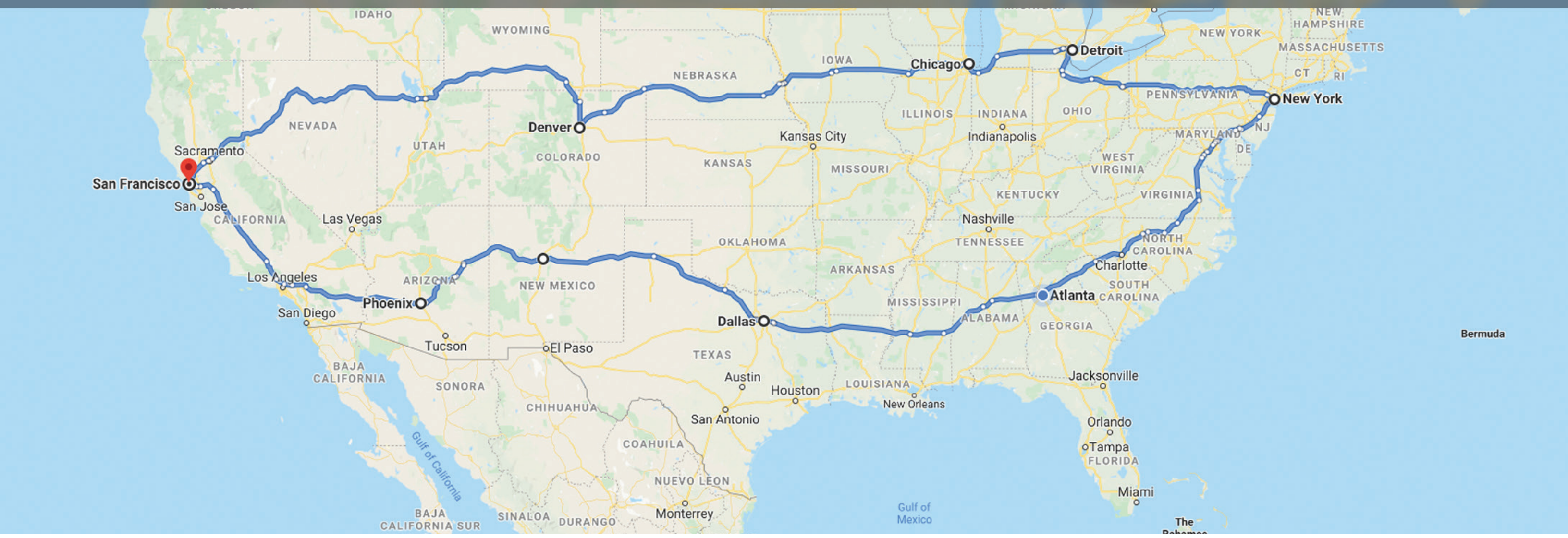
swift NAVIGATION

PLEASE NOTE

This cross-country drive test was conducted in December 2019. Swift Navigation continually works to improve its products, including Skylark. Skylark's performance and accuracy have improved a lot since this paper was published. Up-to-date accuracy information can be found at swiftnav.com/skylark

©2021 Swift Navigation, Inc. All rights reserved

SKYLARK PRECISE POSITIONING CROSS-COUNTRY DRIVE



Swift Navigation successfully completed an ambitious drive test across the United States. The goal of Swift's first-of-its-kind, cross-continental drive, from San Francisco to New York and back, was to measure the performance of Swift's recently expanded Skylark™ precise positioning service and to demonstrate true nationwide GNSS coverage at the accuracy levels required by autonomous applications. This dataset encapsulates the background, set-up, results and data from this extraordinary drive test.

©2021 Swift Navigation, Inc. All rights reserved

Autonomous Navigation

Autonomous navigation continues to evolve and most car manufacturers have now implemented programs involving various levels of autonomy. The key to enabling full autonomous functionality for automotive applications lies within the vehicle's sensor suite. This suite consists of a combination (determined by vehicle manufacturers) of radar, camera, LiDAR, inertial and GNSS (Global Navigation Satellite Systems, of which GPS is a part). GNSS is a vital component of the vehicle sensor suite as it is the only sensor to provide an absolute position, velocity and time estimate. In addition, GNSS has a complementary performance profile, providing the highest performance in environments in which other sensors typically have difficulties or fail.

While various legacy GNSS positioning systems have been available for some time, each have significant limitations and their broad adoption and application to autonomous vehicles still require overcoming some significant challenges, such as:

- Accuracy is required at the decimeter level (lane-level)
- Convergence times must be in seconds, not minutes
- Service coverage needs to be continuous and wide area vs. geographically dispersed
- The system must work with low-cost mass market hardware and automotive-grade antennas
- The positioning information provided by the localization system must be produced with high integrity and trustworthiness

Swift Navigation has created a precise positioning solution that addresses these challenges. The Swift team undertook a drive test across the continental United States (CONUS) to showcase the performance of Swift's precise positioning solution. Swift collected data over a range of geographies, using automotive-grade hardware configurations, demonstrating the configurability and flexibility inherent in the Swift solution. This drive covered 26 states and Washington D.C., with 6,614.7 miles (10,645.4 km) driven over 116 hours and 14 minutes logged by the team at Swift.

This paper captures in detail the set-up and resulting data analysis that demonstrates how Swift technology is the precise GNSS and sensor fusion leader for automotive autonomy and that Swift's positioning solutions meet the needs of today's—and tomorrow's—autonomous vehicle manufacturers.

©2021 Swift Navigation, Inc. All rights reserved

Swift's Positioning Solution

Swift Navigation has developed a unique solution that meets the most stringent requirements of automotive precise positioning. The solution is centered around Skylark, Swift Navigation's GNSS corrections service and Starling®, Swift Navigation's high-precision positioning engine.

Skylark is a state-of-the-art continental-scale corrections service that was developed to address the demanding requirements of the automotive use case. A high-precision, highly-available wide area corrections service, Skylark enables state-of-the-art accuracy, integrity and convergence performance on a global scale. In particular, Skylark enables sub-decimeter accuracy in seconds of convergence time anywhere in CONUS and Europe (and expanding worldwide). This is a significant improvement compared to traditional Real Time Kinematic (RTK) services, with fast convergence times but only regional coverage or Precise Point Positioning (PPP) services with global coverage but long convergence times. In addition, Skylark supports both next generation State Space Representation (SSR) format corrections broadcast for bandwidth-efficient, one-way communication as well as RTCM3.2 Observation Space Representation (OSR) legacy correction delivery.

Starling is a hardware-agnostic precise positioning engine that delivers industry-leading integrity and positioning performance. Ingesting observations from an automotive-grade GNSS measurement engine and IMU, it is able to provide sub-decimeter-level accuracy in Skylark coverage areas. The Starling positioning engine utilizes advanced sensor fusion algorithms fusing GNSS position, Inertial Measurement Unit (IMU) and wheel odometry measurement to maintain lane-level accuracy in most driving conditions.

