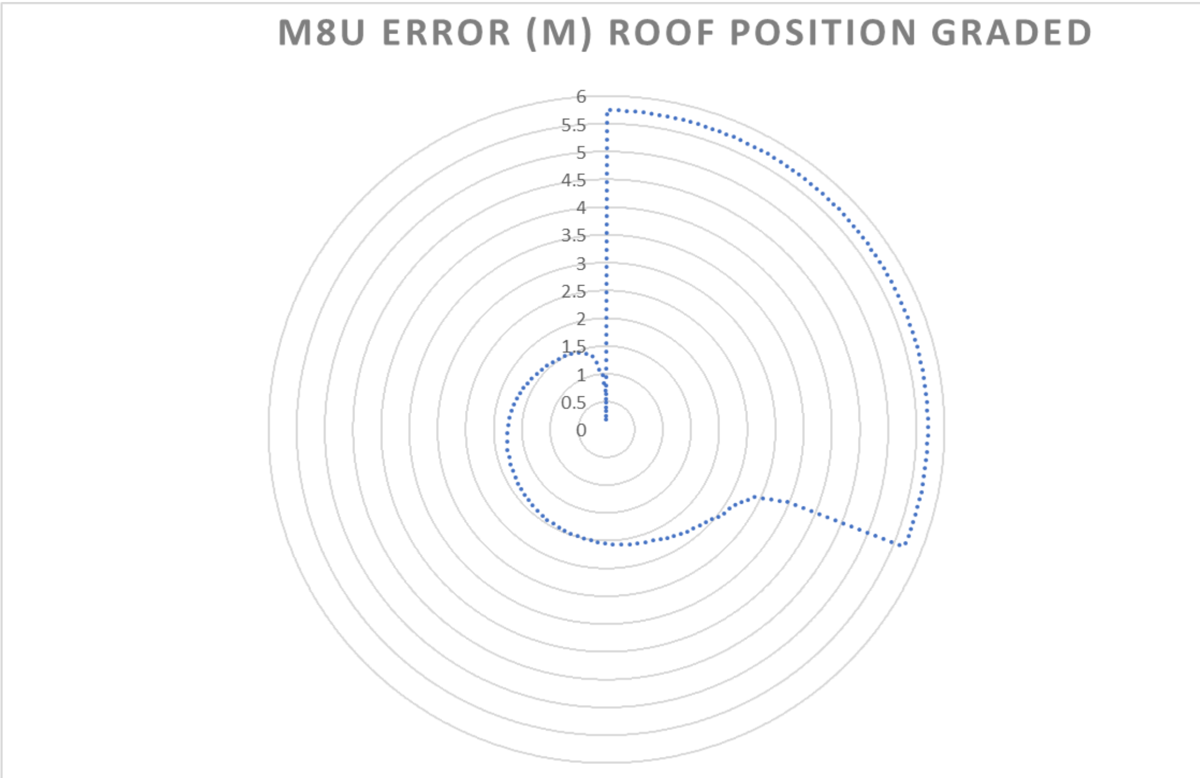

Figure 21: M8U Roof Position Horizontal Accuracy for Graded Course

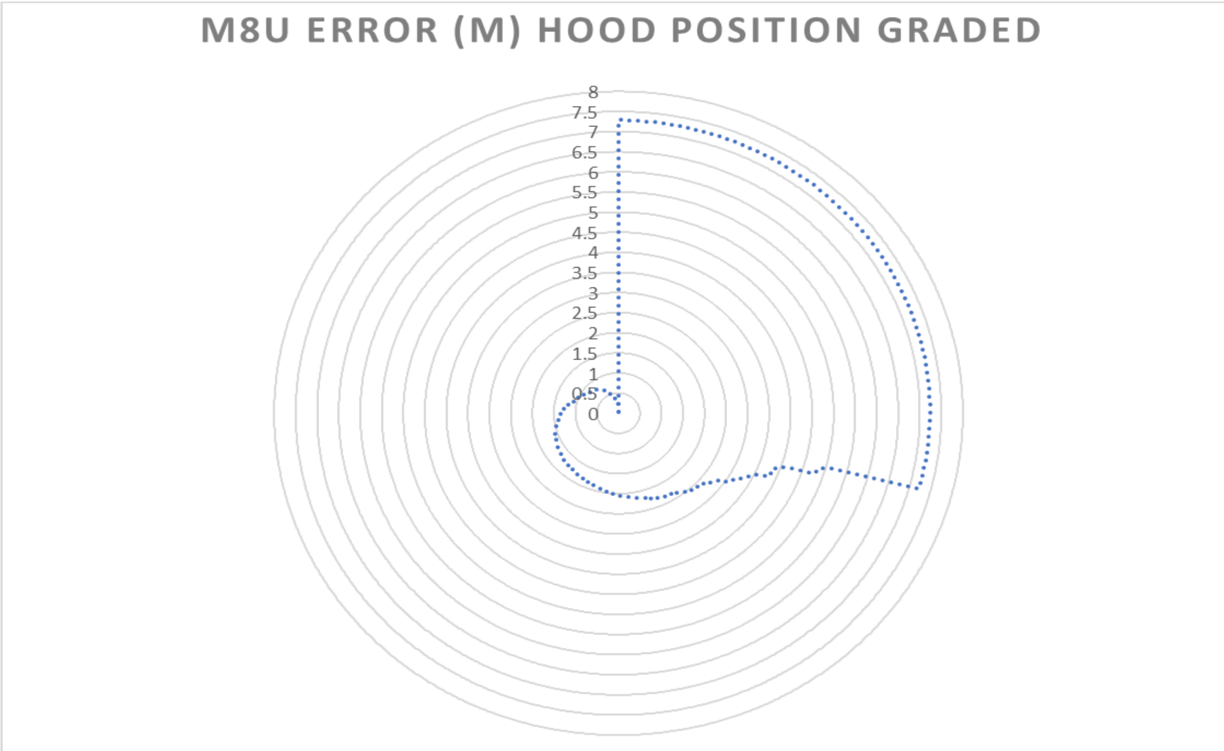

Figure 22: M8U Hood Horizontal Accuracy for Graded Course

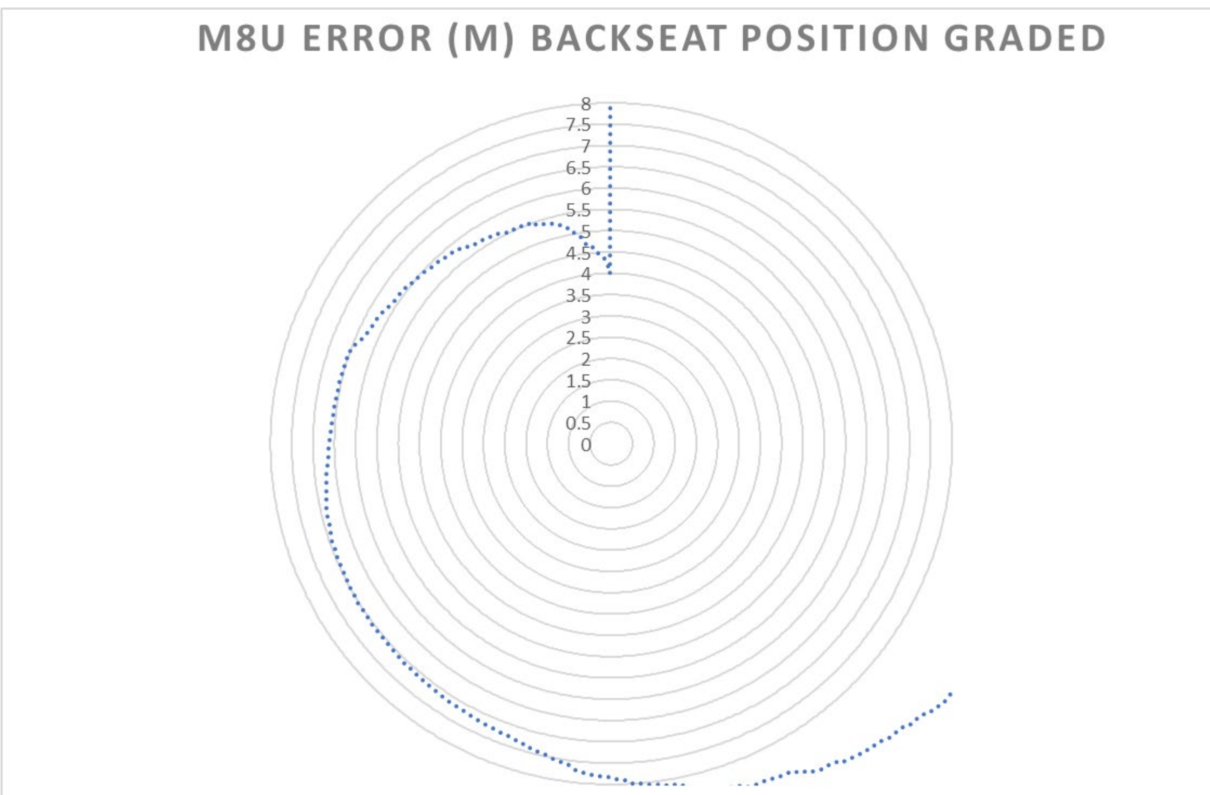

Figure 23: M8U Backseat Position Horizontal Accuracy for Graded Course

The stationary testing for vertical accuracy shows a median error of 2.74 m and a 95% CEP of 2.79 m, putting the M8U well outside the boundaries of the requirements. It is important to recall that the graded course stationary tests overall performed poorly for both devices.

