DEPARTMENT OF TRANSPORTATION

Evaluation of Low-Cost, Centimeter-Level Accuracy OEM GNSS Receivers

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16. Abstract

This report discusses the results of a study to quantify the performance of low-cost, centimeter-level accurate Global Navigation Satellite Systems (GNSS) receivers that have appeared on the market in the last few years. Centimeter-level accuracy is achieved using a complex algorithm known as real-time kinematic (RTK) processing. It involves processing correction data from a ground network of GNSS receivers in addition to the signals transmitted by the GNSS satellites. This makes RTK-capable receivers costly (in excess of $10,000) and bulky, making them unsuitable for cost- and size-sensitive transportation applications (e.g., driver assist systems in vehicles). If inexpensive GNSS receivers capable of generating a position solution with centimeter accuracy were widely available, they would push the GNSS revolution in ground transportation even further as an enabler of safety enhancements such as ubiquitous lane-departure warning systems and enhanced stability-control systems. Recently manufacturers have been advertising the availability of low-cost (< $1,000) RTK-capable receivers. The work described in this report provides an independent performance assessment of these receivers relative to high-end (and costly) receivers in realistic settings encountered in transportation applications.

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Evaluation of Low-Cost, Centimeter-Level Accuracy OEM GNSS Receivers

FINAL REPORT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Global Navigation Satellite Systems (GNSS) is a term used to collectively describe satellite-based positioning and timing systems. The Global Positioning System (GPS), operated by the United States Department of Defense, is perhaps the most well-known and widely used GNSS. The sub-meter accuracy of its position solution has revolutionized the transportation industry worldwide. If GNSS receivers capable of generating a position solution with centimeter-level accuracy were consistently and reliably available, they would push the GNSS revolution in transportation even further as an enabler of safety enhancements, such as ubiquitous lane-departure warning, driver assist, and enhanced-stability control systems.

The process for achieving centimeter-level position accuracy in GNSS involves a complex algorithm known as real time kinematic (RTK) processing (Misra and Enge 2011). RTK-capable receivers require precisely calibrated antennas to process signals transmitted by the GNSS satellites. In addition, they must receive and process corrections data from a ground network of GNSS receivers. These factors made traditional RTK-capable receivers costly (in excess of $10,000) and bulky, making them unsuitable for cost- and size-sensitive applications.

Recently, GNSS equipment manufacturers have started advertising inexpensive (less than $1,000) and compact RTK-capable receivers. However, accuracy claims are often made without context of application and environment. This project performed an independent performance assessment of five low-cost receivers and a mid-range receiver capable of RTK positioning. The receivers selected for analysis were:

- Hemisphere Eclipse P307
- Swift Piksi Multi
- NVS Technologies NV08C-RTK
- Emlid Reach
- u-blox NEO-M8P
- Skytraq S2525F8-RTK

To evaluate these receivers, data was collected in static (i.e. stationary) and dynamic (mobile) configurations. For both scenarios, the receivers were tested in environments with different levels of sky visibility and multipath. For the static tests, data was collected at documented geodetic markers in rural, suburban, and urban environments. For each of these environments, two antennas were used: a high-quality rover antenna, and a low-quality patch antenna. The difference between the precisely-known location of the geodetic marker and the computed position solution of each receiver was used as the metric to assess receiver performance.

For the dynamic tests, the receivers were installed in a vehicle and data was collected at highway speeds along three different routes including rural (open sky), rural with bridges (regular, known occlusions), and urban (high environmental mask angles and opportunities for multipath). In these tests, only the high-quality antenna was used. The dynamic test accuracy metric was based on the difference between the position solution of the high-end Navcom SF-3050 receiver and that of the other receivers.

The static tests showed that the low-cost receivers have 10 cm (95%) or better RTK fixed-integer horizontal accuracy in the rural, low-multipath environment using the high-quality antenna. In the suburban and urban environments with moderate to high multipath, low-cost receiver accuracies degraded to over 1 meter in some cases. The RTK fixed-integer availability ranged from 1.4% to 75.5% using the low-cost antenna, and 10.9% to 95.5% using the high-quality antenna. However, all low-cost receivers had a minimum RTK floating-point or fixed integer availability of 84% and 53.1% using the high-quality and low-quality antenna, respectively. This suggests that the high-quality antenna is favorable for RTK availability.

The results of the dynamic tests suggest that the single frequency receivers are not well suited for dynamic applications. The best single-frequency RTK fixed-integer availability was 25.5%. The multifrequency receivers had RTK fixed-integer availabilities with values ranging from 29.6% to 57.4%. The RTK fixed-integer integer horizontal position accuracies of the low-cost receivers with respect to the SF-3050 range from 1.5 cm to 1.8 m (95%). The RTK floating-point horizontal position accuracies ranged from 1.7 m to 10 m in general, though spurious behavior was observed, which had extreme accuracy values up to 5 km (95%). The bridges route revealed that only two receivers being tested – the Piksi Multi and Eclipse P307 – had an RTK fixed-integer solution consistent enough to warrant RTK fix loss study. The Piksi Multi took twice as long as the Eclipse P307 and more than four times longer than the SF-3050 to reacquire an RTK fixed-integer solution after passing under a bridge.

The cumulative results suggest that L1-only RTK receivers face challenges related to positioning robustness and continuity when applied in more varied environments. However, they have potential in applications that have low-dynamics and open skies. The Piksi Multi receiver showed better performance in continuity in the dynamic scenarios and is recommended for future study for on-vehicle applications. However, it is still susceptible to degraded accuracy in more obstructed and multipath-prone environments.

Considering it is not a low-cost receiver, the Eclipse P307 performed well in static and dynamic tests in all environments. It was versatile in that it used both the low-quality and high-quality antennas for RTK positioning, while the reference receiver could not. However, its cost is an order of magnitude higher than the low-cost receivers.

The results in this report give an idea of the accuracy and continuity of low-cost GNSS receivers relative to established reference receivers. Future studies could examine the effects of future firmware releases on receiver performance, a focused study on better-performing low-cost receivers, or application-specific experiments.

CHAPTER 1: INTRODUCTION

Global Navigation Satellite Systems (GNSS) is a term used to collectively describe satellite-based positioning and timing systems. The Global Positioning System (GPS), operated by the United States Department of Defense, is perhaps the most well-known and widely used GNSS. The sub-meter accuracy of its position solution has revolutionized road, rail, air, and marine transportation systems worldwide. Its timing function is the *de-facto* heartbeat for clocks around the globe in support of operations such as time stamping of banking transactions and synchronizing electrical frequency on interconnected power grids (GPS.gov 2014).

In general, GPS can deliver a position solution with accuracy on the order of several meters. Sub-meter accuracy can be achieved but requires additional processing and external data. For example, centimeter-level accuracy in GNSS is achieved using a complex algorithm known as real-time kinematic (RTK) processing (Misra and Enge 2011). RTK-capable receivers require precisely calibrated antennas that process signals transmitted by the GNSS satellites. In addition, they must receive and process corrections data from a ground network of GNSS receivers. This makes RTK-capable receivers costly (in excess of $10,000) and bulky, making them unsuitable for cost- and size-sensitive automotive applications. If inexpensive GNSS receivers capable of generating a position solution with centimeter-level accuracy were widely available, they would push the GNSS revolution in ground transportation even further as an enabler of safety enhancements such as ubiquitous lane-departure warnings systems, driver assist systems, and enhanced stability control systems.

Recently, GNSS equipment manufacturers have started advertising inexpensive (less than $1,000) and compact RTK-capable receivers. However, data supporting these accuracy claims is not publicly available. The work performed in this project aims to provide an independent performance assessment of six low-cost, RTK-capable receivers. The motivation was to determine the performance of these receivers in a number of realistic scenarios to assess their suitability for intelligent transportation applications. More precisely, the project goal was to answer the following question: Are the new, purportedly RTK-capable, inexpensive receivers able to perform at the same level as high-end, survey-grade receivers such as the Navcom SF-3050, Novatel OEM7700 or Trimble BX982?

A major benefit of and motivation for the work is to aid in the development and evolution of the Minnesota Continuously Operating Reference Station (MnCORS) network. Generating an RTK solution requires processing GNSS satellite signals alongside the information received from a network of stationary base stations. In Minnesota, the primary users of the MnCORS network are land and construction surveyors. If the new RTK-capable receivers can provide centimeter-level accuracy inexpensively, it may lead to a surge in the user base demanding access to the MnCORS network. In order to better understand and predict demand, the MnCORS operators were interested in an evaluation of currently available technology. Interest was in low-cost hardware, which if reliable enough, would be more likely to see rapid adoption.

This report documents the work performed to answer the above question. Chapter 2 introduces the performance metrics used for this study. Chapter 3 describes the experiments performed to collect the receiver evaluation data including the hardware used and the experimental methods used to collect the data. Chapter 4 summarizes the results of the static and dynamic testing performed on the receivers. Chapter 5 discusses the implications of the receivers' performance noted in this study and offers suggestions for future evaluations.

CHAPTER 2: PERFORMANCE METRICS

This chapter describes the metrics used to compare the receivers to one another. The following four metrics were used: Accuracy, Continuity, Availability, and Time to First Fix. These are loosely based off metrics defined in the GPS Standard Positioning Solution Performance Standard (U.S Department of Defense, 2008).

Time to First Fix refers to a receiver's state when it has calculated and is reporting a valid position solution after being powered on. The statistics here are focused on RTK fixed-integer and floating-point solutions. A floating-point solution is an initial estimate of the real-time kinematic (RTK) solution that is a precursor to the more precise fixed-integer solution. A fixed-integer solution is more accurate but it harder to compute. See the proceeding section for more information on these fixes. In what follows, it's assumed that the reader is familiar with the basics of RTK-positioning. The interested reader can refer to standard texts on GNSS to learn more about the difference between float and fixed integer ambiguity resolution.

2.1 USEFUL TERMINOLOGY

This section is included for readers who may be unfamiliar with terms used ahead

GPS Fix – General term for when a receiver is reporting a valid position solution.

Real-time Kinematic Positioning – A family of positioning methods that uses GNSS measurements from a reference station to calculate a position solution and minimize error terms in real time. For a technical introduction of RTK positioning, the reader is referred to (RTK Fundamentals, 2014).

Floating-Point Solution – An initial estimate of the RTK solution that is a precursor to the more precise fixed-integer solution. A floating-point solution has a typical accuracy of 1 m or better.

Fixed-Integer Solution – The RTK solution that is harder to compute as it attempts to resolve the integer ambiguity of carrier-phase cycles. Typical accuracy on the order of 1-10cm, depending on local conditions and baseline length. Resolving the integer ambiguities takes on the order of seconds to minutes.

2.2 ACCURACY

In general, GNSS accuracy is defined as the difference of the calculated position solution and the truth position that is exceeded only 5% of the time in the absence of system errors. Stated another way, this is 95^{th} percentile of the position errors. As an example, a recent FAA study performed at sites around the United States calculated an average standard-position (non-RTK) solution horizontal accuracy of 1.8 meters (95%) for high-end, single-frequency receivers (William J. Hughes Technical Center, 2017). In this project, the receiver accuracy is defined as the 95^{th} percentile of the difference between the calculated RTK position solution and the truth position. It is calculated after an ensemble of position data has been collected.

2.3 CONTINUITY

The formal definition of continuity is the likelihood of a detected but unscheduled navigation function interruption after an operation has been initiated. As shown later, the RTK solution is not always available. Once a receiver has computed an RTK fixed-integer solution, there are situations that may cause the receiver to lose the fixed-integer solution and revert to a floating-point solution. This loss of RTK lock is a loss of continuity. The work here used two additional metrics to characterize continuity:

- **Loss of Lock Frequency** – The number of loss of RTK fixed-integer locks per RTK minute
- **Average Time to Reacquire** – The average time to reacquire the RTK fixed-integer solution after it is lost

The loss of lock frequency is normalized by the amount of time a receiver spent in RTK fixed-integer mode. This was done to make comparisons between receivers that have different RTK availability values.

2.4 AVAILABILITY

The definition of availability used here is not the same as the standard definition of the term used in the navigation community. The RTK availability is defined as the total amount of time as a percentage that a receiver spends in an RTK position solution. An ideal receiver will have an RTK availability close to 100%. RTK availability statistics are reported in two ways:

- **RTK Fixed-Integer Availability** – Total percentage of experimental time spent in a fixed-integer solution
- **RTK Floating-Point and Fixed-Integer Availability** – Total percentage of experimental time spent in a fixed-integer and floating-point solution

2.5 TIME TO FIRST FIX

The time to fist fix (TTFF) is a performance metric of receiver initialization. It is the amount of time that it takes to report a solution from a cold start (no knowledge left over from its previous operational state). A hold-condition of 10 seconds was imposed on the RTK fixed-integer solution. Two TTFF metrics are considered here:

- **TTFF RTK Floating-Point** - Time to compute the initial floating-point solution
- **TTFF RTK Fixed-Integer** - Time to compute the initial fixed-integer solution and subsequently hold the solution for 10 seconds

The requirement of holding the TTFF RTK fixed-integer position for 10 seconds was imposed because it was common for receivers to report a fixed-integer solution initially, then then report it lost the next timestep.