Swift's ability to provide an absolute localization solution (where the vehicle is referenced to a global Earth fixed datum as opposed to relying on positioning relative to local landmarks) is a key benefit of Swift's GNSS positioning technology and allows for positioning in off-road and off-map environments and eliminates the requirement to maintain and update high-definition maps, a significant burden. More information about the importance and relevance of global reference datums and transformation can be found here.

Vehicle Set-Up

A Swift test vehicle was equipped with 20 different GNSS devices utilizing five unique chipsets. In addition, a number of different antennas were utilized, ranging from a high-end, survey-grade antenna to a more price-conscious automotive-grade antenna that would be representative of a typical production

©2021 Swift Navigation, Inc. All rights reserved

solution. The results on the automotive-grade antenna are particularly noteworthy, as most published tests of this nature utilize an antenna that is not feasible, either practical or affordable, for consumer automobiles.

Devices were selected to showcase Swift's solution across a range of configurations, antennas and price points, as shown below.

Table 1: Devices

Device	Corrections (Skylark)	Dead Reckoning
Receiver A	Yes	Yes
Receiver B	Yes	Yes
Receiver C	Yes	No
Receiver D	Yes	Yes
Piksi® Multi	Yes	No
Duro®	Yes	Yes

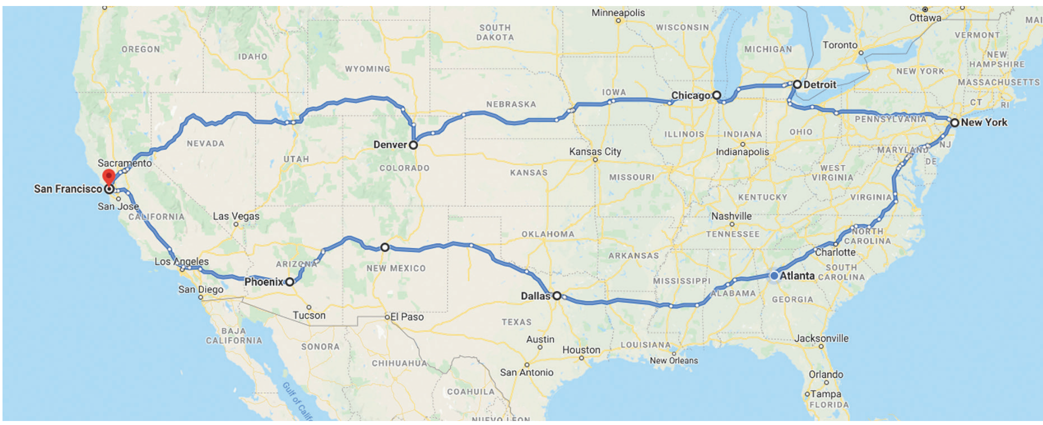
Table 2: Receiver/ Antenna Key

Notation	Hardware Capability
Receiver A	Automotive-grade ME, Supports L1/L2
Receiver B	Automotive-grade ME, Supports L1/L2
Receiver C	Survey-grade ME, Supports L1/L2
Receiver D	Automotive-grade ME, Supports L1 Only
Antenna-A	Automotive-grade antenna Represents current GNSS antenna on vehicles
Antenna-S	Survey-grade antenna Represents higher-efficiency antenna

©2021 Swift Navigation, Inc. All rights reserved

Route Driven

Many companies conduct drive tests in major metropolitan markets or along heavily-populated coastal routes to demonstrate performance. Others drive short or open-sky routes, utilizing ideal performance conditions. Swift chose to undertake an ambitious cross-country drive test to showcase its technology both in scale and performance. This report clearly demonstrates how Swift's solutions meet customer needs by operating over a large coverage area with consistent and reliable precision. This drive test commenced on November 29, 2019 and was completed on December 19, 2019 and traversed the continental United States, covering 26 states and Washington D.C.



COVERED

26 states

& Washington D.C.

LOGGED

116 hrs & 14 min

of drive time

DROVE

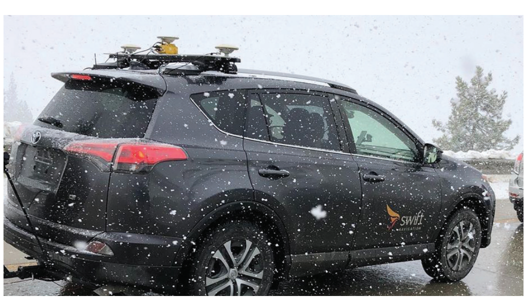
6,614.7 miles

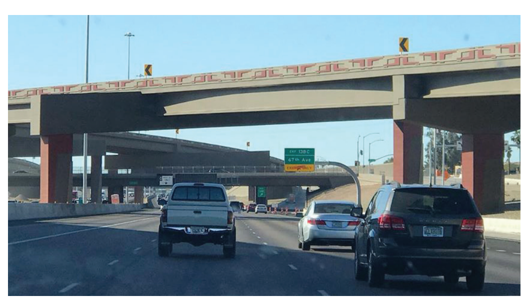
(10,645.4 km)

DRIVEN BY

12 Swift drivers

Throughout the drive





©2021 Swift Navigation, Inc. All rights reserved

Drive Test Results

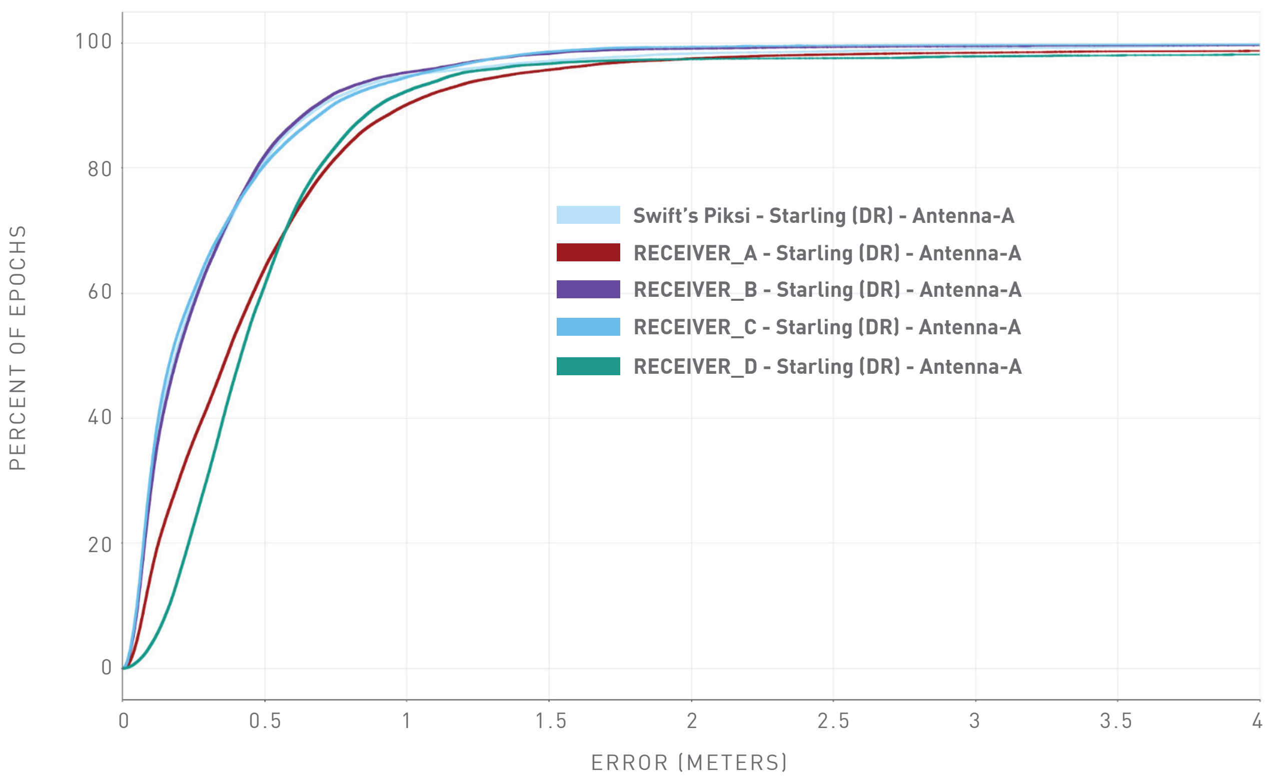
It is important to remember the significance of these data as we evaluate results of this drive test. In the United States, the typical width of a highway lane is 12 feet or 3.6 meters. A typical car width is approximately 2 meters. As such, we can see that targeting an accuracy of less than 1 meter (half the width of a typical consumer vehicle) would enable a majority of safety-critical autonomous applications. Furthermore, to reliably position a vehicle within a typical highway lane, an accuracy of a quarter width of the lane with associated integrity output would be required.

