ANALYZING GPS ACCURACY THROUGH THE IMPLEMENTATION OF LOW-COST COTS REAL-TIME KINEMATIC GPS RECEIVERS IN UNMANNED AERIAL SYSTEMS

THESIS

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Abstract

The focus of this research is investigating the utility of two small, low-cost, commercial-off-the-shelf (COTS), real time kinematic (RTK) GPS systems. The intent was to comprehend if current low-cost COTS technology performed as well as expensive high-end technology; as well as integrate a RTK system into autonomous flight scenarios. The RTK systems were characterized by test via static and dynamic scenarios, in parallel to a truth source. The results show that overall, in the Ublox NEO-M8P (via C94-M8P) performed better than the Swift Navigation Piksi (original). The Ublox NEO-M8P RTK System obtained a maximum DRMS (Distance Root Mean Square) of 1.6 centimeters, and a MRSE (Mean Radial Spherical Error) of 10.1 centimeters. The Piksi RTK system output an inconsistent data stream, and was therefore disregarded for flight test integration.

During the integration of the Ublox NEO-M8P and the 3DR Pixhawk (flight controller) for system flight, an issue of autoconfiguration was found between the 3DR and Ublox. A Drotek Tiny RTK was also evaluated with the 3DR Pixhawk, with the same configuration issues. System reliability issues were evident throughout this research, including, but not limited to signal blockage and multipath errors. It is recommended that research continue to investigate the use of a RTK GPS systems with small UAS (unmanned aerial system) flight controller.

Acknowledgments

To my wife and daughter –XoXo

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Blake T. McCollum

Table of Contents

Page

List of Figures

List of Tables

ANALYZING GPS ACCURACY THROUGH THE IMPLEMENTATION OF LOW-COST COTS REAL-TIME KINEMATIC GPS RECEIVERS IN UNMANNED AERIAL SYSTEMS

I. Introduction and Background Summary

Introduction

This research explored the implementation of a commercial-off-the-shelf (COTS), low-cost, real-time kinematic (RTK) system to increase geolocation accuracy in small unmanned aerial systems (UAS). The endgame of this research was to compare low-cost, COTS, RTK systems to find an economic solution to the GPS accuracy error limitation via flight testing. The investigation started by benchmarking two RTK systems (Ublox's NEO-M8P and Swift Navigation's Piksi) against each other in static and dynamic tests.

The chosen RTK system was then flight tested to determine operational feasibility and utility. Aspects of accuracy, precision, and reliability were investigated. The characterization of these RTK systems will provide an enhanced knowledge of additional applications—specifically for future use on attritable systems.

Problem Background

Over the past few decades, there has been a large influx in the popularity of unmanned aerial systems (UAS) due to the increase in application for military, hobbyist, and commercial users (Atherton, 2015). This is a trend that is not going away. In fact, although the current UAS market share is at a 15/85 split for civilian versus military, "the market for commercial/civilian [UAS] is expected to grow at a compound annual growth rate (CAGR) of 19% between 2015 and 2020, compared with 5% growth on the military side" (BI Intelligence, 2016). By 2024, it is predicted that the "drone" market will be a

~$24 billion marketplace (BI Intelligence, 2016). Due to this upward trend, research and development on subsystems have followed suit. One area in particular, system navigation, has become increasingly affordable and compact - both factors allowing precision navigation to become part of the UAS conversation.

A key component to any UAS, is the navigation system. Typically built around an inertial measurement unit (IMU) and a Global Navigation Satellite System (GNSS) receiver; the GNSS is typically the most influential component of the UAS in terms of geolocation. Position error is inherent to using a GNSS receiver. Classically, there have been several methods used to attain a high level of precision and accuracy to minimize position error in the GNSS solution. In particular, one answer for improving GNSS accuracy has been a RTK system solution. RTK GPS is a subset of Differential Global Positioning Systems (DGPS); however, instead of statically producing position output, RTK is a dynamic approach that pushes error corrections from a stationary GPS receiver to a rover receiver. This process allows for real-time accurate positioning on a centimeter level scale relative to the base station. Due to the immediate processing of error corrections, more processing power is demanded than standard methods.

In the past, large processing boards influenced the design of RTK systems. Furthermore, precision receivers used to cost tens of thousands of dollars, pushing them out of the realm for small UAS use. However, with the recent reduction in size and cost, these newer GNSS receivers are being considered as possible additions to the small, low-cost UAS.

Problem Statement

As the interest rises for attritable UAS solutions to become a reality, it is increasingly important that the UAS are low cost and are able to perform at a high level (CNAS, 2016). Part of the solution is found through the development and verification of a low-cost GPS receiver that executes like a high-end receiver. Applications such as cooperative control, close formation flight, swarming, targeting, etc. will all require precise and accurate geolocation. This research focuses on the feasibility of a small and inexpensive RTK system being the implemented solution to keep functionality high and cost low.

Research Objective

The objective of this research is to evaluate and flight test low-cost, COTS, RTK GPS receivers for use in flight scenarios for small UAS. A comparison is made between low-cost alternatives, as well as a comparison to a high-quality benchmark.

Investigative Questions

1. What is the current achievable accuracy of stock GPS equipment? This investigative question is also found in Hendricks thesis, but is revisited because it is paramount from a baseline standpoint (Hendricks, 2016).
2. How accurate and precise are the low-cost RTK systems; specifically, the Ublox's NEO-M8P and Swift Navigation's Piksi RTK system?
3. What are the limiting factors associated with the low-cost RTK system versus the traditional RTK systems?

4. How reliable are low-cost RTK systems?
5. What are the limitation of these COTS RTK systems being integrated into autonomous flight scenarios?

Scope

The scope of this research was to characterize the performance of the NEO-M8P system (via Ublox C94-M8P application board) produced by Ublox and the Piksi (original – NOT Piksi Multi) RTK system produced by Swift Navigation. Due to the nature of their size, price level, raw measurement output, and RTK-readiness, the NEO-M8P and Piksi RTK systems are qualified subjects of an investigation into a low-cost COTS RTK system solution for GNSS position solution challenges. The research was focused on bench testing, ground testing, and flight testing. The outcome of the tests provide insight into appropriate applications.

Methodology

Due to the fact that RTK GPS receiver characterization does not have a set standard approach, system portrayal will be carried out in relation to the high-end system available for use in the Air Force Institute of Technology's (AFIT) Autonomy and Navigation Technology (ANT) lab. There are three test phases in this research: bench testing, ground testing, and flight testing.

These tests are put into two categories—static and dynamic; bench testing is static, while flight testing is in the dynamic category. Ground tests have both static and dynamic components. The bench testing will be conducted on Swift Navigation's Piksi system and Ublox's NEO-M8P system in relation to AFIT's high-end RTK system.

Baseline tests, without the RTK algorithm engaged, will be performed for both systems. Following the baseline (non-RTK tests), static tests will be conducted with the RTK algorithm engaged.

Upon completion of the static bench tests, dynamic testing will be conducted; this testing will include ground and flight testing. Ground testing will be conducted on AFIT's campus. Tests include continuous motion of receivers and their ability to produce an accurate solution while maintaining satellite lock. Whichever receiver is found to have the highest precision will be integrated into flight testing. Integration flight testing will take place via quad rotors (3DR X-8s) at Wright-Patterson Air Force Base, Ohio. Once in flight, reliability measurements will take place over the flight duration. This final integration test will demonstrate the feasibility of the low-cost, COTS, RTK receiver solution on a UAS.

Limitations & Assumptions

Throughout this investigation, there are some key assumptions that are made during the research process. The first assumption made is that the GNSS receiver units (both the Ublox and Swift Navigation models) are found to be representative and non-defective. It is assumed that these units represent the greater body of the same units and function in exactly the same manner.

One limitation is the firmware updates to the RTK systems. Due to the relative innovation of these RTK systems to the public market, there are still firmware updates being made regularly. In order to maintain positive control over variables, the configuration of the firmware needs to be held constant. With this in mind, the final update to the firmware was to v0.26 for the Swift Navigation Piksi system and v8.23 for the Ublox NEO-M8P system.

The final assumption is a limitation of AFIT's in house, high-end RTK system accuracy. "The AFIT RTK system, has been characterized to have accuracy within several millimeters" (Hendricks, 2016). For comparison reasons of absolute accuracy of the Piksi and Ublox RTK systems, this assumption of accuracy must remain intact.

Definitions

Throughout this research paper, there are a few key terms that show up frequently. These terms include: accuracy, precision, relative accuracy, absolute accuracy, low-cost, COTS, and high-end (AFIT in house). Since many of these terms have different meanings to different communities, the terms are defined below.

- Accuracy—refers to the closeness of a measured value to a known value (NCSU)
- Precision—refers to the closeness of two or more measurements in relation to each other (NCSU)
- Relative Accuracy—represents the uncertainty in the positions relative to the other adjacent points to which they are directly connected (also known as local accuracy) (Higgins, 2015)
- Absolute Accuracy—requires that a position's accuracy be specified with respect to an appropriate truth set such as a national geodetic datum (also known as network accuracy) (Higgins, 2015)
- Low-cost—refers to a total system SUAS cost of less than $10K. This is a starting baseline that can lead to a large UAS system being considered attritable.

- COTS—commercial off the shelf; these items can be purchased as-is by any individual. There is no special clearance or association needed to acquire these items.
- Base unit—the stationary unit of the RTK GPS system. “The base station broadcasts its well-known location together with the code and carrier measurements for all in-view satellites” (Navapedia, 2014).
- Rover unit—the dynamic unit of the RTK GPS system. “The rover [unit] is able to fix the phase ambiguities and determine its location relative to the base with high precision. By adding up the location of the base, the rover is positioned in a global coordinate framework” (Navapedia, 2014).
- Reference RTK system—specifically alluding to the AFIT Novatel DL-V3 RTK system that has been verified at accuracies in the millimeter range; $10K+ for GPS receiver alone.
- Attritable—expendable; having qualities that make it close to disposable, such as a low price tag.

Summary

This research focuses on evaluating and flight testing low-cost, COTS, RTK GPS receivers for use in flight scenarios, which leads to conclusions regarding how this technology can be implemented in applications—where a few years ago would not be possible at this price-point.

The following chapters will explore the characterization and utility of these low-cost, COTS, RTK GPS receivers. Chapter II will update readers on the background of

GPS systems, as well as error mitigation techniques for the geolocation issues inherent to GNSS. Additionally, relevant previous research will be summarized. Chapter III will present in-detail the methodology used to test the systems in question. Chapter IV will render the results and analyses of the tests conducted in this research. Lastly, in Chapter V, conclusions on performance and utility, as well as remarks for further research, will be presented.

II. Background

Chapter Introduction

This chapter will provide a detailed background regarding the topics relevant to this thesis and research. First, a very brief overview of GPS will be presented. From there, the discussion will transition into GPS measurements and inherent error in measurements will be discussed. Additional information is then presented about mitigation efforts to reduce inaccuracies in GPS solutions along with the current state of these mitigation technologies. This chapter wraps up with a review of applicable literature detailing relevant research in the area of RTK-GPS systems.

GPS Overview

GPS theory was conceived in the 1960s, but the GPS constellation was not declared fully operational until 1995 ("GPS.gov: GPS Overview," n.d.). Since that time, it has become the default standard for navigation and timing technology worldwide. The GPS system consists of three segments: space, control, and user. The space segment consists of the constellation of approximately 31 space vehicles (24 nominal - 7 spares) contained within six orbital planes which circle the earth twice a day (Series, n.d.) ("GPS.gov: GPS Overview," n.d.). Satellites are in medium earth orbit (MEO), inclined 60 degrees with respect to the equatorial plane, at an altitude of approximately 12,550 miles (GPS.gov).

The control segment includes a master and alternate control station, 11 command and control antennas, and 15 monitoring sites ("GPS.gov: GPS Overview," n.d.). Lastly, the GPS-user segment consists of all GPS receivers operated by end users. Together, these three segments of the GPS system provide the end user with continuous position and time measurements. Overall, GPS is a multi-use, space-based radio navigation system owned by the US Government and operated by the United States Air Force to meet national defense, homeland security, civil, commercial, and scientific needs (Mai, 2015).The next section will provide a summary of GPS measurements.

Measurements

The three frequency bands (and frequencies) that GPS satellites transmit on are: L1 (1575.42 MHz); L2 (1227.60 MHz); and L5 (1176.45 MHz) (Corporation, 2000). Receivers can be single-frequency, double-frequency, and, just recently, triple-frequency capable (Misra & Enge, 2011). If the receiver is triple-frequency capable, it can track L1, L2, and L5 frequencies (L1 and L2 for dual frequency). Single frequency receivers can only track the L1 frequency. Due to the fact that low-cost GPS receivers typically use only one frequency (L1), this background section will focus on a single frequency position solution.

Each satellite transmits two different codes: a coarse/acquisition (C/A) code, intended for civil use, and the precision encrypted P(Y) code, for military use. The L1 frequency is modulated with both codes, but the L2 frequency is only modulated with the P-code. The C/A-code has a chipping rate of 1.023×10^6 chips per second. The P(Y) code has a chipping rate ten times (1.023×10^7 chips per second) that of the C/A-code and only repeats every 7 days.

A navigation message is also included on each frequency. The navigation message consists of satellite health information, ephemeris (satellite position and velocity), clock bias parameters, and an almanac providing reduced-precision ephemeris data on all satellites in the constellation (Spinelli, 2006). Table 1 shows a summary of the GPS signal structure.

Table 1. Summary of GPS Signal Structure *(Misra & Enge, 2011)*

Carrier	Frequency	Wavelength	Modulation	Chipping Rate	Chip Length
L1	1575.42 MHz	19.03 cm	C/A code	1.023 Mchips/sec	293.0 m
			P(Y) code	10.23 Mchips/sec	29.3 m
			Nav Message	50 bits/sec	
L2	1227.60 MHz	24.42 cm	P(Y) code	10.23 Mchips/sec	29.3 m
			Nav Message	50 bits/sec	

There are two methods that GPS receivers use to produce positional measurements; the first is pseudo-random code tracking, while the other method is carrier-phase tracking.

Pseudo-random Code Tracking

The remainder of this section follows Hendricks in both form and content (Hendricks, 2016):

> The first method uses the Coarse/Acquisition (C/A) code to distinguish the time between when the code sequence was transmitted by the SV to the time that it was received on the ground. Since each satellite has a specific C/A code, referred to as its pseudorandom noise (PRN) code, it is possible to distinguish the amount of time the signal took to reach the user receiver from each of the visible SVs. The time is then multiplied by the speed of light, 299792458 meters per second, to calculate the range from each satellite.
>
> The high-repeat rate of the C/A code (every millisecond) allows for ground receivers to lock onto the signal quickly. In contrast, because the P(Y)-code was designed for high-accuracy military applications, it is a 10^{14} bit sequence, which makes it extremely difficult to lock onto without accurate knowledge of absolute time to within a few microseconds. For this reason most P(Y)-code receivers acquire and track the C/A code signal before handing over to P(Y)-code tracking (Corporation, 2000).

The measurements received from tracking the C/A code are commonly referred to as the “pseudorange”. The range from each satellite is commonly referred to as “pseudorange” due to the measurement of true range being obscured by an unknown error in the receiver clock. There are also several other large errors that affect the range measurement; they are discussed in this chapter as well. Absolute three-dimensional position solutions are obtained by computing pseudorange measurements from at least four SVs. The equation for pseudorange is shown in:

$$\rho = r + c[\delta tu - \delta ts] + I\rho + T\rho + mp + v + S_d \quad (1)$$

where:
ρ = pseudorange (m)
r = true range between the satellite and receiver (m)
c = speed of light (299792458 m/s)
δtu = user (receiver) clock error (sec)
δts = satellite clock error (sec)
$I\rho$ = measurement delay due to ionosphere (m)
$T\rho$ = measurement delay due to troposphere (m)
m_p = measurement delay due to multipath (m)
v = measurement noise (m)
S_d =Signal Deformation bias Errors (m)

Error Sources

Attributed ranging errors in the positional solution can be grouped into the following six classes:

1) Ephemeris data—Ephemeris errors result when the GPS message does not transmit the correct satellite location. Since satellite errors reflect a position prediction, they tend to grow with time from the last control station upload (Wormley, 2010).

2) Satellite clock—GPS satellites carry very accurate atomic clocks, but clock drifts are inevitable and a very small amount can cause significant errors in a receiver on the ground (Series, n.d.).

Before May 1, 2001, there was an intentional clock and ephemeris error called Selective Availability (SA) integrated into the GPS design. Its purpose was aimed at preventing unauthorized users from using the system’s high accuracy. The intended discordance was to cause an open signal user's calculated position to move erratically and unpredictably, in random directions, sometimes quickly and sometimes slowly, out to 328 feet (100 meters)–and occasionally further–from their true position (Reynish, 2000).

3) Ionosphere—Due to free electrons in the ionosphere, GPS signals do not travel at the vacuum speed of light, as they transit this region. The modulation on the signal is delayed in proportion to the number of free electrons encountered (Wormley, 2010). The ionosphere is usually well-behaved and stable in the temperate zones; near the equator or magnetic poles it can fluctuate considerably. One correction technique is a near-real time update, such as the Wide Area Differential GPS system (WADGPS) (Wormley, 2010). Typical ionospheric error is in the 10 meter range. See Figure 1 for an illustrated depiction of Ionospheric and Tropospheric error.

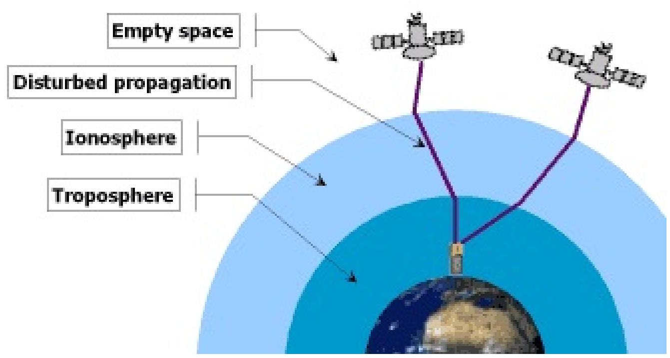

Figure 1. Ionospheric and Tropospheric Error *(Sources of Error in GPS, 2014)*

4) Troposphere—Deviation from the vacuum speed of light is caused by the troposphere. Variations in temperature, pressure, and humidity all contribute to variations in the speed of light of radio waves. Both the code and carrier will have the same delays (Wormley, 2010). Typical tropospheric error is in the 1 meter range. See Figure 1 for an illustrated depiction of Ionospheric and Tropospheric error.

5) Multipath—Multipath is the error caused by reflected signals entering the antenna of the receiver. These effects tend to be more pronounced in a static receiver near large reflecting surfaces (Wormley, 2010). Typical multipath error is in the 0.5 meter range. See Figure 2 for an illustrated depiction of multipath error.

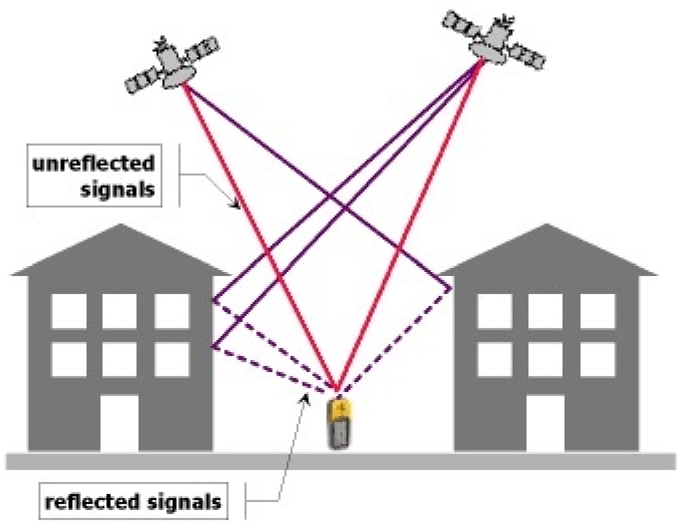

Figure 2. Multipath Error *("Sources of Error in GPS," 2014)*

6) Receiver—Errors in the receiver's measurement of range caused by thermal noise, software accuracy, and biases between receiver channels (Wormley, 2010).