CHAPTER 3: EXPERIMENTAL METHODS

3.1 RECEIVER OVERVIEW

Five low-cost, commercially available, off-the-shelf GNSS receivers were chosen to be evaluated. The selected receivers do not represent an exhaustive list of all possibilities. The key criteria for selecting a receiver was a price of $540 or less and an advertised RTK position solution capability. In addition to the low-cost receivers, the Hemisphere Eclipse P307 was included at the request of MnDOT due to its current use in surveying and other applications at the agency. The Navcom SF-3050 receiver was used as the state-of-the-art, high-end receiver to which the performance of the low-cost receiver whose output would be used as ground-truth in dynamic tests. The performance of the SF-3050 was not being evaluated. Table 3.1 summarizes all the receivers used in the experiment including both the high-end and low-cost receivers.

Since the completion of data collection, multiple manufacturers have released firmware updates for their respective receivers. For example, Swift introduced support for the GLONASS constellation and u-blox, Emlid and Swift have firmware releases that claim to increase RTK robustness.

Table 3.1 Summary of receivers used for testing.

Type	*Receiver*	*Firmware*	*Notes*	*Price*
High-End (ground truth)	Navcom SF-3050	2.0.1	Multifrequency L1/L2	>$ 10,000 (estimate)
Mid-Range	Hemisphere Eclipse P307	5.1	Multifrequency L1/L2	$ 2,300
Low-Cost	Swift Piksi Multi	1.1.27	Multifrequency L1/L2, Firmware supported GPS only	$ 540
	NVS Technologies NV08C-RTK	V0029	Single frequency, L1	$ 490
	Emlid Reach	2.3	Single frequency, L1, Uses u-blox NEO-M8T chip	$ 399
	u-blox NEO-M8P	HPG 1.20REF	Single frequency, L1	$ 235
	Skytraq S2525F8	NS-HP-GL-10S (20170712)	Single frequency, L1	$ 200

Two antennas were chosen for the testing: one high-quality and one low-quality. The high-quality antenna used was a Navcom ANT-3001R antenna with an active gain of 39 dB. The ANT-3001R is a multifrequency antenna that supports survey-grade applications (Navcom 2009). The low-quality antenna was an ANN-MS L1-only (single-frequency) patch antenna with an active gain of 29 dB (u-blox 2017).

3.2 EXPERIMENTAL SETUP

The receivers were connected to a single antenna through a GPS Technologies ALDCV1x8 signal splitter. They were connected to the laptop computer via USB that ran the data collection software. The data collection software is a custom application built in Python. RTK corrections data was provided by the Minnesota Continually Operating Reference Station (MnCORS) Network (MnDOT, 2018a). This service was accessed over the internet by connecting the laptop to a cellular modem. **Error! Reference source not found.** shows a diagram of the experimental setup and **Error! Reference source not found.** shows a diagram of the experimental setup and **Error! Reference source not found.Error! Reference source not found.** shows the experimental setup with low-cost receivers enclosed in a protective container.

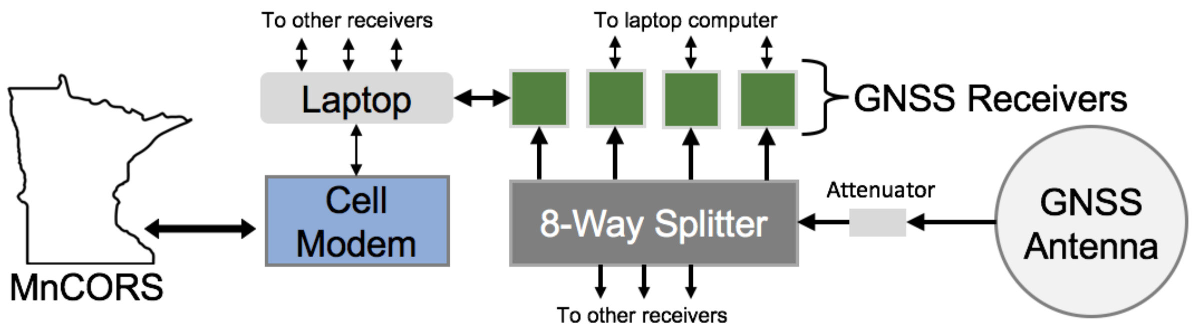


Figure 3.1 Illustration of experimental setup.

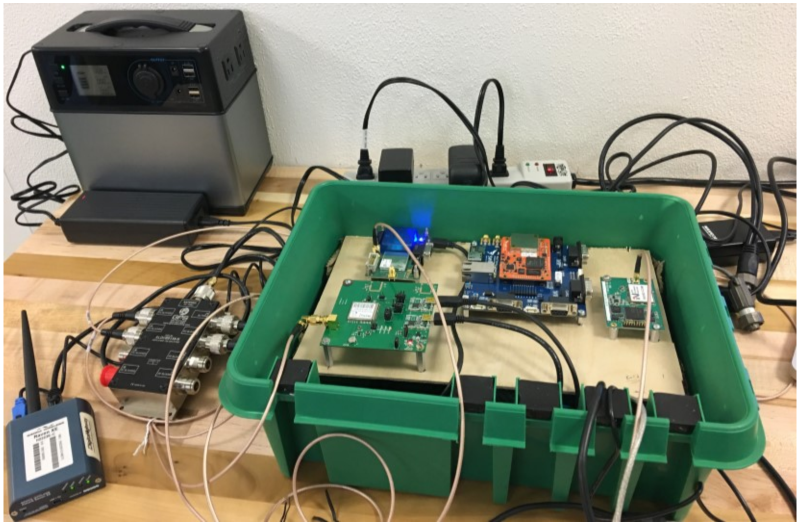


Figure 3.2 Experimental setup enclosed in protective container.

The receiver output was in the form on National Marine Electronics Association (NMEA) strings, a common ASCII format used for reporting calculated positioning products. The GGA string contains the latitude, longitude, position-fix type and other relevant information about the GPS fix of the receiver. An example NMEA string is:

```
$GNGGA,205450.00,4458.86243,N,09314.77762,W,4,12,0.70,250.8,M,-30.9,M,2.0,0527*59
```

Which contains latitude, longitude, GPS fix status, number of satellites and other information. For more information regarding the NMEA standard, refer to the NMEA 0183 V 4.10 standards document.

3.3 STATIC TESTING METHODOLOGY

Static testing was conducted in three different environments using test points found using MnDOT's interactive geodetic monument viewer (MnDOT, 2018b). An example of a survey marker used is shown in Figure 3.3. The three environments were chosen to best reflect the qualitative characteristics of rural, suburban and urban settings. Rural areas have a clear view of the sky with no obstructions or nearby metal structures. Urban areas have tall, metal structures and a narrower view of the sky from the antenna's point-of-view. Suburban areas fall somewhere in-between. The chosen markers were a compromise in the availability of markers and desired environmental features.

Table 3.2 Geodetic markers used for static tests.

Environment	**Marker ID**	**Horizontal Accuracy**	**Vertical Accuracy**
Urban	SCHREIBER	2.13 mm	4.88 mm
Suburban	UNIVERSITY1934	1.01 cm	2.13 mm
Rural	TURKEY MN037	4.88 mm	4.88 mm

Static data was collected in 25-minute-long sessions on 17 days over 4 months. Each antenna-environment combination was repeated a minimum of 6 times to establish significance in the TTFF statistics.

Figure 3.3 SCHREIBER geodetic marker north of the University of Minnesota.

Figure 3.4 Rural Test Site (TURKEY MN037)

Figure 3.5 Suburban Test Site (UNIVERSITY1934)

Figure 3.6 Urban Test Site (SCHREIBER)

3.4 DYNAMIC TESTING METHODOLOGY

The dynamic tests were conducted using a laboratory vehicle outfitted with the Navcom ANT-3001R multifrequency antenna. The low-cost ANN-MS antenna was omitted from the dynamic testing due to poor performance during static testing.

Three routes were chosen for the dynamic testing to reflect the different environments summarized in Table 3.3. The urban route ran through downtown St. Paul and Minneapolis through the Lowry Hill tunnel along interstate 94. The rural route followed Neal Ave. South from Hudson Rd. South to 122^{nd} Ave. South in Woodbury. The last route was a highway with overhead bridges that ran from 94W to U.S. 10 South and back again.

At the beginning of each data collection session, the vehicle was idled for five minutes for the receivers to initialize. Each route took about 20 minutes to drive and was repeated travelling in the opposite direction e.g. northbound and southbound. Each route was repeated 6 times.

Table 3.3 Dynamic testing route descriptions.

Environment	**Route Description**
Urban	94 West Exit 246 to 94 West Exit 230
Bridges	94 West Exit 253 to 494 South to U.S. 10 South to Point Douglas Rd.
Rural	Neal Ave. South from Hudson Rd. South to 122^{nd} St South

CHAPTER 4: EXPERIMENTAL RESULTS

4.1 STATIC TESTING RESULTS

In this section the results of the static tests are presented. Recall that for the static tests the position error that was used to calculate the accuracy metric came from taking the difference between the respective receivers' position solution and the known position of the survey monument where the antennas were located. The values used to populate each figure are found in Appendix A.

4.1.1 Accuracy

Figure 4.1, Figure 4.2 and Figure 4.3 illustrate the horizontal accuracy of each receiver in each environment. In the figures that follow, each bar color represents an antenna type (left to right): blue for the Navcom ANT3001R and orange for the u-blox ANN-MS Patch antenna. The SF-3050 (the ground-truth source for the dynamic tests) requires a specifically designed, multifrequency antenna to operate. As such, for the SF-3050 the only results shown are those using the high-end antenna and are for comparison purposes only.

The most pertinent results are those taken in the rural environment and shown in Figure 4.1 as this can be considered the best-case scenario. Examination of the results indicates that the Eclipse P307 and the NEO-MP8 have performance that is close to the SF-3050 using either antenna.

To get a better picture of RTK fixed-integer errors in the rural environment, an accuracy spread is shown in Figure 4.4 and **Error! Reference source not found.** for the high-quality and patch antennas, respectively. Some receivers exhibit a steep accuracy degradation as its threshold approaches 95%. For the high-end antenna, the Reach and S2525F8-RTK exhibit the degradation around the 75th percentile. For the NEO-M8P and NV08C-RTK, the degradation occurs above the 90th percentile when their spikes occur. For the patch antenna, the NV08C-RTK has poor accuracy from the 50th percentile, while the Piksi Multi degrades after the 70th percentile. This means that the error distribution from these receivers is heavy-tailed relative to a Gaussian distribution. It highlights the fact that receiver manufacturers report their RTK fixed-integer accuracies using different methodologies, such as Circular Error Probability (50th percentile) or 1σ (~68th percentile).

As expected, the suburban and urban environments had a negative impact on the RTK fixed-integer accuracy of the low-cost receivers. Observation of Figure 4.2 and Figure 4.3 show no clear relationship between accuracy in antenna quality. These are environments replete with multipath sources that introduce error into the measured signals, as expected. These challenges are minimized in the open-sky, rural environment. Methods exist for multipath detection and mitigation (Braasch 1995) and are employed by some receivers such as the Eclipse P307, which maintained centimeter-level accuracies across all testing environments. The effects are evident in Figure 4.6 and Figure 4.10, which show the accuracy spread in the urban environment. Using the high-end antenna, most receivers maintain 5 cm accuracy up to the 60th percentile until errors become more pronounced. Using the patch antenna, most receivers have accuracy values worse than 10 cm at the 50th percentile.

Figure 4.8 illustrates the RTK floating-point solution accuracies in the rural environment. While less accurate than the RTK fixed-integer solution, a receiver will return to the floating-point solution if it loses its fixed-integer lock. What is apparent from this figure is that there is no clear relationship between antenna quality and the accuracy of the RTK floating-point solution.

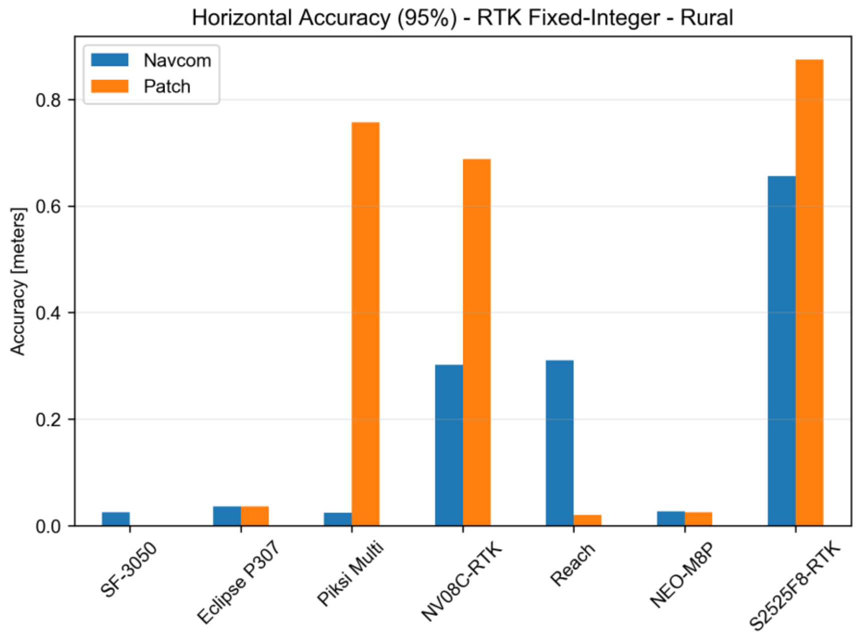


Figure 4.1 Horizontal accuracy for RTK fixed-integer position solutions, rural location.