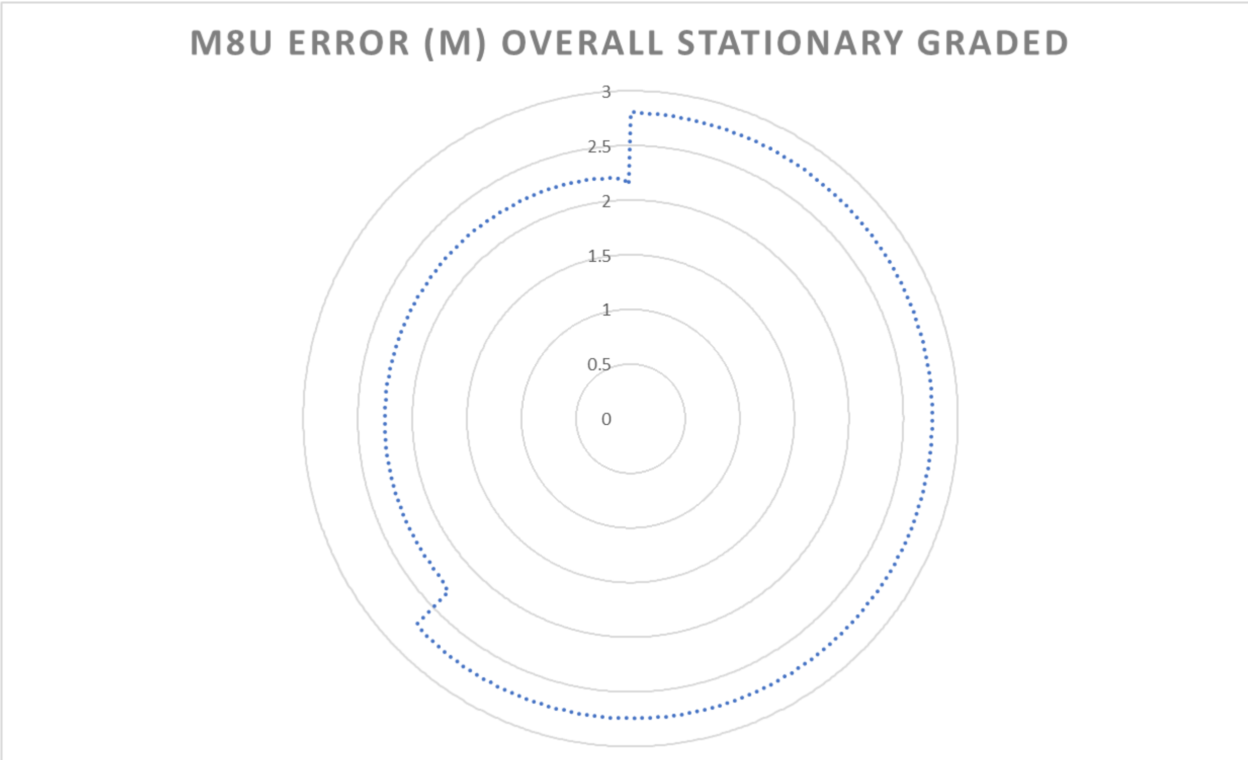

Figure 24: M8U Stationary Vertical Accuracy for Graded Course

4.1.2 uBlox ZED-F9P

Flat Course

The RTK corrections were available for 100% of the runs during the test period on each course. There is no clear indication from the bulk data dump whether or not a fixed solution was provided during that time, although visual inspection seemed to confirm this to be the nominal case, with only the backseat antenna position stuck in floating mode. Overall, the RTK solution meets the RCVW requirements with 0.99 m 50% CEP and is clearly a reliable solution with the 95% accuracy measure of 1.01 m. This can be seen in Figure 25.

One key observation in this analysis is that the RTK is not the sub-meter accuracy as low as 1 cm 50% CEP as detailed within the specification. The tech team believes the likely reason for the 1 m offset is a difference in the perceived location between the TRC base station, used for the ground truth, and the more remote location of the virtual reference station (VRS), used for the RTK unit in the flat course. If the base station is measured to be at a different location according to the other, then there will be a permanent offset. This is likely the case, if using the VRS to measure the location of the TRC base station you would find a persistent offset of around 1 m.

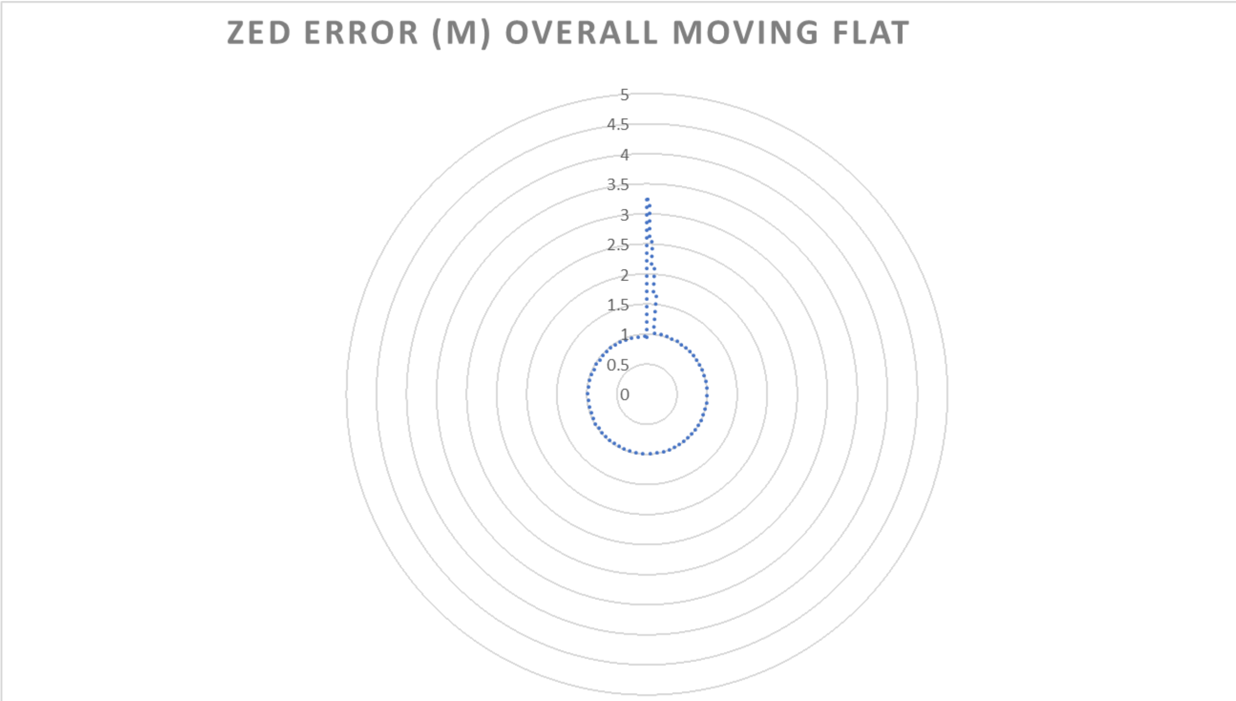

Figure 25: ZED-F9P Nominal Horizontal Accuracy for Flat Course

Likewise, the same performance and stability is seen in the stationary testing on the flat course, with a median of 1.00 m and 95th percentile of 1.01 m.

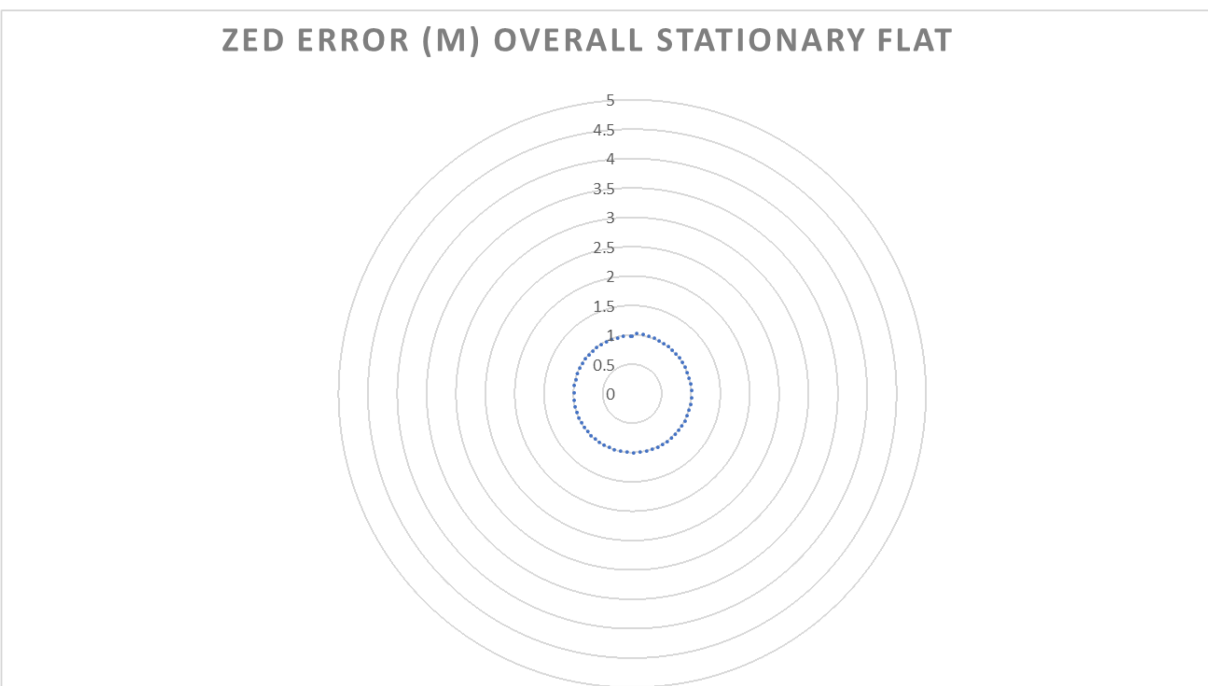

Figure 26: ZED-F9P Stationary Horiztonal Accuracy for Flat Course

Both the roof and hood positions easily meet the requirements with around 1.02 m for 95% CEP. The backseat antenna position does not, however, with only 2.54 m for 95%, although the median (50%) is 1.29 m, with over 65% of the time under the 1.5 m. There is some small instability for the remaining percentage, but it is clearly not the total breakdown seen in the M8U.

