The Role of RTK in the Autonomous System Sensor Suite

An Examination of Moving Baseline RTK, RTK-Based Heading Technology and How RTK-Based Solutions Support Autonomous Vehicle Sensor Edge Cases

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An Introduction to RTK GNSS and the Autonomous Vehicle Sensor Suite

The Autonomous Future Requires Highly-Accurate Sensors for Precision Navigation

Autonomous systems are no longer the distant future— today these systems are navigating around our streets and within our backyards. Despite their increased prevalence, these systems have technological hurdles to overcome as inclement weather, urban canyons and other non-ideal conditions can bring them to a standstill. A key to addressing these challenges is improved sensor synthesis within the autonomous sensor suite that mitigates the limitations of individual sensors. This white paper will explore one sensor, a multi-band, multi-constellation Real-Time Kinematics (RTK) GNSS receiver, that demonstrates the strength of RTK within the autonomous vehicle sensor suite. Specifically, the distinct advantages of Moving Baseline RTK and RTK-Based Heading—two hardware setup configurations that are significant to autonomous systems—will be highlighted.

GPS Alone is Not Sufficient to Meet Autonomous System Challenges

GPS has been the standard sensor for position, navigation and timing (PNT) applications due to its unique ability to provide absolute positioning (a receiver's location on Earth). However, by itself, the GPS found in most applications—like that in a cell phone—is neither accurate nor robust enough for many of the applications within our autonomous future.

The U.S. Department of Transportation's Federal Highway Administration indicates that a typical lane width is approximately 3.6 meters. For comparison, a typical GPS receiver's positional accuracy is 3-5 meters in ideal conditions, and a 2016 PlaceIQ study showed that variances from actual positions from low-cost cell phone GPS receivers within urban environments were closer to 28 meters. Currently, these cell phone receivers are within the same class of receivers used in many mass market automotive applications; it is clear that this type of stand-alone GPS receiver is insufficient for leading-edge applications that require safety-critical accuracy and redundancy, such as self-driving vehicles.

RTK Improves on the PNT Standard With Precise Relative Positioning and Heading

Accurate absolute positioning provided by GNSS is valuable for many autonomous navigation applications. At the most basic level, navigation requires a system to understand where it is, where it is going and how to get between those two points. Although in many use cases, accurate relative positioning information between two moving objects may be sufficient.

RTK provides four types of precision position, navigation and timing outputs

- Absolute positioning
- Relative positioning
- Heading (attitude/orientation)
- Time

RTK can be used to achieve additional benefits beyond standard GNSS. An RTK GNSS system provides centimeter-level accuracy, versus the 3-5 meter accuracy offered by a single point position (SPP) standard GPS solution. Accurate absolute positioning can be achieved with a highly accurate a priori known base station position and precise relative positioning can be achieved with a static or moving base station. The former RTK approach—known as moving baseline RTK—is a differential technique that allows a user to compute heading using relative positioning.

Precision applications for RTK span industries ranging from autonomous automotive applications to agricultural auto-steering applications. Vehicle-to-vehicle docking and machine control systems benefit from relative positioning, while marine, robotic and transportation industries see many applications for heading.

Advantages of Utilizing RTK for Precise Relative Positioning and Precise Heading

Many technologies that support relative positioning and heading fall short of the cost, accuracy, robustness and size requirements necessary to support autonomous system mass adoption. Laser-based sensors—LiDAR, optical and ultrasonic sensors—used for relative positioning have difficulties performing in adverse weather conditions such as rain and snow. LiDAR—a leading sensor in autonomous driving—can be very costly and the system is highly complex. Infrared sensors, which look for heat differentials, can be impacted by environmental factors such as low temperature variants, including those introduced from a fire.

Sensors used for heading—such as inertial and motion sensors like magnetometers—are prone to magnetic effects. Gyroscopes can drift and require calibration. Gyrocompasses identify True North but are expensive and mechanically bulky. Magnetic compasses identify magnetic north but are afflicted by interference issues. Inertial Measurement Units (IMUs) and other inertial sensors experience their own problems. These technologies can be prone to machine vibrations and require time to calibrate while in motion, meaning that vibrations can lead to drift. Once a vehicle has stopped moving, the sources of error may grow, rendering the relative positioning and heading solutions no longer adequate. Many of these sensors are not sufficient on their own to meet the needs for autonomous systems while others, such as ring laser gyroscopes, are too cost-prohibitive in mass market applications or are too limited by availability to support volume OEM-level adoption.

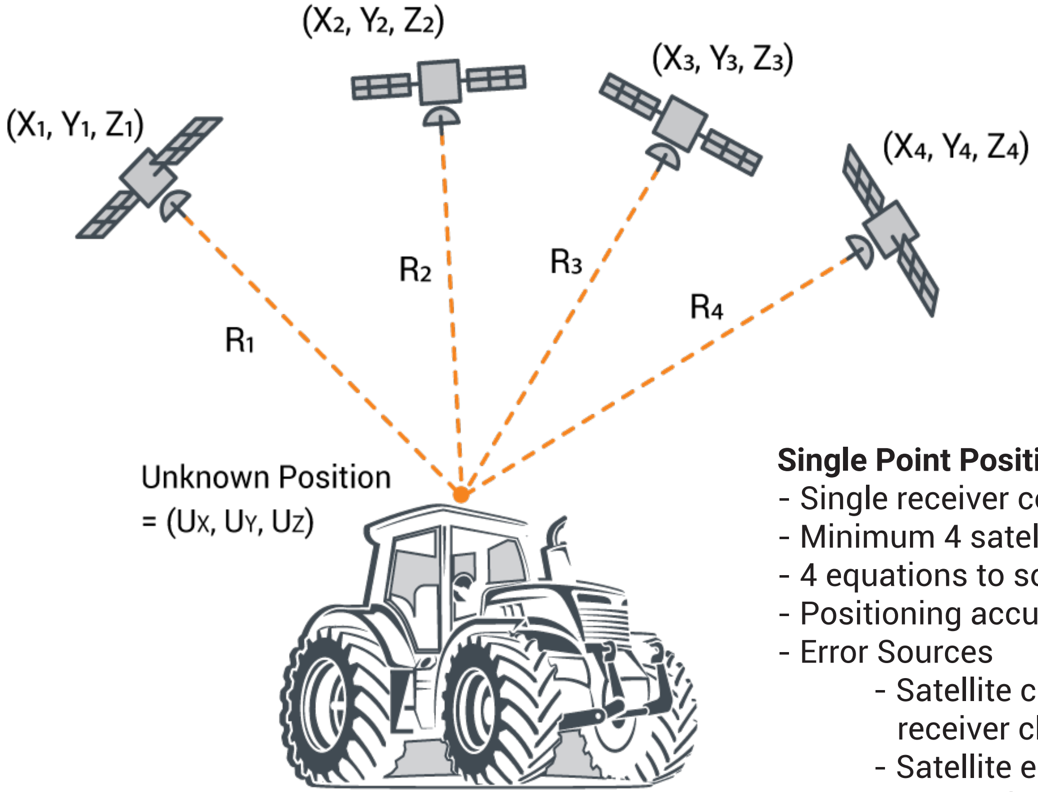
On the other hand, GNSS sensors are immune to magnetic interferences and can operate in a static setting without requiring motion for initial calibration. RTK heading requires no calibration time and the vehicle can be stationary, unlike most systems that require the vehicle to be moving. These characteristics make RTK an ideal technology for applications that require precise relative positioning and robust precision heading. RTK-based sensors are emerging at price-points that can support OEM-level adoption.