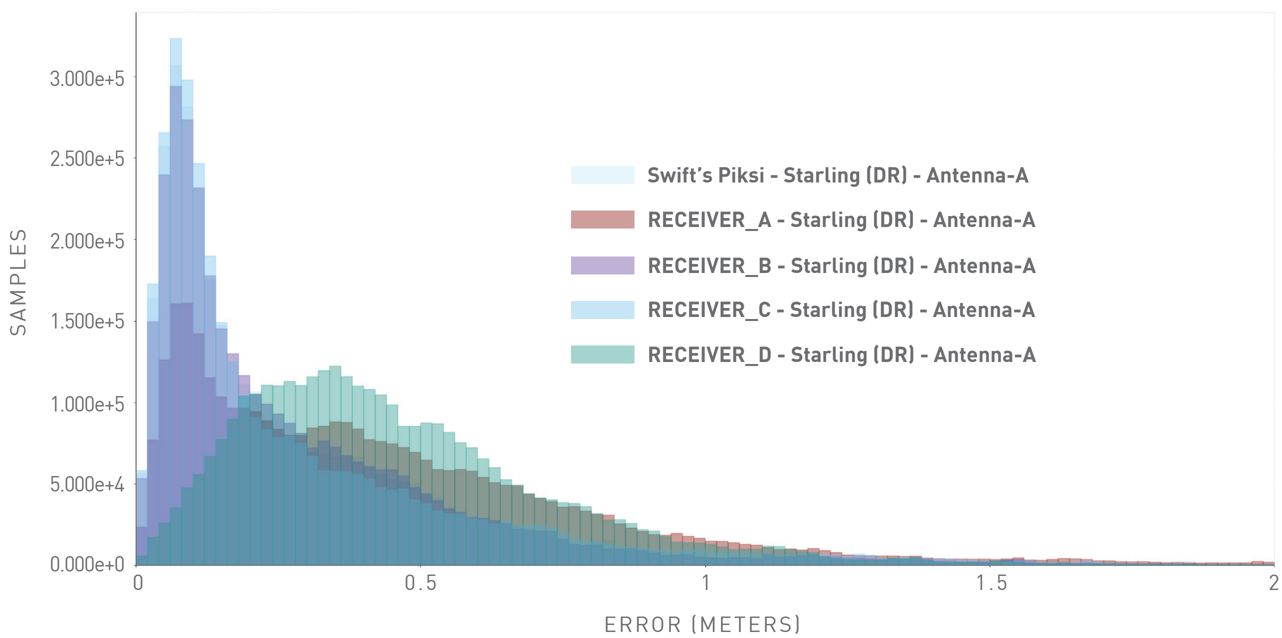
©2021 Swift Navigation, Inc. All rights reserved

ACROSS THE CONTINENTAL UNITED STATES

The data below feature results from Swift's cross-country drive test in its entirety.

Performance of Swift Solution Over Entire CONUS Drive





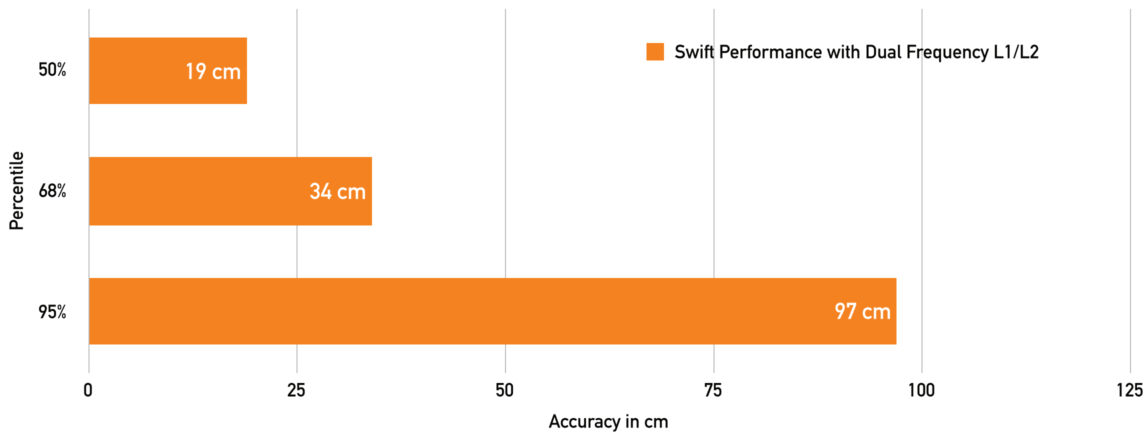
©2021 Swift Navigation, Inc. All rights reserved

Key Takeaways

Variation of performance on different receivers with dual-frequency capabilities

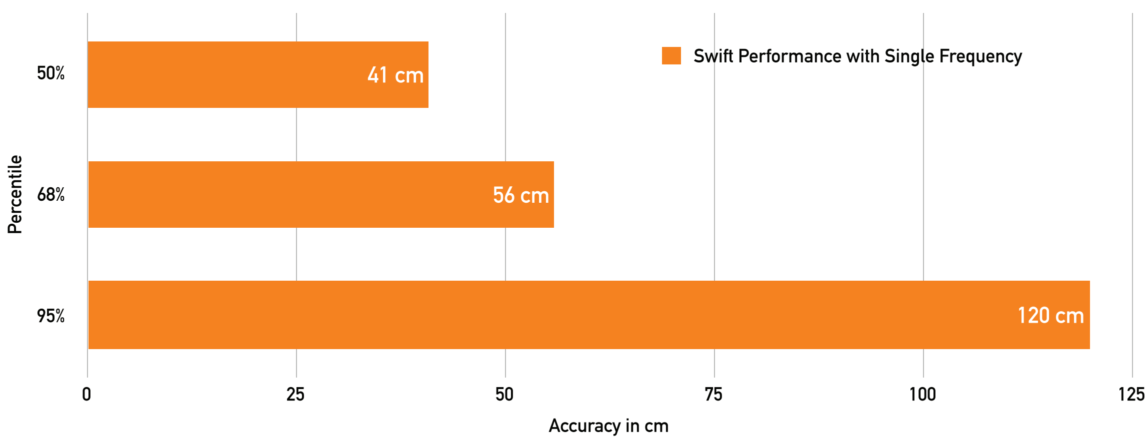
- A 10% variation in drive time for 75 cm or less accuracy
- A 5.3% variation in drive time for 1 m or less accuracy