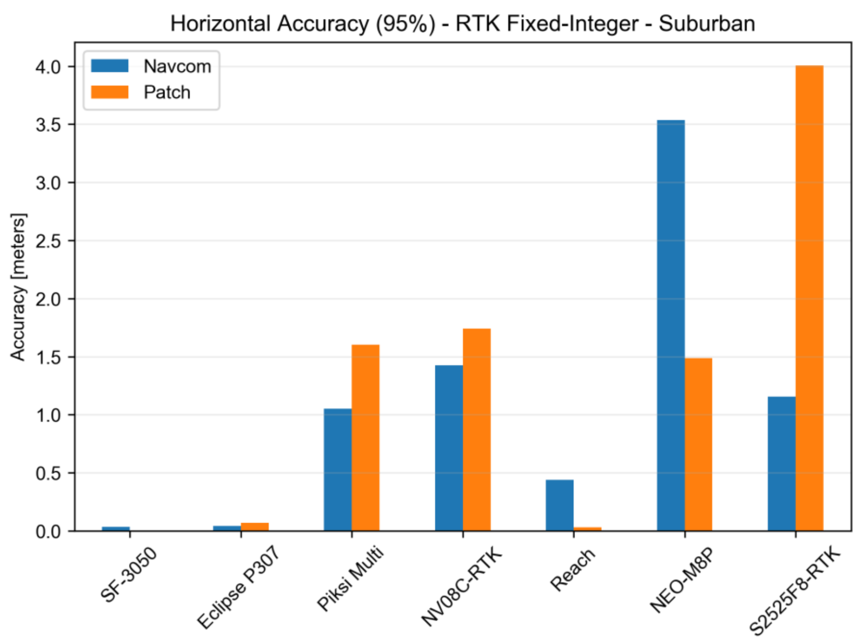


Figure 4.2 Horizontal accuracy for RTK fixed-integer position solutions, suburban location.

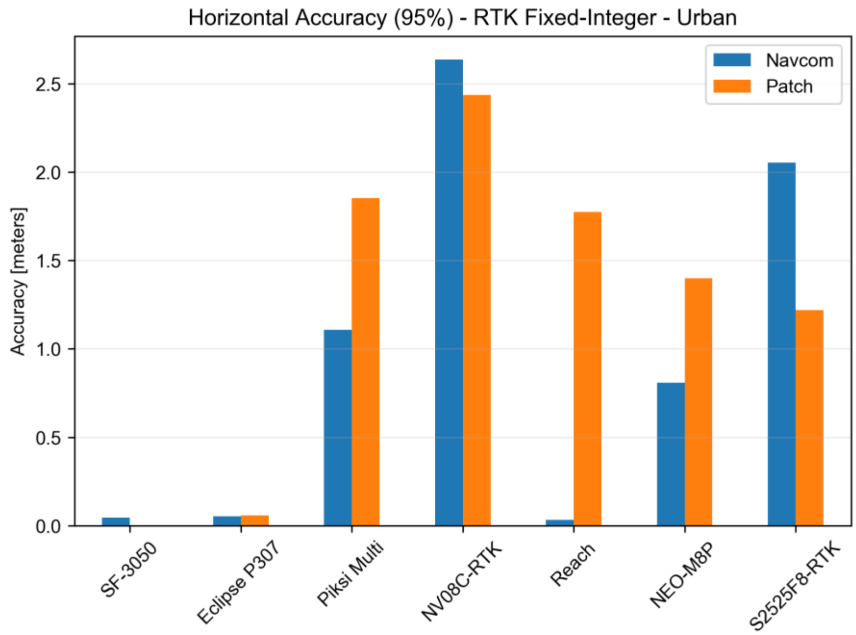


Figure 4.3 Horizontal accuracy for RTK fixed-integer position solutions, urban location.

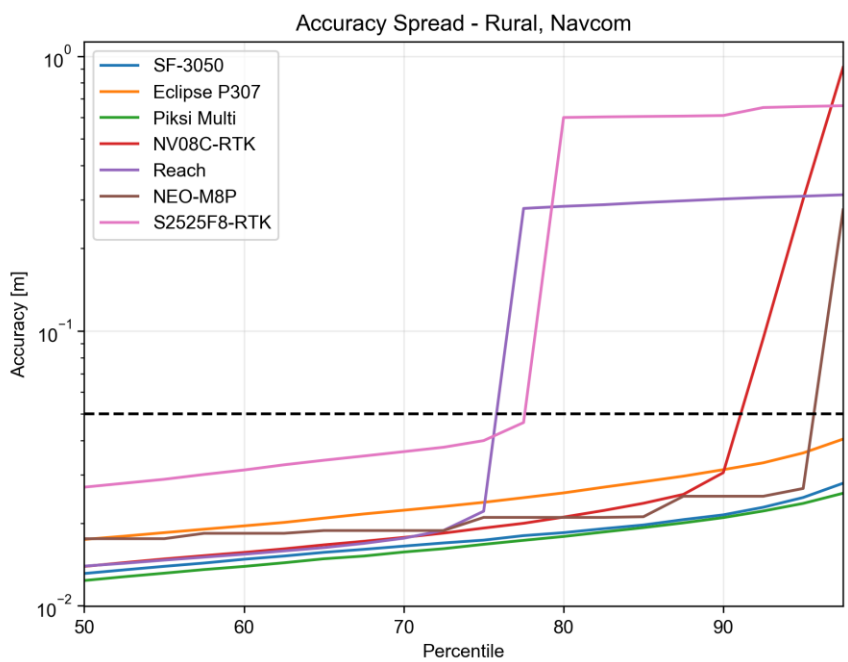


Figure 4.4 Accuracy spread in the rural environment using the Navcom antenna. Black line indicates 5 cm.

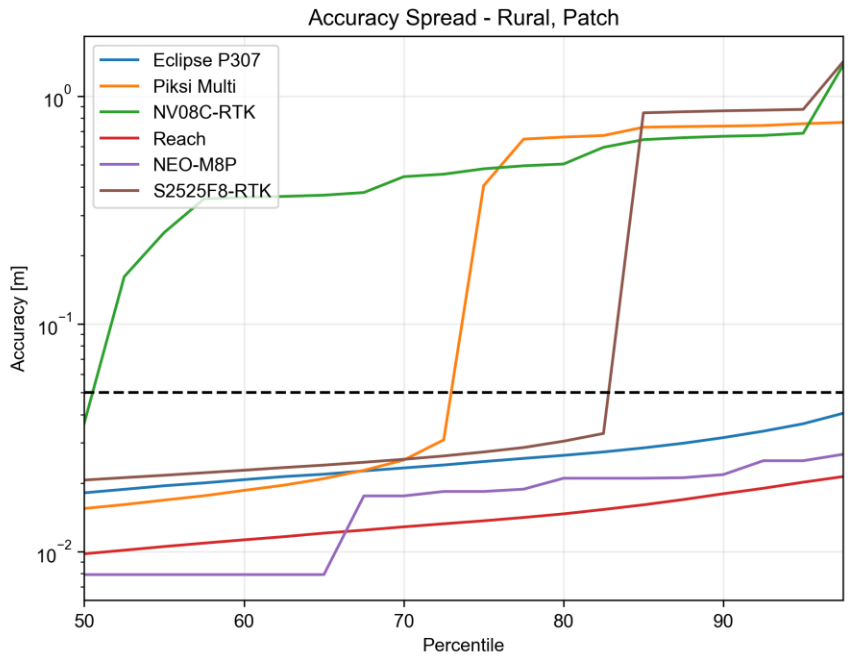


Figure 4.5 Accuracy spread in the rural environment using the patch antenna. Black line indicates 5 cm accuracy.

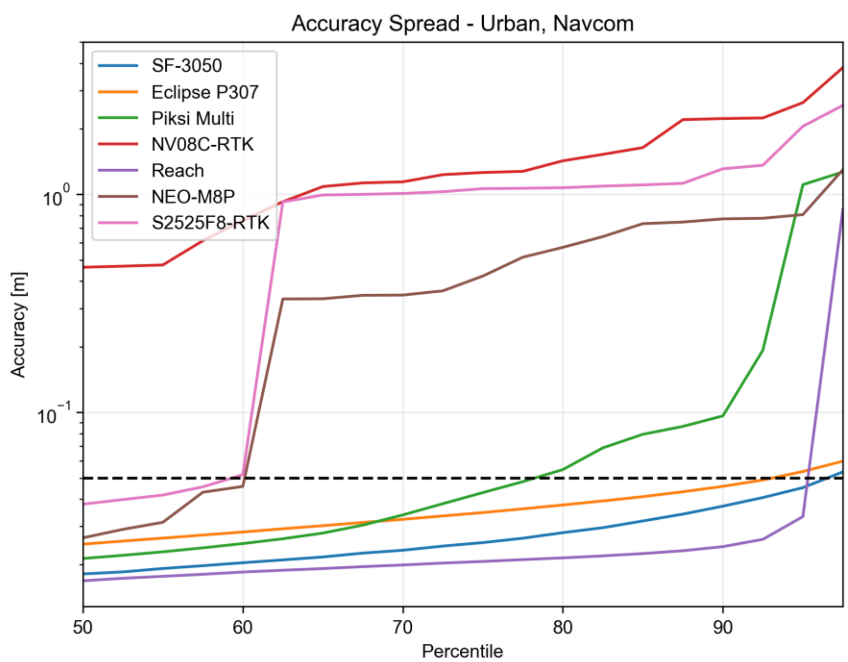


Figure 4.6 Accuracy spread in the urban environment using the Navcom antenna. Black line indicates 5 cm accuracy.

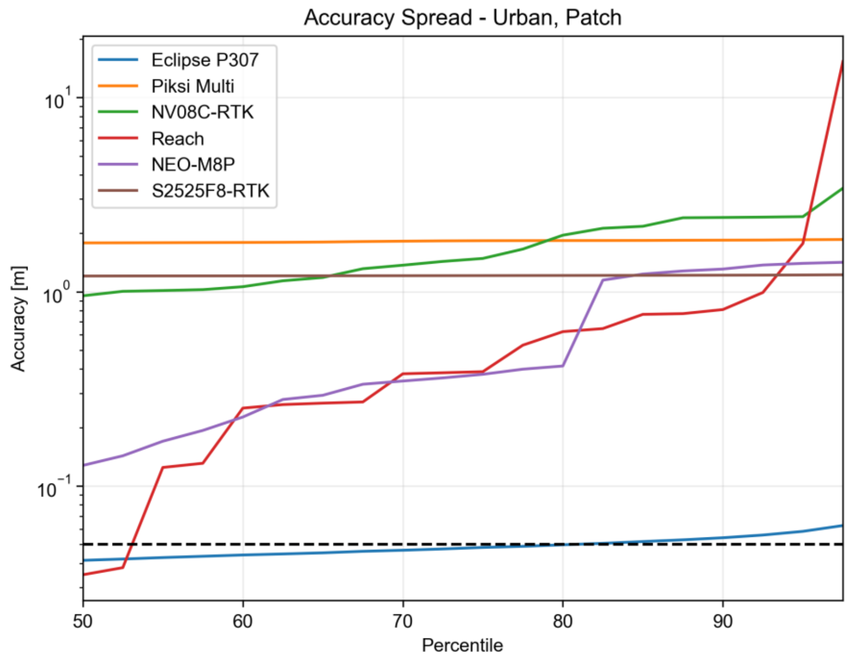


Figure 4.7 Accuracy spread in the urban environment using the patch antenna. Black line indicates 5 cm accuracy.

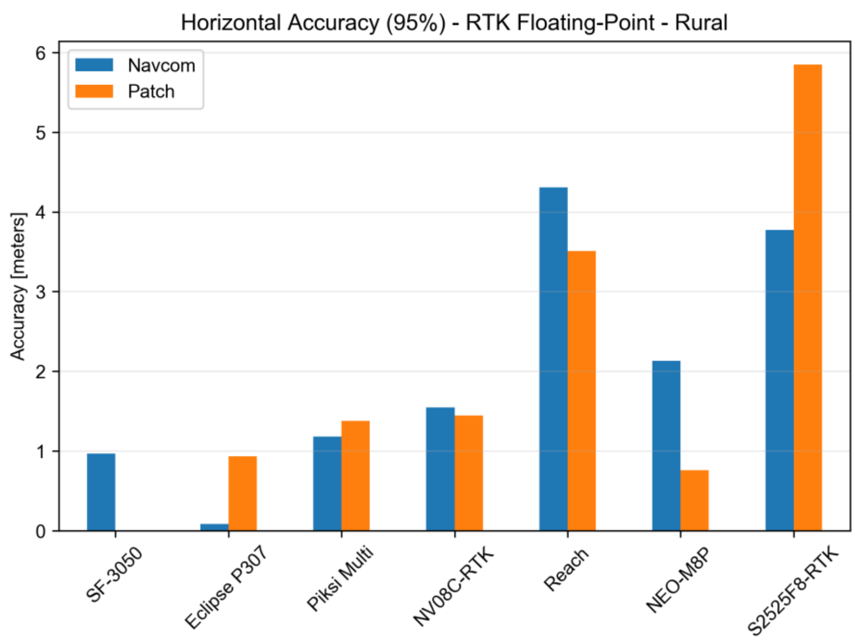


Figure 4.8 Horizontal accuracy for RTK floating-point position solutions, rural location.

4.1.2 Continuity

As noted in Chapter 2, continuity performance was assessed as two metrics. First, the frequency of loss-of-lock was assessed. This metric was computed by observing how often the receivers self-reported a loss of lock over a minute of RTK fixed-integer operation. The receivers' performance in each environment relative to this metric are shown in Figure 4.9, Figure 4.10 and Figure 4.11. Except for the NV08C-RTK and S2525F8-RTK, there was a correlation between environment and the average number of losses where in a rural environment it is less likely to lose an RTK lock. Except for the NV08C-RTK and S2525F8-RTK again, using the high-quality antenna was less likely to result in a loss of lock. The S2525F8-RTK and NV08C-RTK were prone to RTK fixed-integer lock losses in all environments.