An Introduction to RTK and Moving Baseline RTK Technology

Traditional RTK

Traditional RTK enhances the accuracy of position data derived from satellite-based positioning systems.

Figure 1 demonstrates how a typical GPS receiver may use single point positioning (SPP) to determine its position without additional infrastructure. SPP is one of two code-based positioning methods and can measure the unknown location of a receiver with respect to an Earth-based reference frame. The receiver measures a satellite's code observations to determine a pseudorange (range with error) to the satellite, and with four or more satellites in view, the receiver can solve for its position. However, its position can only be measured accurately to approximately 3-5 meters as a result of errors including satellite clock bias, ephemerides and ionospheric and tropospheric delays.



$$R_U = \sqrt{(X_i - U_X)^2 + (Y_i - U_Y)^2 + (Z_i - U_Z)^2} + c(\Delta T_U)$$

Single Point Positioning (SPP)
- Single receiver configuration
- Minimum 4 satellites
- 4 equations to solve for 4 unknowns
- Positioning accuracy: 3-5m
- Error Sources
    - Satellite clock bias and receiver clock error
    - Satellite ephemerides
    - Atmospheric (ionospheric and tropospheric delays)
    - Multipath

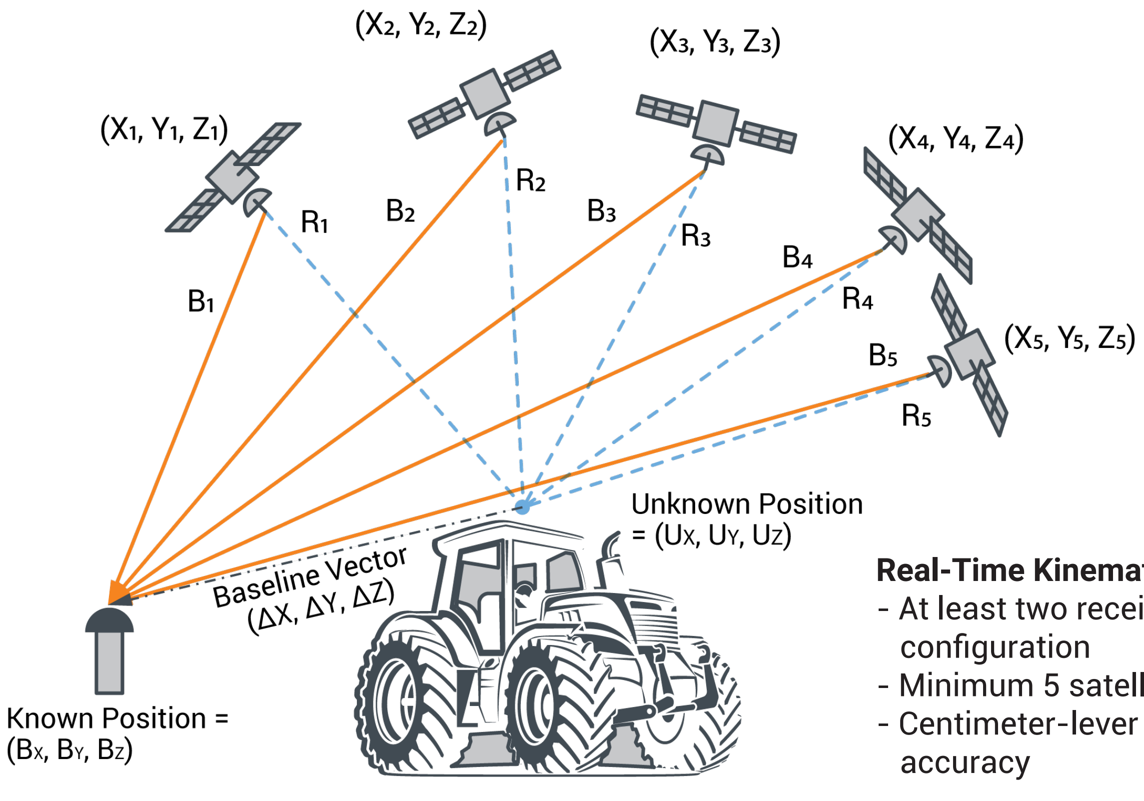
Figure 1 - SPP is Not Sufficient for High-Precision Autonomous Applications

Alternatively, RTK provides centimeter-level position accuracy by leveraging two important architectural and signal differences. Firstly, the use of the carrier phase waveform provides more precise measurements and observations instead of using code-phase observations. Secondly, differential mathematical techniques use two or more receivers (Base Station and Rover(s)) to correct for common errors between them. RTK system receivers broadcast corrections to resolve error sources and output a relative position between receivers. Capturing differences in measurement methods plus a second source of reference allow an RTK receiver to measure its position much more accurately.

RTK receivers may use other GNSS signals as well, although GPS has been the previous PNT standard. For those unfamiliar, GNSS stands for Global Navigation Satellite System, and is the generic term for satellite-based positioning, navigation, and timing (PNT) systems that provide global coverage. This term is inclusive of GPS as well as GLONASS, Galileo, Beidou and may at times also refer to other more regional systems.

Traditional RTK Use Case with a Static Base Station and Moving Rover

RTK requires two independent receiver modules to be connected with a robust communication link so that RTK corrections can be transmitted between them. Figure 2 depicts the traditional use of RTK involving two receivers—the first receiver acting as a fixed base station and the second receiver acting as a moving rover—with the base station receiver configured to transmit RTK corrections. RTK corrections can be transmitted to the receiver through a radio link, cell modem or any other communication link that is capable of supporting the data stream requirements. The roving GNSS receiver is configured to receive RTK corrections sent from the base station and it uses these corrections to solve for the baseline vector (ΔX, ΔY, ΔZ). This vector spans the distance between the units and is accurate to within 1-2 centimeters relative to the base station. If no external reference frame is available, the receiver is only able to achieve a centimeter-accurate relative position between the two receivers.



Real-Time Kinematic (RTK)

- At least two receivers within configuration
- Minimum 5 satellites
- Centimeter-lever positioning accuracy

Figure 2 - Traditional RTK Use Case with Static Base Station Receiver and Mobile Roving Receiver Depicted on a Tractor

On the other hand, if an external reference frame is available, the receiver can achieve centimeter-level accuracy with respect to this fixed reference frame. To achieve an absolute position, with respect to an Earth-based coordinate system (e.g., Earth-Centered, Earth-Fixed (ECEF)), the base station must be placed at a known geodetic location for real-time position processing or alternatively, a Continuously Operating Reference Station (CORS) may be used if post-processing is sufficient.

Moving Baseline RTK Use Case

The major difference in the use of Moving Baseline RTK versus traditional RTK is that in the former, the “base station” is no longer stationary in the global coordinate frame. Moving Baseline RTK offers the capability to do real-time, precise relative positioning between two receivers while both receivers are in motion. With neither receiver directly associated with an external reference frame, the base station terminology may be foregone.

In one configuration, the receivers may be installed on separate vehicles to support applications where precise relative positioning between the vehicles is important. These applications include agricultural and marine towing, unmanned aerial vehicle (UAV) heavy lift payloads, formation or swarm-focused navigation, docking or shipboard landing and neural network algorithm training—as used in autonomous vehicle applications.

In another configuration, two receivers can be installed on a single vehicle to support the computation of RTK-based heading and/or attitude of the rigid body. This can be used to support applications such as automotive and marine heading, as well as communication infrastructure orientation applications.