Carrier Phase Tracking

The remainder of this section follows Hendricks in both form and content (Hendricks, 2016):

> Instead of using the C/A- or P-code to determine distances from the space vehicles (SV), the other method for determining position is carrier-phase tracking. After locking onto the PRN code from each of the visible SVs, carrier-phase measurements track the accumulated Doppler of the carrier frequency (Misra & Enge, 2011). Given that the L1 carrier frequency is about 1,540 times greater than the C/A-code chipping frequency, a higher-precision measurement is obtained, which in-turn corresponds to higher-accuracy position solutions. The high accuracy

leading to a high precision is due to the errors associated with GPS signals being normally distributed around the true position. The downside, however, is that some additional post-processing of the measurement is required in order to determine the distance—since the carrier phase measurement is in units of cycles. The equation for the carrier-phase measurement is shown:

$$\varphi = (1\backslash\lambda)[r + c(\delta tu - \delta ts) - I\rho + T\rho + mp + v] + N \tag{2}$$

Where r, c, δtu, δts, I, T are defined in Equation (2)
φ = Carrier phase Measurement (cycles)
λ = carrier wavelength (m/cycle)
N = integer ambiguity (number of cycles)

As shown in Equation (2), the equation used for carrier-phase tracking is very similar to Equation (1), which is used for pseudorange measurements. There are, however, two primary differences in the equations. The first is the affect that the ionosphere has on the measurement. This is shown by the –Iρ in Equation (2) versus the +Iρ in Equation (1). The other, more troublesome, difference is that Equation (2) is in terms of cycles and requires the ambiguity term, N, be resolved, before determining the distance between the receiver and the SV. There are several techniques that have been developed for resolving the integer ambiguity. Invented by Teunissen, one popular method for resolving the ambiguities is called the Least Squares Ambiguity Decorrelation Adjustment (LAMBDA) method (Raquet, 2016). A full derivation of the LAMBDA method can be found in (Raquet, 2016).

Differential GPS (DGPS)

The remainder of this section follows Hendricks in both form and content

(Hendricks, 2016):

> One of the primary methods used to reduce the amount of error in the GPS position solution is using differential GPS (Spinelli, 2006). DGPS works to reduce spatially-correlated errors by calculating the difference between the known range and the pseudorange, which is used by the receiver to assist in calculating a position solution. It is important to note, that while the spatially-correlated errors, such as troposphere and ionosphere delays are reduced, the non-spatially correlated errors, such as measurement noise and multipath, are [not reduced]. This is a good tradeoff; however, because the spatially-correlated errors are a much larger contributor to the total error than the non-spatially-correlated errors

(Hendricks, 2016). The following two sections will detail single- and double- difference GPS.

Single Differencing

The remainder of this section follows Hendricks in both form and content

(Hendricks, 2016):

Single differencing involves using the differential between two receivers in view of the same SV. Figure 3 shows a schematic of how single difference works between satellite *a* and receivers *x* and *y*.

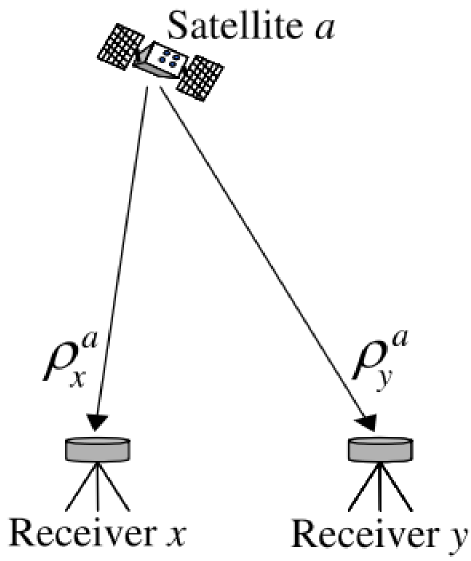

Figure 3. Single Difference Schematic *(Rieke, Foerster, Geipel, & Prinz, 2012)*

The difference between the pseudorange of receiver *x* relative to satellite *a* and receiver *y* relative to satellite *a* is shown in Equation (3).

$$\Delta\rho_{xy}^a = \rho_x^a - \rho_y^a \qquad (3)$$

$\Delta\rho_{xy}^a$ = single difference measurement (m)
ρ_x^a = pseudorange from satellite a to receiver x (m)
ρ_y^a = pseudorange from satellite a to receiver y (m)

By substituting Equation (1) into Equation (3), each of the terms in the pseudorange equation becomes differential terms as shown in Equation (4) below.

$$\Delta\rho_{xy}^{a} = \Delta r_{xy}^{a} + \Delta c\delta t_{u,xy}^{a} - \Delta c\delta t_{xy}^{s,a} + \Delta I_{xy}^{a} + \Delta T_{xy}^{a} + \Delta mp_{xy}^{a} + \Delta v_{xy}^{a} \quad (4)$$

As noted earlier in this section, the satellite clock term is completely eliminated, since that term is common in between the two receivers. The ionosphere and troposphere terms are decreased significantly, if the distance between the two receivers is small. The multipath and measurement noise terms increase by a factor of √2. Following the same steps as were conducted for the pseudorange equations, an equation for single-difference carrier phase measurements is shown in Equation (5).

$$\Delta\varphi_{xy}^{a} = \frac{1}{\lambda}\left[\Delta r_{xy}^{a} + \Delta c\delta t_{u,xy}^{a} - \Delta c\delta t_{xy}^{s,a} - \Delta I_{xy}^{a} + \Delta T_{xy}^{a} + \Delta mp_{xy}^{a} + \Delta v_{xy}^{a}\right] + \Delta N_{xy}^{a} \quad (5)$$

By implementing single difference DGPS, the accuracy of C/A code measurements is improved from 10 meters to about 1 meter. Double differencing can be applied for an even greater improvement in position accuracy.

Double Differencing

In order to reduce the errors even more than what is possible using single differencing, the double difference method can be implemented. Double differencing relies on two receivers receiving information from two SVs simultaneously. If this condition holds, then the receiver-error term is eliminated. Figure 4 shows a schematic for double differencing.

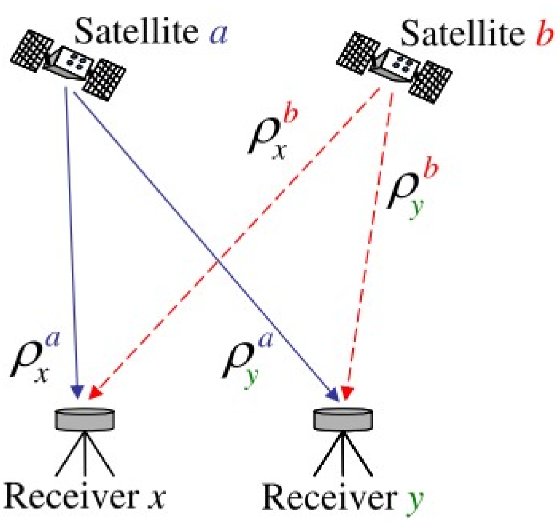

Figure 4. Double Differencing Schematic ***(Rieke et al., 2012)***

Double differencing is very similar to single differencing. The distinction is that, whereas single difference uses the pseudorange or carrier-phase measurements as inputs, double differencing uses the single difference of the pseudorange as inputs. Equation (6) is the formula used to obtain the correction.

$$\Delta\nabla\rho_{xy}^{ab} = \Delta\rho_{xy}^{a} - \Delta\rho_{xy}^{b} \quad (6)$$

$\Delta\nabla p_{xy}^{ab}$ = double difference of receivers x and y relative to satellites a and b (m)
Δp_{xy}^{a} = double difference of receivers x and y relative to satellites a (m)
Δp_{xy}^{b} = double difference of receivers x and y relative to satellites b (m)

By combining Equation (4) and Equation (6), the double difference equation becomes:

$$\Delta\nabla\rho_{xy}^{ab} = \Delta\nabla r_{xy}^{ab} + \Delta\nabla I_{xy}^{ab} + \Delta\nabla T_{xy}^{ab} + \Delta\nabla mp_{xy}^{ab} + \Delta\nabla v_{xy}^{ab}\Delta\nabla \quad (7)$$

The terms for ionosphere and troposphere are further reduced, the receiver clock error term is eliminated, but the error contribution from multipath and noise are increased by a factor of 2 over the single C/A-code tracking. Like single differencing, the method can also be applied to carrier phase measurements (see Equation (8) below).

$$\Delta\nabla\varphi_{xy}^{ab} = \frac{1}{\lambda}\left[\Delta\nabla r_{xy}^{ab} - \Delta\nabla I_{xy}^{ab} + \Delta\nabla T_{xy}^{ab} + \Delta\nabla mp_{xy}^{ab} + \Delta\nabla v_{xy}^{ab}\right] + \Delta\nabla N_{xy}^{ab} \quad (8)$$

By implementing double differencing with carrier-phase measurements, position errors are in the range of 1-3 millimeters, when using high-end GPS equipment (Navigation, n.d.).

Real Time Kinematics (RTK)

The high-precision carrier-phase measurements are utilized by RTK algorithms to calculate a relative position of one receiver to the other. The RTK algorithms onboard any RTK system utilize the double differenced carrier phase measurements to solve for the integer ambiguity in near real-time (Hendricks, 2016). The receiver pre-designated as the base receiver then sends its measured carrier-phase to the mobile receiver. The processors onboard the mobile receiver then compare the carrier-

> phase sent to it from the base receiver to the measured carrier-phase from its own receiver. The comparison of the two carrier-phase measurements, along with information regarding the azimuth and elevation position of the GPS satellites, allow the calculation of a baseline distance, or distance between the two receivers (Hendricks, 2016).

Typically, there can be three phases that a RTK GPS system can cycle through as it is reducing its position errors: RTK Fix, RTK Float, and Single Point Precision (SPP). These are all based off of the N (integer ambiguity) value, referred to in the equations above, that the system is trying to calculate. "If the algorithm finds an integer solution, then the solution is called a 'fix'. This is when maximum accuracy is reached" (Perin, 2016). Otherwise, 'float' means the algorithm colloquial has not converged to a fixed integer solution and the RTK engine is still using floating point numbers to try to converge to a fixed integer solution (Koley, 2010). SPP is "for the positions neither 'fix' nor 'float' (happens if no correction data is received, or if signals are not good enough)" (Perin, 2016).

> The position solutions output from the RTK algorithm are in a relative coordinate frame, typically centered at the base receiver location for simplicity, not an absolute coordinate frame. Absolute measurements can be obtained from the RTK algorithm, if the location of the base receiver's antenna is known in the absolute coordinate frame (Hendricks, 2016).

Industry Assessment of RTK GPS Receivers

Due to recent high activity, there are many COTS components available for implementing high-accuracy positioning (Gakstatter, 2013). However, many of these systems are either too big to fit into a small-UAS or they are above the price threshold for considering the system low-cost. Within this section, a small trade study of the available technology is conducted in order to show the reader how the selected components' capabilities compare to industry-standard components (Hendricks, 2016).

The RC-industry de facto standard for providing accurate, absolute locations is the 3DR Ublox GPS with compass kit (3DR, 2016). The 3DR kit is very low-cost, approximately $35, lightweight, and easily integrated with existing autopilots such as the APM or Pixhawk (3DR, 2016).These autopilots allow, among other features, the capability of waypoint following for COTS small-RC aircraft. The drawback to using this component for high-accuracy geolocation is that the system is not equipped with an on-board processor that will allow for carrier-phase ambiguity resolution or DGPS (Hendricks, 2016). As such, the position solution accuracy will be limited by the pseudorange measurement accuracy.

Representing the other end of the cost spectrum is the SBG Systems Ellipse-D. The system has a much higher level of accuracy relative (claims of 2 cm RTK) to the 3DR component (Systems, 2016). This is made possible by onboard processing to conduct the carrier-phase ambiguity resolution, as well as double differencing GPS. The system is also capable of receiving signals on both the L1 and L2 frequencies, which allows for a more accurate error assessment induced by the signal passing through the ionosphere and, thus, a more precise measurement (Misra & Enge, 2011). However, the primary drawback to the system in regard to this research is the high cost. At ~$11K each, at the time this document was written, the system is well above the cost threshold defined in Chapter 1.

In the middle of the cost-spectrum are two high-accuracy GPS receivers that have become available within the past two years: the Swift Navigation Piksi and the Ublox NEO-M8P. The Swift Navigation Piksi (original - at the time of this research the Piksi Multi was not available) is an out-of-the-box capable RTK GPS system originally developed using money from a Kickstarter campaign (KickStarter, 2014). Since the makers of the system are relatively new to the game, the open-source software running on the field-programmable gate array (FPGA) is constantly being tweaked to allow for faster GPS lock and increasing the algorithm's accuracy. The price of the system is ~$1K for two receivers—allowing the full UAS to remain below the cost threshold.

Swift Navigation's Piksi (original) uses double differencing of the carrier-phase measurements to send error corrections from a base station, with known geo-coordinates, to a rover vehicle. Since the system relies on the user to input the absolute position of the base receiver, the accuracy achieved is only in terms of a local coordinate system centered on the base receiver. The relative accuracy of the system is advertised to be within 10 centimeters. Verifying the value is a goal of this research and will be discussed further in Chapters III and IV. The Piksi system was among the first system to be at the lower end of the RTK cost spectrum; very recently (Spring 2016), the Ublox NEO-M8P receiver module became available.

The recent development of the Ublox NEO-M8P has the GPS RTK world buzzing to know more about this product (Staff, 2016). Claiming to bring cm-level GNSS positioning for the mass market, this product is integrated onto the C94-M8P application board set for a price tag of $399. The base station module sends corrections via the RTCM protocol to the rover module, via a communication link, enabling the rover to output its position relative to the base station. Additionally, the product is marketed as an out-of-the-box solution with RTK algorithms pre-integrated into the module. The relative accuracy of the system is advertised to be within 2.5 centimeters (Ublox, 2016). Verifying the value is one goal of this research and will be discussed further in Chapters III and IV.

RTK GPS Device Testing

To ensure that this thesis is not just a duplication of prior research efforts, an in-depth literature review was performed. Relevant articles and theses are reviewed. The areas where prior research leaves off and this research picks up are annotated.

SUAS Application

The thesis research completed by Captain Kevin Hendricks in 2016 laid some of the foundational groundwork that makes this thesis possible. Much like this thesis, Hendricks explored the effects that a small, COTS, RTK-GPS system would have on a SUAS. Hendricks completed his research in the hypothetical realm by testing Swift Navigation's Piksi RTK System in both static and dynamic settings against a high-end RTK system as the ground truth source; additional tests were run against the hobbyist standard receiver. Results concluded that the Piksi RTK System outperformed the commonly-used GPS receiver (Ublox LEA-6) by a factor of 100 (Hendricks, 2016). Additionally, when tested against the high-end RTK system in a dynamic fashion, the average error was 3.4 cm, -6.6 cm, and 4.3 cm for East, North, and Up, respectively (Hendricks, 2016). The standard deviation was 98.8 cm, 125.2 cm, and 7.5 cm for East, North, and Up, respectively (Hendricks, 2016). There was noted loss of RTK GPS lock during dynamic testing. One important factor to note was, in this research, the Piksi firmware was updated to v0.20 (Hendricks, 2016). The proposed research will incorporate the Piksi firmware updated to v0.22 and will also integrate into a SUAS via flight testing.

Industry

In the past few years, there have been several researchers exploring the area of high-accuracy positioning using low-cost receivers. Hedgecock, Maroti, Sallai, Volgyesi, and Ledeczi‘s approach to the accuracy issues of GPS was not to implement an RTK system, but rather, to implement a localized relative network (Hedgecock, Maroti, Sallai, Volgyesi, & Ledeczi, 2013). Nodes in a network share their raw satellite measurements and use this data to track relative motions of neighboring nodes—as opposed to computing their own absolute coordinates (like RTK). Their research was a proof of concept that worked to obtain accuracies on the scale of centimeter level with an update rate of 1 Hz (Hedgecock et al., 2013). However, this methodology is still limited to the accuracy of the base station.

Eling, Klingbeil, and Kuhlmann’s research in 2014 focused on the in-house development and implementation of a tightly coupled RTK-GPS and GPS attitude determination algorithms to obtain precise real-time positioning of lightweight UAVs (Eling, Klingbeil, & Kuhlmann, 2014). Following the RTK GPS model of having a master station and rover, their research was conducted using a Ublox LEA-6T GPS receiver on a HiSystems GmbH Mikrokopter Okto X1 (Rotocopter). Results of flight tests were compared against two other GNSS software packages: RTKLIB and Leica Geo Office. The team’s proprietary setup achieved height differences of “mostly less than 5 mm" and no visible differences in the north and east components (Eling et al., 2014). Results presented in this research were relative and not absolute.

Pilz, Gropengieber, Walder, Witt, and Werner's research in 2011 was concentrated on using low-end, single frequency receivers and open source RTK algorithms to obtain accurate outdoor positioning. The setup for the RTK-GPS system consisted of a Ublox LEA-4T as the reference receiver and a Ublox LEA-6T as the rover receiver (Pilz, Gropengieber, Walder, Witt, & Werner, 2011). The raw data was passed through RTKLIB and corrections were sent back to the rover to obtain a more precise location. The static 2-sigma results for 2D, 3D, and height were 0.0842 m, 0.1983 m, and 0.1794 m, respectively (Pilz et al., 2011). The research theorized outdoor trajectory (dynamic) tracking control using RTK GPS but did not include results in the report.

In an effort to collect historical context, an article from 2002 was investigated. Pohlman's research in 2002 explored the difficulties of achieving real-time, centimeter-level, relative positioning between vehicles within a formation (Pohlman, 2002). In this approach, the author used two lighter-than-air vehicles (blimps) in an indoor GPS laboratory (several Pseudolites). Using Mitel Orion receivers, the RTK-GPS approach was used, with each vehicle to transmit its GPS sensor measurements over the radio link established with the ground station; the ground station estimated the new control commands and sent them to each vehicle. As a proof-of-concept-test, a single vehicle was commanded to fly to a new landing spot. Upon landing the horizontal dilution of precision (HDOP) was 1.25; errors were blamed on multi-path error and high noise levels. A second test, 3D formation flight, was performed; the deltas in x-position, altitude, and yaw were all captured and annotated. Statistics and analyses were not presented for the dynamic test (Pohlman, 2002).

Matias, Oliveira, Almeida, Dias, Ferreira, Martins, and Silva's research in 2015 explored the use of low-cost RTK-GPS in an unmanned surface vehicle (USV) scenario. Researchers acknowledged, "there are an increasingly large number of application scenarios where an USV can play an important role, such as, security and safety missions, coastal water environment monitoring and 3D mapping" (Matias et al., 2015). With these applications in mind, they established a system architecture that included a low-cost GNSS receiver (NV08C-CSM) with a Tallysman TW2405 antenna, and a high-end Septentrio double frequency receiver was the ground-truth source. Through static and dynamic modes, testing was conducted. In static mode tests, the mean error was 0.45 cm with a standard deviation of 1.28 cm; it was unclear whether this mean error was distance root mean squared (DRMS) or mean radial spherical error (MRSE). In dynamic mode testing, mean errors of 7.18 cm, 8.39 cm, and 6.21 cm with standard deviations of 5.62 cm, 6.87 cm, 7.26 cm were found for North, East, and Up, respectively. Of note was that the "maximum range of base to rover is 10 up to 20 kilometers" (Matias et al., 2015).

In a time where "low-cost single-frequency GPS antennas and receivers [were] not considered applicable to precise positioning by RTK-GPS," Takasu and Yasuda(2008) set out to see if this perception was correct (Takasu & Yasuda, 2008). They tested a large variety of consumer-grade GPS receivers and antennas against a geodetic-grade receiver (NovAtel OEMV-3) and antenna (GPS-702-GG). The highest price for the consumer-grade receiver and antenna was $285 and $200, respectively; while the price for the geodetic-grade receiver and antenna was $7,995 and $995, respectively. Through static testing over a 24-hour period, the geodetic-grade pair outperformed the best consumer-grade combination with a DRMS and MRSE of 4.44cm and 8.89cm; the consumer-grade sequence had a DRMS and MRSE of 7.07cm and 12.91cm (Takasu & Yasuda, 2008). Although this research was not conducted in a dynamic fashion, it provided insight into the historical differences in high end GPS products versus low-cost products.