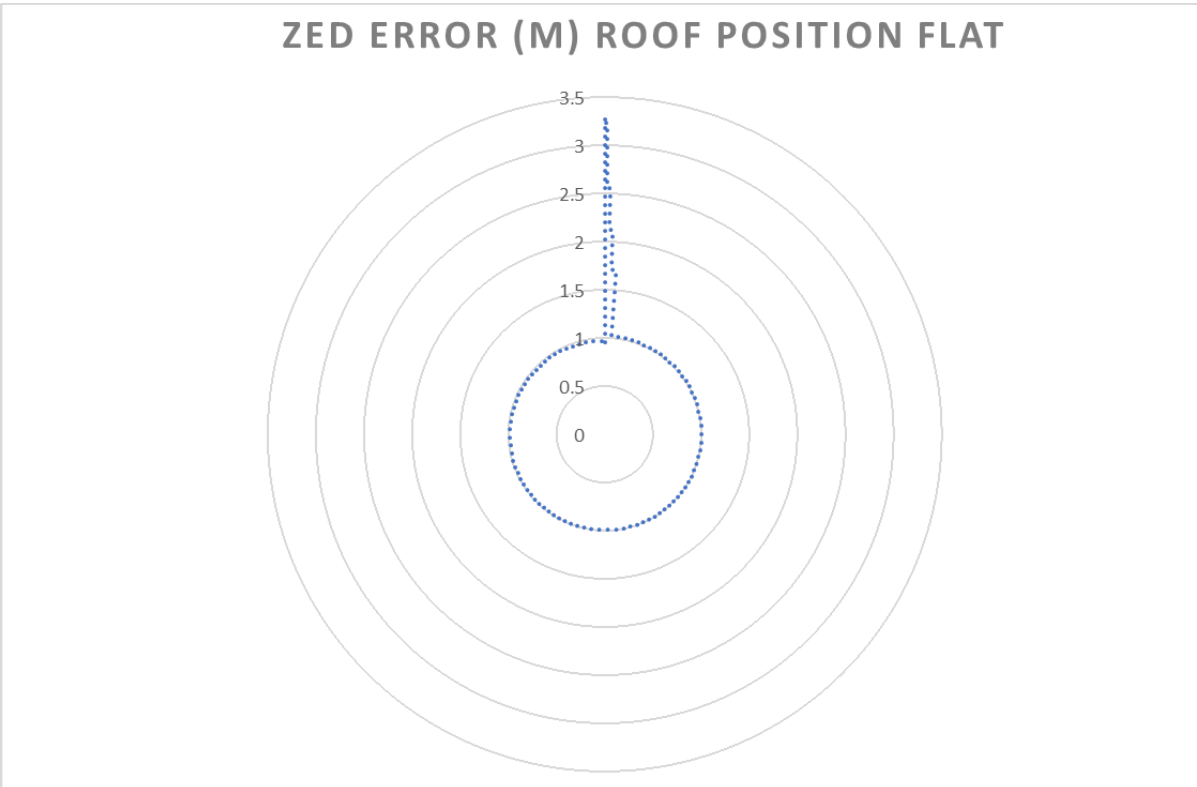

Figure 27: ZED-F9P Roof Position Horizontal Accuracy for Flat Course

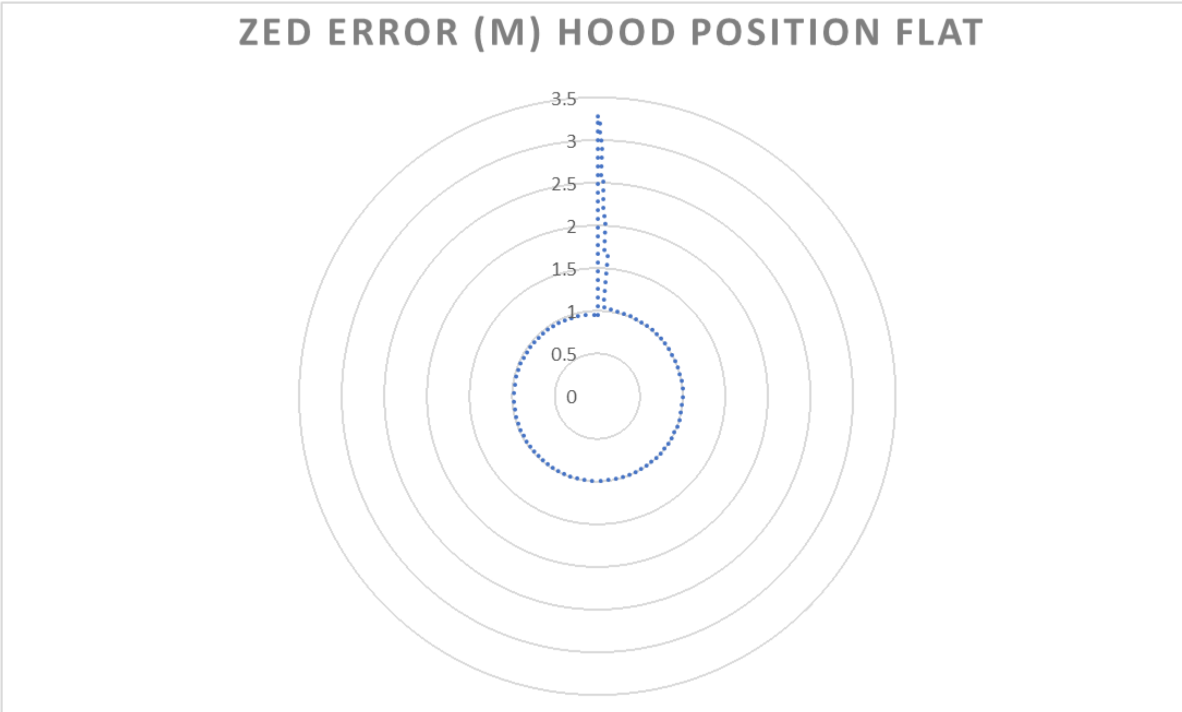

Figure 28: ZED-F9P Hood Position Horizontal Accuracy for Flat Course

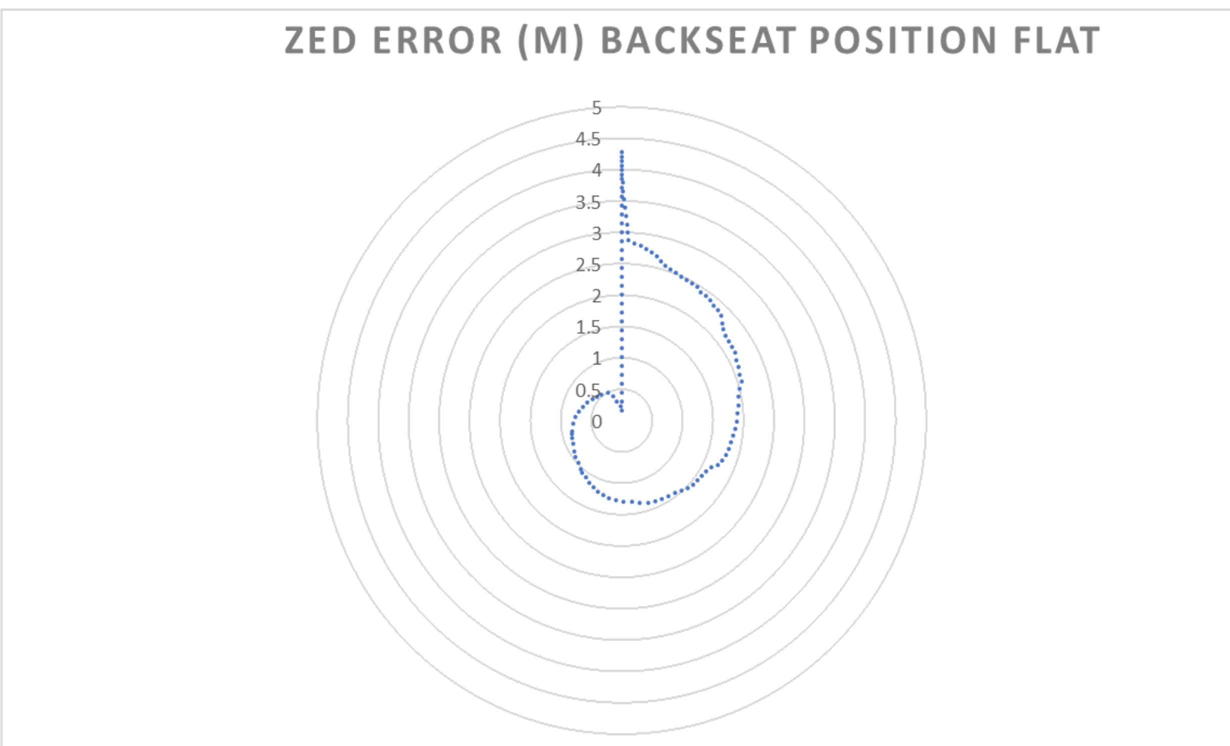

Figure 29: ZED-F9P Backseat Position Horizontal Accuracy for Flat Course

Graded Course

The nominal accuracy of the RTK system on the graded course outperforms that of even the flat course, with an overwhelming majority of the time under 1 m. This is likely due to the use of a different reference base station because the graded course is off property from the TRC course. The information that the positional accuracy for RTK is highly dependent on choice of the base station, as well as the proximity, is most useful in practical deployment scenarios. In this case, both the ground truth and the uBlox unit measures to the same base station, and the median accuracy value is 0.25 m, much better than on the flat course, and closer to advertised error. The 95% CEP is 0.97 m, still well within the application requirements. There are only a couple of dozen data points in all the runs that go past the 1.5 m requirement, making this a very stable and accurate solution for the application.

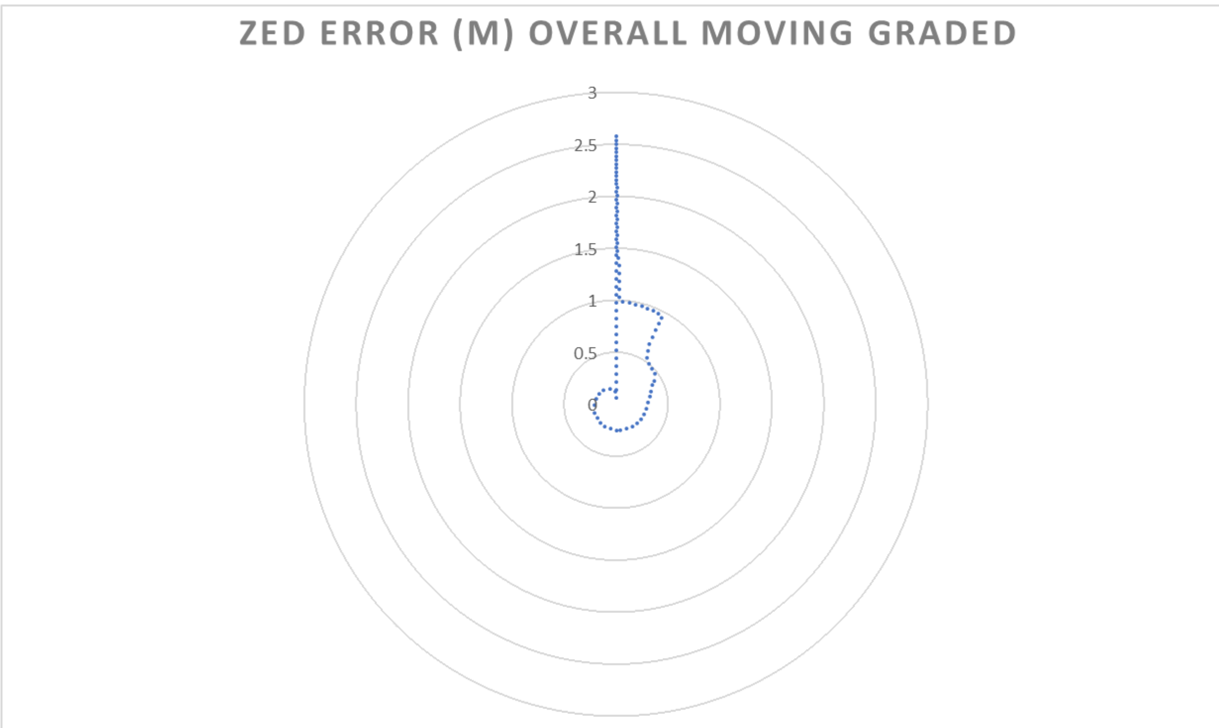

Figure 30: ZED-F9P Nominal Horizontal Accuracy for Graded Course

Unfortunately, the stationary test for the ZED-F9P suffers from the same inaccuracy problem as in the M8U, including a noticeable jump during the transition from roof to hood. In fact, it is overall worse. It is not clear why the accuracy is so poor on the graded course stationary test as compared to the flat course, so further information from the manufacturer may be necessary.