The second metric is the average time taken by the receiver to reacquire the RTK fixed-integer solution shown in Figure 4.12, Figure 4.13 and Figure 4.14 for each environment. Using the patch antenna resulted in cases where RTK fixed-integer reacquisition did not take place within the experimental time, such as the Eclipse P307 in the rural and urban environments. This isn't to say it would not reacquire the RTK fixed-integer solution ever, but that it may have taken longer than the data run to do so. In the rural environment, the high-quality antenna usually led to quicker RTK reacquisition times. In the other environments, there is no clear relationship between antenna quality and the RTK reacquisition time. Curiously, the Piksi Multi reported a reacquisition time greater than 800 seconds in the suburban environment using the high-quality antenna.

The reacquisition times reported here are generally well below the RTK fixed-integer initialization times reported later, as the requirement for this statistic was defined less stringent than the RTK initialization time. However, care should be taken in interpreting these results. Since it is not known what the criteria each receiver uses for defining the quality of their RTK locks, it is difficult to say that the absolute performance of one receiver is better than the other.

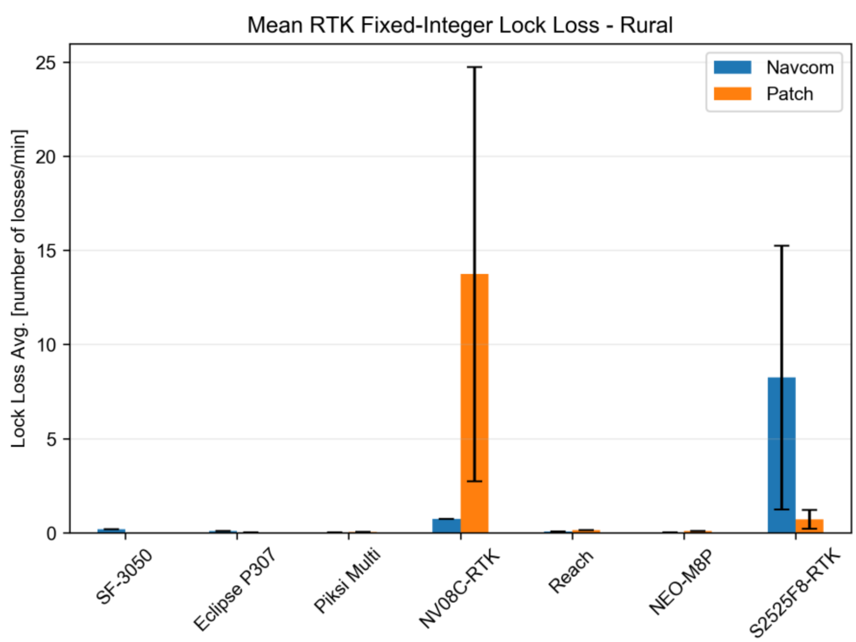


Figure 4.9 Average number of times an RTK fixed-integer solution was lost per RTK minute. Black bars indicate value of one standard deviation. Rural location.

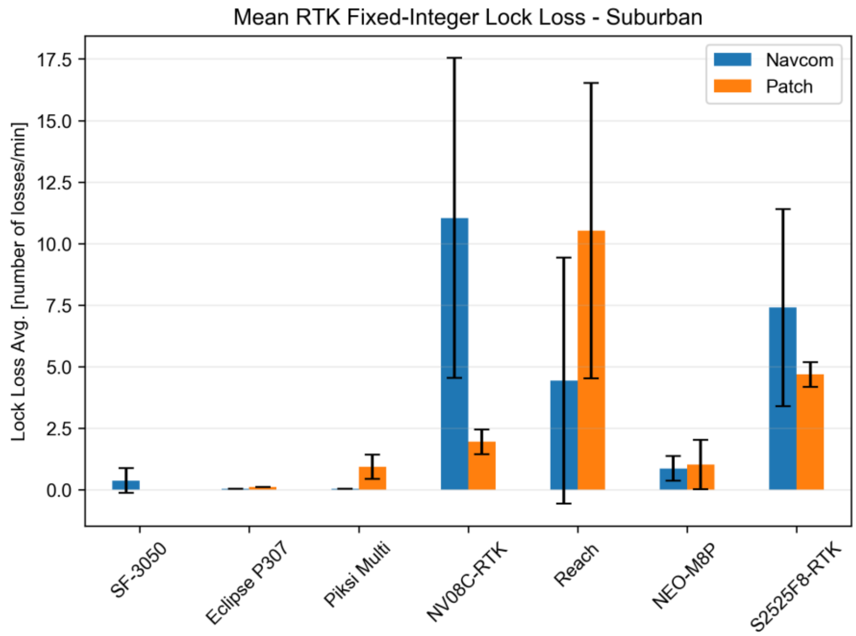


Figure 4.10 Average number of times an RTK fixed-integer solution was lost per RTK minute. Black bars indicate value of one standard deviation. Suburban location.

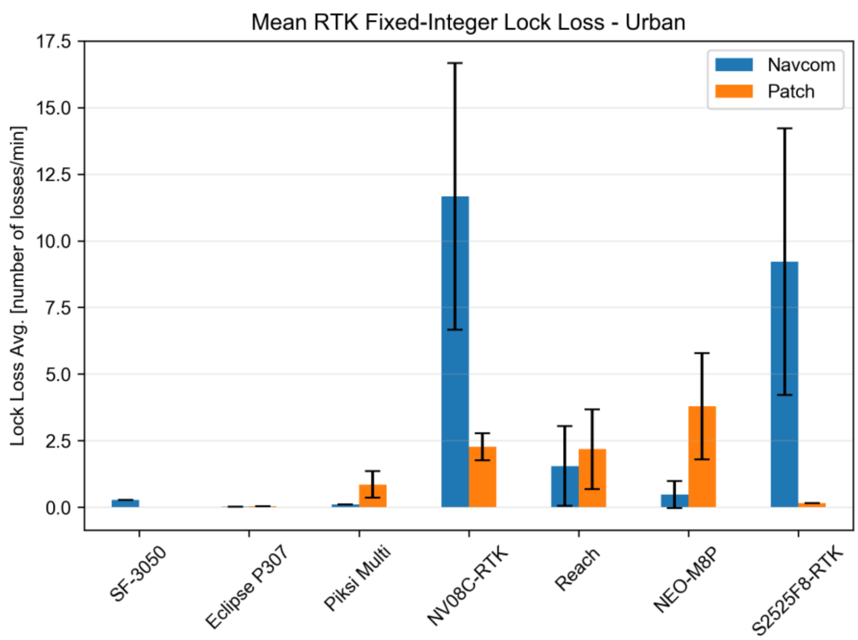


Figure 4.11 Average number of times an RTK fixed-integer solution was lost per RTK minute. Black bars indicate value of one standard deviation. Urban location.

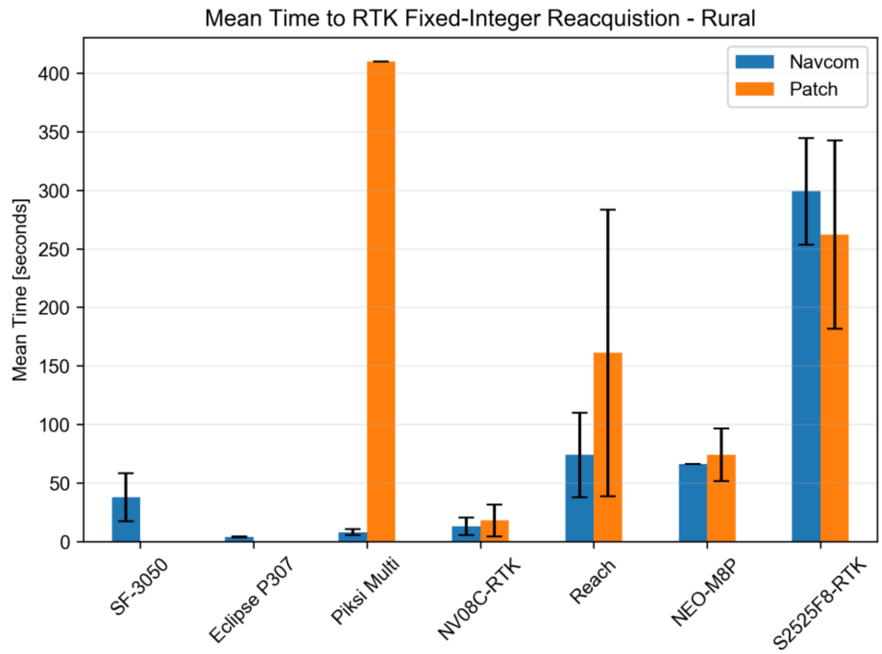


Figure 4.12 Average time to reacquire an RTK fixed-integer solution after a loss. The Eclipse P307 was unable to reacquire an RTK fixed-integer solution after losing it with the patch antenna. Black bars indicate value of one standard deviation. Rural location.

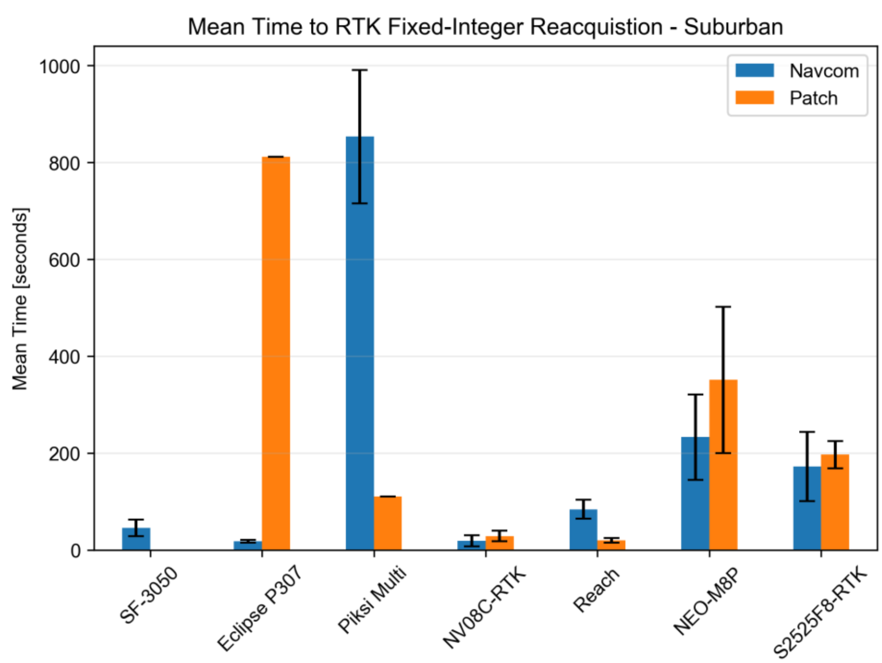


Figure 4.13 Average time to reacquire an RTK fixed-integer solution after a loss. Black bars indicate value of one standard deviation. Suburban location.

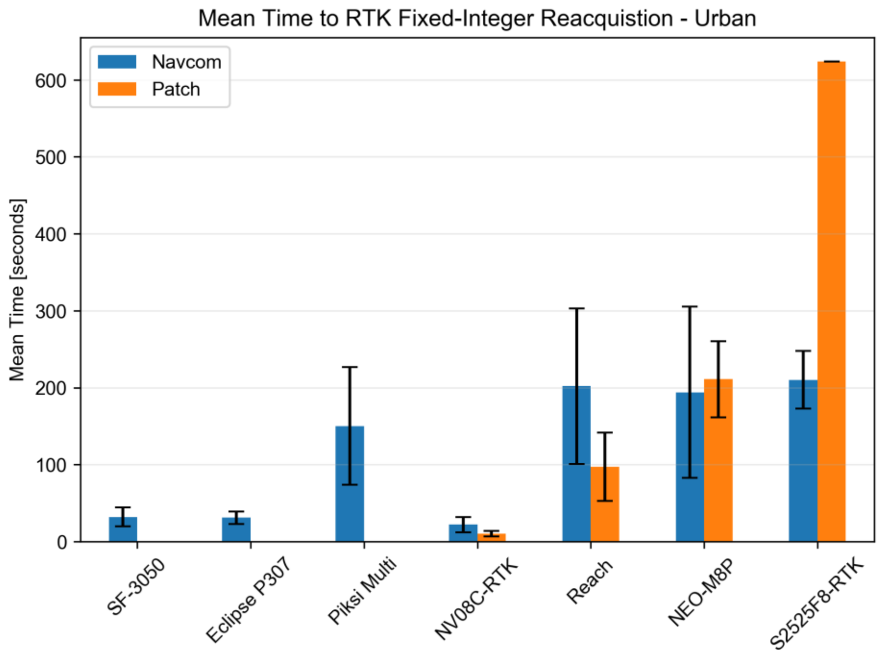


Figure 4.14 Average time to reacquire an RTK fixed-integer solution after a loss. Black bars indicate value of one standard deviation. The Eclipse P307 and Piksi Multi were unable to reacquire an RTK fixed-integer solution after losing it with the patch antenna. Urban location.

4.1.3 Availability

The total percentage of time that a receiver spend in RTK fixed-integer or floating-point mode are shown in Figure 4.15, Figure 4.16 and Figure 4.17 for each environment. Nearly all the receivers spent more time in RTK fixed-integer mode in the rural, open-sky environment regardless of antenna choice. The worst availability was generally observed in the urban environment.