RTK-based heading is deduced by the angle, discussed within measured clockwise, between True North and the baseline vector between two fixed antennas. An advantage of this method is that it provides heading in stationary and slow moving applications, such as when a car stops at a stoplight or a tractor is slowly traversing. This methodology can be used to determine orientation (roll, pitch, yaw) of a vehicle using knowledge of the baseline vector, as supported by adjustments to the hardware configuration setup.

Figures 3 and 4 depict Moving Baseline RTK and RTK-Based Heading configurations to show how the hardware deployment influences these approaches within the same application.

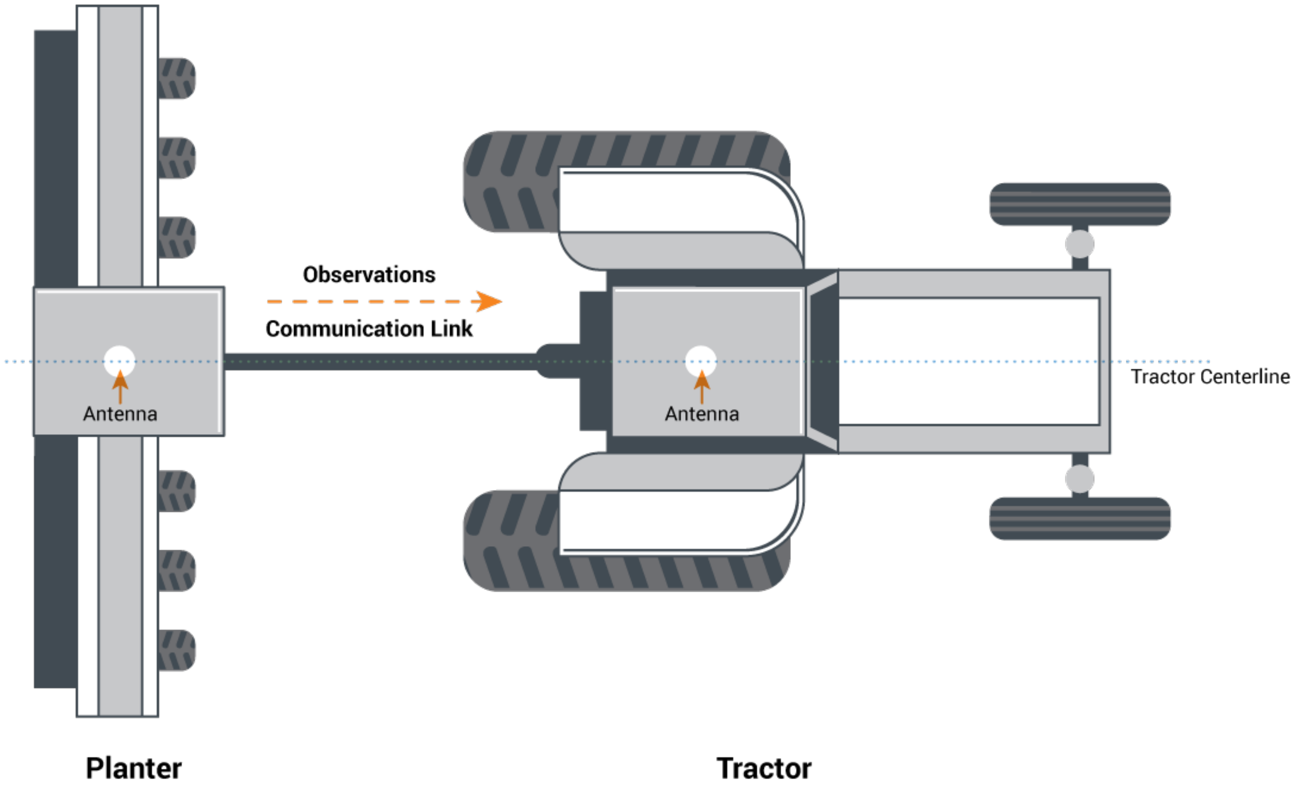


Figure 3 - Moving Baseline RTK Configuration

In Figure 3, a tractor is pulling a passive planter that has no steering intelligence. RTK receiver, antenna and communication link hardware are installed in a moving baseline configuration to provide precise relative positioning between the tractor and planter. In this example, it is assumed that the tractor intends to tow the planter in a straight path. As the tractor tows the planter, the centerlines of the tractor and planter are ideally in line with one-another; however, if the hitch angle between the tractor and planter changes, this adjustment is sensed by the change in the baseline vector. To calculate the baseline vector, the planter's receiver sends GNSS observations over a communication link to the receiver on the tractor, which outputs a baseline vector (ΔX, ΔY, ΔZ) relative to the planter. This precise relative positioning information can be used to feed data back into an auto-steering system to support semi-autonomous or autonomous farming operations. It is typically the planter that has a desired path, although it is the tractor that guides it along that path.

Benefits of RTK GNSS

- Can be used for absolute and relative positioning
- Performs well at low speeds
- Can provide heading when stationary
- Can determine attitude and orientation of a vehicle
- Does not require external inputs to initialize
- Sensors do not drift, including when stationary
- Sensors are immune to magnetic interference and typical machine vibration

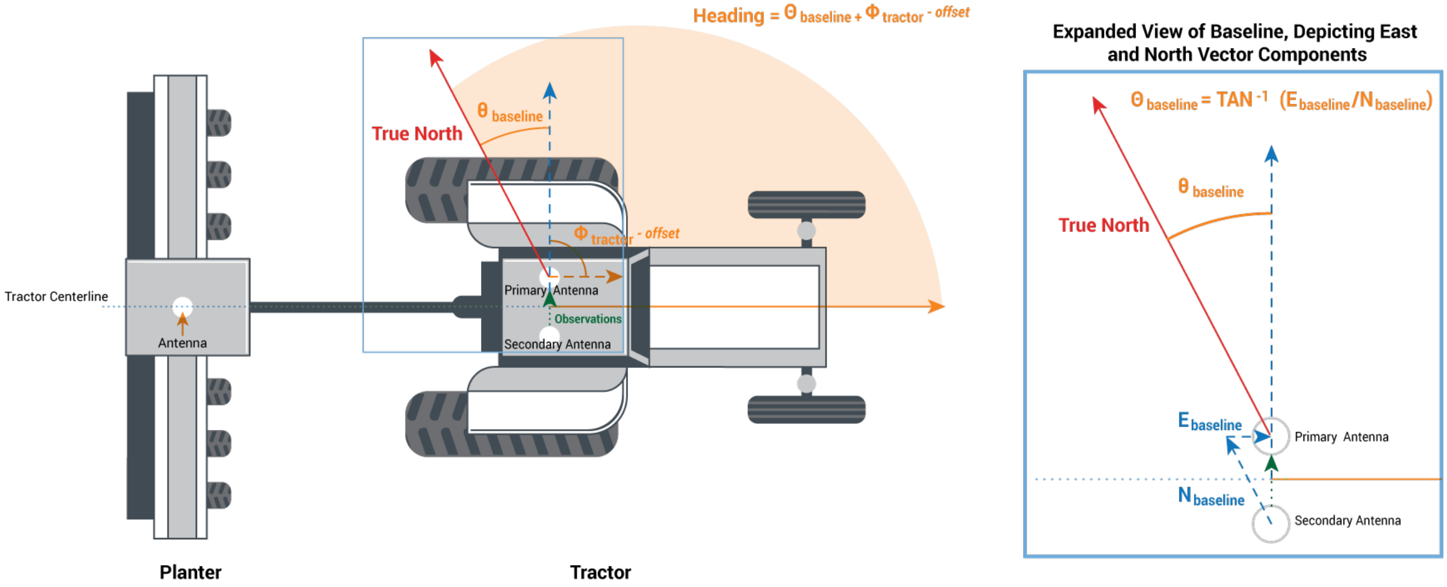


Figure 4 - RTK-Based Heading Configuration

Figure 4 shows the same tractor, without the antenna mounted on the towed planter implement, that intends to traverse a field that has been recently tilled. To support the tractor's traverse through this rough terrain in semi-autonomous or autonomous mode, a primary and secondary antenna are co-located on the tractor—mounted at a fixed distance on the roof—to aid computation of the tractor's heading that can be fed back into the control system. The secondary receiver sends GNSS observations over a data link to the primary receiver and the primary receiver can then output RTK-based heading. The heading is derived from the baseline vector and considers the heading offset shown in Figure 4.