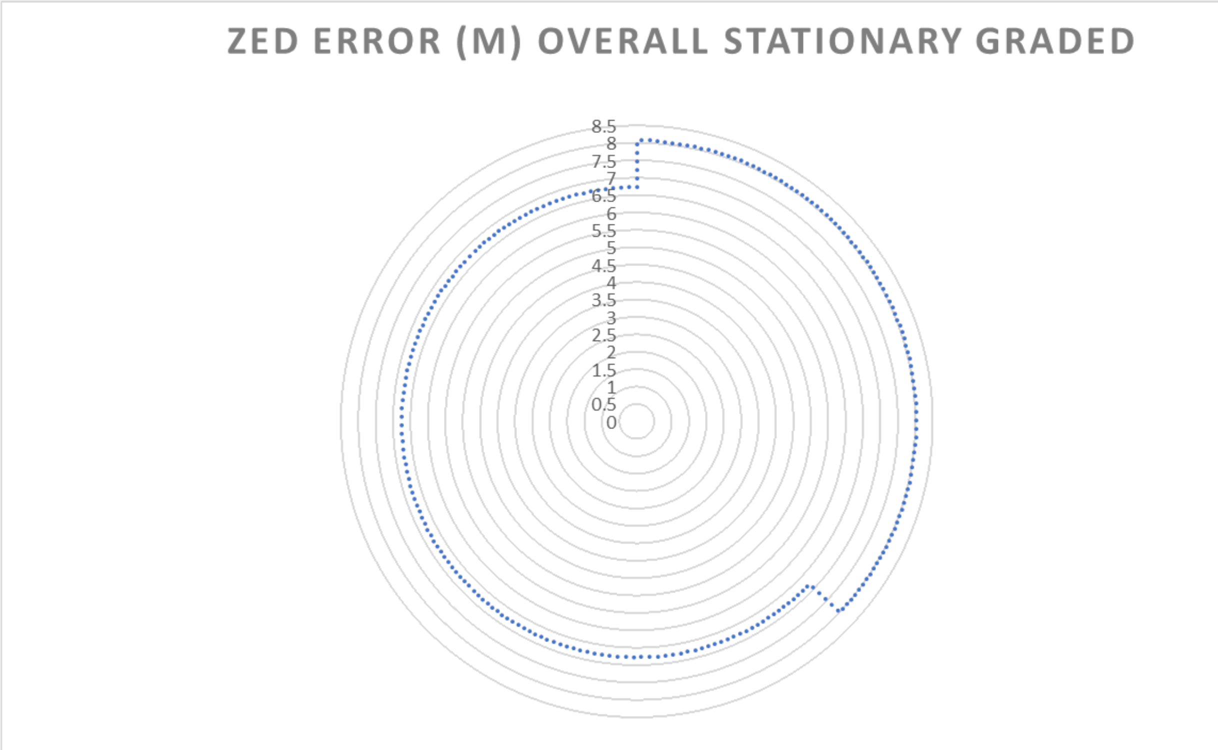

Figure 31: ZED-F9P Stationary Horizontal Accuracy for Graded Course

Discounting the stationary tests, the accuracy of both the rooftop and the hood position is well under 1 m, median values of 0.25 m and 0.54 m, respectfully.

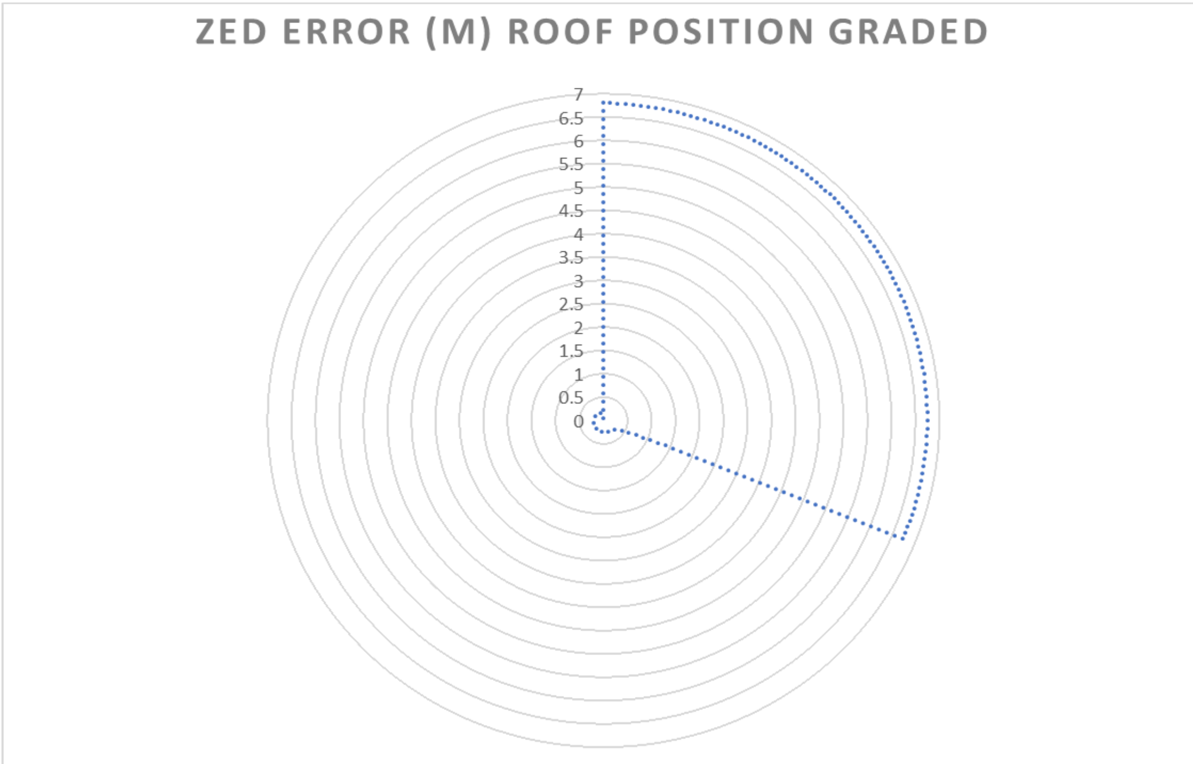

Figure 32: ZED-F9P Roof Position Horizontal Accuracy for Graded Course

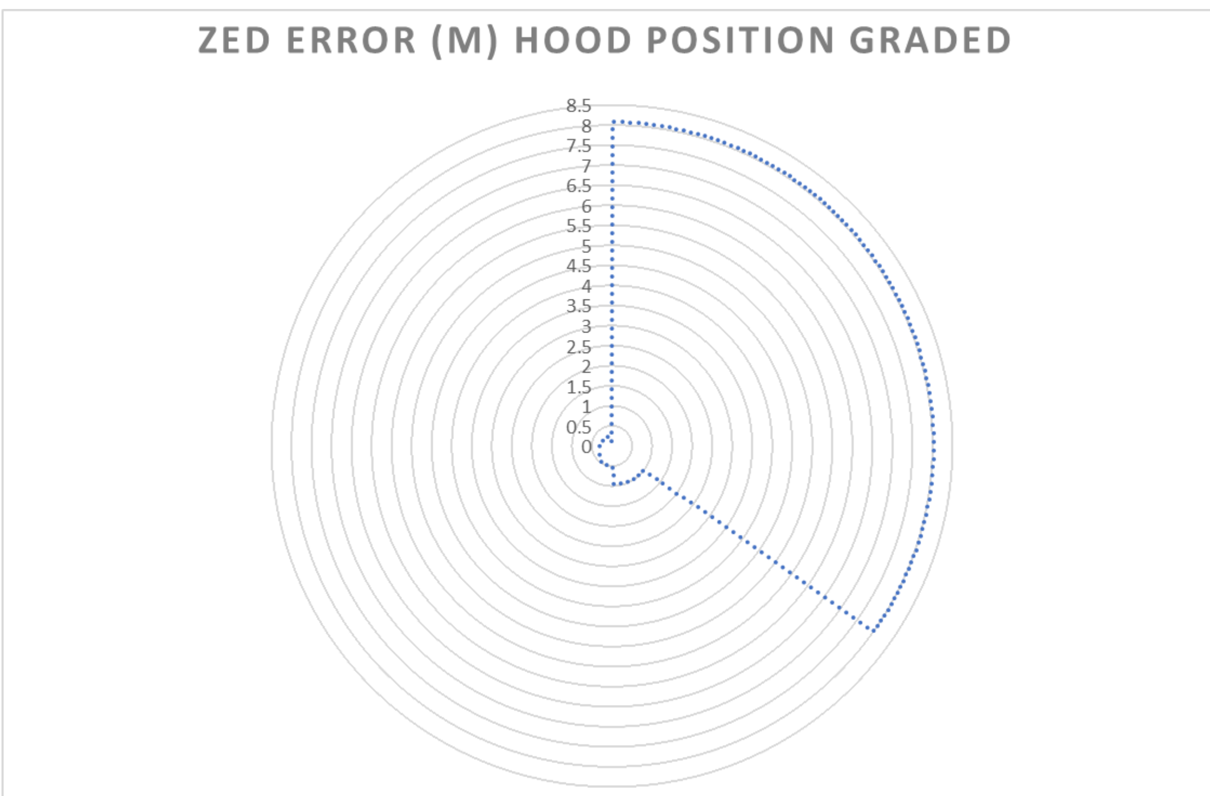

Figure 33: ZED-F9P Hood Position Horizontal Accuracy for Graded Course

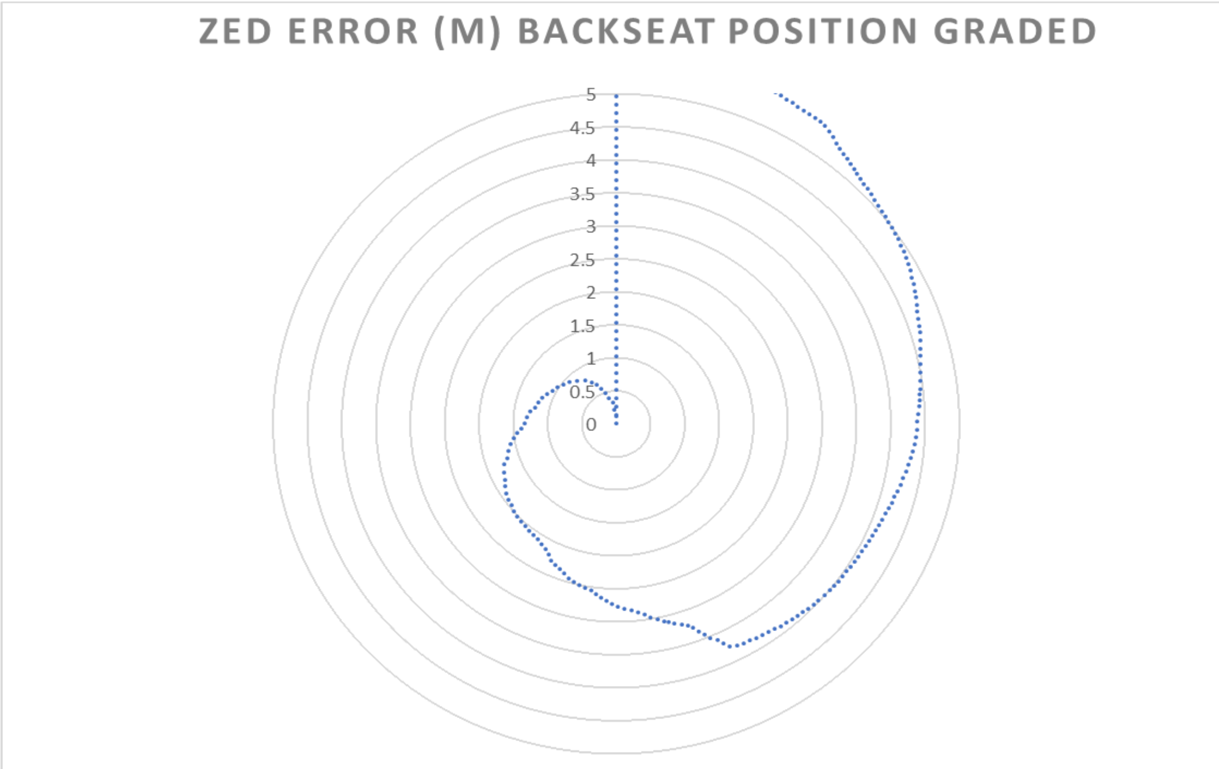

Figure 34: ZED-F9P Backseat Position Horizontal Accuracy for Graded Course

The vertical accuracy for the graded course is clearly way off, although it is very consistent. The median value is 18.02 m and 95th percentile value is 18.07 m.