With dual-frequency receivers and "Antenna-A", Swift achieved the following accuracies with Starling and Skylark



- Swift solution also achieved 1 m accuracy for a full 95.2% of the drive
- 75 cm of accuracy for 92% of the entire drive

With single-frequency receivers and "Antenna-A", Swift achieved the following accuracies with Starling and Skylark

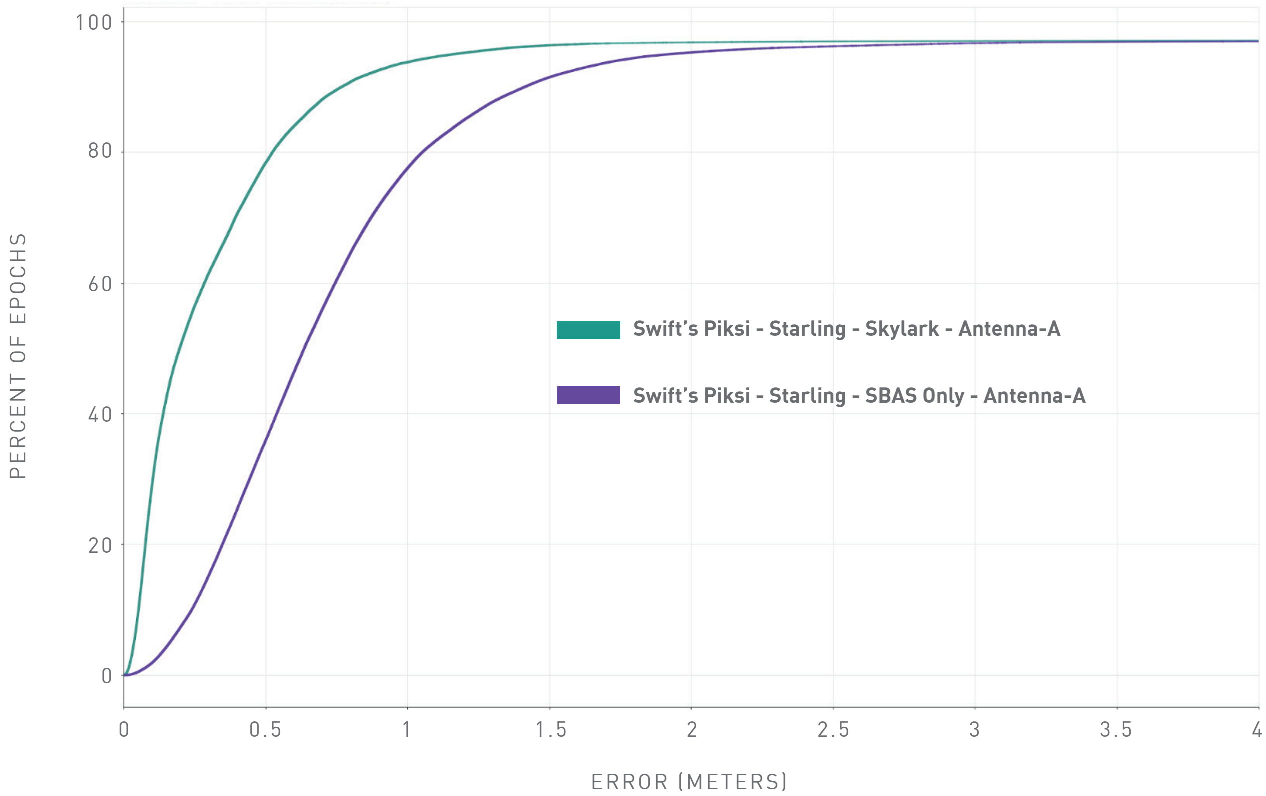


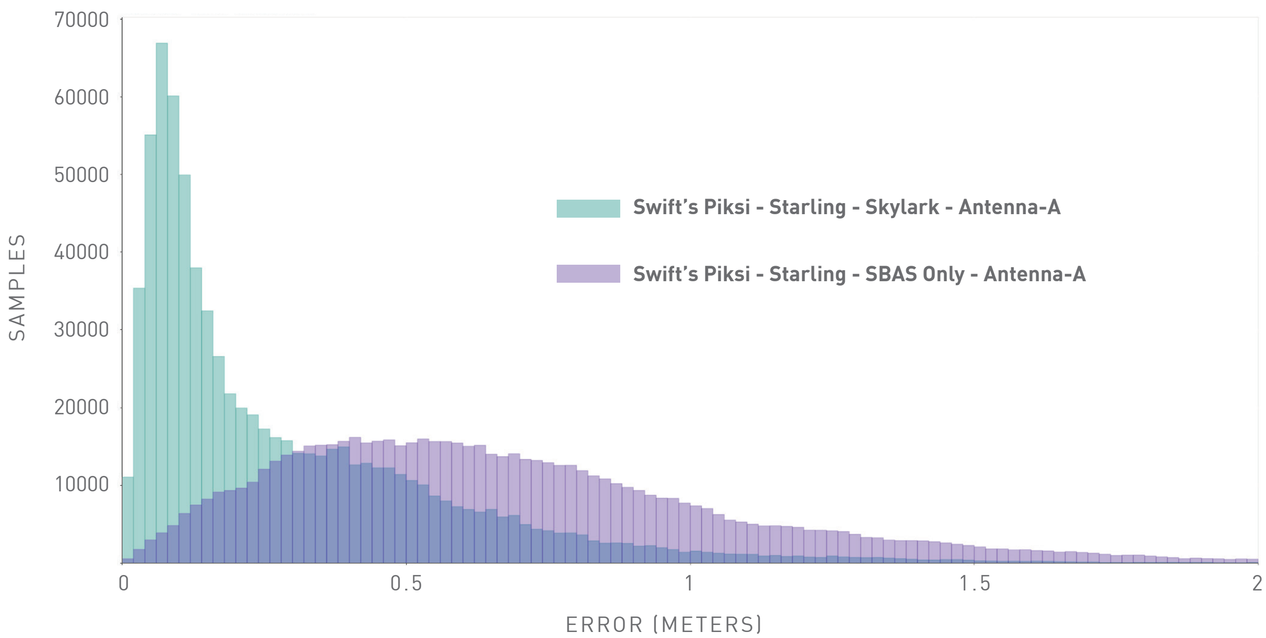
- Swift's solution also achieved 1 m accuracy for 92.4% of the drive
- 75 cm of accuracy for 83.2% of the entire drive

©2021 Swift Navigation, Inc. All rights reserved

These findings demonstrate that the Swift precise positioning solution can achieve less than 75 cm of accuracy more than 92% of the drive time even without additional standard vehicle inputs such as wheel odometry. With wheel odometry, Swift has the capability to utilize sensor fusion to further improve accuracy.