Hardware Configuration Within Greater Context

Systems Architecture within the Context of Moving Baseline RTK and RTK-Based Heading Hardware Setup

Figure 5 depicts a moving baseline RTK configuration within the system concept of shared resources. In this example, a vehicle and a drone both utilize Piksi® Multi RTK GNSS receivers.

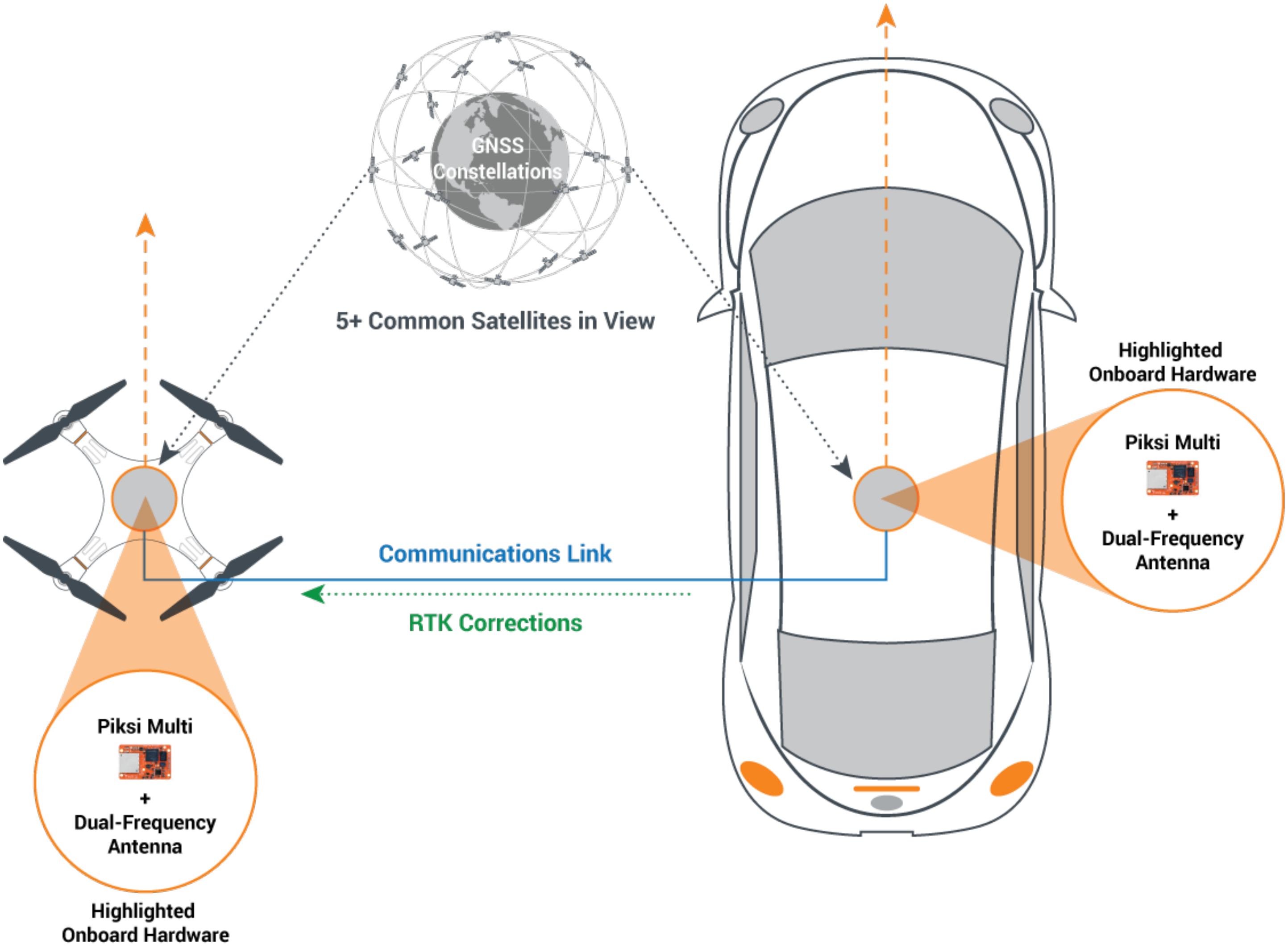


Figure 5 - High-Level System Diagram for UAV-to-Vehicle Docking Concept Demonstrated with Piksi Multi

In this system architecture, GNSS satellite observations are received at two locations. The first is a receiver hardware setup installed on a vehicle referred to as the target. The second is a receiver hardware setup installed on a UAV, referred to as the chaser. Each hardware setup includes at least one of the following: a Piksi Multi GNSS receiver, a dual-band antenna (to maximize the benefits of the dual-frequency receiver), one part of a paired communication link and a power source. Several drone example missions are outlined below to help relay the significance of moving baseline RTK as it relates to the relative positioning between target and chaser vehicles.

"Fetch Rover Fetch" Mission: An example of this system architecture is when a human occupant within the vehicle initiates a specific UAV "fetch" mission through the vehicle's navigation or infotainment system. The mission may be for the UAV to pick-up a payload. Once the payload is picked up, the UAV chaser may then proceed back toward its home base on the target vehicle. Using moving baseline RTK technology, proximity operations like this UAV approach and vehicle-to-vehicle docking can be supported by knowledge of the relative distance between the two vehicles without need for precise absolute positioning.

In this example, the target and chaser hardware setups are both in motion and moving relative to each other within a moving reference frame. For simplicity, the heading offset is assumed to be zero. Both the UAV and vehicle can independently use its hardware setup to determine the single point position of its respective body (with a 3-5 meter absolute accuracy) but by operating as a paired receiver set, centimeter-level relative positioning can be gained. This moving baseline RTK technology provides a relative distance vector between the two receivers, which is used to guide the approach of the UAV to the vehicle's roof structure. RTK-based heading and velocity information for each receiver can be used to develop target vehicle and chaser UAV projected trajectories to support the UAV's rendezvous and docking with the target vehicle (see Figure 6).