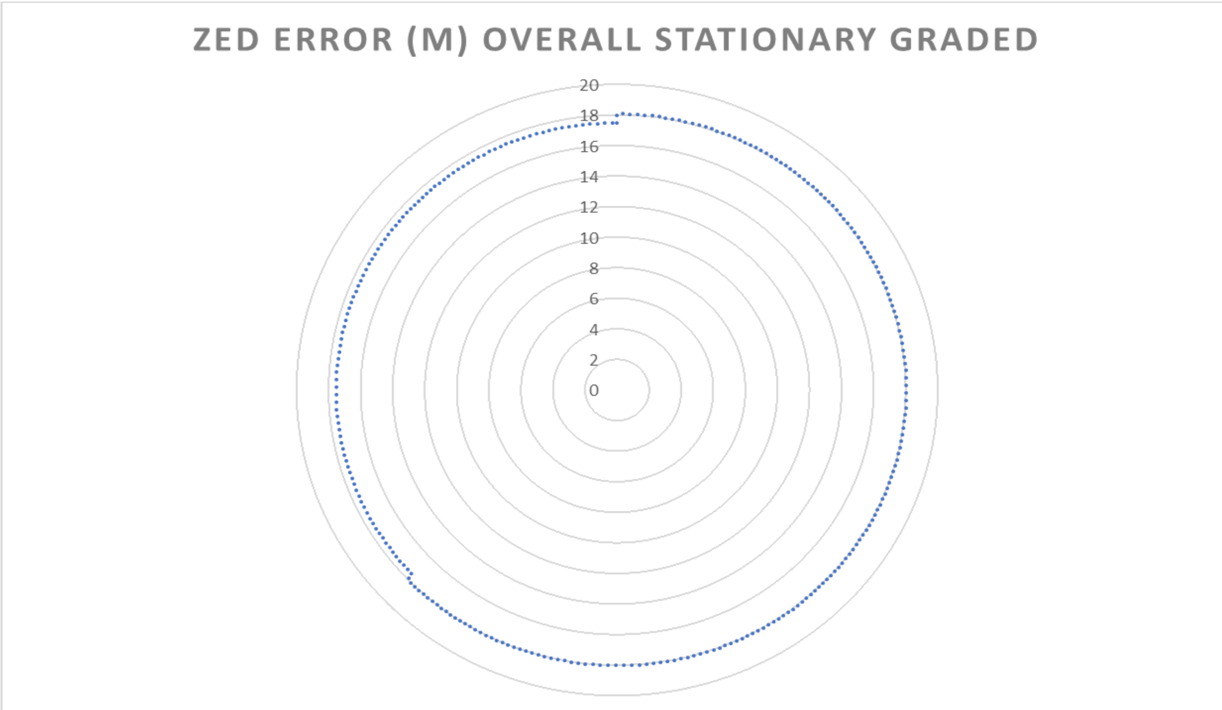

Figure 35: ZED-F9P Stationary Vertical Accuracy for Graded Course

4.2 Velocity

The speed accuracy tests were restricted to the flat course because the steep grade makes cruise settings difficult. Likewise, the lower speeds of 15 and 25 mph were thrown out since accelerator settings are more practical at the higher speeds. Within these parameters, both devices performed surprisingly well for velocity measurements, as they are nearly identical to ground truth for the nominal case. Assuming the vehicle telemetry is more accurate than even the ground truth GNSS measure, then it should be expected that some horizontal position error is incurred using the position solution velocity in lieu of the CAN. That said, both units perform within the requirements, yet would probably lead to noncompliance in the worst-case combination expected from the units' location error.

4.3 uBlox NEO-M8U

When compared to the ground truth, the M8U device had a median inaccuracy of only 0.01 mph and 95th percentile of 0.04 mph. Clearly, the unit's velocity measurements compare very favorably to the more expensive, professional grade GNSS system. When estimating the position error due to the variation from the expected test speed, the unit has a 50% CEP of 0.56 m and a 95% CEP of 1.19 m, well within the requirement.

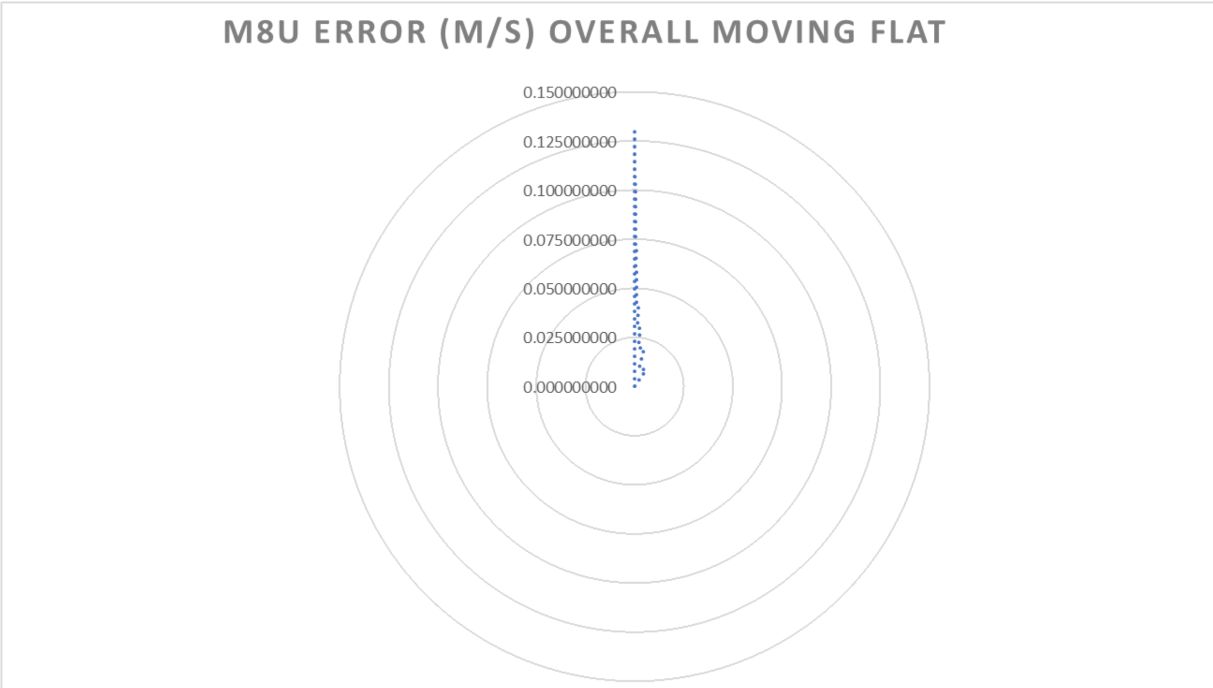

Figure 36: M8U Nominal Velocity Accuracy for Flat Course

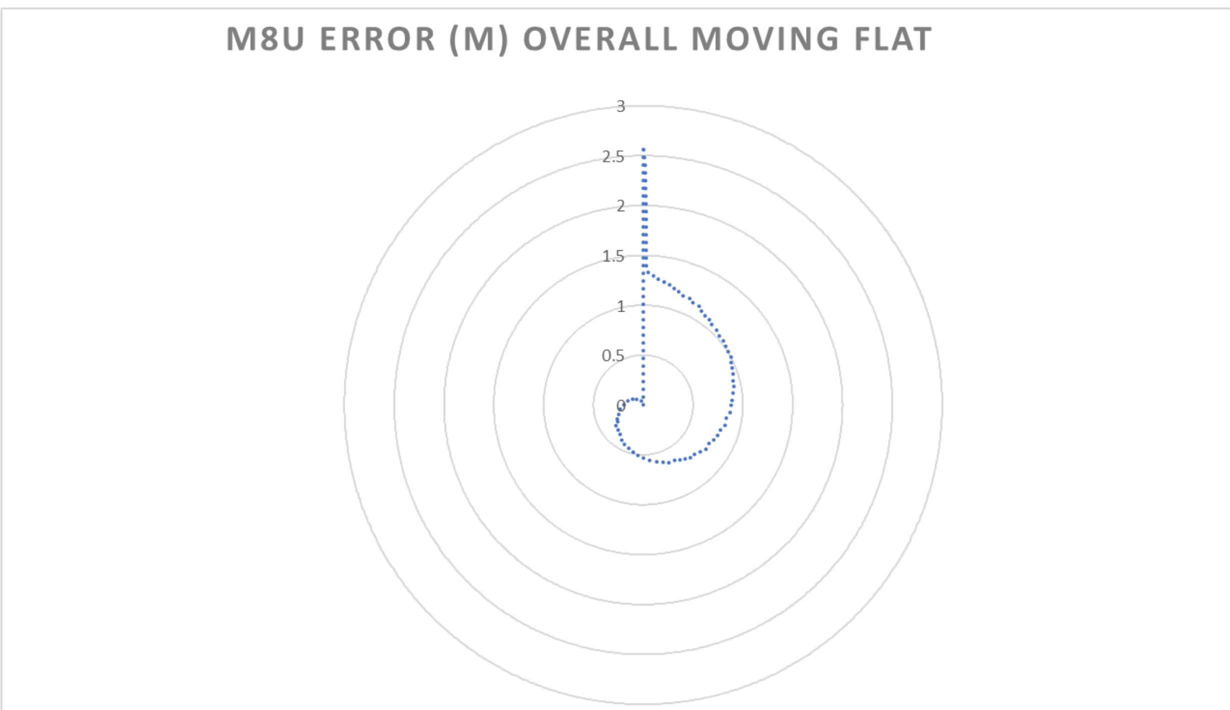

Figure 37: M8U Estimated Velocity Error for Flat Course

4.3.1 uBlox ZED-F9P

Much like the M8U, the RTK system displays very minimal velocity inaccuracy in the nominal case compared to the ground truth, with a median measure of 0.01 mph and 95th percentile of

0.03 mph. The estimated 50% horizontal position error from the velocity inaccuracy is 0.51 m and the 95% error is estimated to be 1.21 m.