Summary

This chapter started with an overview of the GPS system, known errors in the GPS solution, and mitigation techniques used to obtain up to centimeter-level accuracy. Then, a brief academic survey was discussed in order to show how the COTS systems being investigated fits within the GPS market. Finally, a literature review of academic research was conducted to show how the results of this research will help propel the technology in this area. The following chapter will describe the methodology used to characterize the selected COTS RTK- GPS system, the Swift Navigation Piksi and Ublox NEO-M8P.

III. Methodology

Introduction

This chapter discusses the methods used to test and characterize the low-cost RTK-GPS systems: Swift Navigation Piksi and Ublox NEO-M8P. There is not a recognized standard for characterizing RTK GPS receivers; therefore, characterizing the system will be done relative to high-quality, high-cost components available for use at AFIT (Novatel DL-V3). Much of this methodology is modeled from the groundwork of Captain Kevin Hendrick's thesis completed in 2016 (Hendricks, 2016). This methodology first presents fundamental information to understand testing procedures and statistics used in this research, and then provides detail on each individual test procedures.

Testing goals

To answer the investigative question, "What is the current achievable accuracy for everyday (hobbyist) users?", a short baseline test will be conducted using the current standard GPS unit commonly implemented with commercially-available autopilots. For the next three investigative questions, "How accurate and precise are the low-cost RTK systems? Specifically, the Ublox's NEO-M8P and Swift Navigation's Piksi RTK system", "What are the limiting factors associated with the low-cost RTK system versus the traditional RTK systems", and "What kind of reliability can be expected out of low-cost RTK system?" the Swift Navigation Piksi and Ublox NEO-M8P RTK GPS systems are evaluated in ground testing conditions. To answer the last investigative question, “Can these COTS RTK systems be integrated in autonomous flight scenarios?” a flight test is performed.

Testing of the two RTK GPS systems will be a three-part process. First, a zero-baseline test will be conducted in order to determine the receiver’s single point accuracy. Next, the DGPS (RTK mode) accuracy will be characterized relative to a high-accuracy differential system; this will be done in both static and dynamic fashions. Finally, integration tests via 3DR’s Pixhawk flight controller will be conducted to show the utility on a small UAS; this will be done as a flight test.

Key Equations

Absolute Coordinate Frame to Local-Level Coordinate Frame

Typically, “GPS receivers are [configured] to output position solutions in degrees of latitude, degrees of longitude and height above ellipsoid in meters” (Hendricks, 2016). Due to the difficulty in easily interpreting the difference between two solutions in degrees of latitude and longitude, a coordinate frame transformation must be performed. The coordinate frame transformation implemented in this research is a transformation of an absolute coordinate frame to a local-level coordinate frame. This conversion allows for the quick interpretation of data points; the local-level coordinate frame has an origin that is specified by the researcher, while other points are relative to the origin. The axis of the local-level coordinate frame is aligned with local north, east, and down.

The calculation of the relative distance between two points expressed in latitude, longitude, and height can be done using the following equations (Hendricks, 2016):

$$p_e = \left(\frac{a}{(1 - e^2 \sin^{-1}\varphi)^{1/2}} + h\right)\cos\varphi\Delta\lambda \tag{9}$$

$$p_n = \left(\frac{a(1 - e^2)}{(1 - e^2 \sin^{-1}\varphi)^{3/2}} + h\right)\Delta\varphi \tag{10}$$

$$p_u = \Delta h \tag{11}$$

where

p_e = east position relative to local level coordinate frame (meters)

p_n = north position relative to local level coordinate frame (meters)

p_u = height relative to local level coordinate frame (meters)

$\Delta\lambda$ = change in longitude relative to origin (radians)

$\Delta\varphi$ = change in latitude relative to origin (radians)

Δh = change in latitude relative to origin (radians)

a = semi-major axis of Earth (6378.137 km)

e = Earth eccentricity (0.0818191908426)

Most software programs have this transformation feature built-in; however, if this is not the case, a simple program in MATLAB can suffice.

Statistics

The accuracy of the Piksi and NEO-M8P receivers were calculated using the two-and three-dimensional versions of the root-mean square metric. The need to break apart the analysis of the two-dimensional statistics from the three-dimensional statistics is due to the known inaccuracy of GPS height measurements (Hendricks, 2016). The equation commonly used for the two-dimensional and three-dimensional accuracy, denoted distance root mean square (DRMS) and mean radial spherical error (MRSE), are found in the following equations (Hendricks, 2016):

$$DRMS = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(p_e^i\right)^2 + \left(p_n^i\right)^2\right]}{n}} \tag{12}$$

$$MRSE = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(p_e^i\right)^2 + \left(p_n^i\right)^2 + \left(p_u^i\right)^2\right]}{n}} \tag{13}$$

Where

$p_e^i = i^{th}$ east position relative to the true solution (meters)

$p_n^i = i^{th}$ north position relative to the true solution (meters)

$p_u^i = i^{th}$ height relative to the true solution frame (meters)

As noted in the variable descriptions, all positions are relative to the truth solution (Novatel). By definition, for DRMS, there is a 65% probably that the position solution lies within the 2-dimensional (2D) circle; for MRSE, there is a 61% probability that the position solution lies within the 3-dimensional (3D) sphere. DRMS and MRSE will be the accuracy standards for 2D and 3D, respectively.

System Reliability

In addition to the equations used to measure the accuracy and precision of the components, a limitation of the RTK GPS systems was uncovered during previous testing, which resulted in the need to derive a metric. The metric, referred to as system reliability, is a measure of how often the RTK GPS system outputs a RTK position solution at the desired interval. This is a ratio of when there is an RTK lock (more commonly known as RTK Fix) present in the data sample to total number of samples; this is presented as a percentage in the following equation.

$$\text{System Reliability} = (t_{fixed} / t_{total}) * 100 \qquad (14)$$

Where

t_{fixed} = time when system is in RTK Fixed

t_{total} = total time of system test

To understand the background of why this derived statistic is needed: typically, there can be three phases that a RTK GPS system can cycle through as it is reducing its position errors: RTK Fix, RTK Float, and Single Point Precision (SPP). These are all based off of the N (integer ambiguity) value, referred to in the equations above, that the system is trying to calculate. “If the algorithm finds an integer solution, then the solution is called a ‘fix’. This is when maximum accuracy is reached” (Perin, 2016). Otherwise, ‘float’ means your RTK has not converged to a fixed integer solution and the RTK engine is still using floating point numbers to try to converge to a fixed integer solution (Koley, 2010). SPP is “for the positions neither ‘fix’ nor ‘float’ (happens if no correction data is received, or if signals are not good enough)” (Perin, 2016). Because of these three RTK phases, the derived statistic in Equation (13) is needed as a system measure.

Hobbyist Standard

In order to understand the accuracy and precision of the hobbyist's standard, a 3DR GPS kit was evaluated (Hendricks, 2016). With an update rate of 5Hz, the GPS kit under scrutiny incorporates the HMC5883L digital compass and a Ublox LEA-6 GPS module, to bring "the best GPS module [that] significantly outperform(s) the Mediatek GPS" (3DR, 2016). In this testing sequence, the 3DR kit is placed at a known location relative to the high-end receiver (AFIT's Novatel DL-V3). The relative error of the 3DR kit is found by subtracting the distance between the two units (3DR and Novatel); statistics are then run on the data to determine the accuracy and precision. This test was performed in a static and dynamic fashion.

Standalone Baseline Test

A "baseline test is a common test used for characterizing GPS receivers. It allows the researcher to isolate the errors in the receiver algorithms from the multitude of other errors affecting GPS measurements" (Hendricks, 2016). For this research, both the Piksi and NEO-M8P were tested in stationary positions against a known surveyed location via the AshTech antenna on the roof of AFIT's ANT Labratory. This head-to-head performance was executed with each GPS receiver acting as a standalone receiver.

The key data type evaluated is the position solutions output by the GPS receivers under test. Due to the known surveyed location, this methodology gives insight into the individual performance as a GPS receiver and isolates the error in the RTK communication process in further tests. Any deviation from the surveyed location is measured error. The configurations for the stationary baseline tests can be found in Figure 5 and Figure 6.

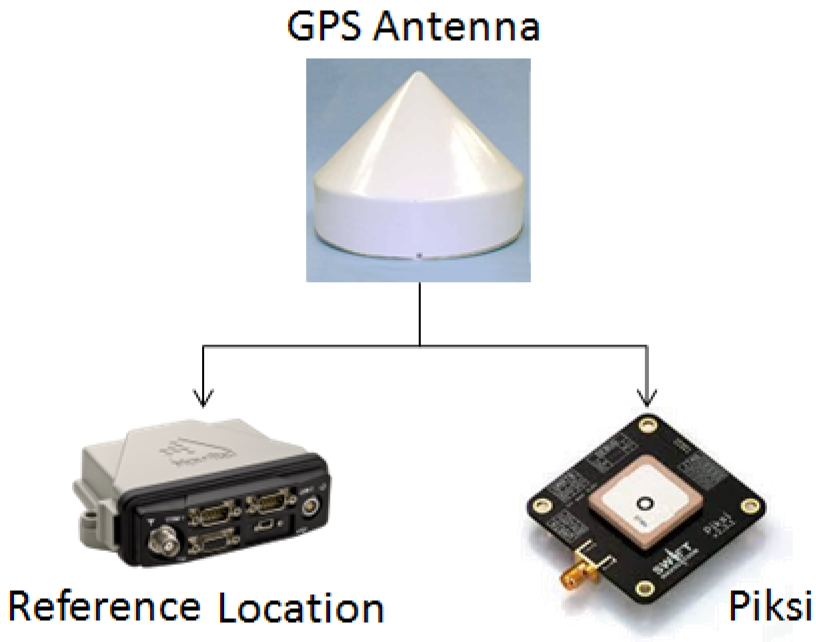

Figure 5. Swift Navigation Piksi Setup for Stationary Single Receiver Test

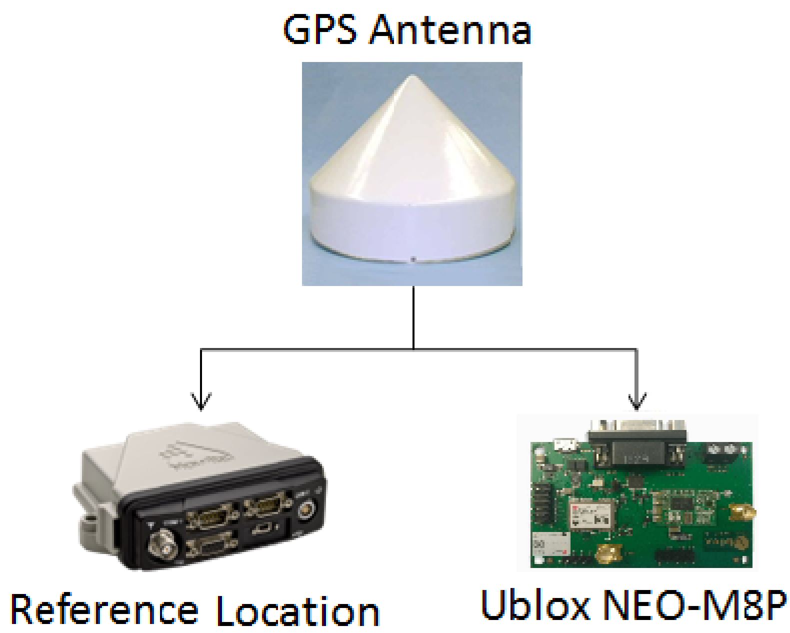

Figure 6. Ublox NEO-M8P Setup for Stationary Single Receiver Test

RTK Test Setup

In addition to the standalone baseline test, a RTK static test needs to be conducted. In this testing setup, the GPS receivers-in-question (Piksi and NEO-M8P) are put into RTK mode in accordance with their respective RTK configurations (for more details on how to setup see Appendix A – Ublox C94-M8P User's Guide and Appendix B – Swift Navigation User's Guide). While in RTK mode, the receivers were tested against the known surveyed location via the AshTech antenna on the roof of the ANT Lab. The concise configuration for the RTK baseline tests can be found in Figure 7, Figure 8, and Figure 9 below.

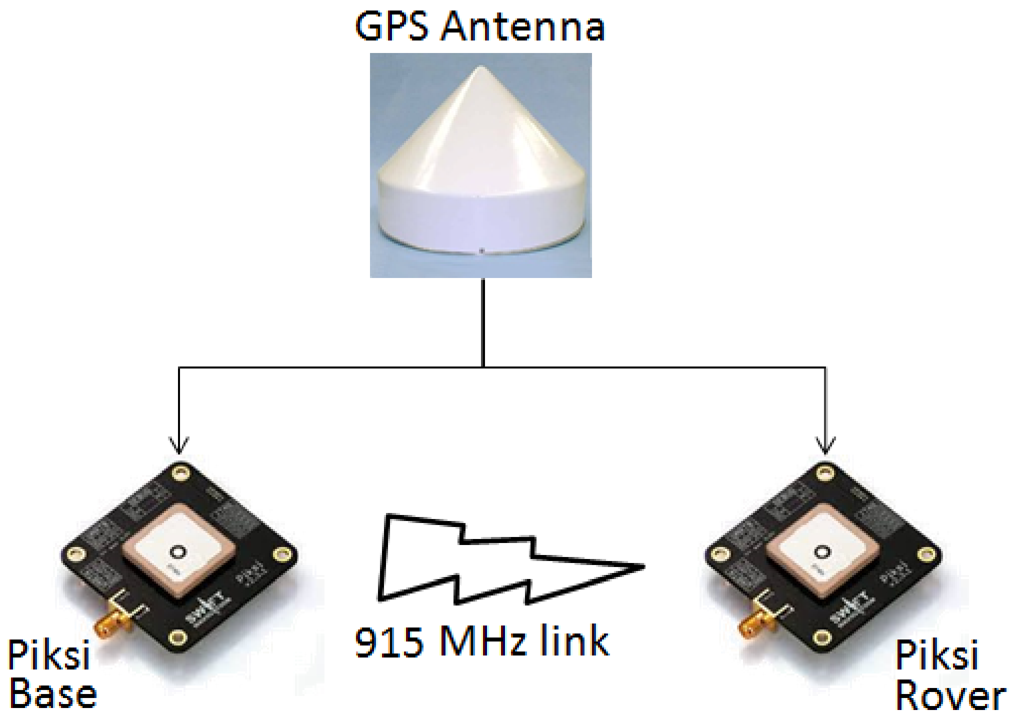

Figure 7. Swift Navigation Piksi RTK Baseline Setup

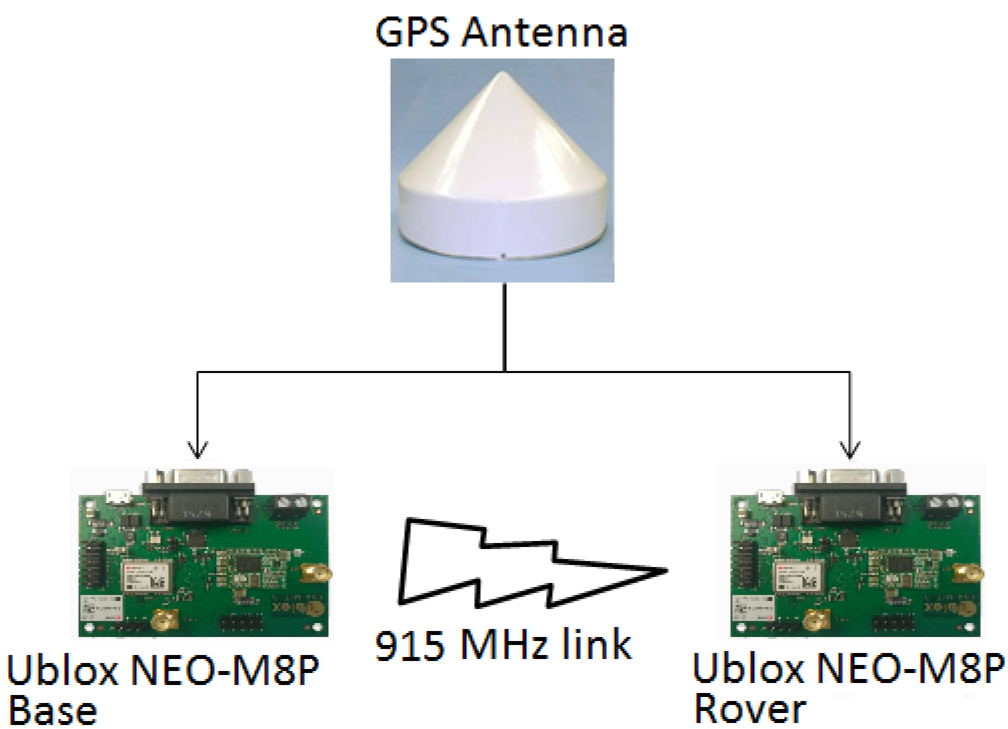

Figure 8. Ublox NEO-M8P RTK Baseline Setup

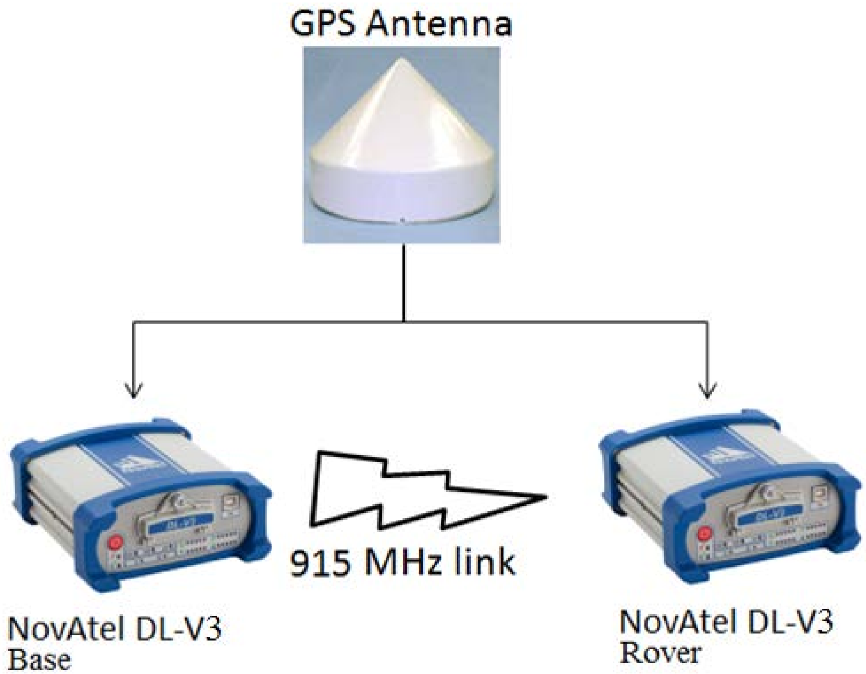

Figure 9. AFIT's ANT Lab High-end NovAtel DL-V3 RTK Baseline Setup

Similar to the baseline standalone test, the RTK static test captures positional data. The difference in the RTK testing is that the positional solution is relative to the base station (the distance between the base and rover receivers).

> "This measurement, referred to as the baseline, is measured in a local-level, north-east-down coordinate frame, with the origin at the base station location. Since both the receiver-at-question, and the high-end receiver, are getting measurements from the same antenna, the baseline measurements should be near zero. Any deviation from zero is the error in the RTK position solution" (Hendricks, 2016).

Additionally, since the exact location of the base station is surveyed, the rover location can be derived in latitude, longitude, and altitude form.

RTK Static and Dynamic Ground Tests

To get an understanding of how these RTK systems would operate in a field environment, ground tests were conducted prior to flight tests. The performance of the

Piksi RTK system and Ublox NEO-M8P RTK system were tested against the existing high-end RTK system held by AFIT, referred to as the AFIT RTK system; as the truth source. "The AFIT RTK system, which has been characterized to have accuracy within several millimeters, utilizes a Novatel receiver as the base station to determine the error corrections communicating via an Ethernet bridge to a Novatel dual-frequency receiver mounted on a golf cart as the mobile station" (Hendricks, 2016). Figure 10 depicts AFIT's mobile GPS unit via a golf cart loaded with the high-end RTK system; components of the Piksi RTK and AFIT RTK systems are labeled.

Figure 10. AFIT RTK System Shown in Parallel with Piksi RTK System via AFIT's Mobile GPS Unit (Golf Cart)

The testing of these RTK systems were accomplished using different test setups to show how changes in configuration may effect position solutions in varying applications.