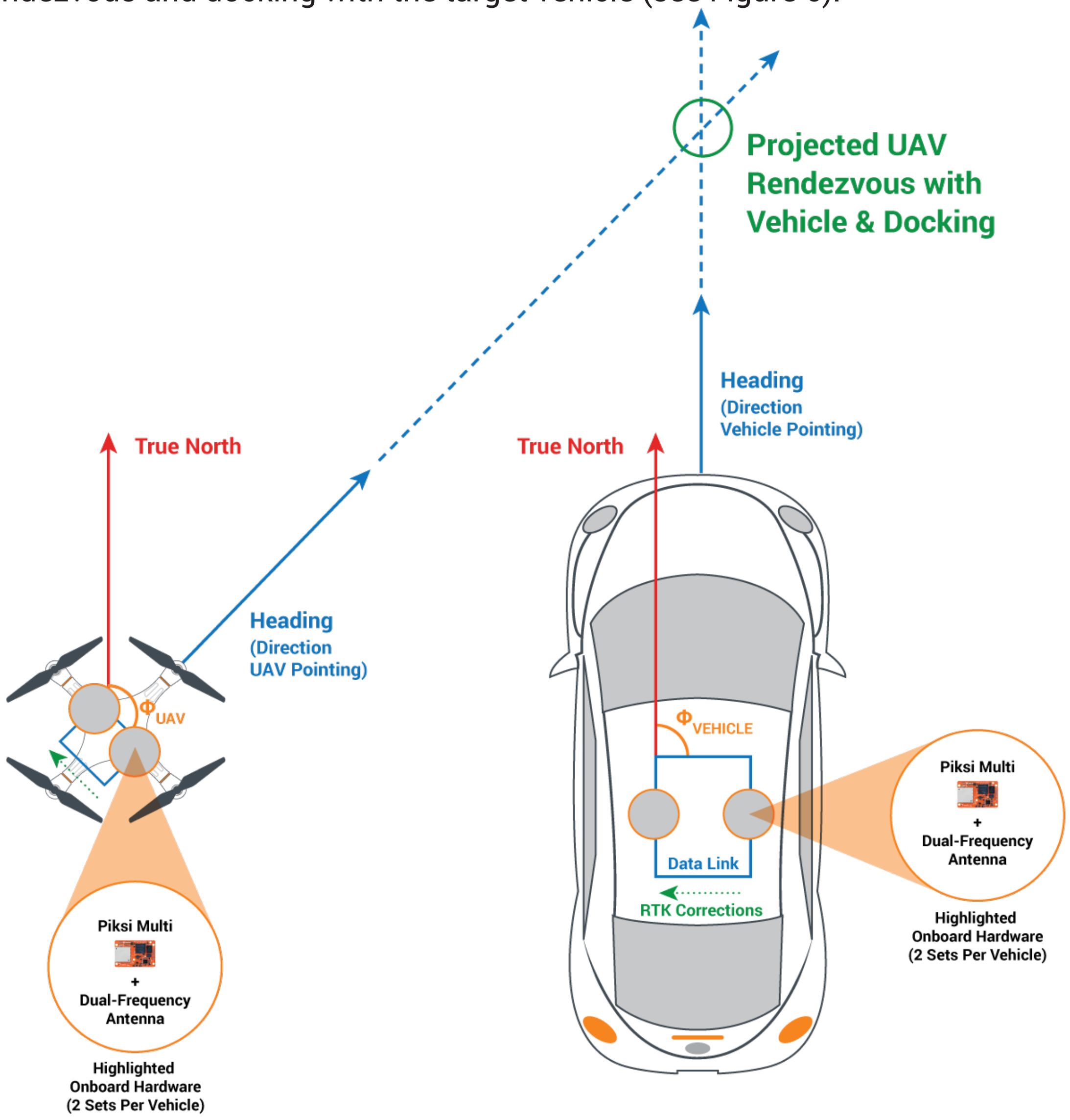


Figure 6 - High-Level System Diagram for Heading Hardware Configuration

As part of the docking process, the UAV may drop-off the payload to complete its version of a last mile delivery and then go into a hibernation mode until the UAV is triggered for a subsequent mission.

"Map Rover Map" Mission: A second example of this high-level system architecture utilizes the chaser UAV to scout and provide the target vehicle with information that is beyond the capabilities of the target vehicle's local sensor suite. As depicted in Figure 7, an autonomous vehicle using LiDAR may have a sensing range of approximately 200 meters with sub-meter accuracy, whereas the UAV can theoretically extend this range to improve the sensing range with centimeter-level accuracy.

In this example, the target vehicle might recognize that its current maps are no longer accurate due to a recent area earthquake or construction event. The vehicle could trigger the UAV to traverse the local region and send back information to assist with sense and avoidance of new obstacles, to further train its mapping algorithm.

Figure 7 - RTK Can Aid in Extending Mapping Sensors Beyond the Autonomous Vehicle Local Sensor Suite

The Results | Demonstrating a GNSS RTK Receiver in Action

The Swift Navigation test vehicle was used to analyze the Piksi Multi GNSS receiver accuracy within a fixed-distance moving baseline configuration [Test Case 1] and for computation of a heading solution [Test Case 2] using data captured from the April 2017 Self-Racing Cars (SRC) autonomous vehicle event. This data was captured in tandem with data used to demonstrate the Swift Navigation advanced automotive positioning solution performance that has been previously published at http://data.selfracingcars.com/ for the Thunderhill Raceway event located in Willows, CA.

In addition to the SRC heading vehicle testing, static data was captured and used to compute RTK-based heading in two environments. The first of these was during a short duration field test in Brisbane, CA [Test Case 3] and the second was a longer duration lab test in San Francisco, CA [Test Case 4].

These four test cases, including the test result validation method, are summarized in the following table.

Test Case	Configuration	Location	Scenario	Method of Results Validation
1	Moving Baseline RTK	SRC Event (Willows, CA)	Fixed Distance Moving Baseline RTK	Piksi Multi Computed Baseline Compared Against Known Fixed Distance Between Antennas
2	RTK-Based Heading	SRC Event (Willows, CA)	In-Motion Heading Field Test	Piksi Multi Computed Heading Compared Against Estimated Heading from Post-Processed Novatel FlexPak 6 with IMU Data
3	RTK-Based Heading	Field (Brisbane, CA)	Stationary Heading Field Test	Piksi Multi Heading Comparison Against Established RTK Heading Product - Trimble MB-One
4	RTK-Based Heading	Lab (San Francisco, CA)	Stationary Heading Lab Test	Piksi Multi Heading Comparison Against Established RTK Heading Product - Trimble MB-One

The highlighted hardware and software configurations and are summarized in the following table, with further development of each test case thereafter. All receivers were configured to run with a solution rate of at least 2 Hz.

Location	Test Case	Receivers	Constellation Frequencies	Corrections Source	Antenna(s)
SRC Event (Willows, CA)	1	Piksi Multi 1	GPS L1/L2	Piksi Multi 2 (2nd Receiver)	Mini Survey GPS500
	2	Piksi Multi 1	GPS L1/L2	Piksi Multi 2 (2nd Receiver)	Mini Survey GPS500
		Novatel FlexPak 6 with IMU-IGM-S1	GPS L1/L2, GLONASS L1/L2	Continuously Operating Reference Station (CORS)	Mini Survey GPS500
Field (Brisbane, CA)	3	Piksi Multi 1	GPS L1/L2	Piksi Multi 2 (2nd Receiver)	Mini Survey GPS500
		Trimble MB-One	GPS L1	Same Dual Antenna Receiver	
Lab (San Francisco, CA)	4	Piksi Multi 1	GPS L1/L2	Piksi Multi 2 (2nd Receiver)	Survey Antenna
		Trimble MB-One	GPS L1	Same Dual Antenna Receiver	

SRC Event [Test Cases 1, 2]

The Piksi Multi receivers used for moving baseline and heading computations were installed in the Swift Navigation test vehicle and connected to their own respective vehicle roof-mounted dual-frequency Mini Survey GPS500 antennas. The antennas were installed with a known fixed baseline (distance between the two antennas) of 0.78 meters and a heading offset of 90 degrees was applied in post-processing. The Piksi Multi GNSS receivers were running v1.0.0-branch-100, a pre-release build of the Piksi Multi 1.1 firmware and physically connected by a RS-232 data link to pass data between them.