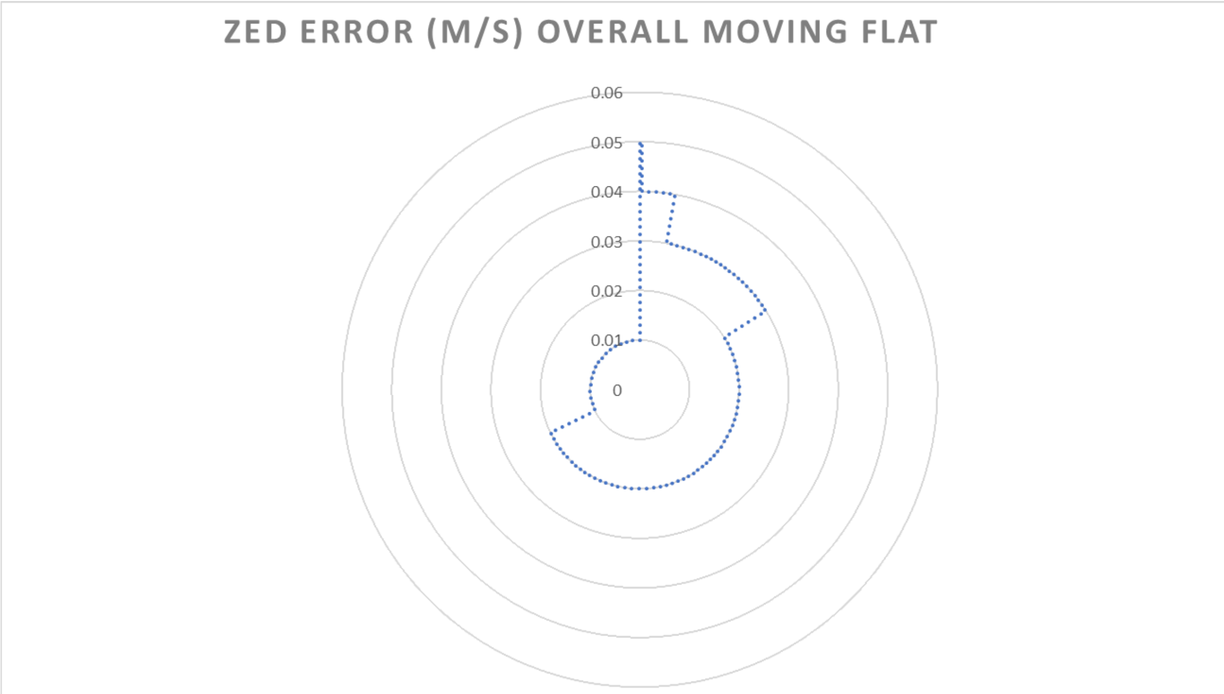

Figure 38: ZED-F9P Nominal Velocity Accuracy for Flat Course

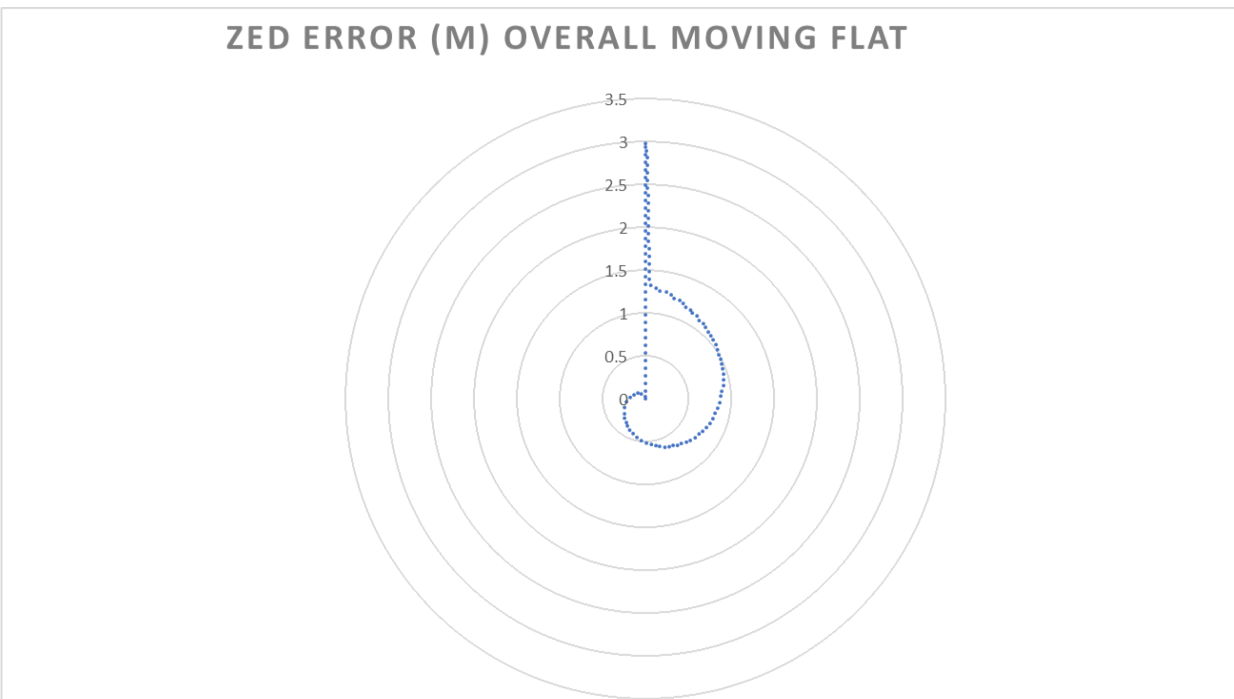

Figure 39: ZED-F9P Estimated Velocity Error for Flat Course

4.4 Timing

There is no easy way to determined exactly how far off two clocks are, but this study estimates this by considering any positional error that exists in excess to the value calculated by comparing the location from the GNSS system to ground truth, then dividing by the speed at that point. The obvious target, even if unrealistic, is a 0 ms clock difference between the GNSS unit and the ground truth, which constitutes a 0 m error. As stated in section 3.3, this positional error beyond expected is assumed to be from timing errors, and it is the combination of both sources that must comply with the necessary 1.5 m accuracy requirement. While it is possible that the two positional errors add together fully, there is an equal chance that the two cancel each other by erroring in opposite directions. However, here we consider the worst case.

4.4.1 uBlox NEO-M8U

The SBAS system again performs fairly well in the nominal case on the flat course but fails to meet the requirements necessary on the graded course. For the flat course, the positional inaccuracy incurred most likely from timing errors has a median measure of 0.06 m and a 95th percentile of 0.48 m. This means that we can expect up to 50 cm of inaccuracy due to timing, which varies from the 5.3 ms in median to 56.3 ms at 95%. On the graded course, the median error is 0.47 m and the 95th percentile of 1.88 m, which violates the requirement. The estimated timing errors are 50.4 ms for 50% and 173.3 ms for 95%.