Many of these tests were performed in concurrence with fellow AFIT student Andrew Knisely (Knisely, 2017). The test configurations are specified in Table 2.

Table 2. Test Configurations

Test #	RTK System	Roving Antenna	Truth Source	Motion	Testing*
1	NEO-M8P	Novatel	Yes	Static	R, A, P
2	NEO-M8P	Native	Yes	Static	R, A, P
3	NEO-M8P	Novatel	Yes	Dynamic	R, A, P
4	NEO-M8P	Native	Yes	Dynamic	R, A, P
5	NEO-M8P	Native	No	Static	R, RA
6	NEO-M8P	Native	No	Dynamic	R, RA
7	NEO-M8P	Native	No	Static	R
8	NEO-M8P	Native	No	Dynamic	R
9	Piksi	Novatel	Yes	Static	R, A, P
10	Piksi	Native	Yes	Static	R, A, P
11	Piksi	Novatel	Yes	Dynamic	R, A, P
12	Piksi	Native	Yes	Dynamic	R, A, P
13	Piksi	Native	No	Static	R
14	Piksi	Native	No	Dynamic	R

*R=reliability; A=accuracy; P=precision; RA=relative accuracy

The ground tests were conducted in a static and dynamic manner. The configuration settings for each RTK system (Piksi and NEO-M8P) were set at the manufacturer-recommended settings (See Appendix A – Ublox C94-M8P User's Guide and Appendix B – Swift Navigation User's Guide).

The antenna used at the base unit (except for relative tests [test #5, #6, #7, #8, #13, and #14]) was the AshTech Choke-ring antenna.

> "The Ashtech Choke-ring antenna is a stationary dual frequency antenna located on the roof of AFIT at a surveyed absolute position. The Choke-ring integrated into the antenna provides multipath rejection. By knowing the absolute location of the base antenna, it is then possible to determine the absolute error of the relative position vector that is output by the [RTK system]" (Hendricks, 2016).

The rover unit used both the Novatel Pinwheel antenna and each system's respective native antenna. "The Novatel Pinwheel antenna is a dual frequency antenna that, similar to the Ashtech Choke-ring antenna, is designed to reject multipath errors. An antenna splitter was used when utilizing the Novatel Pinwheel as the mobile antenna. This allowed the same measurements to be sent to both the [RTK system] receiver and the [AFIT RTK system] truth source" (Hendricks, 2016).

Tests #5, #6, #7, #8, #13, and #14 were all performed in a manner where there was no truth source. The setup for these tests were that of a fixed (known) distance between the base and rover receivers, using native antennas for both the base and rover units. Any variation of this fixed distance was noted and statistically analyzed in the following chapter. These tests were performed in both static and dynamic fashions. Reliability was also evaluated concurrently. See Figure 11 for test setup for relative tests (test #5 and test #6).

Figure 11. Relative Accuracy and Precision Test Setup (test # 5 and #6) – Known Distance of 15 Feet (4.572 m)

The results from each of the tests in Table 2 are presented both statistically, in tabulated results, and visually, in a plotted solution, in Chapter 4.

Flight Testing

Following ground testing, an analysis was performed to determine which RTK system performed the best in dynamic conditions. That RTK system was integrated into a flight test vehicle. A 3DR X-8 Octocopter was chosen as the vehicle to be used for flight test. An octocopter is similar to a quadcopter, except it has eight motors instead of four. “Quadcopters are a popular experimental platform for unmanned aerial vehicle (UAV) research, because of their simplicity of constructions, their ability for vertical takeoff and landing (VTOL) and their ease of maintenance. The increased safety features are a further advantage” (Pilz, 2010). Modifications to standard AFIT X-8 setup included the onboard use of an RTK GPS system antenna as its primary GPS unit. An example of the flight set-up (using Ublox NEO-M8P RTK system) is shown in Figure 12 below:

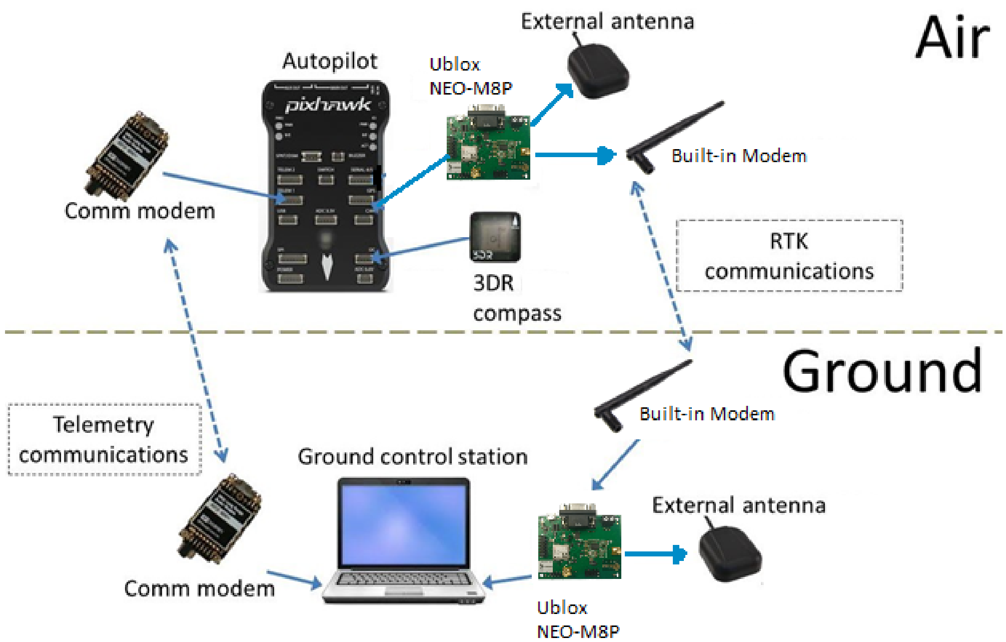

Figure 12. UAS Flight Set-up with Ublox NEO-M8P (C94-M8P)

There are two types of flight tests that will be presented within this thesis. First, a qualitative test of RTK GPS integration; this test is a proof-of-concept test. This test is used to answer investigative question, “Could the RTK GPS system be integrated into a SUAS for autonomous flight?”.

Pending results from the first test, the second flight test is a location hold test. This test is structured by commanding the SUAS to go to a set location and hold that location until told otherwise. A subsidiary goal for these tests was to determine system reliability (as defined earlier in this chapter) for flight tests.

For these flight tests, an autonomous flight pattern was programmed via Mission Planner on the ground station as an arbitrary set of way points for the X-8 to pass through. The second flight test is conducted by commanding the SUAS to go to a set location and hover. Variations in position were noted; errors included, but were not limited to, GPS error, wind, and control surface error. Of note, the HUD in Mission Planner can distinguish between a GPS 3D fix, GPS DGPS, and GPS RTK. This was used to determine system reliability (as referenced earlier in this chapter) in flight. Results are presented in the following chapter.

The flight tests were conducted at the flight line on Area B–Wright Patterson Air Force Base, Ohio.

Summary

Chapter III presented the methodology used to collect the pertinent data for this research. This chapter first led readers through an explanation of a coordinate frame transformation and a detailed background on the statistics used. Next, the approach to collect data using the hobbyist standard (3DR GPS kit) was discussed. This chapter then continued to detail how the two RTK systems were ground tested via the AFIT's ANT Lab set-up. Finally, readers are led through the process of system flight test selection and flight test details. The following chapter will discuss the results of the tests and procedures laid out in this chapter.

IV. Analysis and Results

Chapter Overview

This chapter will discuss the results of the tests outlined in the methodologies above (Chapter III). In chronological order, what is presented is Hobbyist Standard Characterization, Single Receiver Baseline Testing, Ublox NEO-M8P RTK Static and Dynamic Testing, Piksi Static and Dynamic Testing, and Flight Testing.

Hobbyist Standard (3DR GPS Kit) Characterization

Typically, investigative questions from previous theses are not reiterated verbatim; however, due to the significance of the results of the hobbyist standard as a baseline for this research, Hendrick's research was reviewed in-depth (Hendricks, 2016). The rational of the 3DR GPS Kit Characterization was to understand the baseline GPS accuracy and precision that a typical hobbyist would expect. This test gives insight into an overall improvement of performance that a RTK GPS system would provide.

As a side note, it should be noted that Hendrick's hobbyist standard research was performed with a Ublox LEA-6 (part of the 3DR GPS Kit). Transitioning from this model, today's hobbyist standard arguably is the Ublox NEO-M8 series chip set. This newer chipset has an updated crystal oscillator and the ability to integrate with GPS, GLONASS, and the BeiDou GNSS systems.

The following were the resultant of the prequel to this thesis. Hendricks tested the 3DR GPS Kit in Fall 2015. His tests were performed relative to the high-end AFIT RTK system (as the truth source). "The truth position was obtained by taking the time averaged absolute position output by the AFIT RTK system from 60 minutes of data. This absolute truth position was the origin of the local level coordinate frame for the calculation of the statistics related to the 3DR GPS kit" (Hendricks, 2016). The 3DR GPS Kit North-East position solutions are shown in Figure 13.

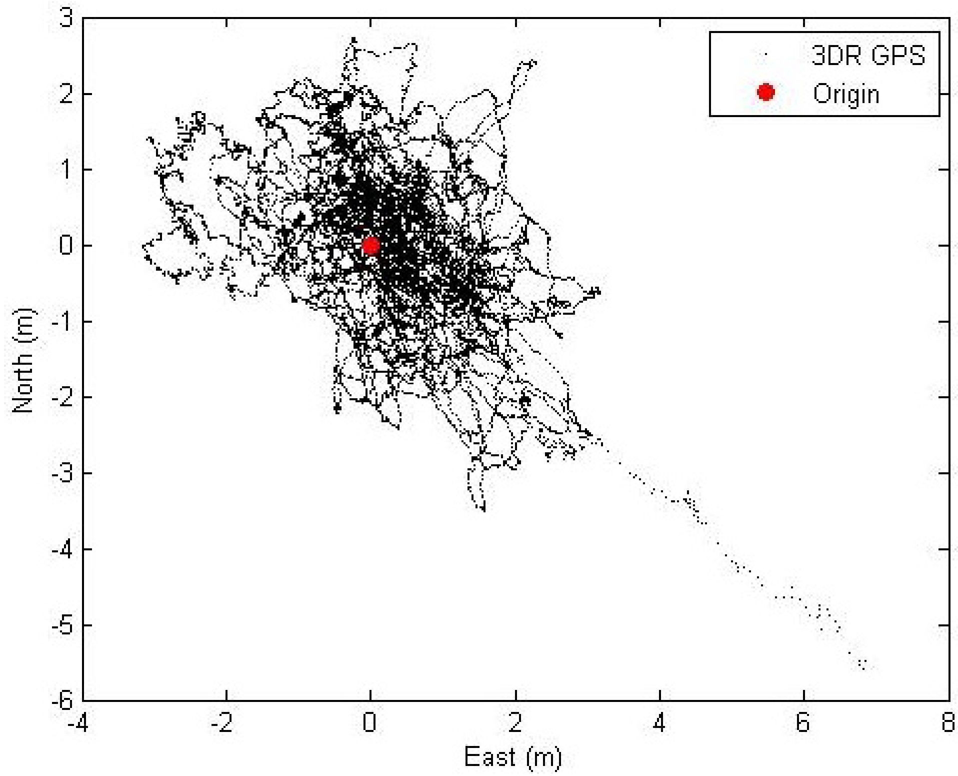

Figure 13. 3DR GPS Kit North-East Position Solutions in Local-Level Coordinate Frame (Hendricks, 2016)

Plotted individually, "the error in each direction over the sixty-minute test time is displayed" below in Figure 14.

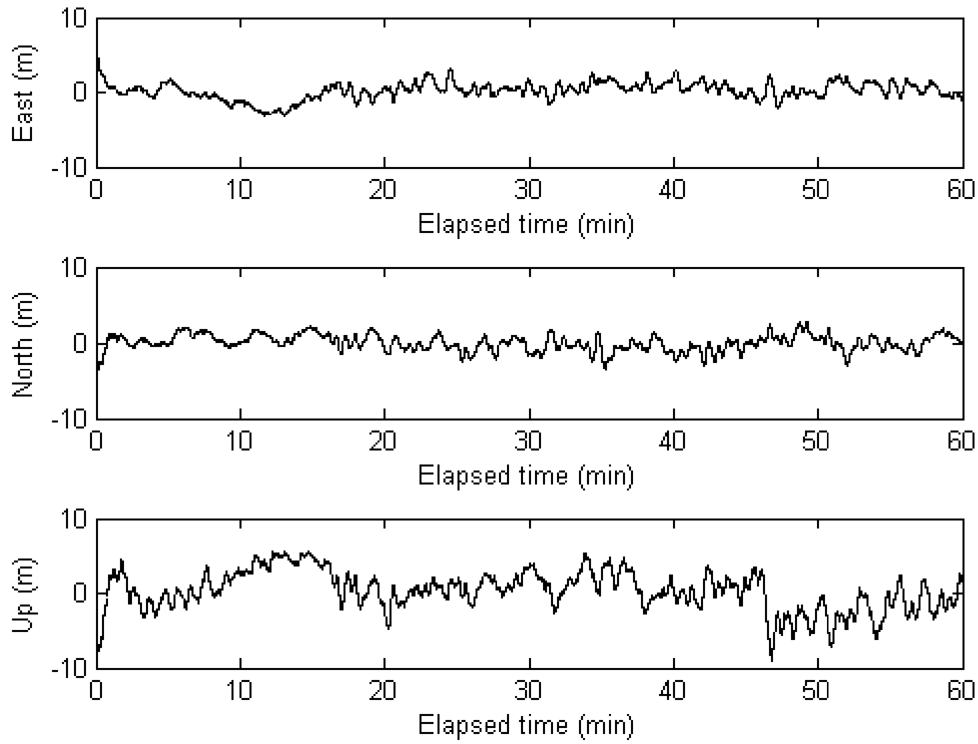

Figure 14. 3DR GPS Kit Position Solution Directional Error (Hendricks, 2016)

"As shown in the figure above, the position error is about equal in the North and East components of the position solution. As expected, the Up component displays a standard deviation that is above twice the magnitude of the East and North components" (Hendricks, 2016). This is more evident in Table 3 as errors are broken down into individual directions.

Table 3. 3DR GPS Kit Directional Error Statistic (Hendricks, 2016)

	Mean (m)	Std dev (m)
North	0.01	1.06
East	0.25	1.15
Down	0.26	3.97

Using the equations from Chapter 3, the 3DR GPS Kit accuracy and Precision measures are presented in Table 4.

Table 4. 3DR GPS Kit Accuracy and Precision Measures (Hendricks, 2016)

	Mean (m)
DRMS	1.58
MRSE	3.08

Single Receiver Standalone Baseline Test

For the single receiver baseline tests, a single receiver from both of the RTK GPS systems was tested. By isolating a single receiver, positional error is localized to hardware and not the RTK software. RTK software algorithms are evaluated once paired in RTK setup. The single receiver baseline test for the Swift Navigation Piksi was performed by Hendricks in Fall 2015. A summary of his findings is found below; a full analysis of his tests can be found in his thesis (Hendricks, 2016). The other RTK GPS System under review, Ublox NEO-M8P, was evaluated under single receiver conditions in this thesis.

Swift Navigation Piksi – Single Receiver Baseline

The single receiver baseline testing and analysis of the Swift Navigation Piksi was performed by Hendricks in Fall 2015. This was the original Piksi module, not the Piksi Multi. A summary of his directional error findings can be found in Table 5; DRMS and MRSE measures were not provided.

Table 5. Piksi - Single Receiver Directional Error (Hendricks, 2016)

	Mean (m)	Std dev (m)
North	0.108	3.697
East	-0.08	3.044
Down	18.89	9.858

What Hendricks discovered in his testing was that as a single receiver, the Swift Navigation Piksi, performed relatively well in the East and North directional components; however, with a mean error of 18.9m, the Down component did not perform well. Essentially, the Piksi performed well 2-dimensionally, but is not recommended for 3-dimensional use. It also should be noted that the baseline 3DR GPS (Ublox LEA-6) unit outperformed the receiver in standalone mode when all directional components are considered.

Ublox NEO-M8P – Single Receiver Baseline

A standalone baseline was conducted using a single receiver from the Ublox NEO-M8P RTK GPS System. Similar to the Piksi test discussed above, a single receiver was used in order to evaluate the accuracy and precision of one part of the RTK system. This was done to eventually give insight into the performance of the Ublox NEO-M8P RTK System when in RTK mode.

As described in Chapter III, this test consisted of the single Ublox NEO-M8P (Ublox C94-M8P application board) receiver using the Ashtech Choke-ring stationary dual frequency antenna located on the roof of AFIT at a surveyed absolute position

(39.78226424 deg; -84.08222623 deg; 270.795 m). Over time, the location of the Ublox NEO-M8P was compared to the known location. Error results in the local level coordinate frame are shown in Figure 15.

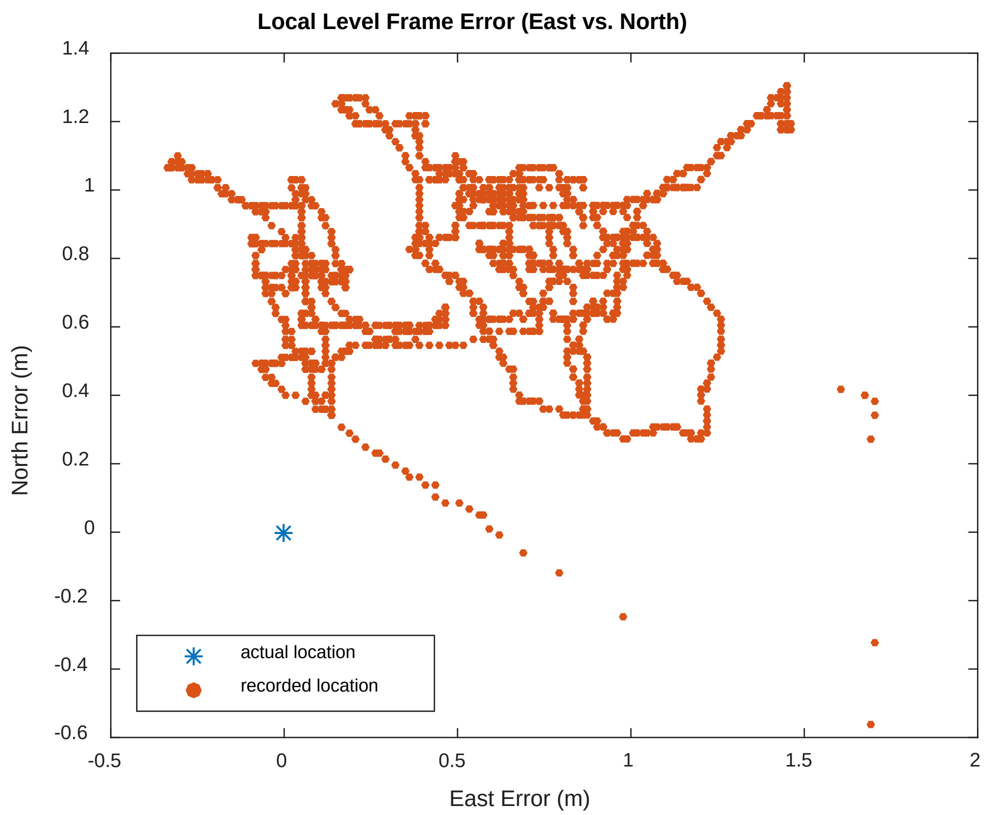

Figure 15. NEO-M8P Single Receiver North-East Position Solution Local Level Coordinate Frame

The Ublox NEO-M8P position location was shown to vary as much as 1 meter east-west and 1 meter north-south. To better illustrate the individual components of the error in the single receiver (Ublox NEO-M8P) over time, see Figure 16 for local level coordinate frame components.