The receivers were set to time-matched mode and data was captured over several drive laps to evaluate overall Piksi Multi performance. Moving baseline and heading feature evaluation, while not the primary focus on race day, were computed through post-processing to assess the receivers' representative performance. Figure 8 shows the antenna hardware setup at SRC where two inline antennas were used for Test Cases 1 and 2 as well as for Test Case 3, detailed later.

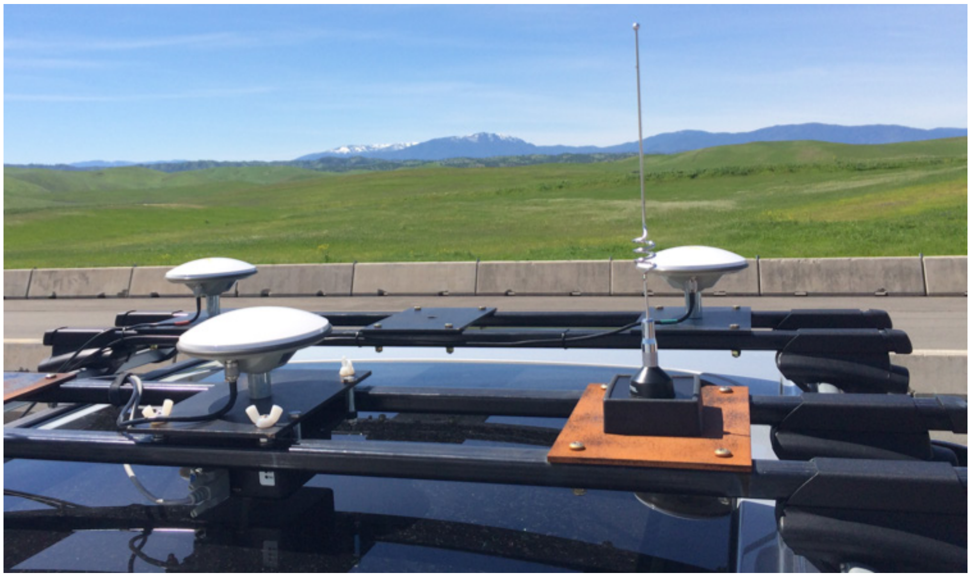


Figure 8 - Antenna Setup on Swift Navigation Test Vehicle

Additionally, the Swift Navigation test vehicle was equipped with a Novatel FlexPak 6 and IMU-IGM-S1 which was used as a point of comparison for computed heading only within this analysis. The FlexPak 6 was used to capture raw GNSS observables and IMU data that was later used to produce a highly-accurate reference trajectory with Novatel Inertial Explorer software. A UNAVCO CORS station (P336) located approximately 8 kilometers away was used as the reference station and the inertial data was tightly coupled within the solution. This reference trajectory was then used to calculate an estimated heading for comparison with the Piksi Multi receivers.

Results were computed using a single lap from the test day and presented within Test Case 1 and Test Case 2.

For Test Case 1, a simplistic analysis approach was taken to assess the moving baseline performance; the baseline vector's magnitude was computed and compared against the known fixed baseline. The RTK algorithms computing the baseline had no constraint or knowledge that the baseline magnitude was unchanging.

Figure 9A shows the computed results over time relative to the known value. The histogram in Figure 9B depicts that the baseline error difference (comparison between the known and computed baseline) remained dominantly within 1 cm of error. The table summarizes the results shown in Figure 9A which had an average computed baseline vector magnitude of 0.775 meters, with a standard deviation of 0.003 meters, relative to the actual known baseline of 0.78 meters.

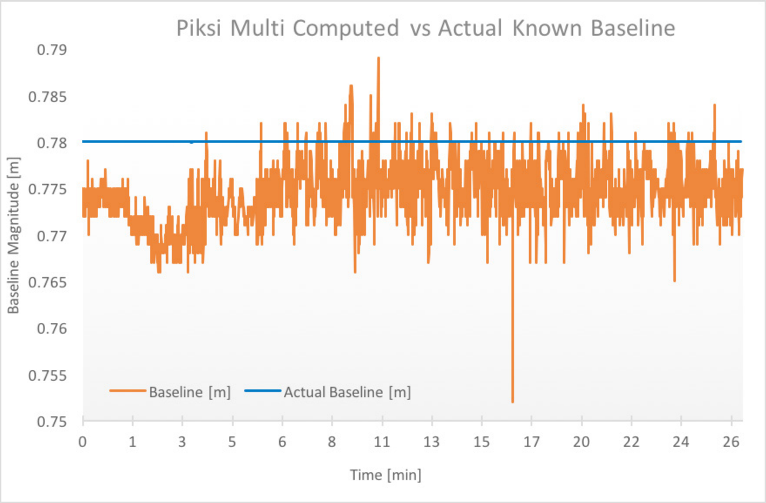


Figure 9A - Piksi Multi Computed Baseline Compared Over Time (Minutes) to the Known Baseline of 0.78 m

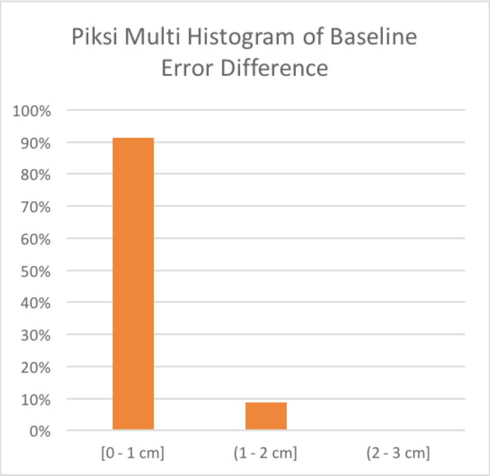


Figure 9B - Piksi Multi Computed Baseline Histogram of Error Relative to the Known Baseline of 0.78 m

GNSS Receiver	Computed Baseline	Actual Baseline	Standard Deviation
Piksi Multi / Known Baseline Comparison	0.775 m	0.78 m	0.003 m

Test Case 1 - Moving Baseline Test Results

For Test Case 2, two Piksi Multi receivers computed an RTK moving baseline in real time. The heading derived from this moving baseline was compared against a post-processed heading result from the Novatel FlexPak 6 receiver with IMU and software. The heading data was normalized to a 0-360 degree standard range for comparison purposes.

Figure 10A indicates that the Piksi Multi's computed heading tracked closely to the estimated Novatel FlexPak 6 heading. Further, the results for both heading products tracked consistently between the laps around the race track. Figure 10B shows the time series difference in heading results between the two receivers and Figure 10C shows the distribution function for the comparative heading difference in degrees. The table summarizes the values at 50%, 68%, 95% and 99% using the difference distribution function. It may be important to note that the Novatel product was being used as a comparative industry reference and not a truth source, thus this is not identified as an error but instead a difference between the heading results.