Skylark Performance

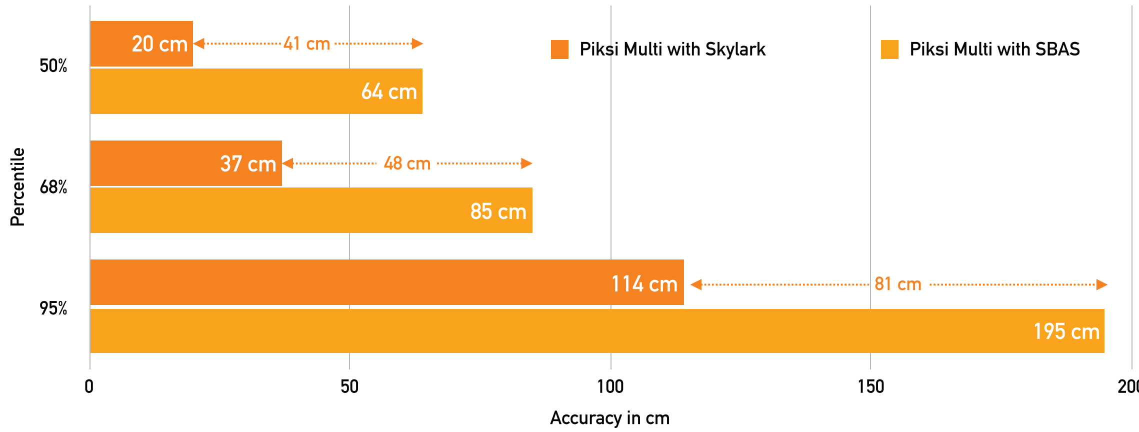




©2021 Swift Navigation, Inc. All rights reserved

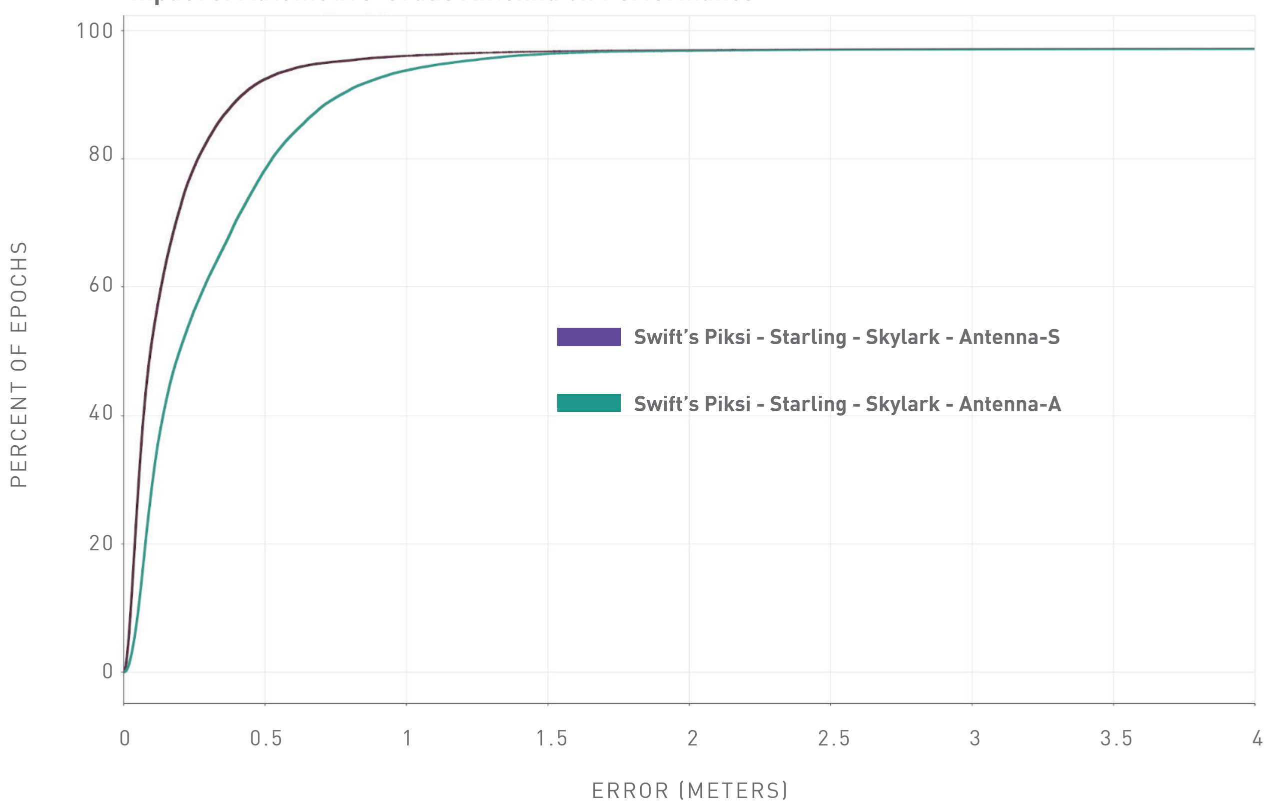
Key Takeaways

Swift's Skylark performance improvements below with "Antenna-A" Comparing Piksi Multi + Skylark with Piksi Multi + SBAS (without corrections) solution