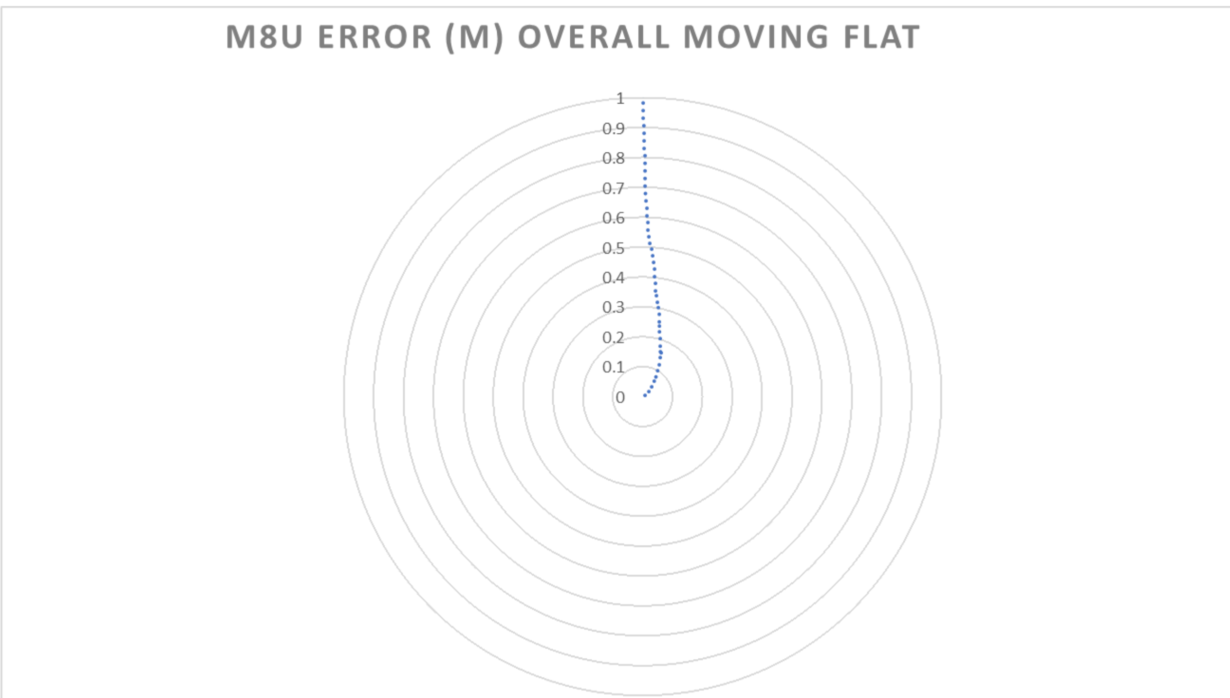

Figure 40: M8U Nominal Timing-Incurred Position Error for Flat Course

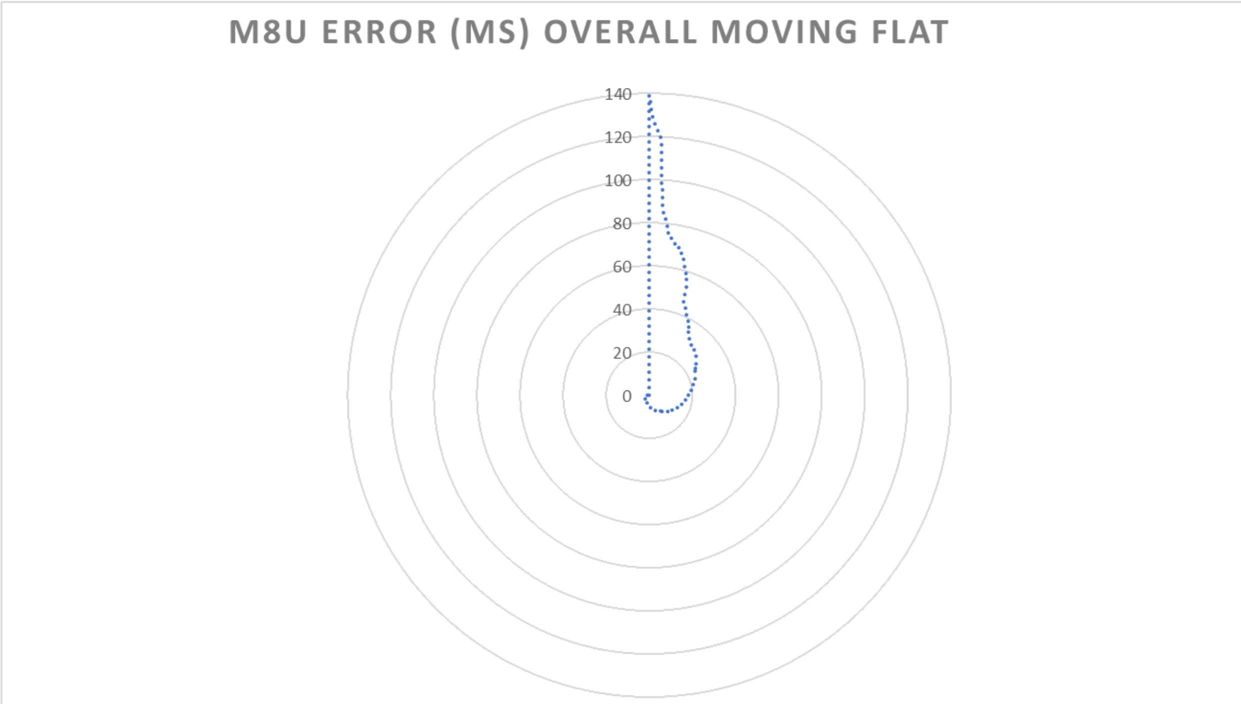

Figure 41: M8U Estimated Clock Error for Flat Course

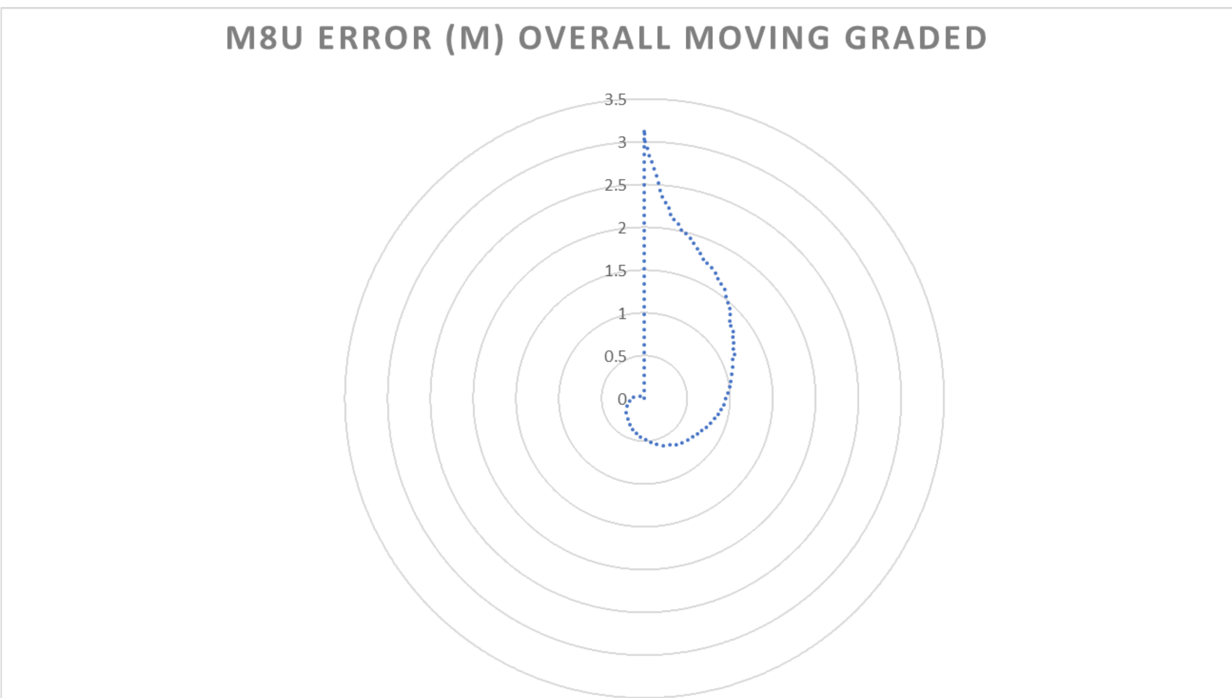

Figure 42: M8U Nominal Timing-Incurred Position Error for Graded Course

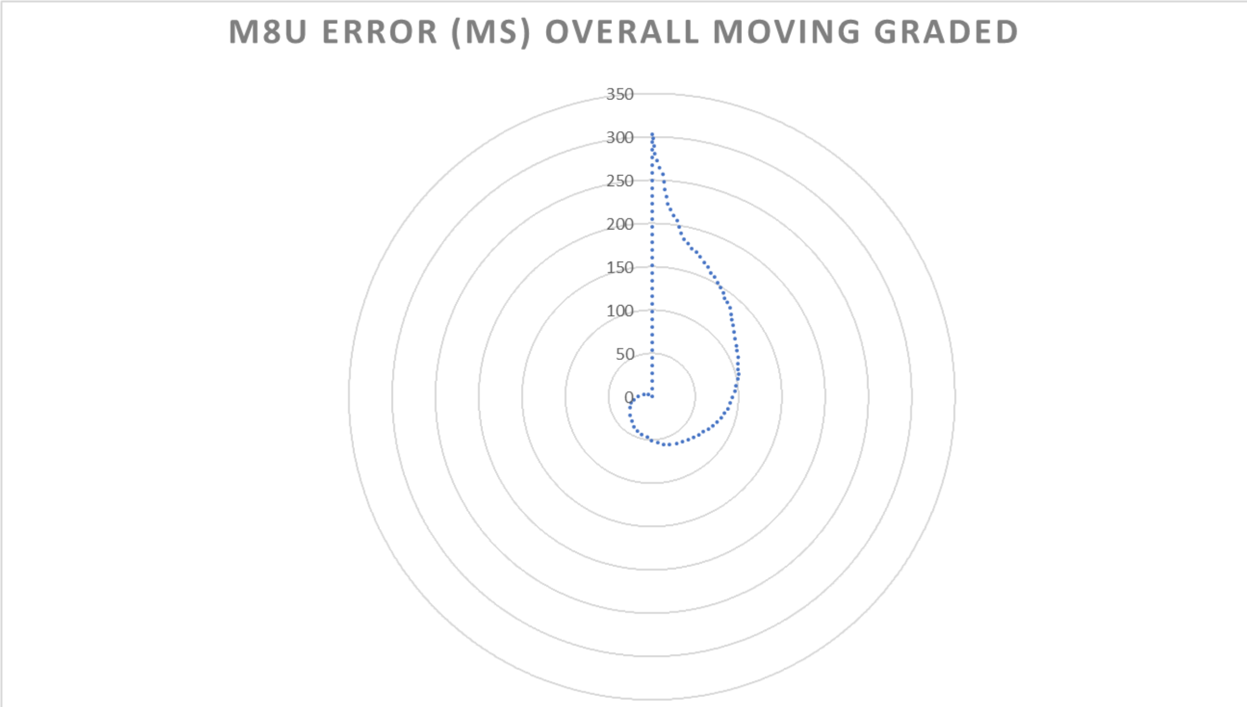

Figure 43: M8U Estimated Clock Error for Graded Course

4.4.2 uBlox ZED-F9P

The nature of the RTK system should lend itself well to timing accuracy since the correction is applied to the carrier wave, thus synchronizing the timing signals as close as possible. Therefore, it should not be surprising that the positional error of the ZED-F9P incurred from timing errors is consistently within a small number of centimeters. In fact, for the flat course, the median error is 0.0051 m (1/2 of a cm) and the 95th percentile is 0.01 m. The median estimated clock error for these is 0.5 ms and the 95% error is 1.4 ms. For the graded course, the median positional error is 0.019 m with a 95th percentile of 0.19 m from the estimated clock error from 2.0 ms median to 13.4 ms 95th percentile.