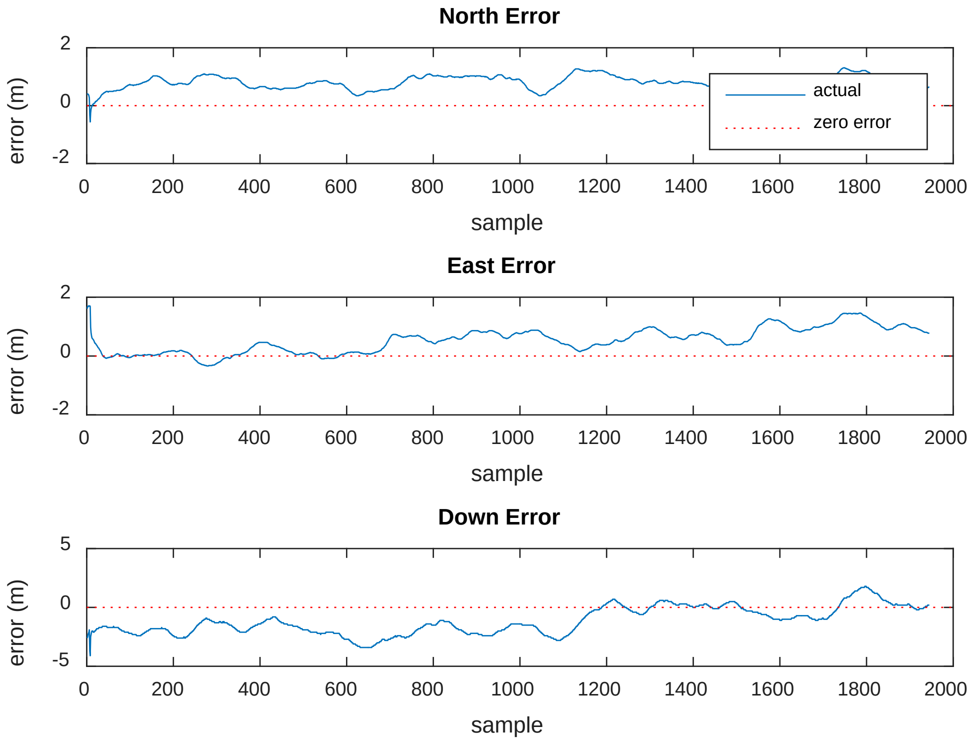

Figure 16. NEO-M8P Single Receiver Directional Errors in Position Solution

The largest source of error for the Ublox NEO-M8P, performing as a stationary single receiver, is the down component. There were times that this was off nearly 5 meters. Further information regarding the accuracy and precision of the Ublox NEO-M8P single receiver can be found in the tabulated error statistics in Table 6.

Table 6. NEO-M8P Single Receiver Baseline Statistics

	Mean (m)	Std dev (m)
North	0.8021	0.2431
East	0.5341	0.4240
Down	-1.1649	1.1602
DRMS	1.0804	
MRSE	1.9671	

Coincidentally, by viewing Table 6 and Table 4, a comparison of the Ublox NEO-M8P and the current hobbyist standard, it is clear that the Ublox NEO-M8P outperforms the hobbyist standard as a single receiver. The same comparison holds when compared to the Piksi in stand-alone mode (considering all three dimensions). The DRMS values are 1.08 m and 1.58 m, respectively for NEO-M8P vs. hobbyist standard; the MRSE values are 1.97 m and 3.08 m, respectively for NEO-M8P vs. hobbyist standard.

Ublox NEO-M8P RTK GPS System Testing

The rationale of conducting the Ublox NEO-M8P RTK GPS System characterization was to understand the precision and accuracy of this RTK GPS system. The system architecture in this configuration included the Ublox NEO-M8P onboard a Ublox C94-M8P application board. This board was chosen as the host for the NEO-M8P due to the versatility that it provided as well as the documentation provided by Ublox on functionality. See Figure 17 to view the Ublox C94-M8P and all integration ports.

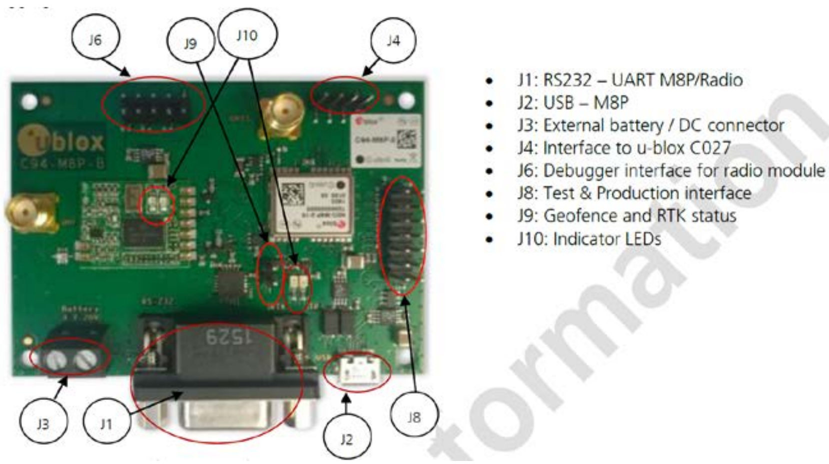

Figure 17. Ublox C94-M8P Application Board Interface Ports

Per Table 2, in Chapter 3, the tests conducted with the Ublox C94-M8P included static and dynamic tests, varying antennas (both native patch antenna [Figure 18] and Novatel [Figure 19]) set-ups, and tests with and without a truth source (AFIT's High-End RTK system [Novatel DL-V3 RTK system]). These tests give insight into the overall improvement that this RTK system would provide users.

Figure 18. Ublox Native Patch Antenna

Figure 19. Novatel Pinwheel Antenna

Static with Truth Source

In tests #1 and #2, the NEO-M8P was tested in static conditions against a truth source (Novatel DL-V3 RTK system). For both tests, the base unit used the Ashtech Choke ring antenna located on top of AFIT's ANT lab in a verified location. In test #1 a Novatel pinwheel antenna was used for the rover unit; in test #2, the Ublox native patch antenna was used for the rover unit. Results are shown below.

Novatel Antenna

For test #1, the NEO-M8P was tested in a static condition against the Novatel DL-V3 RTK system. The antenna used for the NEO-M8P rover unit was the Novatel Pinwheel antenna. The areas of interest in this test were: reliability, accuracy and precision.

Reliability is represented by the percentage of time the system was in 'RTK Fix' mode over the lifetime of the test. Accuracy is in relation to the high-end RTK system and is shown in the North, East, and Down components. Precision is also in relation to the high-end RTK system and shown in the North, East, and Down components; further the DRMS and MRSE statistics were evaluated. For statistical equations, refer to Equations (12) and (13). After testing was complete, analysis was performed on the results; data is represented graphically below.

System reliability for this test setup was 64.5%, as the system was in RTK Fixed mode for 64.5% of the time. Figure 20 and Figure 21 both show position solutions for the test set up compared to the position solutions of the truth source (High-end RTK System).Figure 20 represents the position solutions while the RTK system is in RTK

Fixed mode. Figure 21 represents the position solutions while the RTK system is in RTK Float mode.

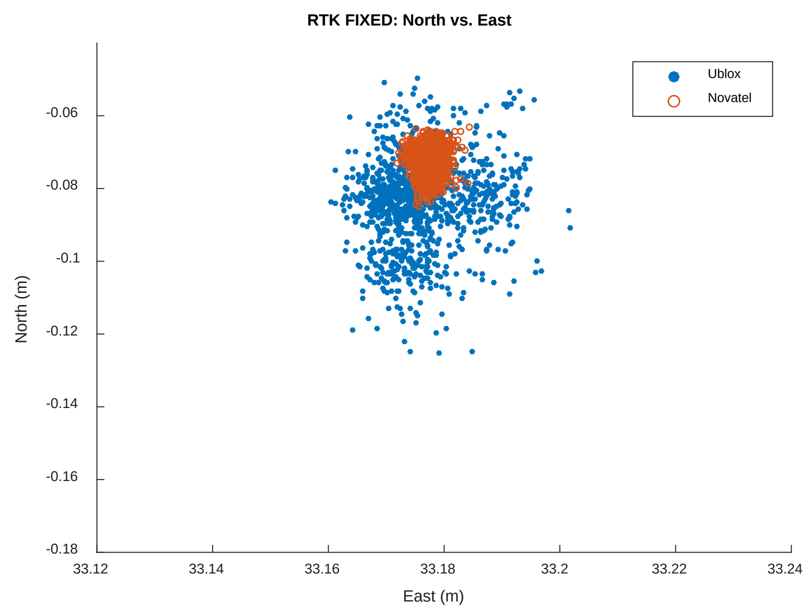

Figure 20. Ublox NEO-M8P Static Test with Novatel Antenna Position Solutions with Truth Source -RTK Fixed Mode

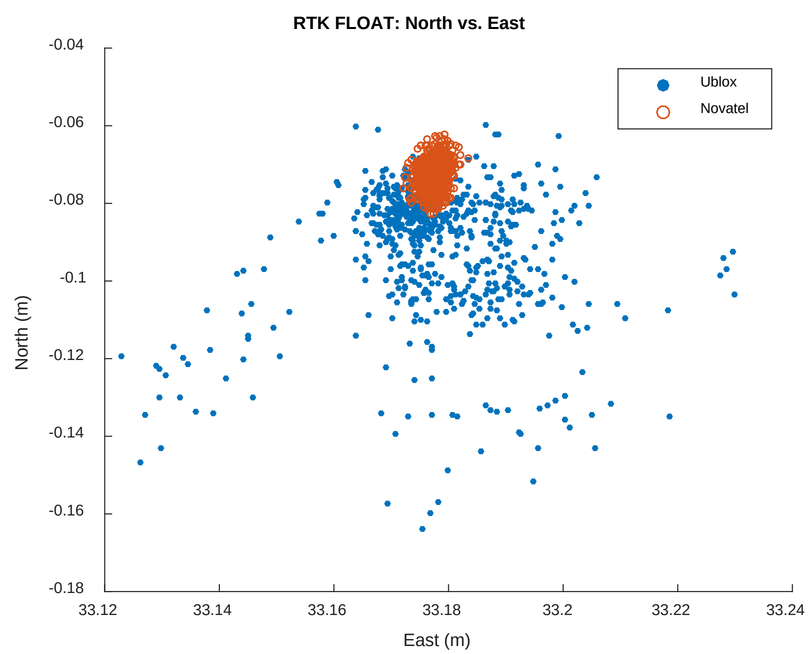

Figure 21. Ublox NEO-M8P Static Test with Novatel Antenna Position Solutions with Truth Source -RTK Float Mode

The contrast of Fixed mode and Float mode is portrayed in Figure 20 and Figure 21 as they are on the same axis scale. The Ublox NEO-M8P position solutions are much more tightly coupled around the Novatel position solutions in Figure 20 (Fixed mode). To better understand Figure 20 and Figure 21, they are broken down into directional components represented over time for RTK Fixed and Float modes; deviations from the truth source (AFIT's Novatel RTK system) are shown for each directional component. These are graphically represented in Figure 22 and Figure 23.

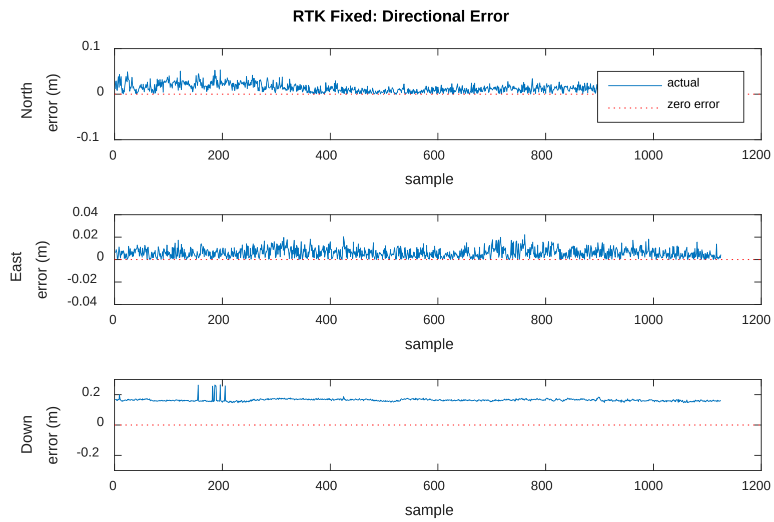

Figure 22. Ublox NEO-M8P Static Test with Novatel Antenna Directional Component Error with Truth Source -RTK Fix Mode

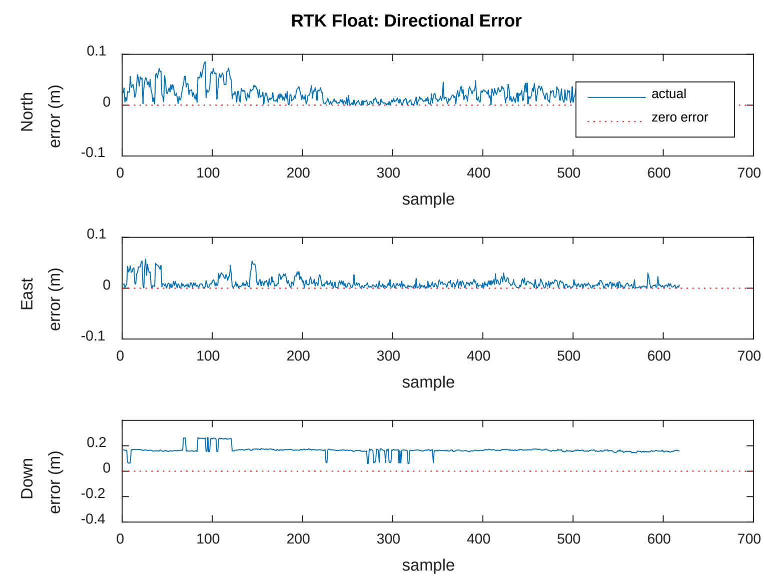

Figure 23. Ublox NEO-M8P Static Test with Novatel Antenna Directional Component Error with Truth Source -RTK Float Mode

Figure 22 shows that the directional error output of the Ublox NEO-M8P is much smaller in the North and East directions than in the Down direction. Comparing Figure 22 and Figure 23 show the directional error is more tightly coupled to the zero error line (red dashed) in the RTK Fixed than the RTK Float mode. The directional component statistical analyses can be seen in Table 7.

Table 7. Ublox NEO-M8P Static Test with Novatel Antenna and Truth Source Local-Level Component Level Statistical Analysis

	All Data		RTK Float		RTK Fix	
	Mean (m)	Std dev (m)	Mean (m)	Std Dev (m)	Mean (m)	Std Dev (m)
North	0.0154	0.0116	0.0200	0.0156	0.0129	0.0075
East	0.0068	0.0067	0.0095	0.0099	0.0052	0.0030
Down	0.1649	0.0191	0.1659	0.0292	0.1643	0.0098
DRMS	0.0215		0.0288		0.0161	
MRSE	0.1674		0.1709		0.1654	

Table 7 represents all the statistical results from test #1. For this test setup, the Ublox NEO-M8P has a 2-dimentional (horizontal) accuracy of 2.1 cm and a 3-dimensional accuracy of 16.7 cm. When in RTK Fixed mode, the 2D accuracy is 1.6 cm, while 3D accuracy is 16.5 cm. Of note was that in this test configuration there is not a significant difference in Fixed mode and Float mode statistics.

Native Antenna

For test #2, the NEO-M8P was tested in static conditions against the Novatel DL-V3 RTK system. The antenna used for the NEO-M8P rover unit was the Ublox native patch antenna. The areas of interest in this test were: reliability, accuracy and precision.

System reliability for this test setup was 30.2%. Figure 24 and Figure 25 both show position solutions for the test set up compared to the position solutions of the truth source (High-end RTK System). Figure 24 represents the position solutions while the RTK system is in RTK Fixed mode. Figure 25 represents the position solutions while the RTK system is in RTK Float mode.

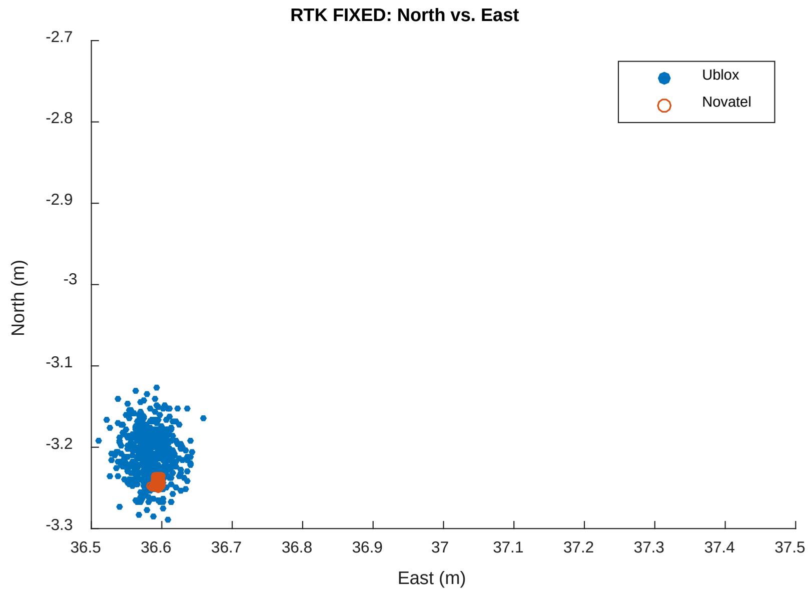

Figure 24. Ublox NEO-M8P Static Test with Native Patch Antenna and Truth Source -RTK Fixed Mode – Local Level Coordinate Frame

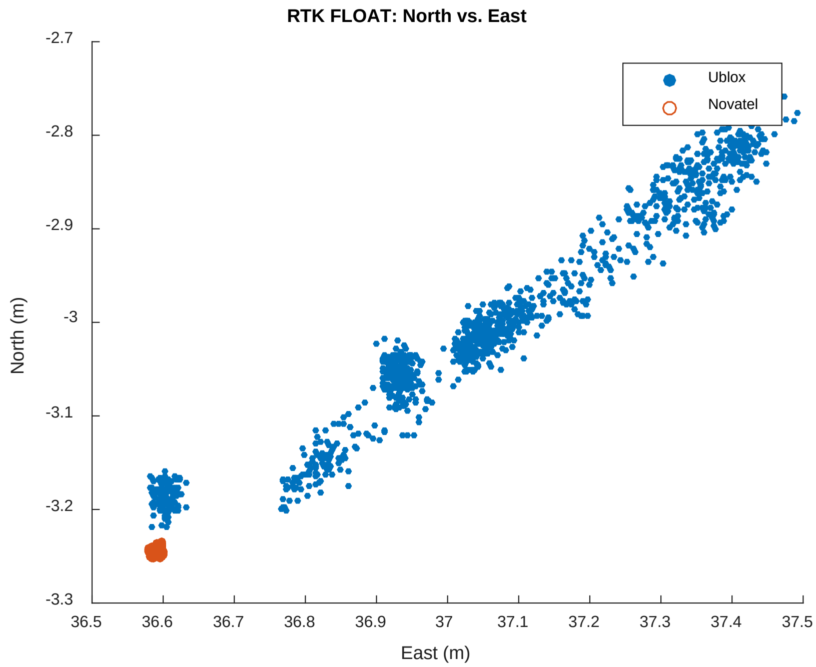

Figure 25. Ublox NEO-M8P Static Test with Native Patch Antenna and Truth Source -RTK Float Mode – Local Level Coordinate Frame

The contrast of Fixed mode and Float mode is portrayed in Figure 24 and Figure 25 as they are on the same axis scale. The Ublox NEO-M8P position solutions are much more tightly coupled around the Novatel position solutions in Figure 24. The spacing in Figure 25 can best be explained by the algorithm locating the N integer in Equation (2) for the carrier-phase measurement. To better understand Figure 24 and Figure 25, they are broken down into individual directional components for RTK Fixed and Float modes; deviations from the truth source (AFIT's Novatel RTK system) are shown for each directional component. These are graphically represented in Figure 26 and Figure 27.