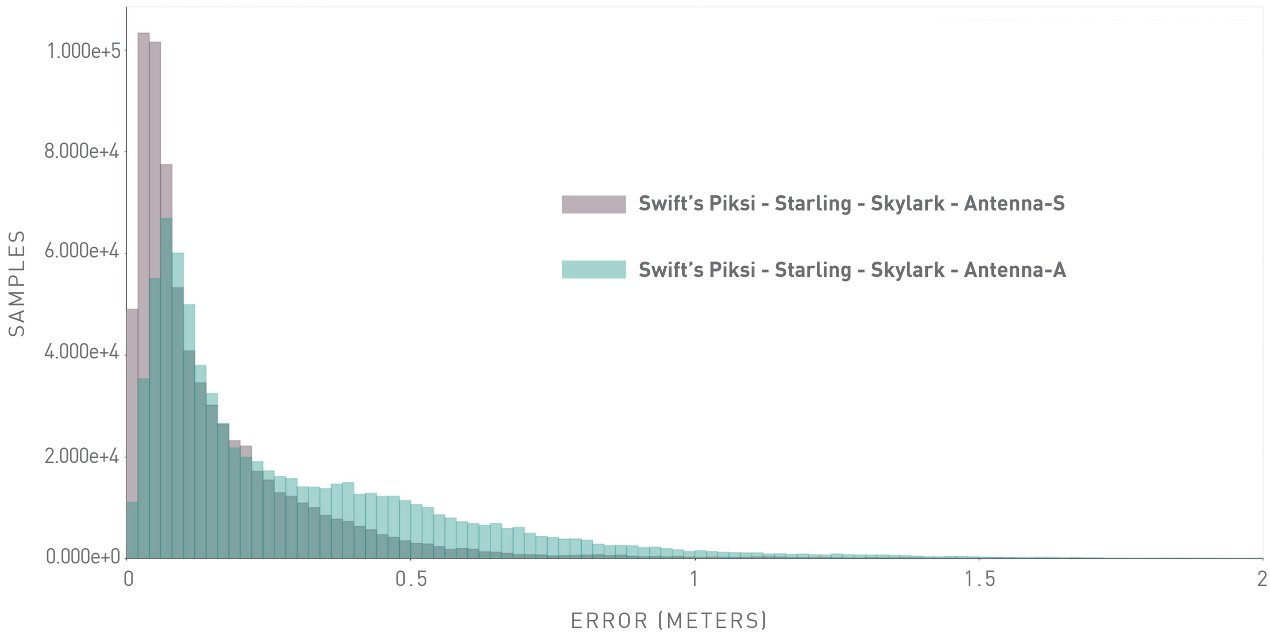


The results demonstrate that Skylark improved accuracy of 75 cm to 89.7% from 60% of the total drive with an automotive-grade antenna.

Impact of Automotive-Grade Antenna on Performance

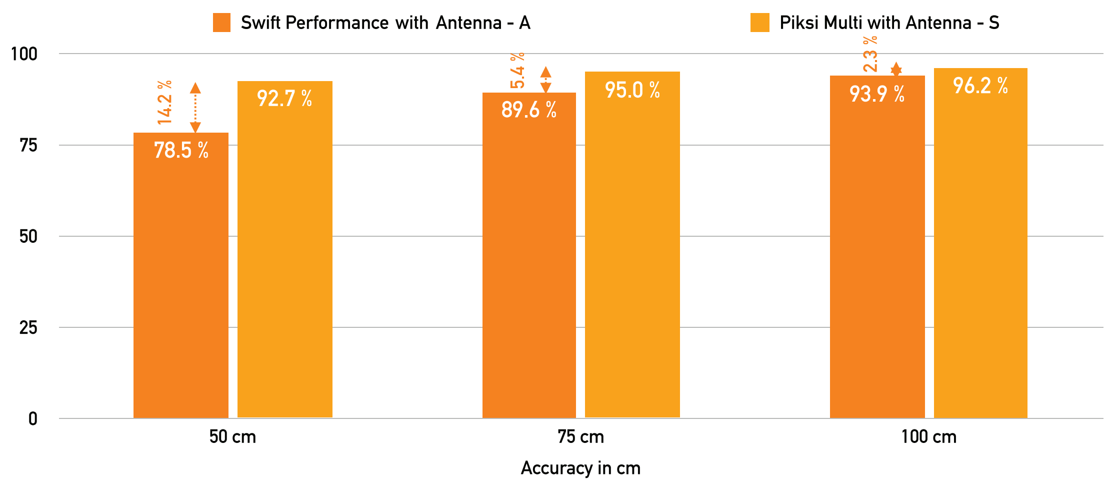


©2021 Swift Navigation, Inc. All rights reserved



Key Takeaways

Automotive-grade antenna impact on Swift performance compared to survey-grade antenna



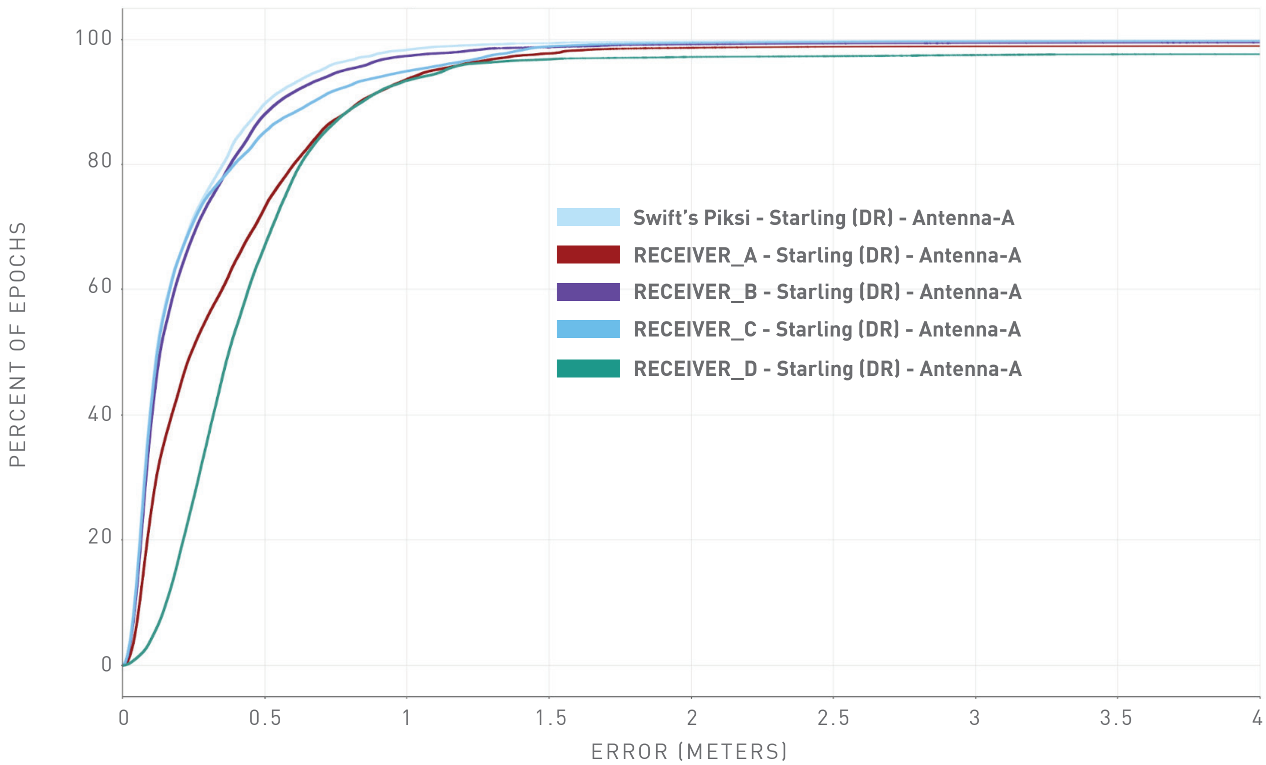
These results clearly demonstrate that Swift's positioning solution is able to achieve accuracy results with automotive antennas that meet the highest of automotive requirements, with only approximately a 6% degradation in results with <75 cm accuracy compared to a high-end geodetic antenna.