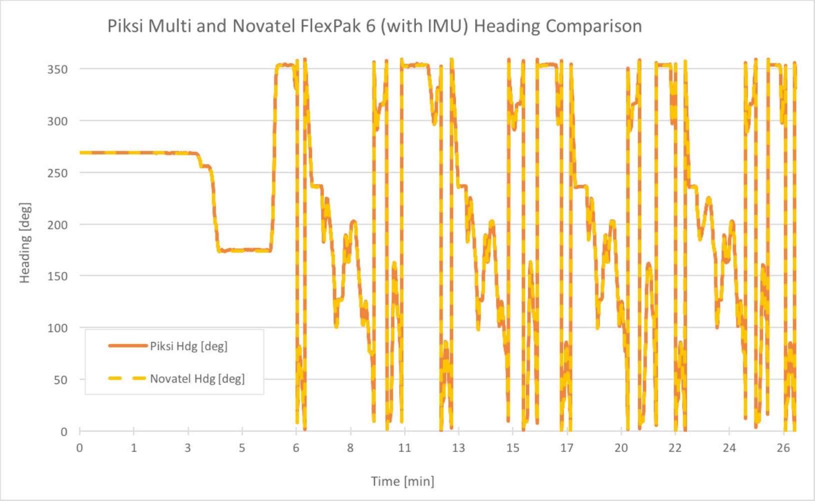


Figure 10A - Piksi Multi Computed Heading Compared Over Time (Minutes) to Estimated Novatel FlexPak 6 (with IMU) Heading

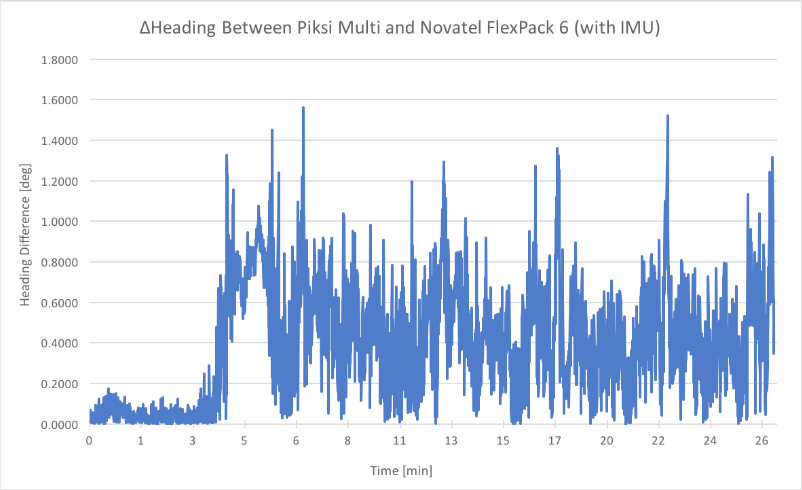


Figure 10B - Piksi Multi and Novatel FlexPak 6 (with IMU) Heading Difference Comparison Over Time

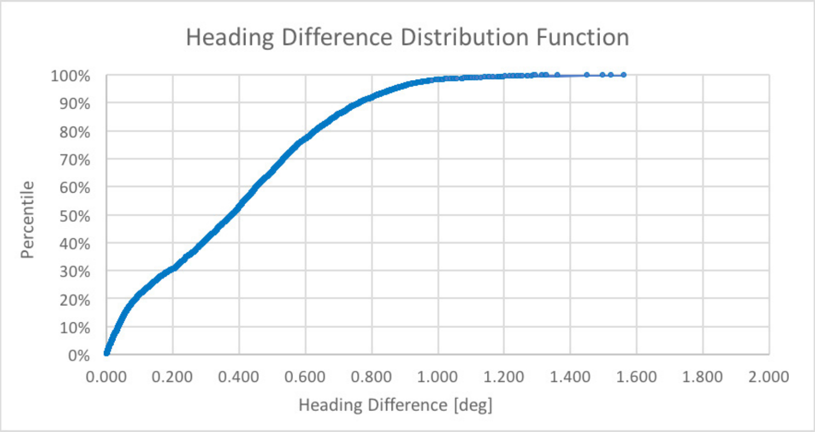


Figure 10C - Distributive Function of Piksi Multi and Novatel FlexPak 6 (with IMU) Heading Difference

GNSS Receivers	50%	68%	95%	99%	Standard Deviation
Piksi Multi / Novatel FlexPak 6 with IMU Comparison	0.38°	0.52°	0.87°	1.11°	0.28°

Test Case 2 - Comparative Heading Difference Test Results

Stationary RTK-Based Heading [Test Cases 3, 4]

Static RTK-based heading data was captured in two environments using the Piksi Multi GNSS RTK Receiver and a secondary comparison receiver, an established product in the RTK heading space, with the results presented for each environment.

For Test Case 3, the Swift Navigation test vehicle was used to capture approximately 10 minutes of static heading data in early May 2017 while parked in Brisbane, CA. The Piksi Multi receiver and the Trimble MB-One comparison receiver, both with heading support, were tested using the same signal chain—the same mini survey GPS500 antenna and GPS splitter. The Piksi Multi receivers were running v1.1.19—a pre-release build of the Piksi Multi 1.1 firmware—and physically connected by a RS-232 data link to pass data between them.

Piksi Multi heading was outputted at rate of 5 Hz with a mean heading of 152.78 degrees and standard deviation of 0.13 degrees and the Trimble MB-One outputted at a rate of 2 Hz with a mean heading of 152.69 degrees and a standard deviation of 0.11 degrees. The table summarizes the comparative heading results.

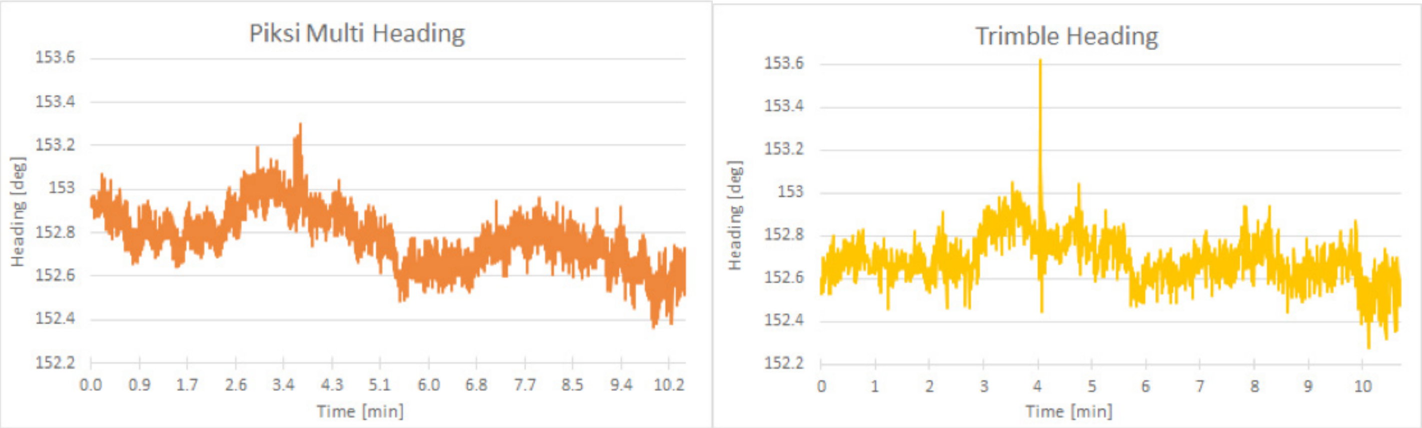


Figure 11 - 10 Minute Static Heading (Degrees) Comparison Test Utilizing the Piksi Multi GNSS Receiver and Trimble MB-One

GNSS Receivers	Solution Rate	Mean Heading	Standard Deviation
Piksi Multi	5 Hz	152.78°	0.13°
Trimble MB-One	2 Hz	152.69°	0.11°

Test Case 3 - Comparative Heading Results

For Test Case 4, the Swift Navigation lab was used to further test static RTK-based heading over a time period of approximately 24 hours. The test setup employed two Piksi Multi RTK GNSS receivers; both were installed on an indoor test bench and a cable drop from an open-sky rooftop location was used to connect a dual-frequency antenna to each Piksi Multi receiver. In this instance, the Piksi Multi receivers were running v1.1.29—a post-release build of the Piksi Multi 1.1 firmware. The baseline length between the two rooftop mounted survey antennas was measured to be 1.31 meters with an estimated bearing of 357.84 degrees. It is important to note that this bearing was estimated using the same Trimble MB-One receiver that computed the average heading over a previous 24 hour test.