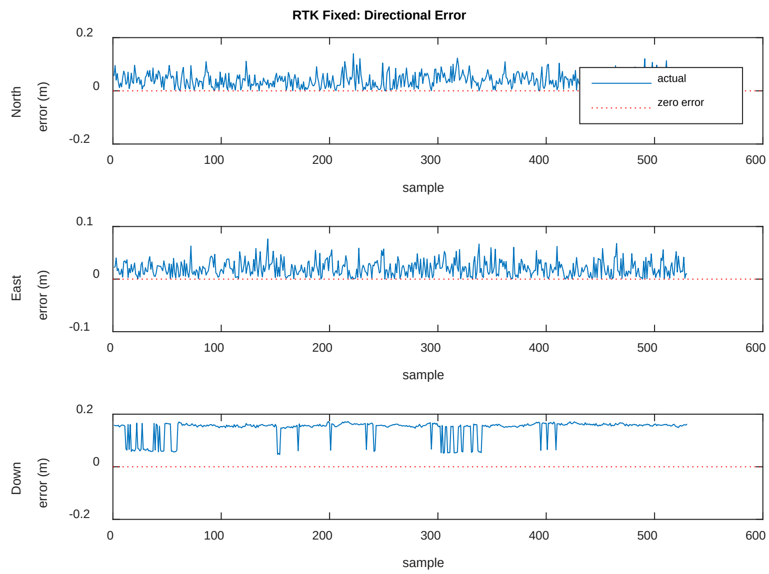

Figure 26. Ublox NEO-M8P Static Test with Native Patch Antenna Directional Component Error with Truth Source -RTK Fix Mode

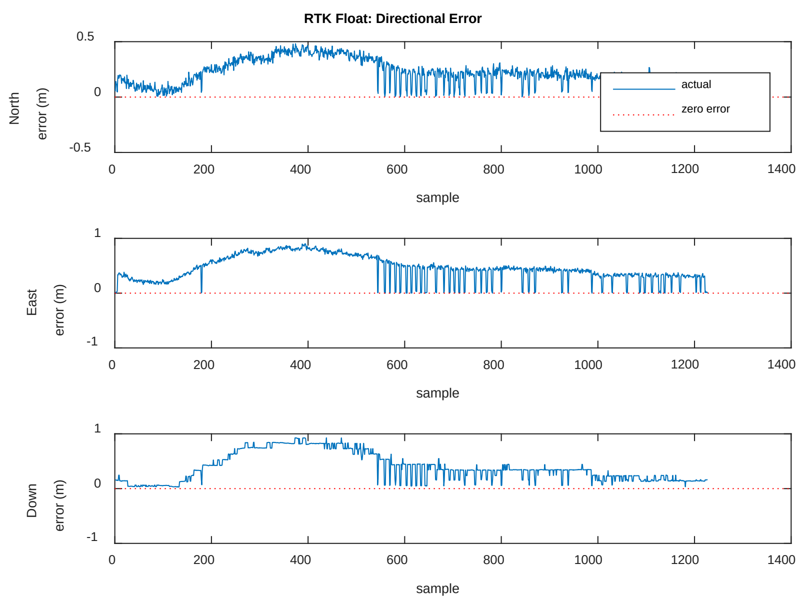

Figure 27. Ublox NEO-M8P Static Test with Native Patch Antenna Directional Component Error with Truth Source -RTK Float Mode

Figure 26 portrays the mean difference of the truth source is higher in the Down direction compared to the North and East directions; this is shown by the offset in the Down error subplot. This deviation can be seen in Table 8 as well. Comparing Figure 26 and Figure 27 show the directional error is more tightly coupled to the zero error line (red dashed) in the RTK Fixed than the RTK Float mode. The directional component statistical analyses can be seen in Table 8.

Table 8. Ublox NEO-M8P Static Test with Native Patch Antenna and Truth Source Local-Level Component Level Statistical Analysis

	All Data		RTK Float		RTK Fix	
	Mean (m)	Std dev (m)	Mean (m)	Std dev (m)	Mean (m)	Std dev (m)
North	0.1643	0.1266	0.2193	0.1137	0.0373	0.0080
East	0.3140	0.2772	0.4451	0.2303	0.0105	0.0066
Down	0.3113	0.2443	0.3825	0.2612	0.1464	0.0326
DRMS	0.4674		0.5587		0.0401	
MRSE	0.6123		0.7257		0.1553	

Table 8 represents all the statistical results from test #2. For this test setup, the Ublox NEO-M8P has a 2-dimentional (horizontal) accuracy of 46.7 cm and a 3-dimensional accuracy of 61.2 cm. When in RTK Fixed mode, the 2D accuracy is 4.0 cm, while 3D accuracy is 15.5 cm. The difference in RTK Fixed mode and Float mode is significant in this configuration.

It can be seen (via Table 7 and Table 8) that there is significant degradation of accuracy and precision when the native antenna is used instead of the Novatel antenna. As no other variables were changed, this can be best explained by the improved multipath rejection of the Novatel antenna; thus leading readers to the conclusion that the Novatel antenna is a better choice for a more accurate position solution.

Dynamic with Truth Source

In tests #3 and #4, the NEO-M8P was tested in a dynamic fashion against a truth source (Novatel DL-V3 RTK system). For dynamic testing, the AFIT ANT center GPS testing rig (Figure 10) was driven in an oval pattern approximately 150m x 20m. Testing took place outside of AFIT's ANT laboratory and ran parallel with AFIT buildings (see Figure 28). For both tests, the base unit used the Ashtech Choke ring antenna located on top of AFIT's ANT lab in a verified location. In test #3, a Novatel pinwheel antenna was used for the rover unit; in test #4, the Ublox native patch antenna was used for the rover unit. Results are shown below.

Figure 28. Dynamic Testing Orientation on Wright-Patterson Air Force Base

Novatel Antenna

For test #3, the NEO-M8P was tested in a dynamic fashion against the Novatel DL-V3 RTK system. The antenna used for the NEO-M8P rover unit was the Novatel pinwheel antenna. The areas of interest in this test were: reliability, accuracy and precision.

System reliability for this test setup was 0%; the RTK system was never able to get an RTK fix throughout the whole test duration. Figure 29 shows position solutions for the test set up compared to the position solutions of the truth source (High-end RTK System). There is no figure to represent the position solutions while the RTK system is in RTK Fixed mode due to not getting an RTK Fix. Figure 29 represents the position solutions while the RTK system is in RTK Float mode.

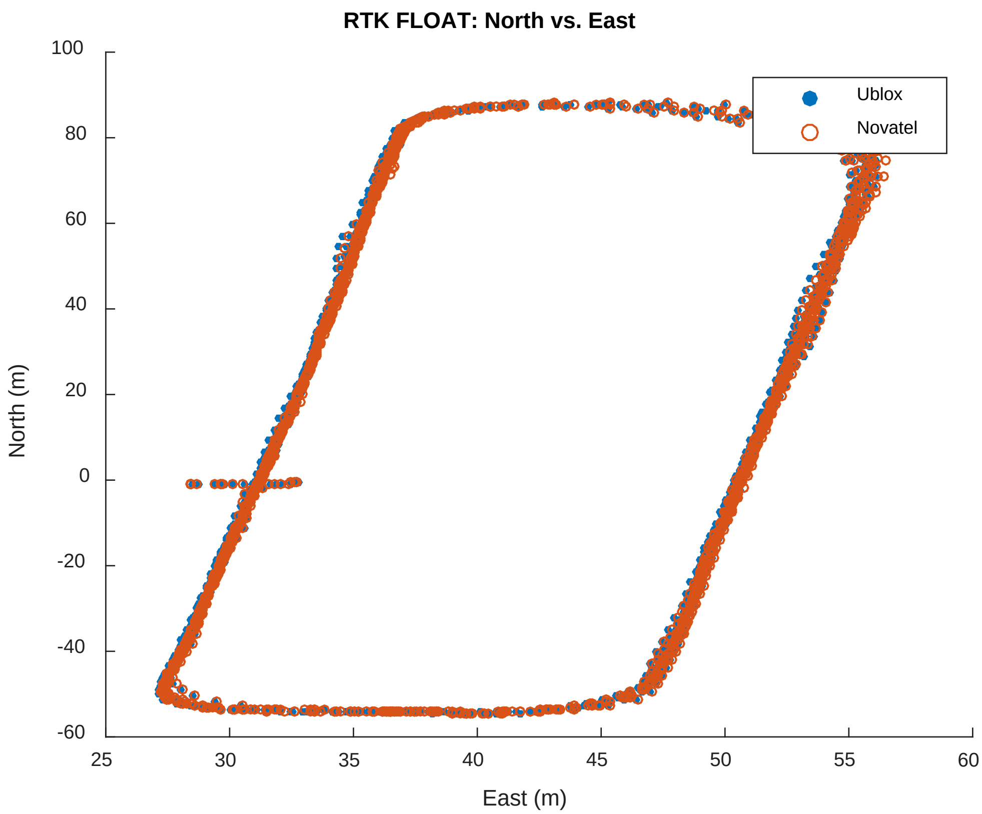

Figure 29. Ublox NEO-M8P Dynamic Test with Novatel Pinwheel Antenna and Truth Source -RTK Float Mode

To better understand Figure 29, it is broken down into directional components for RTK Float mode; deviations from the truth source (AFIT's Novatel RTK system) are shown for each directional component. There is no graph to represent this test setup in RTK Fixed mode as the system reliability was 0%. The graphical representation of RTK Float mode is presented in Figure 30.

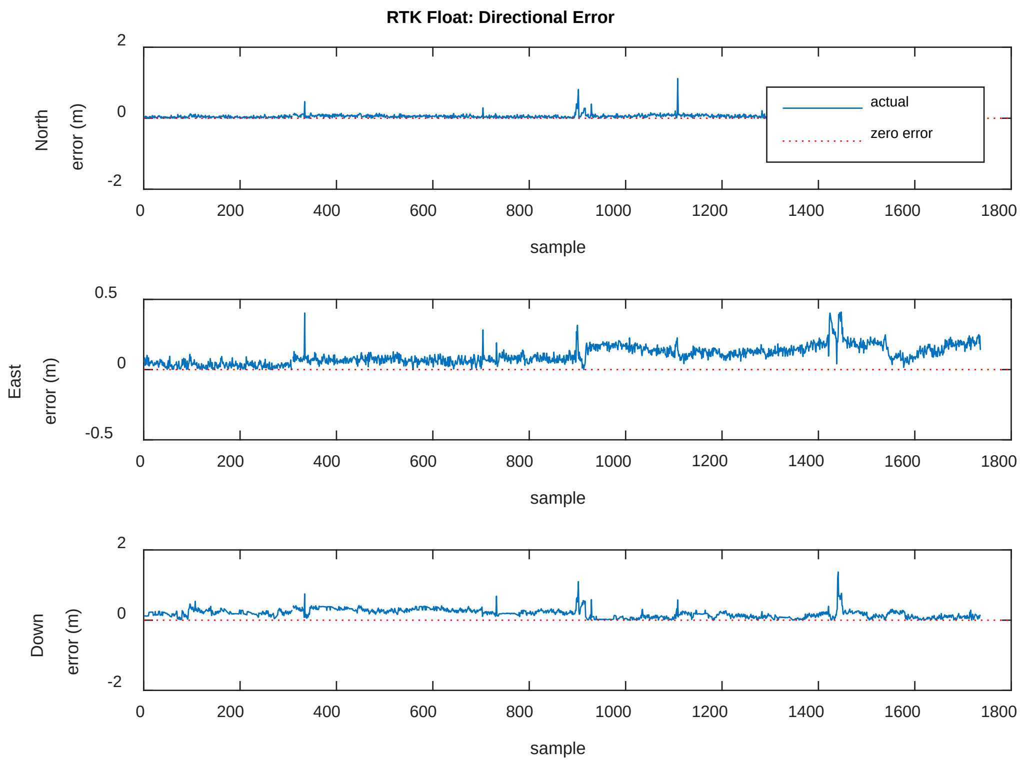

Figure 30. Ublox NEO-M8P Dynamic Test with Novatel Pinwheel Directional Component Error with Truth Source -RTK Float Mode

Due to the fact that this configuration never achieved an RTK Fix, there is no figure to contrast with Figure 30. Figure 30's directional component statistical analyses can be seen in Table 9.

Table 9. Ublox NEO-M8P Dynamic Test with Novatel Antenna and Truth Source Local-Level Component Level Statistical Analysis

	All Data		RTK Float		RTK Fix	
	Mean (m)	Std dev (m)	Mean (m)	Std dev (m)	Mean (m)	Std dev (m)
North	0.0474	0.0508	0.0474	0.0508	n/a	n/a
East	0.1025	0.0612	0.1025	0.0612	n/a	n/a
Down	0.1903	0.1223	0.1903	0.1223	n/a	n/a
DRMS	0.1381		0.1381		n/a	
MRSE	0.2649		0.2649		n/a	

Table 9 represents all the statistical results from test #3. For this test setup, the Ublox NEO-M8P has a 2-dimentional (horizontal) accuracy of 13.8 cm and a 3-dimensional accuracy of 26.5 cm. For this test, the system never obtained an RTK Fix; therefore, no statistics are available. Overall, as expected, the position accuracy is degraded when transitioning from dynamic to static testing.

Native Antenna

For test #4, the NEO-M8P was tested in a dynamic fashion against the Novatel DL-V3 RTK system. The antenna used for the NEO-M8P rover unit was the Ublox native patch antenna. The areas of interest in this test were: reliability, accuracy and precision.

System reliability for this test setup was 8.3%. Figure 31 and Figure 32 both show position solutions for the test set up compared to the position solutions of the truth source (High-end RTK System). Figure 31 represents the position solutions while the RTK system is in RTK Fixed mode. Figure 32 represents the position solutions while the RTK system is in RTK Float mode.

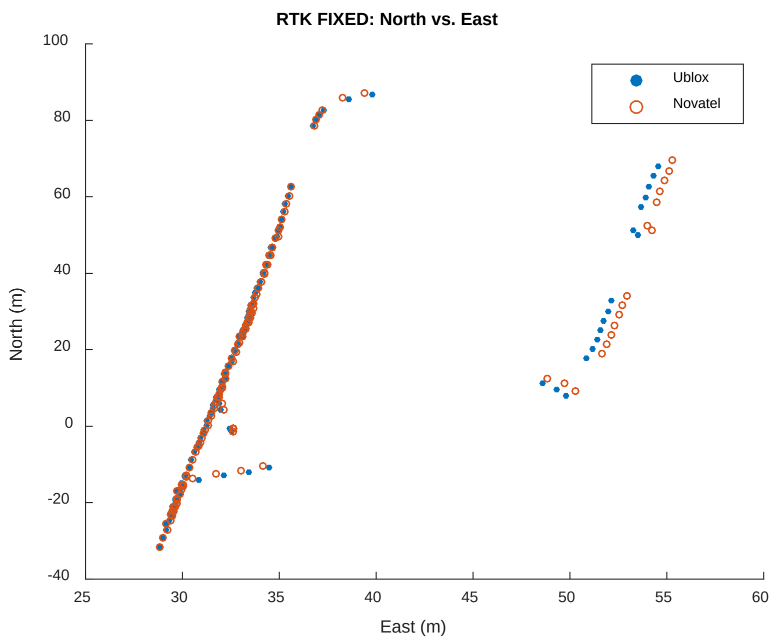

Figure 31. Ublox NEO-M8P Dynamic Test with Native Patch Antenna and Truth Source -RTK Fix Mode

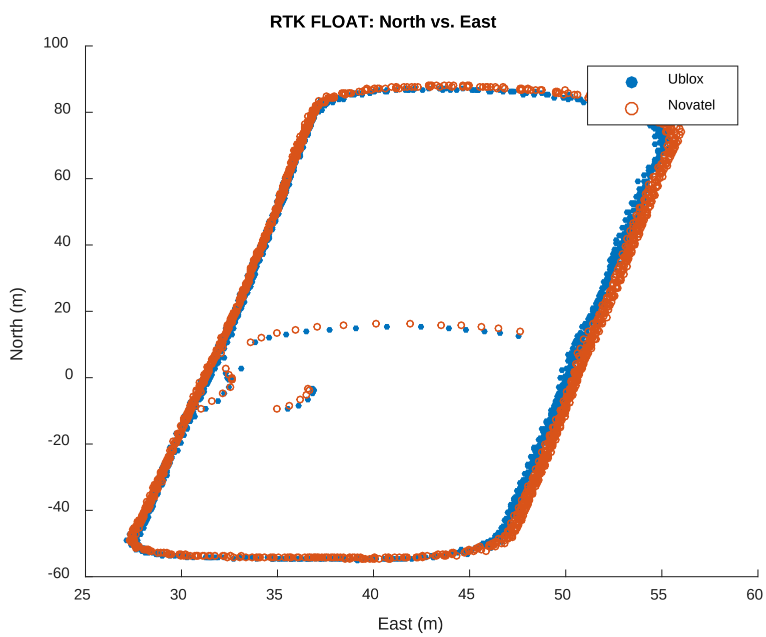

Figure 32. Ublox NEO-M8P Dynamic Test with Native Patch Antenna and Truth Source -RTK Float Mode

The data points in Figure 31 and Figure 32 show the dynamic nature of the tests. Data points appearing in the middle of the figures were due to a test obstruction, where due to the continuous nature of the test, the rover unit had to deviate from the planned path.

To better understand Figure 31 and Figure 32, they are broken down into directional components for RTK Fixed and Float modes; deviations from the truth source (AFIT's Novatel RTK system) are shown for each directional component. These are graphically represented in Figure 33 and Figure 34.

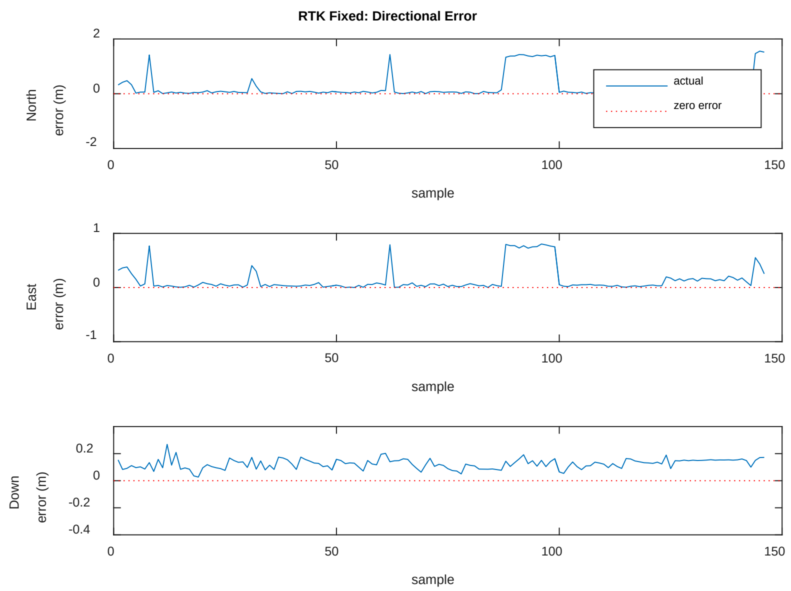

Figure 33. Ublox NEO-M8P Dynamic Test with Native Patch Antenna Directional Component Error with Truth Source -RTK Fix Mode

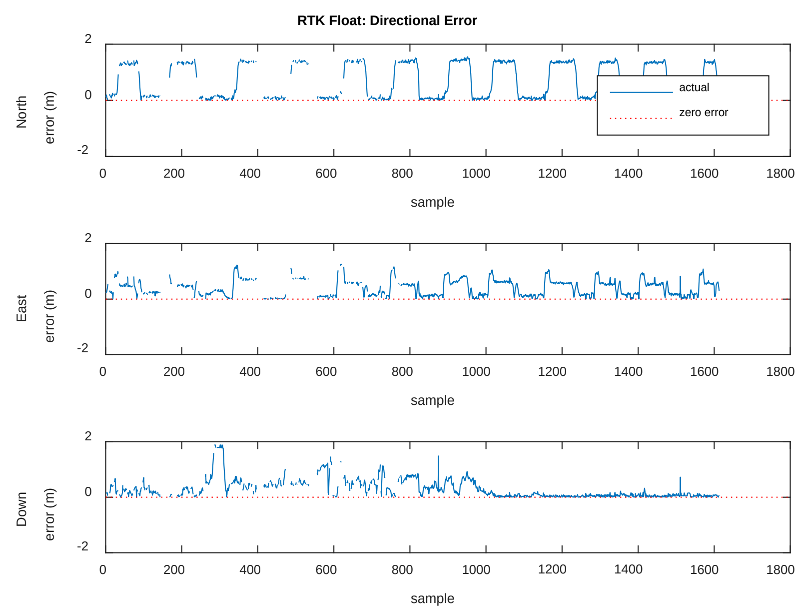

Figure 34. Ublox NEO-M8P Dynamic Test with Native Patch Antenna Directional Component Error with Truth Source -RTK Float Mode

The spikes in the data error offset can be best explained by the nature of turns in the dynamic course driven. The consistently jagged curves in Figure 34 are representative in the changes in respective components as a direct correlation to the continuous dynamic motion driven in Figure 28. The directional component statistical analyses can be seen in Table 10.