©2021 Swift Navigation, Inc. All rights reserved

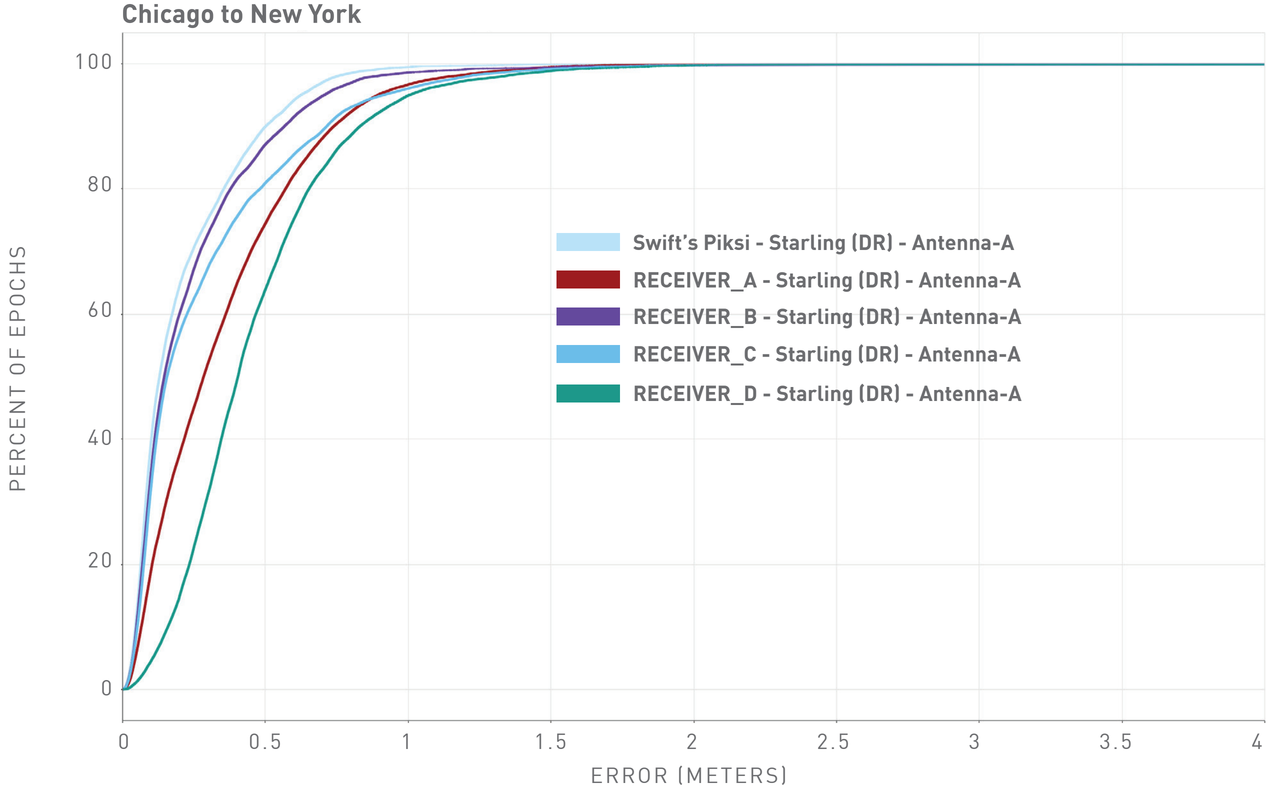
DRIVE DATA ACROSS REGIONS

The data below feature a breakdown of results from major stretches of this cross-country drive test.