The Trimble MB-One was also in the lab using two rooftop mounted survey antennas to gather additional heading data for comparison with Piksi Multi.

Time series data from the lab test is shown in Figure 12A. Piksi Multi heading was outputted at a rate of 5 Hz with a mean heading of 357.98 degrees and standard deviation of 5.51 degrees and the Trimble MB-One outputted at a rate of 2 Hz with a mean heading of 357.85 degrees and a standard deviation of 0.12 degrees. The Piksi Multi data included several heading outliers that passed over the 360 degree threshold that unjustly skewed the standard deviation. On accounting for this artificial threshold, the Piksi Multi had a mean heading of 358.01 degrees with a standard deviation of 0.12 degrees. The Piski Multi and Trimble MB-One data was plotted on a similar angular scale for visualization purposes.

Figures 12B and 12C show the distribution functions for Piksi Multi and Trimble MB-One, respectively, for th heading error in degrees. The table summarizes the uncorrected comparative heading results computed against the known bearing and further includes the values at 50%, 68%, 95% and 99% using the difference distribution function. As a reminder, the Trimble MB-One was essentially being compared against itself, since it was used to estimate the heading the two receivers were compared against.

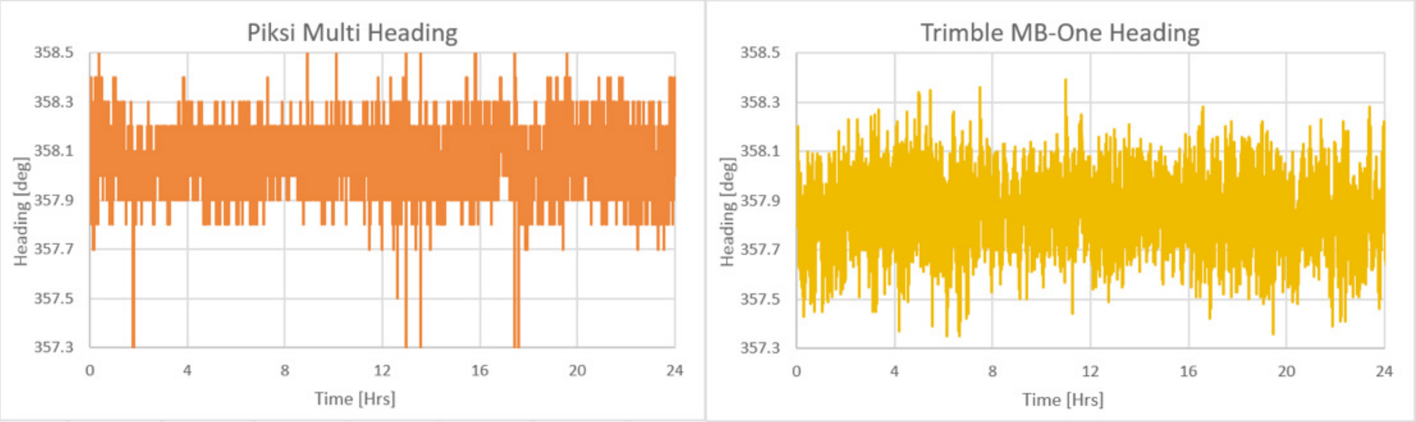


Figure 12A - Long Duration Test Results for Static Heading (in Degrees) for Piksi Multi Heading and Trimble MB-One Receivers

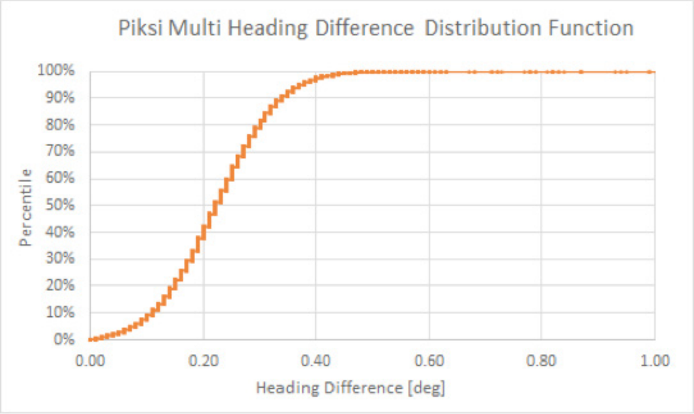


Figure 12B - Distributive Function of Piksi Multi Relative to Known Bearing

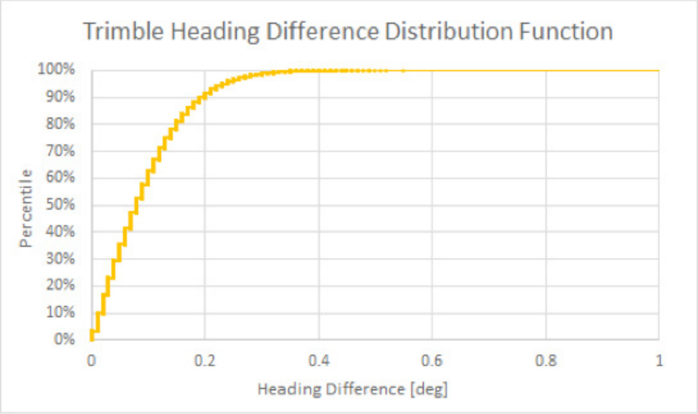


Figure 12C - Distributive Function of Trimble MB-One Relative to Known Bearing

GNSS Receiver	Solution Rate	Mean Heading	Standard Deviation	50%	68%	95%	99%
Piksi Multi	5 Hz	357.98°	0.11°	0.22°	0.26°	0.38°	0.44°
Trimble MB-One	2 Hz	357.85°	0.12°	0.08°	0.12°	0.23°	0.31°

Test Case 4 - Comparative Heading Error Distribution Results

Conclusion

These Piksi Multi demonstrated performance results coupled with GNSS RTK technology's innate advantages provide significant evidence of the GNSS sensor's rightful place within the autonomous system sensor suite.

Piksi Multi is specifically primed to make a customer impact for systems requiring highly accurate PNT that can support difficult sensor edge cases such as stationary-based heading. At a fraction of the cost of competitive products with comparable performance, Piksi Multi is ideal for OEM wide-scale deployments.

This sensor technology is not only valuable for its ability to provide absolute position information but can propel relative positioning applications, like dynamic map building, to the next level. Scouting GNSS RTK rover sensors using a moving baseline configuration are capable of taking sensing beyond a vehicle's own sensing range to help refine a map before the primary vehicle even arrives.

Piksi Multi began shipping in 2017 and will continue to see feature and performance improvements as part of no cost firmware updates, including GLONASS constellation support. For more information on the Piksi Multi Moving Baseline RTK and RTK-Based Heading features discussed, refer to the respective “Piksi Multi - Moving Baseline” and “Piksi Multi - Heading” articles located at Swift Navigation's Support Site.