The antenna had a clear effect on the availability of the multifrequency receivers, the Eclipse P307 and the Piksi Multi. Using the high-end antenna, both receivers reported an RTK fixed-integer position more than 95% of the time. However, the availability drops off when the patch antenna was used. This behavior is observed in all environments for the multifrequency receivers.

This relationship is less clear for the single-frequency receivers. In the rural environment, the RTK availability for the single-frequency receivers is nearly the same regardless of antenna quality. In the suburban and urban environments, the high-end antenna more often results in a higher RTK availability (both fixed-integer and floating-point). This could be a result of the build quality, the higher signal gain, or phase-center stability characteristics of the high-quality antenna.

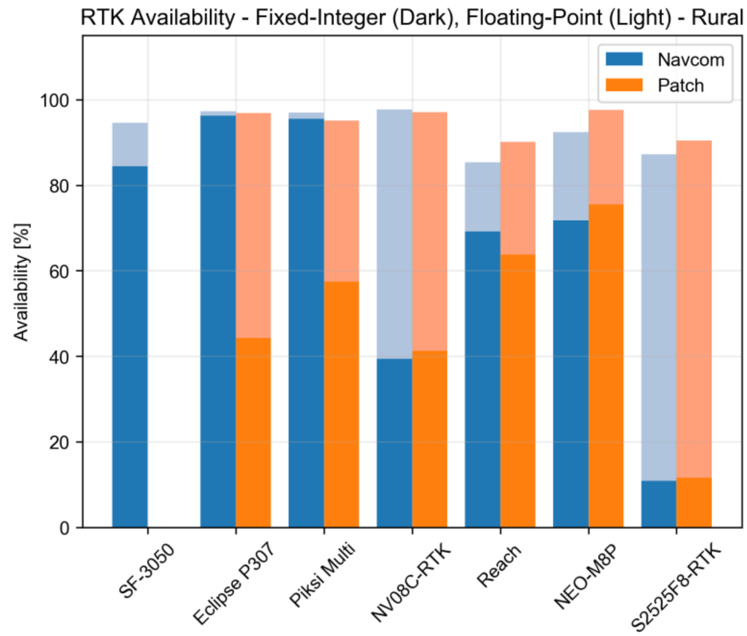


Figure 4.15 Percent of time a receiver reported an RTK solution. Dark bars indicate RTK fixed-integer solution, and light bars indicate RTK floating-point solution. Rural location.

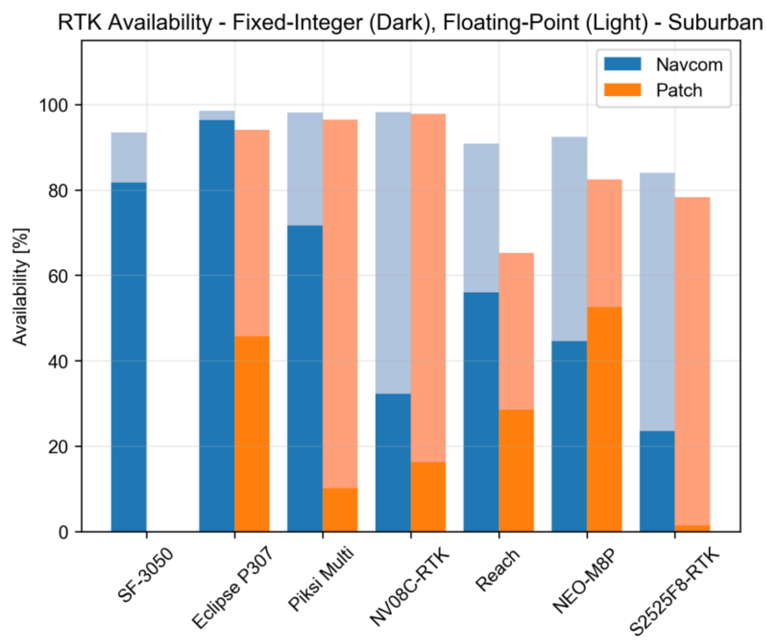


Figure 4.16 Percent of time a receiver reported an RTK solution. Dark bars indicate RTK fixed-integer solution, and light bars indicate RTK floating-point solution. Suburban location.

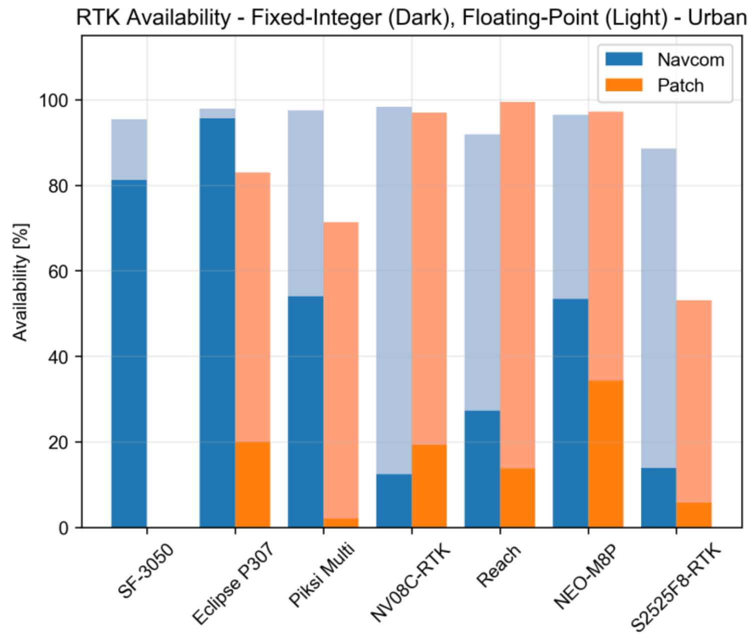


Figure 4.17 Percent of time a receiver reported an RTK solution. Dark bars indicate RTK fixed-integer solution, and light bars indicate RTK floating-point solution. Urban location.

4.1.4 Time to First RTK Solution

The average time to first RTK fixed-integer solution held for 10 seconds are shown in Figure 4.18, Figure 4.19 and Figure 4.20 for each environment. The time to acquire an RTK solution is dependent on the quality of the received GNSS signals (which is affected by propagation errors as well as antenna phase center motion) and the algorithm built into its firmware. Calculating an RTK floating-point solution is relatively simple once a receiver computes its initial position solution and begins to receive corrections data from MnCORS. Thus, the focus is on the fixed-integer solution performance only.

Examining the RTK initialization in the rural environment in Figure 4.18, there is a clear benefit to using the high-quality, multifrequency antenna with the multifrequency receivers. By using two or more frequencies, a receiver essentially has double or more information at hand which will make RTK initialization quicker. This benefit is lost when using the single-frequency patch antenna. Observing the single-frequencies suggest that the initialization process is slightly worsened with the high-quality antenna though the initialization times are nearly the same for the NEO-M8P.

RTK floating-point initialization for the rural environment is presented in Figure 4.21. All receivers had an initialization time under one minute with no dependence on antenna quality. Rather, a receiver would calculate its initial RTK floating-point solution as soon as it had its first valid 3D position fix and MnCORS correction data available. RTK floating-point initialization times did not vary greatly between testing environments.

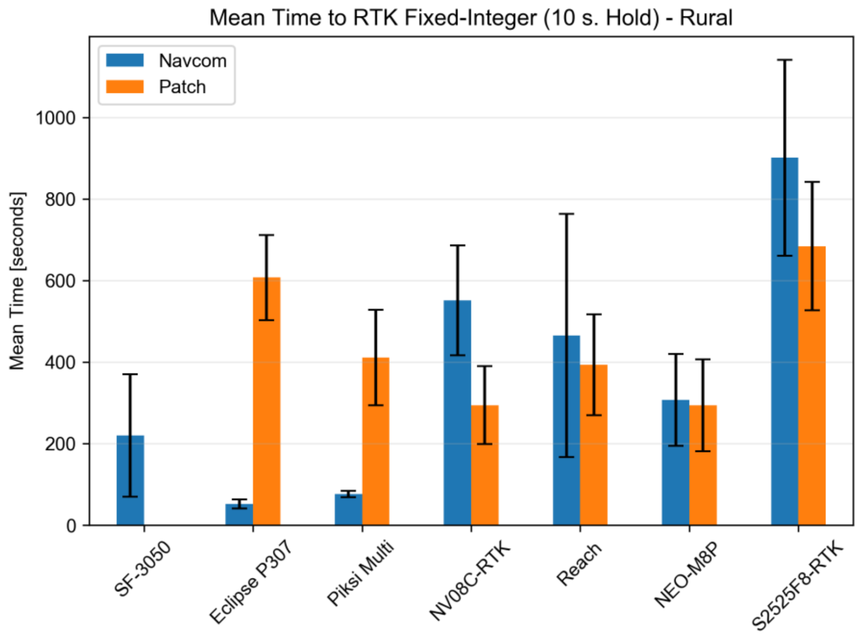


Figure 4.18 Time to first RTK fixed-integer solution held for at least 10 seconds. Black bars indicate value of one standard deviation. Rural location.

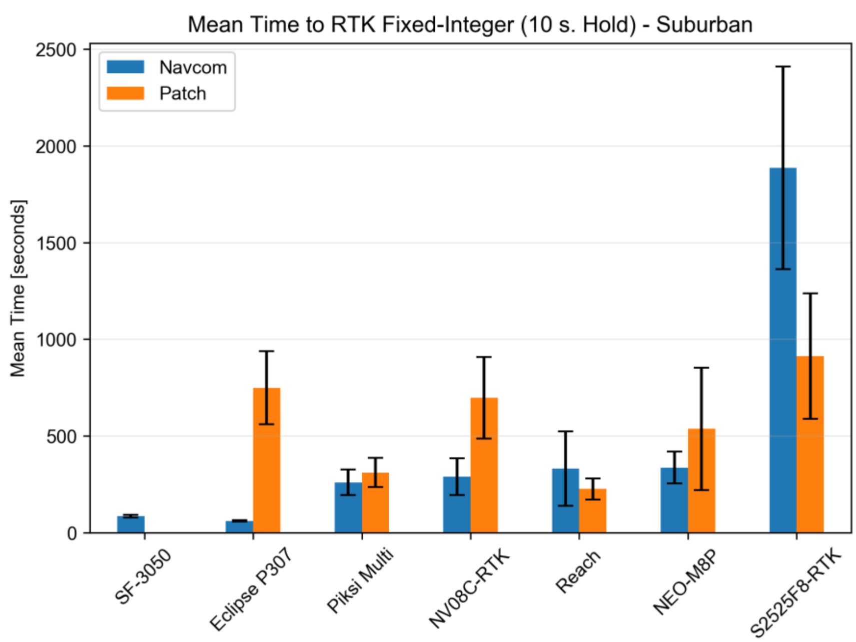


Figure 4.19 Time to first RTK fixed-integer solution held for at least 10 seconds. Black bars indicate value of one standard deviation. Suburban location.

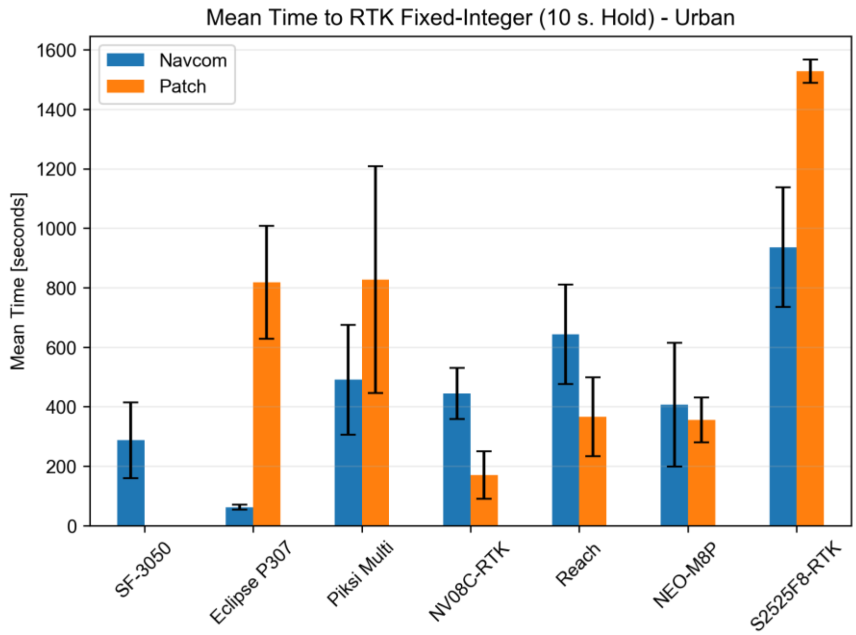


Figure 4.20 Time to first RTK fixed-integer solution held for at least 10 seconds. Black bars indicate value of one standard deviation. Urban location.