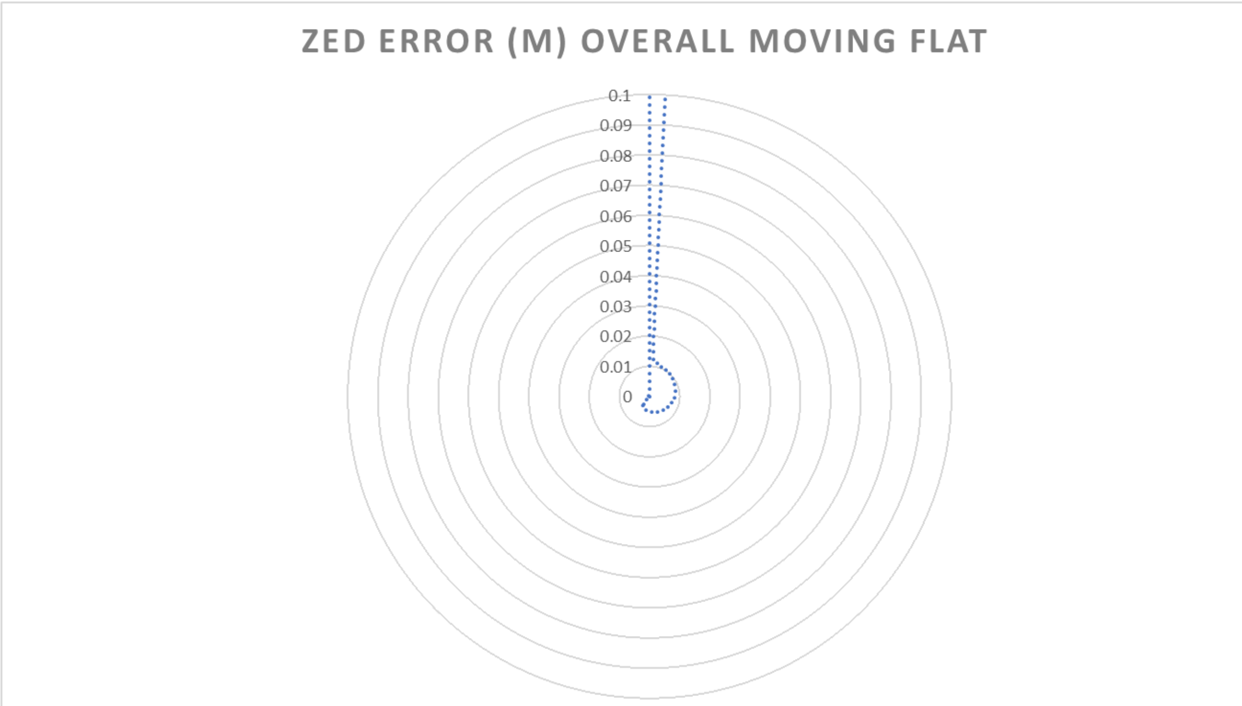

Figure 44: ZED-F9P Nominal Timing-Incurred Positional Error for Flat Course

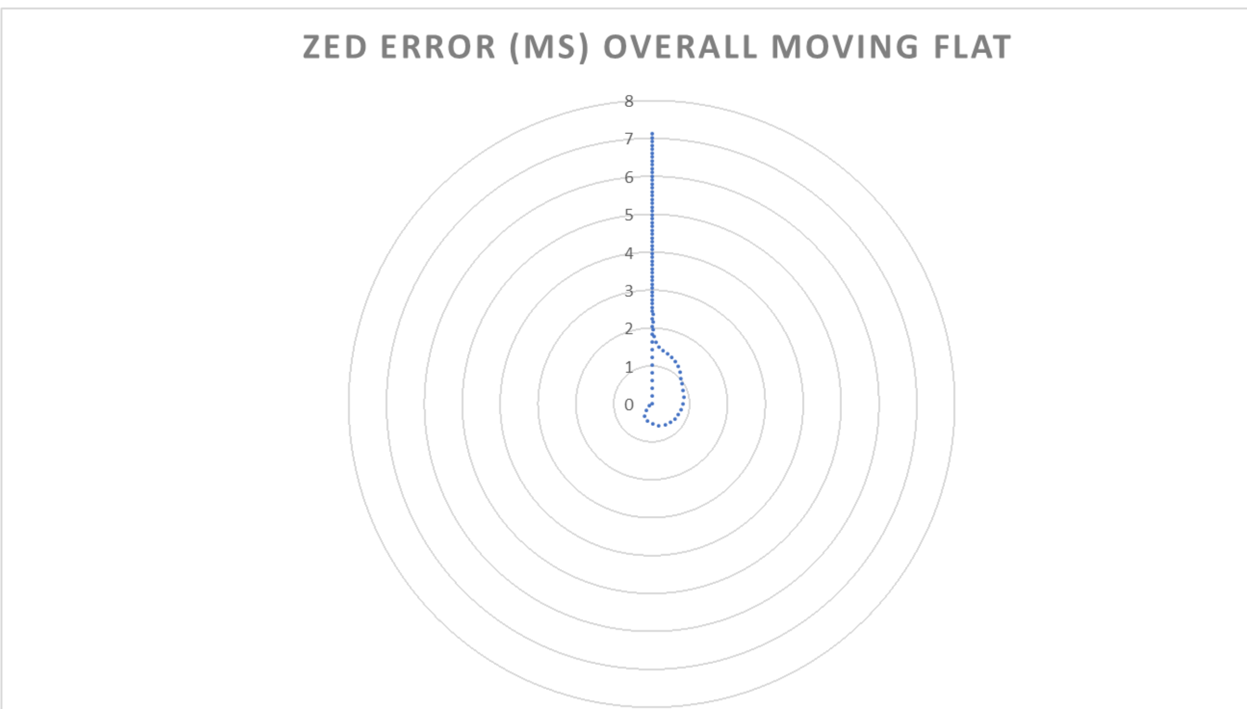

Figure 45: ZED-F9P Estimated Clock Error for Flat Course

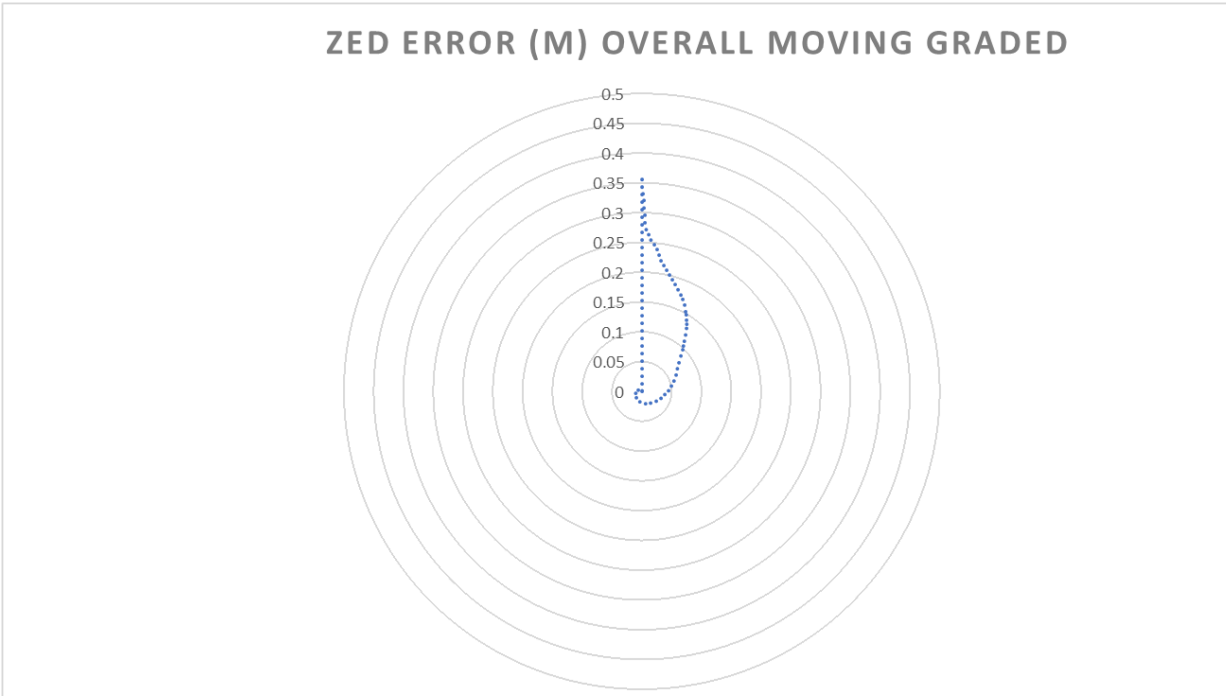

Figure 46: ZED-F9P Nominal Timing-Incurred Positional Error for Graded Course

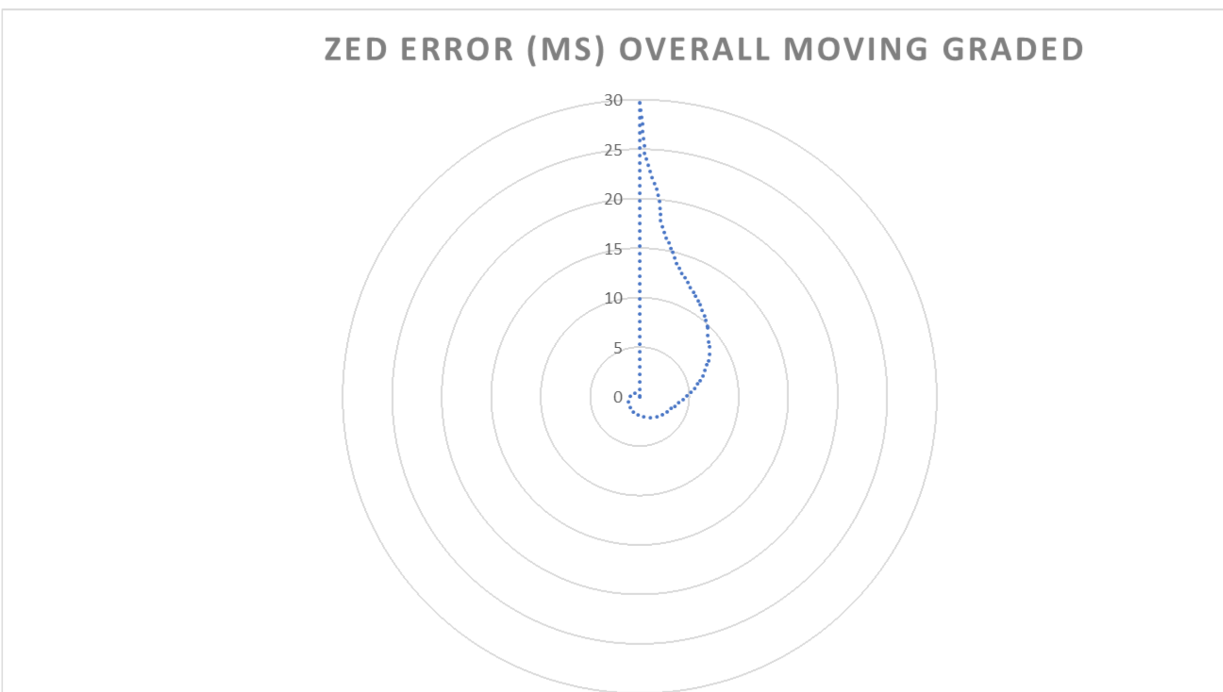

Figure 47: ZED-F9P Estimated Clock Error for Graded Course

5. Conclusions

Despite reasonably good performance by the SBAS unit in the best-case scenario, that is on the flat course in the roof position, the overall reliability of this performance is poor. In other words, it is possible if not probable that the system would fail to perform in numerous cases, particularly on the graded course. On the other hand, the RTK system exhibits highly reliable performance across the board with consistent 1 m accuracy on the flat course and sub-meter accuracy on the graded course. This would seem to imply that the RCVW system would function within required parameters nearly all the time using an RTK solution. Therefore, the recommendation from this study is to prefer RTK over SBAS corrective units.

There are a few caveats to consider, however. The NEO-M8U from uBlox comes with an integrated inertial measurement unit (IMU) in order to perform dead reckoning during brief periods of GNSS outage. This alone may be useful for the application, but more importantly, perhaps, is that the IMU aids in boosting the accuracy along with using the SBAS correction. It is suggested, then, that the RTK rover unit also include a DR IMU as well to utilize the same benefits.

Secondly, the RTK system is highly dependent on the base station used. Therefore, it is recommended that the RTK solution utilize a base station within the RBS equipment and should be pre-configured with the antenna position or have some self-survey mode. The same unit should be able to generate its own correction values based on the known position and broadcast them locally through the existing DSRC radio in lieu of adding addition communication equipment. The receiving radio in the VBS must then relay the corrections into the unit to apply them. Since all approaching vehicles will therefore use the exact same base station, it should be expected that horizontal accuracy is more consistently within decimeter or centimeter levels. However, the ability to transmit and apply the corrections quickly is a potential source of trouble since each unit requires some number of seconds to obtain a fixed integer solution for the RTK. For the ZED-F9P, the documented convergence time is under 10 seconds initially.

The study looked at variations in accuracy due to the antenna position. It should come as no surprise that the clear recommendation is to have outside antennas for highest accuracy, as depicted in the definition of the nominal case. However, it is also clear that the rooftop position provides the highest level of accuracy, compared to the hood position, most likely due to the reduced multipath errors incurred due to the lower elevation. This is particularly the case for the graded course.

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Abbreviations and Acronyms

ACRONYMS	EXPLANATION
CEP	Circular Error Probable
DSRC	Dedicated Short-Range Communication
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
RTK	Real-Time Kinematics
RCVW	Rail-Crossing Violation Warning
SBAS	Satellite-Based Augmentation System