San Francisco to Chicago

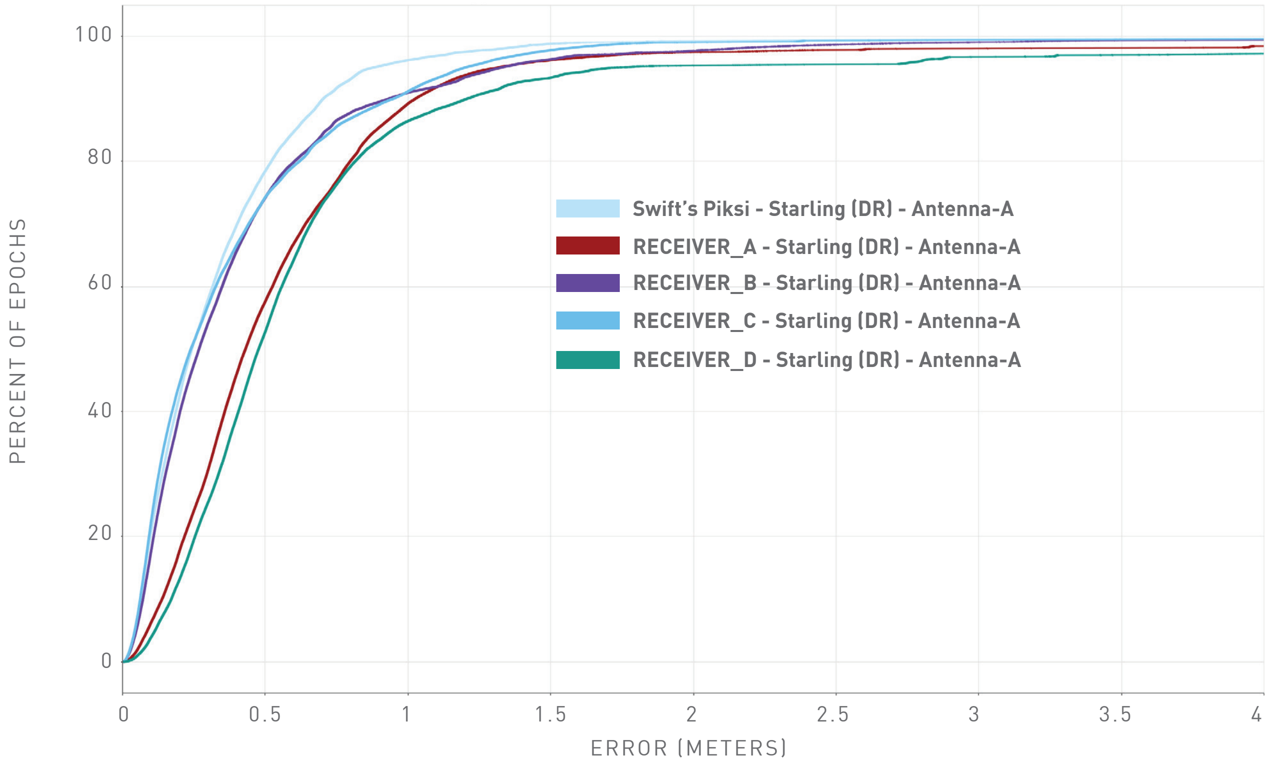


Chicago to New York

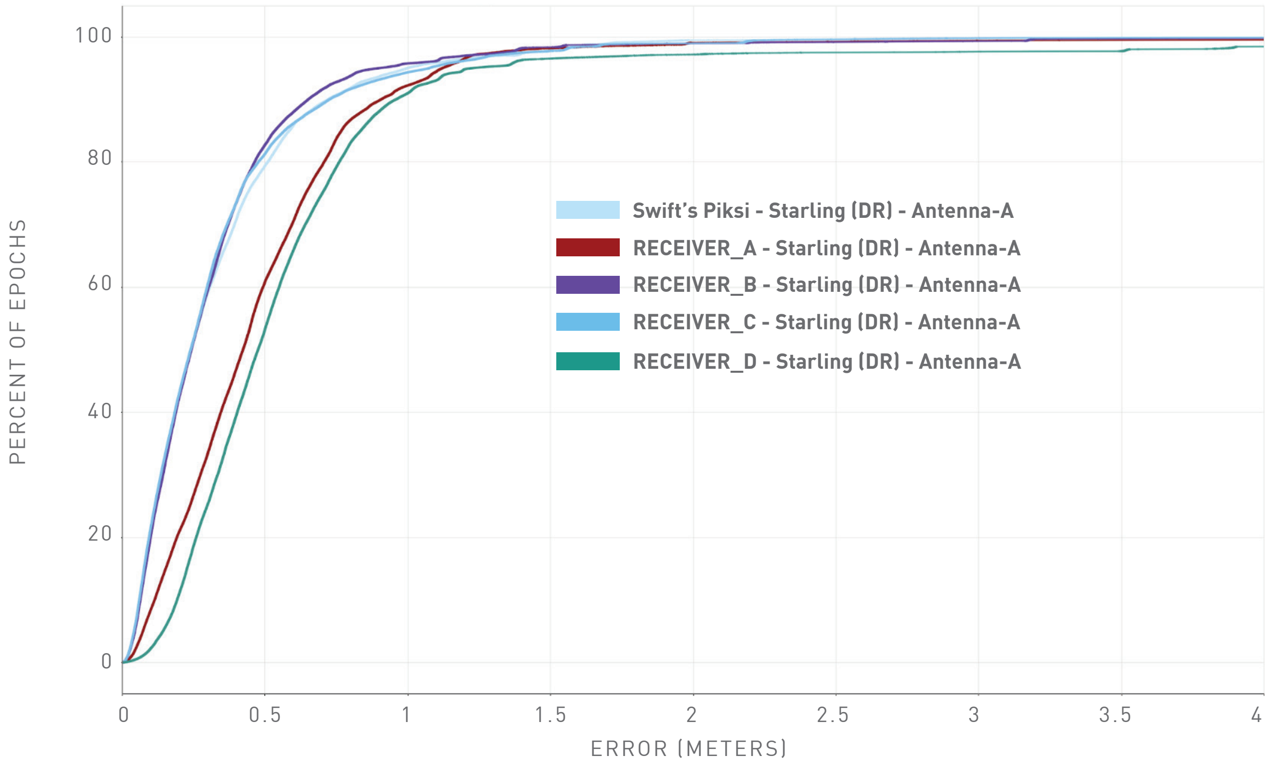


©2021 Swift Navigation, Inc. All rights reserved

New York to Atlanta

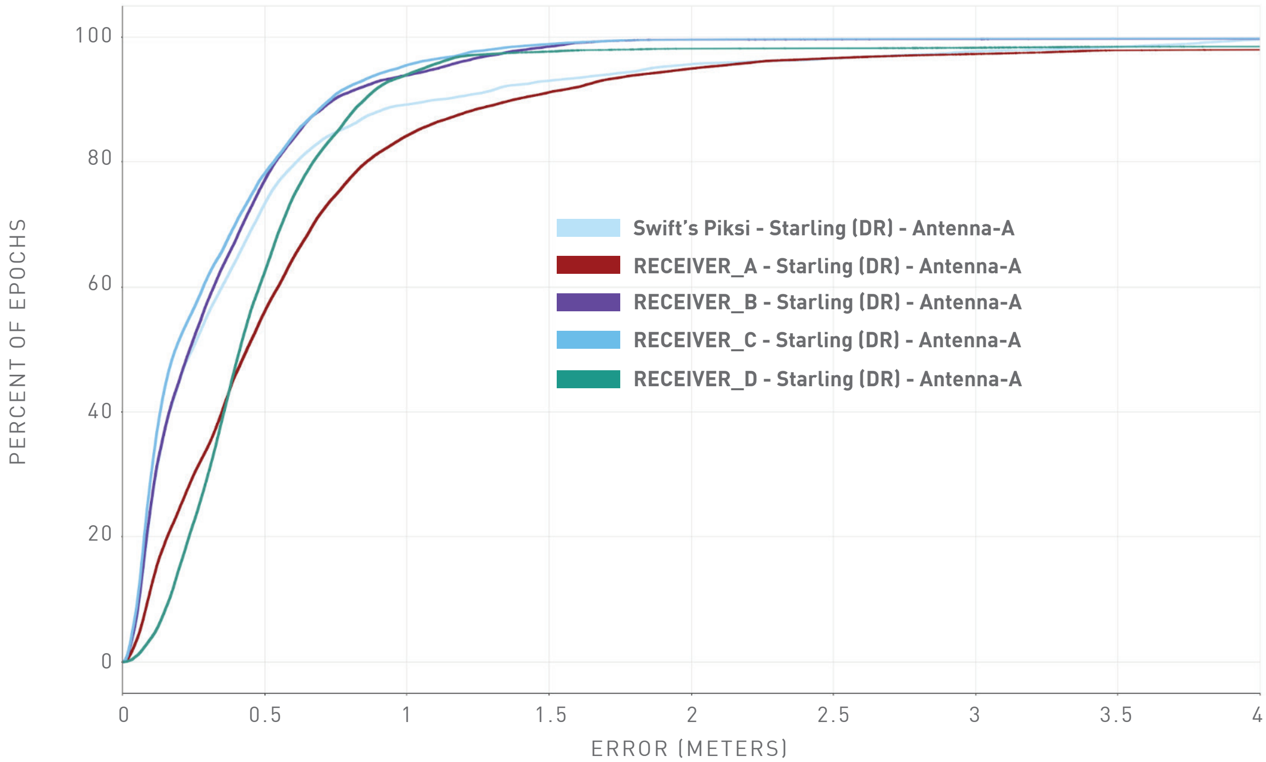


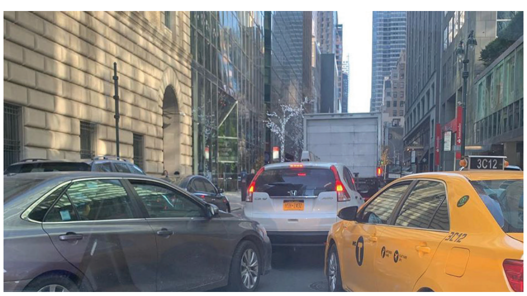
Atlanta to Dallas



©2021 Swift Navigation, Inc. All rights reserved

Dallas to San Francisco





Conclusion

This drive test took a Swift test vehicle through a wide variety of environments as it traversed the United States. From snow in the Sierras of California, to the streets of some of the world's most bustling metropolises to open roads across the continent. Under all conditions, Swift's positioning solution demonstrated its ability to consistently deliver the <75 centimeter accuracy required to keep a vehicle safely positioned in its lane.

Since this drive test occurred, Swift's engineering team has continued its work on core positioning and sensor fusion algorithms to improve the availability, accuracy and integrity of the overall Swift precise positioning solution.

For more information about how Swift's precise positioning solution can benefit your autonomous application contact Swift at sales@swiftnav.com.

©2021 Swift Navigation, Inc. All rights reserved