Table 10. Ublox NEO-M8P Dynamic Test with Native Patch Antenna and Truth Source -- Local-Level Component Level Statistical Analysis

	All Data		RTK Float		RTK Fix	
	Mean (m)	Std dev (m)	Mean (m)	Std dev (m)	Mean (m)	Std dev (m)
North	0.6250	0.6145	0.6660	0.6159	0.2309	0.4370
East	0.3770	0.2921	0.4011	0.2879	0.1453	0.2240
Down	0.2800	0.3351	0.2960	0.3480	0.1246	0.0367
DRMS	0.9369		0.9638		0.5603	
MRSE	1.0227		1.0538		0.5751	

Table 10 represents all the statistical results from test #4. For this test setup, the Ublox NEO-M8P has a 2-dimentional (horizontal) accuracy of 93.7 cm and a 3-dimensional accuracy of 102.2 cm. When in RTK Fixed mode, the 2D accuracy is 56.0 cm, while 3D accuracy is 57.5 cm. The difference in RTK Fixed mode and Float mode is significant in this configuration; almost a factor of two.

It can be seen (via Table 9 and Table 10) that there is significant degradation of accuracy and precision when the native antenna is used instead of the Novatel antenna. As no other variables were changed, this can be best explained by the improved multipath rejection of the Novatel antenna; thus leading readers to the conclusion that the Novatel antenna is a better choice for a more accurate position solution.

Relative Testing

After analysis of tests #1-#4, and paying particular attention to reliability, it was hypothesized that there may be some interference (most likely multi-path) from being too close to AFIT's buildings. Tests #5 and #6, were defined in order to prove this hypothesis; these tests were thoughtfully conducted away from structures that could cause multi-path errors. The setup included having the base unit and the rover unit placed 15 ft (4.572 meters) apart as shown in Figure 11. Both the rover and base units used a Ublox native patch antenna. There was no true truth source for these tests because the location of the base unit was not at a verified location like tests #1-#4; its location was determined using the survey-in feature built into the Ublox Ucenter software (see Figure 35). Due to there not being a truth source, these tests are all considered relative to the measured distance of the base and rover units.

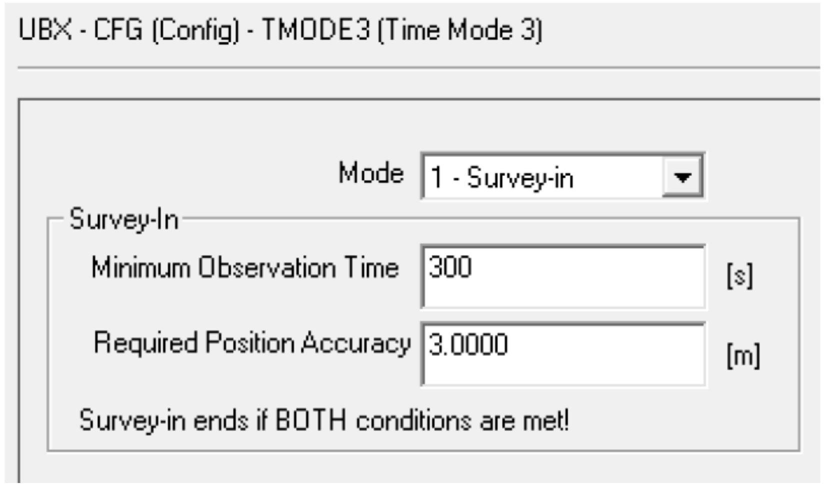

Figure 35. Setting in Ublox Ucenter to Configure Base Unit to Perform Survey-In for Position

Static

For test #5, the NEO-M8P was tested in a static fashion against the measured distance of 15 ft (4.572 meters). The antenna used for both the base and rover units was the Ublox native patch antenna. The areas of interest in this test were: reliability and relative accuracy. Because the test was not limited to a two-dimensional position solution (z-axis was not isolated), only a MRSE statistical analysis was conducted.

System reliability for this test setup was 73.7%. Figure 36 shows position solutions for the rover station relative to the base station over the testing lifespan.

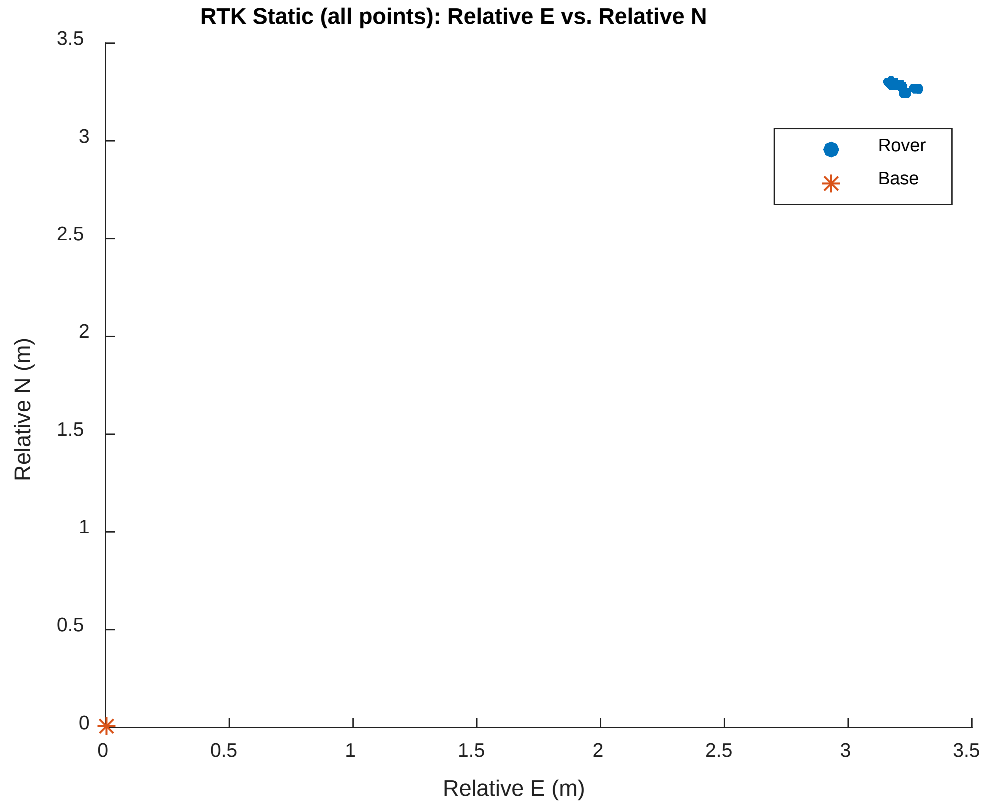

Figure 36. Ublox NEO-M8P Static Relative Testing with Native Patch Antennas - Position Solutions – Rover Station Relative to Base Station

Figure 36 represents the relative nature of the test. The rover unit can be seen to have an approximate relative distance to the base unit of 4.572 meters (15 feet). Figure 37 shows all position solutions (relative to base station) on a closer scale; this figure represents both RTK fix and RTK float modes.

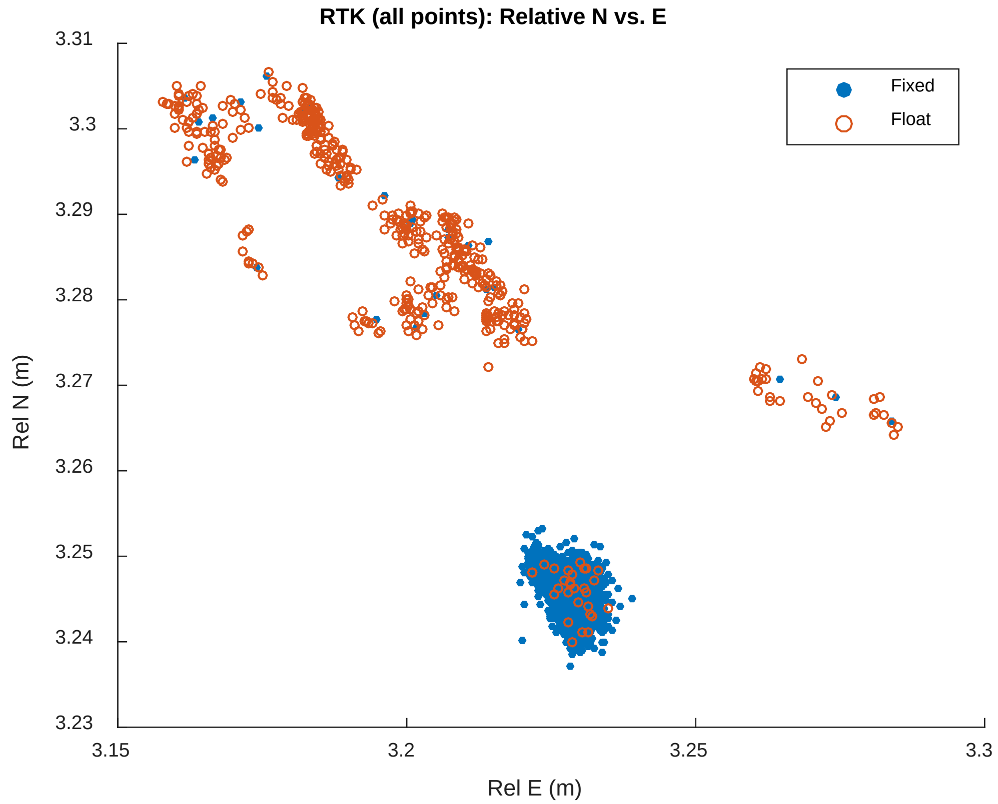

Figure 37. Ublox NEO-M8P Static Relative Test with Native Patch Antennas - All (RTK Fix and Float) Position Solutions – Zoomed-in

It is easy to see, in Figure 37, the data points that are tightly grouped are the position solutions for RTK Fixed mode and that the others, the data points that are spread out, are for RTK Float mode. The position solutions in Figure 36 and Figure 37 are statistically analyzed against the measured distance of 15 ft (4.572 meters). The MRSE statistical analysis can be seen in Table 11.

Table 11. Ublox NEO-M8P Static Relative Test with Native Patch Antenna – MRSE Only Statistical Analysis

	All Data	RTK Float	RTK Fix
MRSE (m)	0.0089	0.0159	0.0065

Table 11 represents all the statistical results from test #5. For this test setup, the Ublox NEO-M8P has a 3-dimensional relative accuracy of 0.9 cm. When in RTK Fixed mode, the 3D relative accuracy is 0.7 cm. These MRSEs are a significant improvement from any of the previously tested configuration (tests #1-#4). This leads to the logical deduction that the proximity to the building were, indeed, causing multi-path errors in the positions solutions.

Dynamic

For test #6, the NEO-M8P was tested in a dynamic fashion against the measured distance of 15 ft (4.572 meters). Using a taught tape measure of 15 ft (4.572 meters), the rover unit was walked in a circular manner around the stationary base unit. The antenna used for both the base and rover units was the Ublox native patch antenna. The areas of interest in this test were: reliability and relative accuracy. As in the previous test (test #5), this was a three dimensional test, so only a MRSE statistic was produced.

System reliability for this test setup was 35.8%. Figure 38 shows position solutions for the rover station relative to the base station over the testing lifespan. Figure 39 represents and distinguishes position solutions (relative to base station) for both RTK fix and RTK float modes.

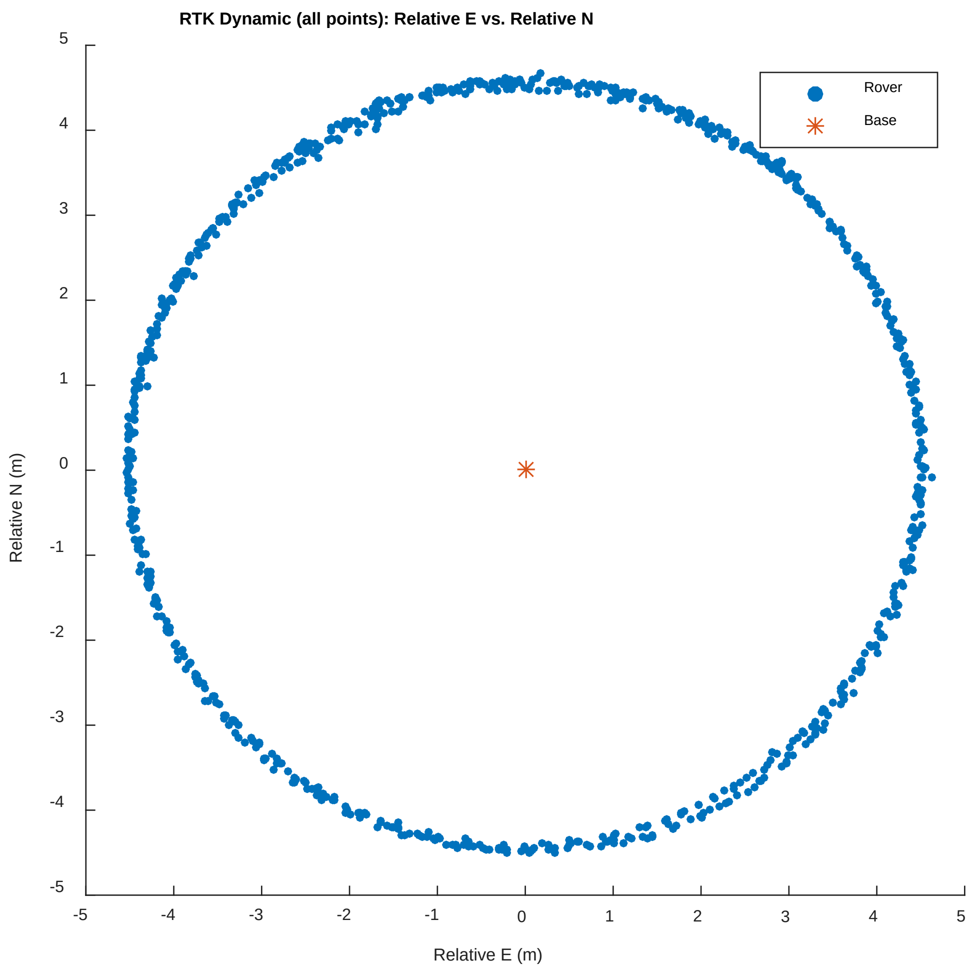

Figure 38. Ublox NEO-M8P Dynamic Relative Testing with Native Patch Antennas - Position Solutions – Rover Station Relative to Base Station

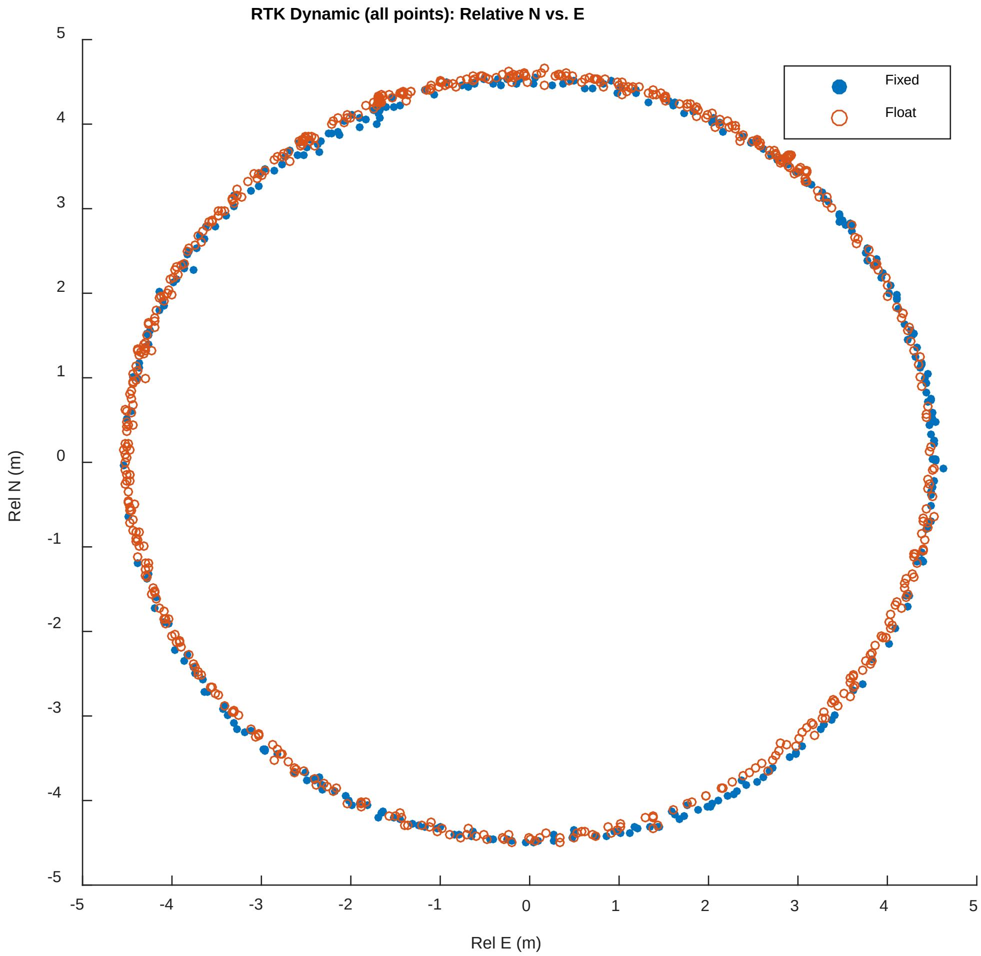

Figure 39. Ublox NEO-M8P Dynamic Relative Test with Native Patch Antennas - All (RTK Fix and Float) Position Solutions

The position solutions in Figure 38 and Figure 39 are statistically analyzed against the measured distance of 15 ft (4.572 meters). The MRSE statistical analysis can be seen in Table 12.

Table 12. Ublox NEO-M8P Dynamic Relative Test with Native Patch Antenna – MRSE Only Statistical Analysis

	All Data	RTK Float	RTK Fix
MRSE (m)	0.0738	0.0534	0.0613

Table 12 represents all the statistical results from test #6. For this test setup, the Ublox NEO-M8P has a 3-dimensional relative accuracy of 7.4 cm; in RTK Fixed mode, the 3D relative accuracy is 6.1 cm. Interestingly enough, the accuracy for this test is better in RTK Float mode, than when in RTK Fix mode. Because the deviation of the two is only less than a centimeter, and the precision is better in the RTK Fix mode, this observation can be written off as an anomaly.

Additionally, despite the drop in reliability from the previous test (test #5), the position solution relative accuracy is very good. This solidifies the conclusion that multi-path error played a large part in the position solution error of previous tests.

Reliability-only Testing

To further investigate the problem of system reliability (RTK fix mode percentage), two more tests were conducted (test #7 and test #8). Specifically targeting system reliability, a simple time based trial was conducted for static and dynamic testing. For hardened multi-path error mitigation, testing took place over ¼ miles (402.34 m) from any building. Figure 40 details the locations of the reliability only tests.

Figure 40. Ublox NEO-M8P Reliability Testing Location for Static and Dynamic Testing

Static

Focusing purely on reliability, test #7 was conducted in the field to the East of AFIT. Both the base unit and rover unit were left stationary for the entirety of the test. Each unit used the Ublox native patch antennas. Figure 41 graphically shows the position solutions for the static test.