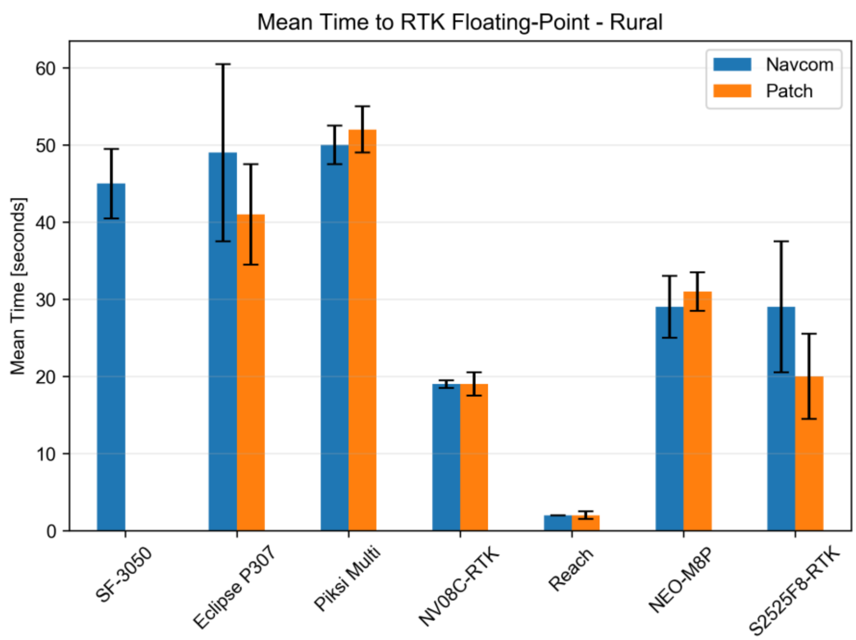


Figure 4.21 Time to first RTK floating-point solution. Black bars indicate value of one standard deviation. Urban location.

4.2 DYNAMIC TESTING RESULTS

The dynamic test metrics are broken down in the same manner as the static test metrics. Time to first RTK solutions have been omitted as they don't contribute to the analysis of the dynamic test cases. The values used to populate each figure are found in Appendix B.

4.2.1 Accuracy

The calculated position output of the Navcom SF-3050 receiver was used as the truth position to calculate the low-cost receiver accuracies. The horizontal accuracies of the fixed-integer solutions are shown in **Error! Reference source not found.**. In the figures that follow each bar color represents a different location (left to right): red for the rural route, brown for the bridges route, and purple for the urban route. The multifrequency receivers maintained an accuracy of 16 cm or better on all routes, whereas the others did not. The Reach maintained accuracies of 2 cm on the suburban and urban routes and NEO-M8P had an accuracy of 15 cm on the bridges route, but worse accuracies on the other routes.

To resolve the poor accuracy characteristics in dynamic testing, a range of accuracies was illustrated. Many receiver manufacturers report 50% or 1σ (~68%) accuracy rather than 95% accuracy. Accuracy spread plots that range from the 50th to 95th percentile are shown in Figure 4.23 and Figure 4.24 for the rural and urban environments. At the 50th and 68th percentiles, accuracies for most receivers is still 10 cm or better. However, once the 90th percentile is reached, many receivers accuracies diverge towards 1+ meters.

The accuracy of the RTK floating-point solutions was within expected ranges, save for the Reach and NEO-M8P. An accuracy spread plot is shown in Figure 4.25. Whereas most receivers maintain floating-point accuracies on the order of 1 meter, anomalies occurred with the Reach and NEO-M8P that resulted in divergent position solutions. The worst of these divergent errors was on the order of 1 kilometer.

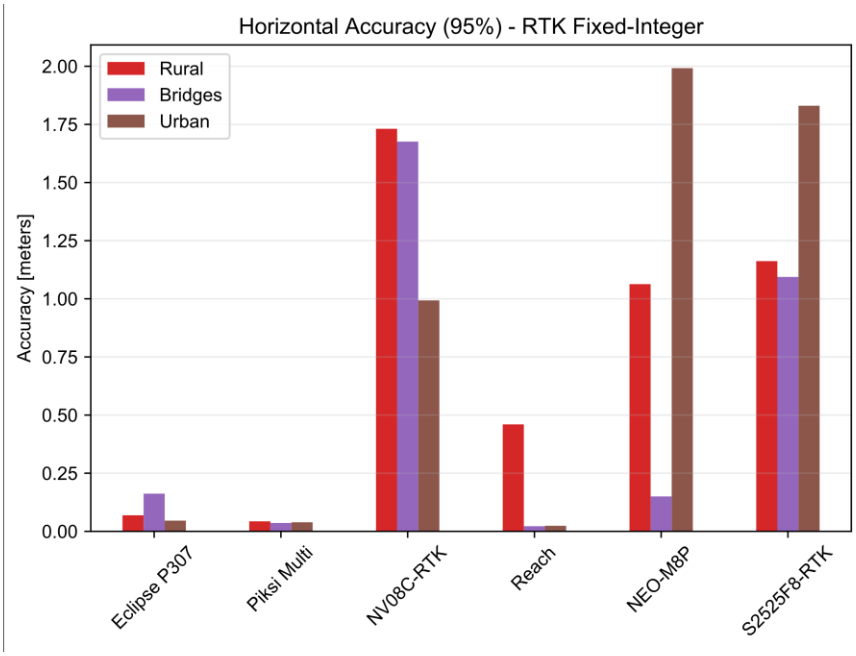


Figure 4.22 Horizontal accuracy for dynamic RTK fixed-integer position solutions.

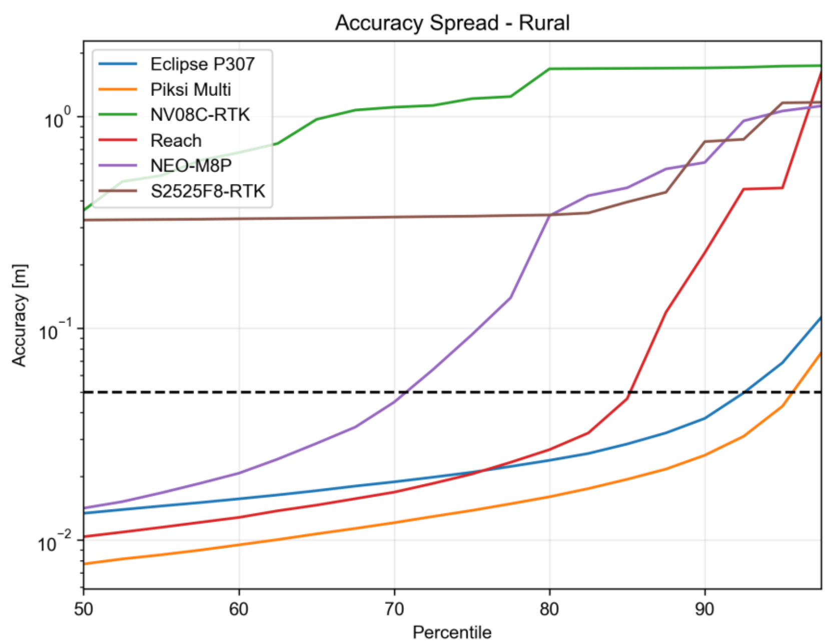


Figure 4.23 Fixed-integer dynamic accuracy spread in the rural environment. Black line indicates 5 cm accuracy.

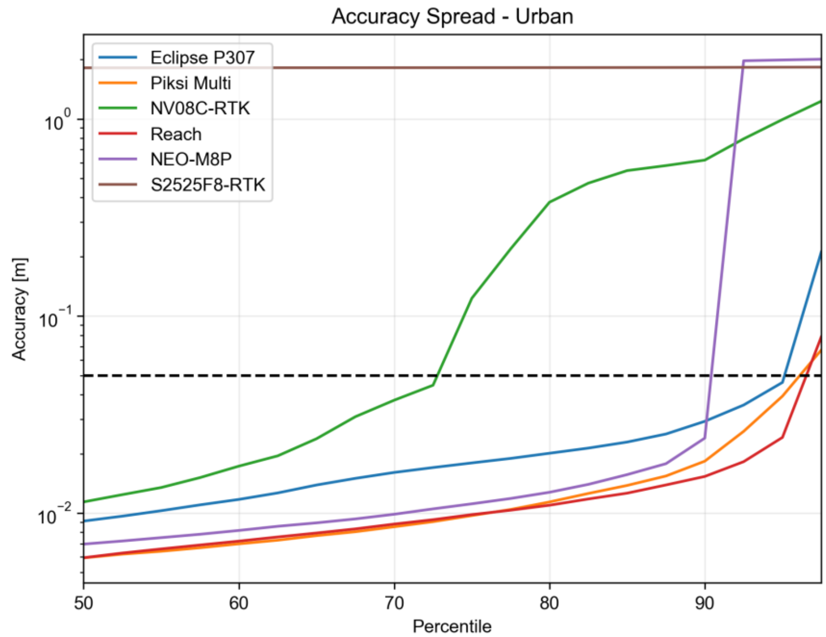


Figure 4.24 Fixed-integer dynamic accuracy spread in the urban environment. Black line indicates 5 cm accuracy.

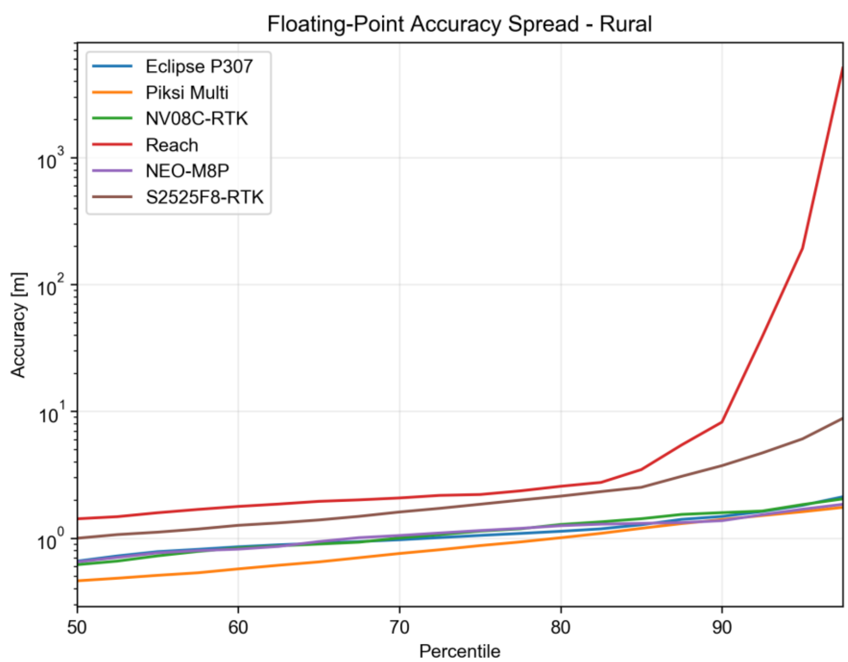


Figure 4.25 Floating-point dynamic accuracy spread in the rural environment.

4.2.2 Continuity

The dynamic route with bridges was chosen specifically to explore the explicit RTK fixed-integer loss of lock frequency and reacquisition time when travelling under bridges. The only receivers that had an RTK fixed-integer lock consistent enough to evaluate the effects of bridges were the Piksi Multi and Eclipse P307. **Error! Reference source not found.** contains information about the mean number of RTK fix losses. These three receivers have the same mean loss of RTK instances in the bridges route.

There was no distinction made in the data between a loss of RTK due to bridges or a different cause e.g. a hauling truck or a retaining wall. However, Figure 4.28 and Figure 4.29 show a portion of the bridge route with colors corresponding to RTK-position fix type. The Eclipse P307 fell into an RTK floating-point solution almost immediately, then reacquired the RTK fixed-integer solution 19 seconds later. The Piksi Multi completely lost its RTK solution after travelling under a bridge and takes about 41 seconds to reacquire an RTK fixed-integer solution. The SF-3050 reacquired its RTK lock in 7 seconds.

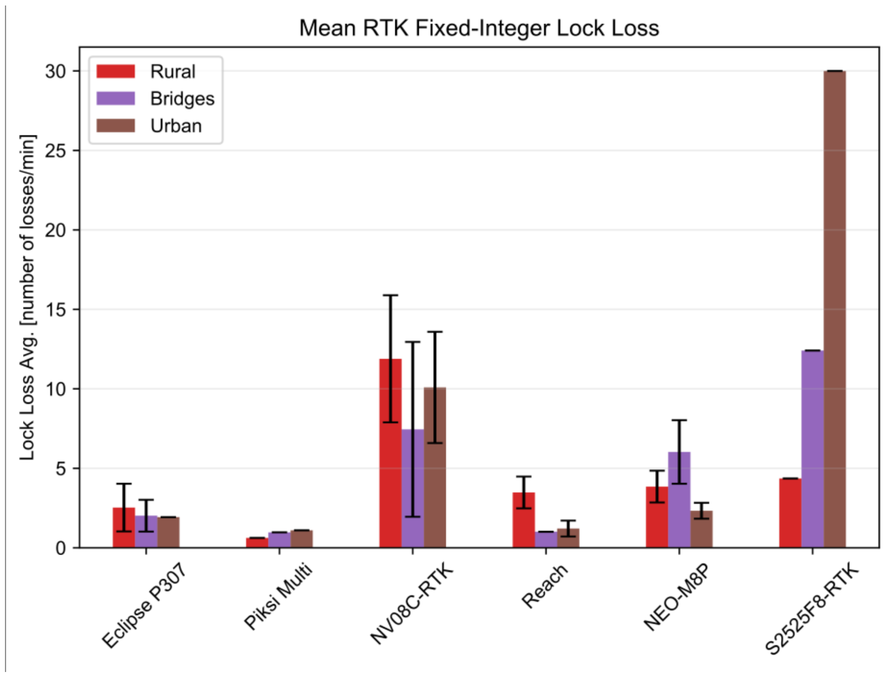


Figure 4.26 Mean Number of RTK Fixed-Integer Lock Losses

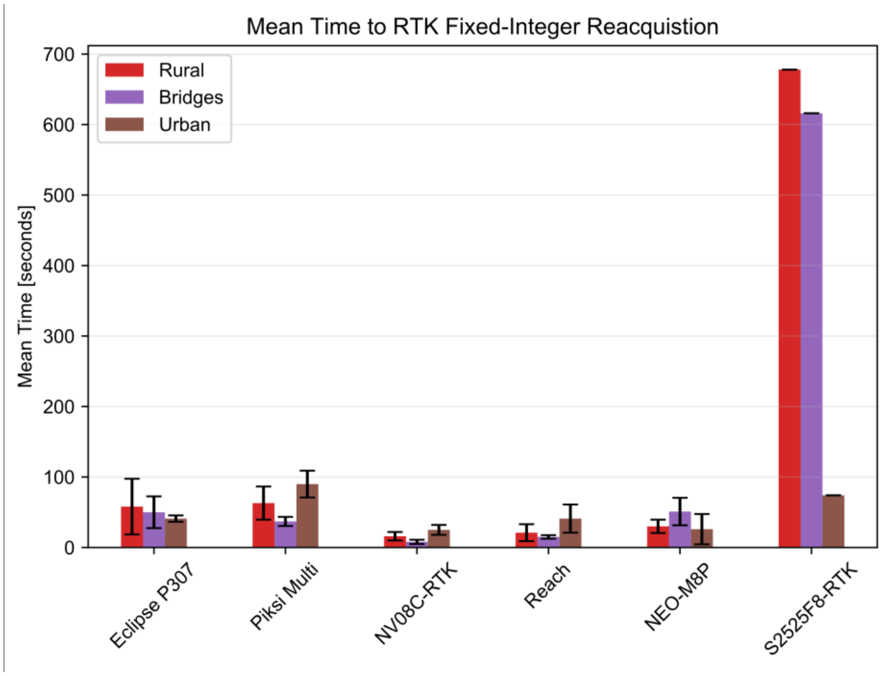
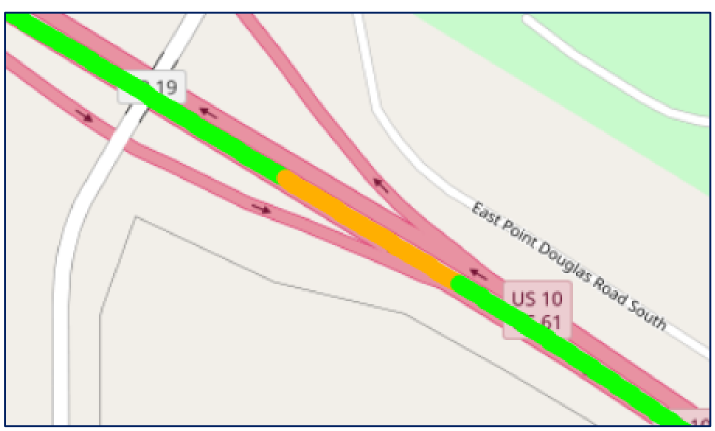


Figure 4.27 Mean Time to RTK Fixed-Integer Reacquisition

A: Piksi Multi

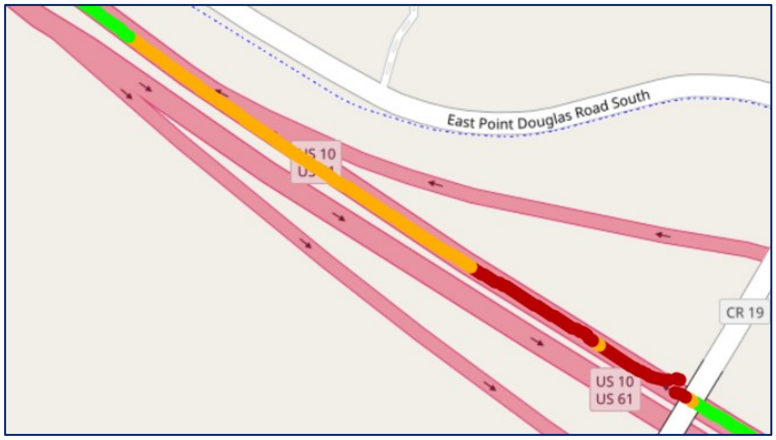
B: Eclipse P307



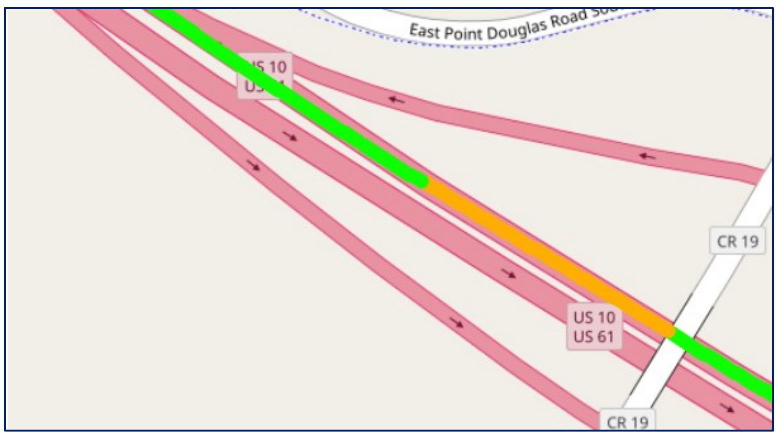
C: SF-3050

Figure 4.28 RTK losses and reacquisitions on the southbound bridges route.

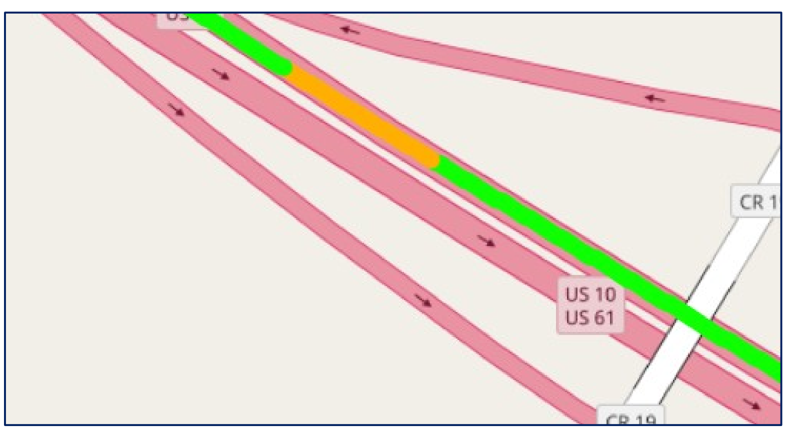
Green are fixed-integer solutions, orange are floating-point solutions, and red is any other fix type.



A: Piksi Multi



B: Eclipse P307



C: SF-3050

Figure 4.29 RTK losses and reacquisitions on the northbound bridges route.

Green are fixed-integer solutions, orange are floating-point solutions, and red is any other fix type.

4.2.3 Availability

The RTK availability for each receiver is shown in Figure 4.30. The availability of the RTK fixed-integer solution was much lower for all receivers in the dynamic case than the static case. The single-frequency receivers had a best-case fixed-integer availability of 27% (the NEO-M8P on the rural route). When both RTK fixed-integer and floating-point solutions were considered, all the receivers perform similarly. The Piksi Multi and Eclipse P307 had similar RTK fixed-integer availability on all routes. The multifrequency receivers overall had a higher availability, with the worst-case of the Piksi Multi in the urban environment outperforming all of the single-frequency receivers.

Overall, these availability numbers are poorer than anticipated and short follow-up tests are being completed to discern any effects the apparatus may have had on the results.

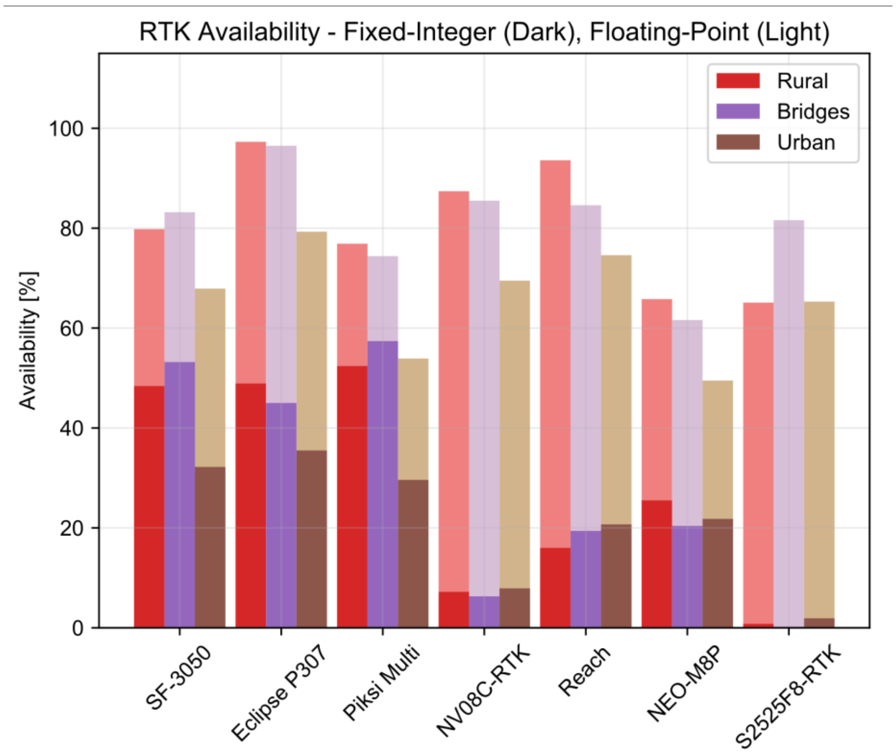


Figure 4.30 Mean Time in RTK Fixed-Integer Solution

CHAPTER 5: CONCLUSIONS

5.1 DISCUSSION AND RECOMMENDATIONS

This work evaluated a set of low-cost (costing less than $540 USD), RTK-capable receivers to determine whether their performance was comparable to that of existing, high-end (and expensive) receivers. The receivers evaluated were the Swift Piksi Multi, NVS Technologies NV08C-RTK, Emlid Reach, u-blox NEO-MP8 and Skytraq S2525F8. In addition, one mid-grade ($1,000 - $2,000 USD) receiver, the Hemisphere Eclipse P307, was evaluated. The receivers were tested in static and dynamic use-cases. The performance was measured relative to the metrics of 95th percentile accuracy, continuity (frequency of loss of a fixed-integer RTK solution and the time required to reacquire it), availability (fraction of the time receiver is generating a fixed-integer RTK solution and float RTK solution) and time to first fix or TTFF (time to acquire a fixed-integer RTK solution and remain in it for at least 10 seconds). For static tests, the receivers were placed at a known survey marker. For the dynamic tests, the position output of the receivers was compared to the output of the Navcom SF-3050, a high-quality, survey-grade receiver.

The results of this evaluation showed that the low-cost receivers, in general, do not perform at a level of existing high-end receivers. It is difficult to rank the receivers from best to worst because different receivers excelled with respect to one metric but performed poorly relative to another one. Despite this ambiguity, the following observations can be made about all of the L1-only, low-cost receivers evaluated in this work:

1. They can achieve centimeter-level accuracy in static applications in rural environments.
2. They perform better when using a high-quality antenna versus a low-quality antenna.
3. They cannot hold an RTK fixed-integer solution for any significant time in dynamic applications.
4. They spend most of their time in an RTK floating-point solution.

The multifrequency Swift Piksi performed better than the L1-only, low-cost receivers but displayed the same shortcomings (degraded accuracy, worse availability) in the suburban and urban environments during static testing. It had consistent performance across all metrics during the dynamic testing, having better metrics across the board than the single-frequency receivers. However, it did take longer than the reference receiver and the Eclipse P307 to reacquire an RTK fixed-integer lock after travelling under a bridge.

The mid-range receiver's (Hemisphere Eclipse P307) performance during static testing compared favorably to the high-end, survey-grade receiver. It maintained consistent accuracy, availability and continuity statistics in all environments using the high-quality antenna. During the dynamic testing, its performance was on-par with the other multifrequency receivers including the SF-3050, and it outperformed all of the single-frequency receivers.

While the data collected considered performance in urban, suburban and rural settings, extended discussions are limited to the rural environment performance only. This is valid because the rural environment represents the most benign GNSS operational scenario and thus represents the upper bound (or best) performance that can be expected from these receivers.

5.1.1 Static Applications

The best-case static statistics for each receiver operating in the rural environment are shown in Table 5.1. Except for the NV08C-RTK and S2525F8-RTK, all the receivers had an RTK fixed-integer accuracy of 3.6 cm or better. For some receivers, the low-quality patch antenna provided better performance in some metrics, including total RTK availability and the time to first RTK fixed-integer solution (held for 10 seconds). However, RTK fixed-integer availability is better with the high-quality antenna except for the NEO-M8P and S2525F8-RTK, which had a slightly better (though still low) availability with the patch antenna.

While the RTK fixed-integer position is the most-desired output, many of the low-cost receivers spent more time in RTK floating-point mode than fixed-integer mode. While the SF-3050 and Eclipse P307 maintained a floating-point accuracy of 1 meter or better, all the low-cost receivers had cases where accuracies were 1 meter or worse.

Table 5.1 Best-case statistics for each receiver from static testing in the rural environment.

Receiver	**Accuracy [centimeters]**	**Loss of Lock [losses / min]**	**Reacquisition Time [seconds]**	**Fixed-Integer Availability**	**Total RTK Availability**	**TTF RTK Fix (10 second hold)**
Eclipse P307	3.6	0.09	4	96.2%	97.3%	52
Piksi Multi	2.4	0.03	8	95.5%	97%	76
NV08C-RTK	30.2	0.73	13	39.4%	97.7%	294*
Reach	2.0*	0.07	74	69.2%	90.1%*	393*
NEO-M8P	2.5*	0.03	66	75.5%*	97.6%*	294*
S2525F8-RTK	65.7	0.72*	262*	11.6%*	90.4%*	684*

* - using the patch antenna.

5.1.2 Dynamic Applications

For dynamic applications, the statistics for each receiver are contained in Table 5.2 for the rural route, as it should be considered the ideal setting. The low-cost receivers exhibited poor performance for most metrics. The only single-frequency receiver with decent 95% accuracy was the Reach, though it was marred with a fixed-integer availability of 16%. Considering again Figure 4.23, the accuracies are centimeter-level at low percentiles, but outlier position errors worsen the accuracy at higher percentiles. Among the multifrequency receivers, the Piksi Multi had an accuracy of 4.8 cm and the Eclipse P307 had an accuracy of 6.9 cm. Their continuity and availability statistics were similar, though the total RTK availability of the Eclipse P307 was less.

Table 5.2 Statistics for each receiver from dynamic testing on the rural route.

Receiver	**Accuracy [centimeters]**	**Loss of Lock [losses / min]**	**Reacquisition Time [seconds]**	**Fixed-Integer Availability**	**Total RTK Availability**
Eclipse P307	6.9	1.24	41	48.9%	97.3%
Piksi Multi	4.3	2.53	58	52.4%	76.9%
NV08C-RTK	173.1	0.62	63	7.2%	87.4%
Reach	46.0	11.89	16	16%	93.6%
NEO-M8P	106.9	3.48	21	25.5%	65.8%
S2525F8-RTK	116.2	3.85	30	0.8%	65.1%

5.2 ERROR SOURCES

For completion, a brief discussion will be had on possible sources of error in this study. There were some unexpected inconsistencies in the results whose sources can only be inferred at this point. One unknown systematic factor is the effect of using an active 8-way signal-splitter with a gain of 13dB to share GNSS signals (GPS Networking, 2015). A gain of 13dB gain with the high-end antenna's gain of 39db results in an effective signal gain of 52dB, which may cause gain saturation. Other effects may involve group or phase delay, though the splitter was designed to minimize these. Follow-on testing is being conducted to determine if the splitter had a significant effect.

The tests were conducted over different days, though it was not coordinated to take place at the same times. Thus, there may be unintended consequence of satellite constellations with geometries that are worse than others affecting the final accuracy values.

For dynamic testing, event-based signal interference was not considered. These events include driving past a large semitruck, retaining wall or other obstruction that would block the antenna. In addition, there were points where the cell-phone signal could have been weaker or lost completely, meaning corrections data from MnCORS was delayed or unavailable. There was no method in place to record this loss for analysis.

5.3 FUTURE RESEARCH

Future studies of low-cost GNSS receivers could focus on fewer receivers. A smaller, more in-depth study of the highest-performing low-cost receivers may be warranted. These could be tested rigorously alongside a high-end receiver like the SF-3050, or even a mid-range receiver like the Hemisphere Eclipse P307. In addition, mid-range quality antennas are recommended for further study.

A trove of position output data has been collected from this project, and a more detailed analysis could be performed that incorporates other position and quality of solution outputs not discussed here (dilution of precision, age of differential corrections, etc.).

The program developed for interfacing with receivers and collecting data could be greatly expanded to become a robust, useful research tool for GNSS studies. Future features that could be incorporated include:

- Automatic software cold-start of receivers between testing
- Manual event logging for correlation studies, e.g., a large semi-truck driving by
- Graphical, real-time plotting of positions
- Built-in tools for precision post-processing using custom or existing tools, e.g., RTKLIB

5.4 CONCLUSION

A comprehensive study of low-cost RTK capable receivers was performed. The study included three environments (rural, suburban and urban) with static and dynamic test regimes to gauge the effects of multipath on the performance of the receivers. The low-cost receivers were compared with a high-end receiver and found to have a less consistent performance across the different testing environments.

For static applications, low-cost receivers may be a viable option depending on the accuracy and continuity requirements. Not surprisingly, the low-cost receivers had nominal performance in the rural environment where there was minimal multipath interference. Three of the five low-cost receivers had a horizontal RTK fixed-integer position accuracy of 2.6 cm (95%) or better while the other two had sub-meter accuracy. In the rural environment, the single-frequency receivers had poorer RTK availability and time to first RTK fix compared to the multifrequency receivers.

For dynamic applications, none of the L1-only receivers performed at a level that warrants future study due primarily to their low RTK fixed-integer availability and continuity. In addition, some single frequency receivers had large position errors relative to the reference receiver's position solution. Rather, only multifrequency receivers are recommended for future studies of dynamic applications as the exhibited sub-10 cm RTK fixed-integer accuracy (with respect to the reference receiver's position solution) and had better continuity and availability statistics.

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APPENDIX A
STATIC TESTING TABLES

Table A.1 Horizontal accuracy for RTK fixed-integer positions.

Fix Horizontal Accuracy [m]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	0.037	0.025	0.034	0.045	--	--	--
Eclipse P307	0.048	0.036	0.041	0.054	0.036	0.069	0.058
Piksi Multi	0.968	0.024	1.050	1.108	0.757	1.603	1.853
NV08C-RTK	1.663	0.302	1.427	2.637	0.688	1.741	2.437
Reach	0.392	0.310	0.438	0.033	0.020	0.029	1.773
NEO-M8P	1.484	0.027	3.536	0.808	0.025	1.488	1.400
S2525F8	1.325	0.656	1.156	2.054	0.875	4.008	1.220

Table A.2 Horizontal accuracy for RTK floating-point positions.

Float Horizontal Accuracy [m]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	0.950	0.967	0.687	1.016	--	--	--
Eclipse P307	1.265	0.082	0.804	1.364	0.935	1.040	1.835
Piksi Multi	13.885	1.183	3.134	19.68	1.379	4.033	23.007
NV08C-RTK	2.795	1.544	1.726	3.593	1.445	3.814	4.131
Reach	16.972	4.305	2.970	2.522	3.509	34.324	10.434
NEO-M8P	3.323	2.130	3.445	1.366	0.757	1.216	0.781
S2525F8	7.074	3.771	6.858	8.397	5.850	6.585	10.045

Table A.3 Mean number of RTK fix losses per RTK minute.

RTK Losses [loss/min]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	0.29	0.20	0.37	0.28	--	--	--
Eclipse P307	0.05	0.09	0.03	0.03	0.02	0.11	0.04
Piksi Multi	0.21	0.03	0.03	0.11	0.04	0.93	0.86
NV08C-RTK	7.91	0.73	11.04	11.66	13.74	1.95	2.27
Reach	2.81	0.07	4.43	1.55	0.13	10.53	2.18
NEO-M8P	1.02	0.03	0.86	0.48	0.09	1.02	3.79
S2525F8	5.73	8.24	7.40	9.22	0.72	4.68	0.16

Table A.4 Mean time to reacquire an RTK fixed-integer lock.

RTK Reacq. Time [s]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	36	38	46	32	--	--	--
Eclipse P307	98	4	18	31	--	812	--
Piksi Multi	299	8	853	150	410	110	--
NV08C-RTK	17	13	19	22	18	29	10
Reach	132	74	84	202	161	20	97
NEO-M8P	195	66	233	194	74	351	211
S2525F8	253	299	172	210	262	197	624

Table A.5 RTK fixed-integer availability.

Time in RTK Fix [%]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	50.8	84.4	81.7	81.2	--	--	--
Eclipse P307	72.2	96.2	96.3	95.6	44.3	45.7	20.0
Piksi Multi	51.3	95.5	71.7	54.0	57.5	10.2	2.1
NV08C-RTK	26.9	39.4	32.2	12.4	41.3	16.3	19.3
Reach	43.4	69.2	56.0	27.3	63.8	28.5	13.8
NEO-M8P	55.0	71.8	44.6	53.4	75.5	52.6	34.3
S2525F8	12.6	10.9	23.5	13.9	11.6	1.4	5.8

Table A.6 RTK floating-point and fixed-integer availability.

Time in Any RTK [%]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	58.0	94.6	93.4	95.4	--	--	--
Eclipse P307	95.6	97.3	98.5	97.9	96.9	94.1	83.0
Piksi Multi	93.5	97.0	98.1	97.5	95.1	96.4	71.4
NV08C-RTK	97.8	97.7	98.2	98.3	97.1	97.8	97.0
Reach	88.3	85.4	90.8	91.9	90.1	65.2	99.5
NEO-M8P	93.6	92.4	92.4	96.5	97.6	82.4	97.2
S2525F8	81.6	87.2	84.0	88.6	90.4	78.3	53.1

Table A.7 Mean time to first RTK fixed-integer solution.

Time to RTK Fix [s]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	173	92	84	157	--	--	--
Eclipse P307	319	50	61	62	607	749	818
Piksi Multi	350	76	260	491	411	281	827
NV08C-RTK	52	60	76	65	35	28	37
Reach	263	440	95	204	206	605	160
NEO-M8P	273	307	247	357	293	139	218
S2525F8	831	842	1153	918	558	507	910

Table A.8 Mean time to first RTK fixed-integer solution, held for 10 seconds.

Time to RTK Held [s]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	256	220	86	287	--	--	--
Eclipse P307	319	52	61	62	607	749	818
Piksi Multi	353	76	260	491	411	311	827
NV08C-RTK	376	551	290	445	294	697	170
Reach	432	465	332	643	393	226	366
NEO-M8P	360	307	337	407	294	537	356
S2525F8	1073	901	1887	936	684	913	1528

Table A.9 Mean time to first RTK floating-point solution.

Time to RTK Float [s]		High-Quality Antenna			Low-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban	Rural	Suburban	Urban
SF-3050	126	45	66	76	--	--	--
Eclipse P307	56	49	46	50	41	74	89
Piksi Multi	61	50	53	54	52	62	107
NV08C-RTK	20	19	21	18	19	22	22
Reach	2	2	2	2	2	2	2
NEO-M8P	36	29	34	34	31	51	44
S2525F8	41	29	33	42	20	50	94

APPENDIX B
DYNAMIC TESTING TABLES

Table B.1 Horizontal accuracy for RTK fixed-integer positions.

Fix Horizontal Accuracy [m]				
Receiver	All Data	Rural	Bridges	Urban
Eclipse P307	0.088	0.069	0.162	0.046
Piksi Multi	0.038	0.043	0.036	0.039
NV08C-RTK	1.696	1.731	1.676	0.993
Reach	0.076	0.460	0.022	0.024
NEO-M8P	0.969	1.063	0.150	1.992
S2525F8	1.828	1.162	1.094	1.830

Table B.2 Horizontal accuracy for RTK floating-point positions.

Float Horizontal Accuracy [m]				
Receiver	All Data	Rural	Bridges	Urban
Eclipse P307	2.448	1.815	2.576	2.776
Piksi Multi	1.747	1.615	1.92	1.805
NV08C-RTK	2.152	1.839	2.127	2.885
Reach	99.493	192.831	5000.717	37.748
NEO-M8P	4998.053	1.692	4999.902	5001.144
S2525F8	8.078	6.064	7.526	10.079

Table B.3 Mean number of RTK fix losses per RTK minute.

RTK Losses [num/min]	High-Quality Antenna			
Receiver	All Data	Rural	Bridges	Urban
SF-3050	1.50	1.24	1.05	2.15
Eclipse P307	2.14	2.53	2.02	1.93
Piksi Multi	0.89	0.62	0.97	1.10
NV08C-RTK	9.81	11.89	7.45	10.09
Reach	2.01	3.48	1.01	1.21
NEO-M8P	4.10	3.85	6.03	2.33
S2525F8	15.59	4.36	12.41	30.0

Table B.4 Mean time to reacquire an RTK fixed-integer lock.

RTK Reacq. Time[s]		High-Quality Antenna		
Receiver	All Data	Rural	Suburban	Urban
SF-3050	49	41	45	59
Eclipse P307	50	58	50	41
Piksi Multi	65	63	37	90
NV08C-RTK	17	16	8	25
Reach	27	21	15	41
NEO-M8P	36	30	51	26
S2525F8	456	678	616	74

Table B.5 RTK fixed-integer availability.

Time in RTK Fix [%]		High-Quality Antenna		
Receiver	All Data	Rural	Bridges	Urban
SF-3050	44.9	48.4	53.2	32.2
Eclipse P307	43.2	48.9	45.0	35.5
Piksi Multi	46.8	52.4	57.4	29.6
NV08C-RTK	7.1	7.2	6.3	7.9
Reach	18.7	16.0	19.4	20.7
NEO-M8P	22.4	25.5	20.4	21.8
S2525F8	1.0	0.8	0.2	1.9

Table B.6 RTK floating-point and fixed-integer availability.

Time in any RTK [%]		High-Quality Antenna		
Receiver	All Data	Rural	Bridges	Urban
SF-3050	77.2	79.8	83.2	67.9
Eclipse P307	91.2	97.3	96.5	79.3
Piksi Multi	68.6	76.9	74.4	53.9
NV08C-RTK	80.9	87.4	85.5	69.5
Reach	84.3	93.6	84.6	74.6
NEO-M8P	58.6	65.8	61.6	49.5
S2525F8	71.2	65.1	81.6	65.3