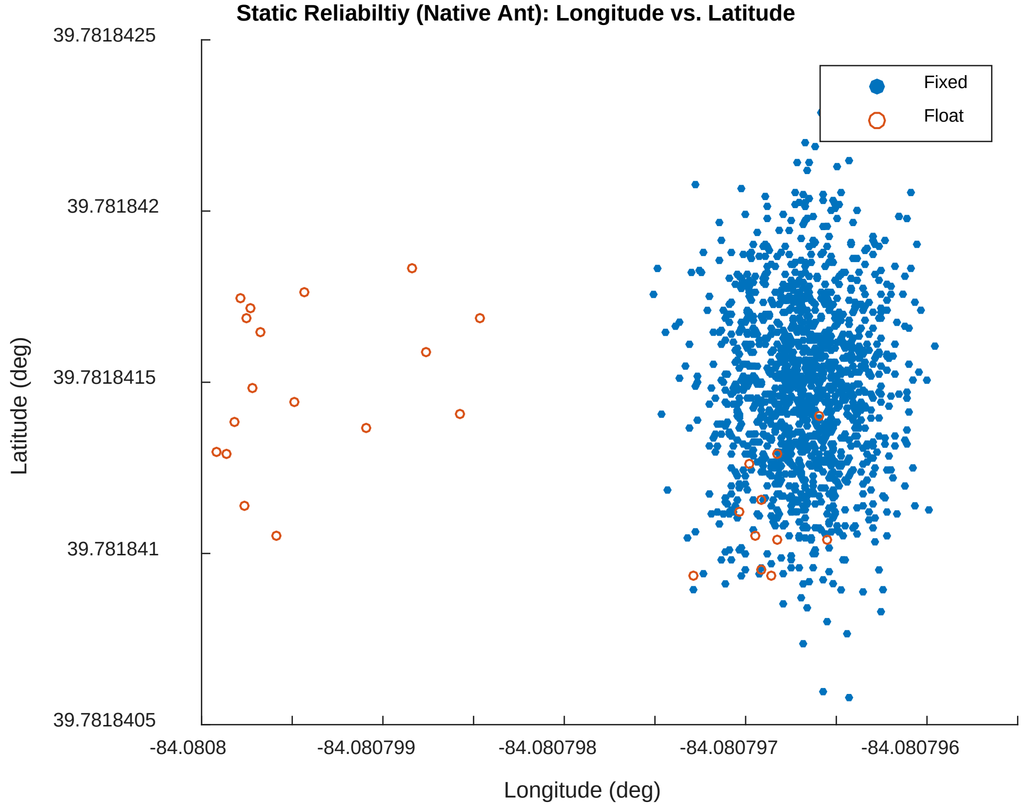

Figure 41. Ublox NEO-M8P Static Reliability Test Position Solutions – Both RTK Fix and Float Modes

Due to the nature of the test (reliability only), the base location was not noted; therefore, Figure 41 was unable to be transformed into the local-level coordinate frame like the other figures found in this chapter. By inspection, the contrast of Fixed data points to Float data points portrays high system reliability. In fact, system reliability for this test setup was 97.9%. No other statistical analysis was performed on test #7.

Dynamic

Focusing purely on reliability for a moving rover unit, test #8 was conducted in the field to the East of AFIT. The base unit was left static, while the rover unit was moved around the base station for the entirety of the test as shown in Figure 40. Each unit used the Ublox native patch antennas. Figure 42 graphically shows the position solutions for the dynamic test.

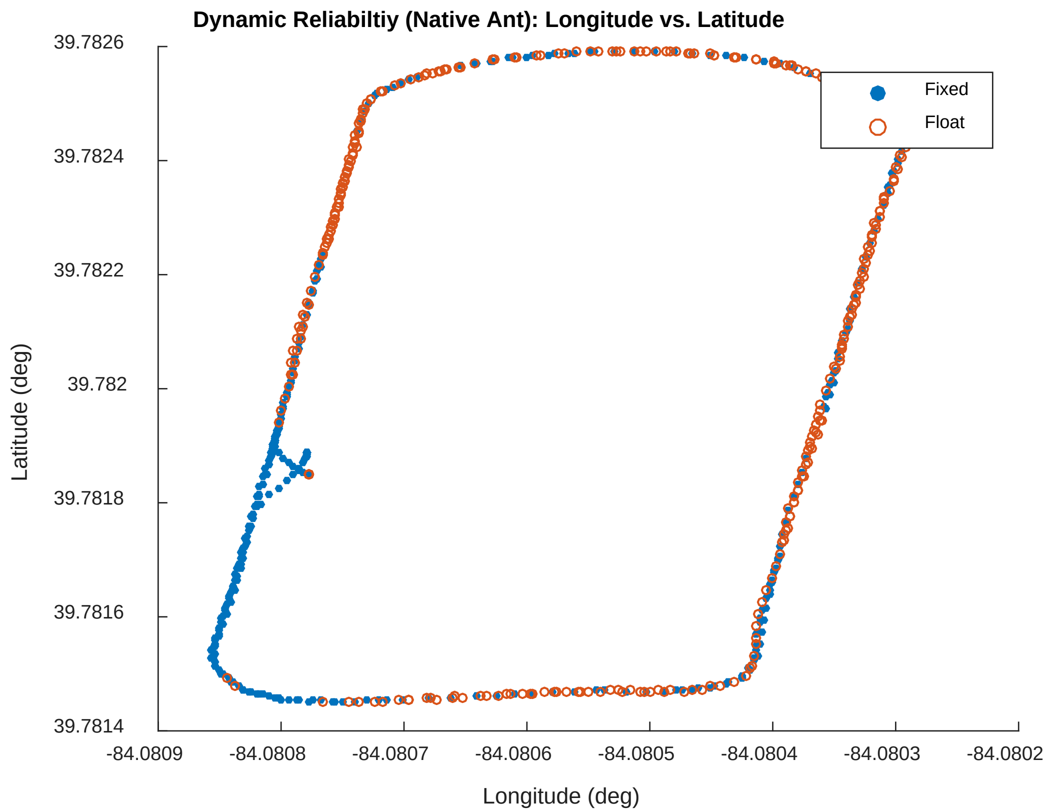

Figure 42. Ublox NEO-M8P Dynamic Reliability Test Position Solutions – Both RTK Fix and Float Modes

Due to the nature of the test (reliability only), the base location was not noted; therefore, Figure 42 was unable to be transformed into the local-level coordinate frame like the other figures found in this chapter. The small x pattern on the left side of Figure 42 represents testing start and testing ending points. System reliability for this test setup was 59.1%, as the system was in RTK Fixed mode for 59.1% of the time. No other statistical analysis was performed on test #8.

There is a noted difference in reliability in tests #5 and #6 compared to tests #7 and #8. There is no obvious explanation except for these tests were conducted about 500 meters apart with slightly different terrain (notably a telephone pole located nearby to test setup for test #5 and #6).

Swift Navigation Piksi RTK GPS System Testing

Tests on the Swift Navigation Piksi RTK GPS System were done in conjunction with AFIT master's student Andrew Knisely of the Electrical Engineering Department.

The rational for conducting the Swift Navigation Piksi RTK GPS System characterization was to understand the precision and accuracy of this RTK GPS system. See Figure 43 to view the Piksi RTK GPS system.

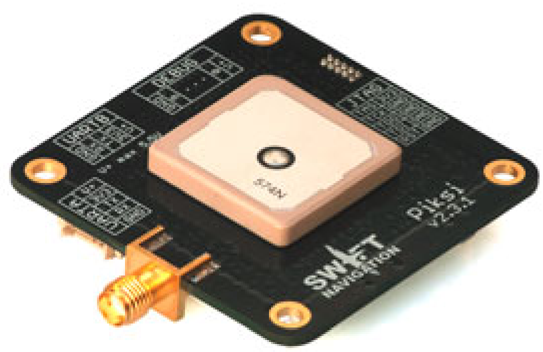

Figure 43. Swift Navigation's Piksi RTK GPS System

Per Table 2, in Chapter 3, the tests planned to be conducted with Swift Navigation's Piksi RTK GPS system included static and dynamic tests, varying antennas (both native patch antenna [Figure 44] and Novatel [Figure 19]) set-ups, and tests with and without a truth source (AFIT's High-End RTK system [Novatel DL-V3 RTK system]). However, during analysis of test #9 and test #11, test #10 and tests #12-#16 were aborted due to inconsistent data output by the Piksi RTK system; this will be discussed further in this chapter. Only test #9, and test #11 were conducted fully. These tests give insight into the overall improvement that this RTK system would provide users.

Figure 44. Swift Navigation's Piksi Native Patch Antenna

Static with Truth Source

In test #9, the Piksi RTK system was tested in static conditions against a truth source (Novatel DL-V3 RTK system). For the test, the base unit used the Ashtech Choke ring antenna located on top of AFIT's ANT lab in a verified location. In test #9 a Novatel pinwheel antenna was used for the rover unit. Results are shown below.

Novatel Antenna

For test #9, the Piksi RTK system was tested in a static condition against the Novatel DL-V3 RTK system. The antenna used for the Piksi RTK rover unit was the Novatel Pinwheel antenna. The base unit and rover unit were placed at an arbitrary distance apart and were not moved for the entirety of the test. The areas of interest in this test were: reliability, accuracy and precision.

Due to the nature of output data from the Piksi RTK system, only RTK Fix data was able to be analyzed. Although this test was not able to capture all of the data necessary for a full RTK Fix and Float analysis, this test was sufficient to capture RTK

Fixed mode statistics. The reason for the partial analysis, is that the Piksi RTK system only output a consistent data stream during RTK Fixed mode.

System reliability for this test setup was 48.4%. Figure 45 shows the Piksi RTK system's position solutions over time compared to the position solutions of the truth source (High-end RTK System); this is shown in the North, East, and Down components.

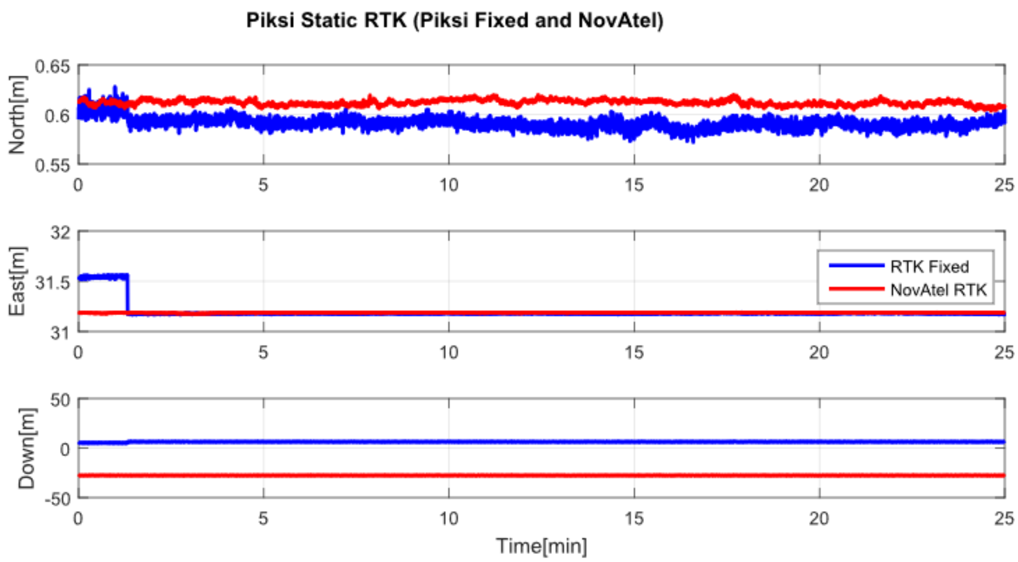

Figure 45. Piksi System Static Testing with Novatel Antenna Position Solutions Over Time - RTK Fixed Mode Only - North, East, and Down Components (Knisely, 2017)

Although not sufficient to conduct a full statistical analysis, Figure 45 is tabulated for better understanding into Table 13.

Table 13. Piksi Static Test with Native Patch Antenna – RTK Fix Mode Only

	RTK Fix	
	Mean (m)	Std dev (m)
North	0.0205	0.0057
East	0.0100	0.0430
Down	-8.1809	0.1390
DRMS	0.0541	
MRSE	8.1809	

Table 13 represents all the statistical results from test #9. For this test setup, RTK Fixed mode was the only component to get statistical analysis. When in RTK Fixed mode, the 2-dimensional accuracy is 5.4 cm and the 3-dimensional accuracy is 818.1 cm. The deviation found in this system is the Down component accuracy; this is an area of concern for the Piksi RTK System and is what caused the MRSE to be significantly higher than the DRMS. The Down component positional error being significantly higher than the other directions is a finding that is echoed in Henricks' research (Hendricks, 2016).

Dynamic with Truth Source

In test #11, the Piksi RTK system was tested in dynamic conditions against a truth source (Novatel DL-V3 RTK system). The track used for dynamic testing was the same used for the Ublox NEO-M8P (see Figure 28). For the test, the base unit used the Ashtech Choke ring antenna located on top of AFIT's ANT lab in a verified location. In test #11 a Novatel pinwheel antenna was used for the rover unit. Results are shown below.

Novatel Antenna

For test #11, the Piksi RTK system was tested in a dynamic condition against the Novatel DL-V3 RTK system. The antenna used for the Piksi RTK rover unit was the Novatel Pinwheel antenna. The base unit was stationary while the rover unit was moved in an orientation seen in Figure 28. The areas of interest in this test were: reliability, accuracy and precision.

Due to the nature of output data from the Piksi RTK system, only RTK Fix data was analyzed. Although this test was not able to capture all of the data necessary for a full RTK Fix and Float analysis, this test was sufficient to capture RTK Fixed mode statistics. Again, the reason for the partial analysis, is that the *Piksi RTK system only output a consistent data stream during RTK Fixed mode*.

System reliability for this test setup was 36.7%. Figure 46 details the position solutions in the dynamic orientation of the test. Figure 47 shows the Piksi RTK system's position solutions over time compared to the position solutions of the truth source (High-end RTK System); this is shown in the North, East, and Down components.

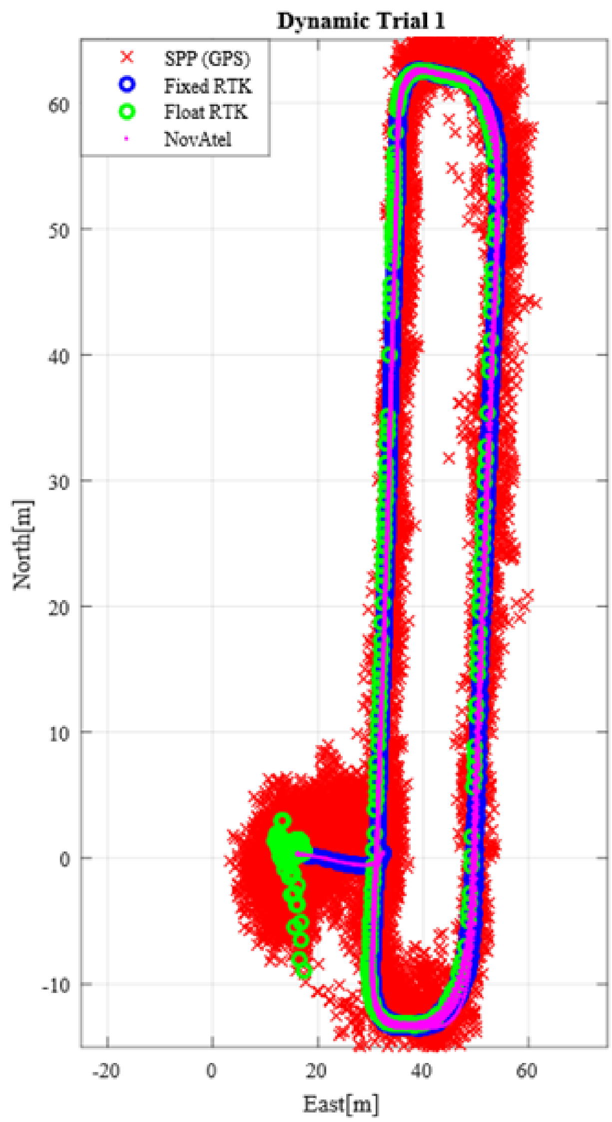

Figure 46. Piksi Dynamic Test with Novatel Pinwheel Antenna Position Solutions (Knisely, 2017)

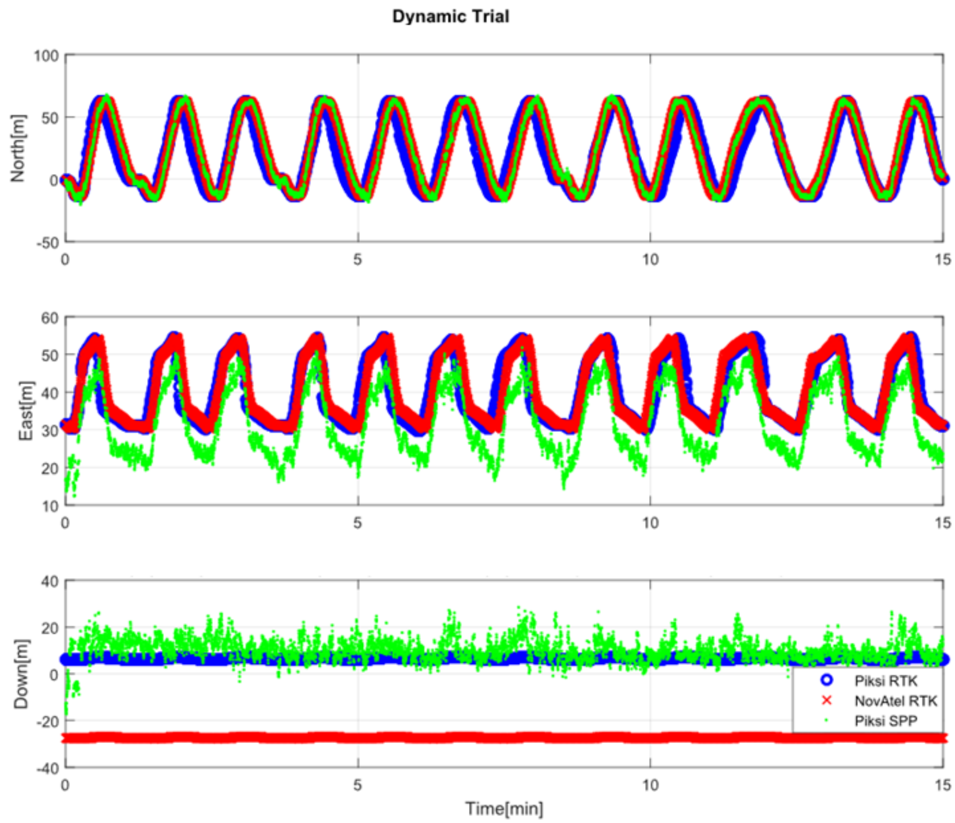

Figure 47. Piksi System Dynamic Test with Novatel Antenna Position Solutions Over Time - RTK Fixed Mode and SPP Only - North, East, and Down Components (Knisely, 2017)

The jagged curves in Figure 47 are representative in the changes in respective components as a direct correlation to the continuous dynamic motion driven in Figure 28. Although not sufficient to conduct a full statistical analysis, Figure 47 is tabulated for better understanding into Table 14.

Table 14. Piksi Dynamic Test with Native Patch Antenna – RTK Fix Mode Only

	RTK Fix	
	Mean (m)	Std dev (m)
North	0.0283	0.0140
East	0.0116	0.0089
Down	10.6598	0.1701
DRMS	0.0341	
MRSE	10.8721	

Table 14 represents all the statistical results from test #11. For this test setup, RTK Fixed mode was the only component to get statistical analysis. When in RTK Fixed mode, the 2-dimensional accuracy is 3.4 cm and the 3-dimensional accuracy is 1087.2 cm. The huge deviation found in this system is the down component accuracy; this is an area of concern for the Piksi RTK System and is what caused the MRSE to be significantly higher than the DRMS. However, the largest area for concern of the Piksi RTK system is its inconsistent data output.

Flight Testing

There were two types of flight tests reported within this thesis. First, a qualitative test of RTK GPS integration; this test was a proof-of-concept test. Could the RTK GPS system be integrated into a SUAS for autonomous flight?

Pending results from the first test, the second flight test was a location hold test. This test was structured by commanding the SUAS to go to a set location and hold that location until told otherwise. A subsidiary goal for these tests was to determine system reliability (as defined earlier in this chapter) for flight tests.

Flight Testing Selection for RTK System

Before flight tests took place, there was a decision made about which RTK GPS system to integrate into the SUAS; the Ublox NEO-M8P (using the Ublox C94-M8P application board), or the Swift Navigation Piksi RTK GPS system. The choice was not a hard one.

Although the Piksi RTK system proved to be accurate in the 2-dimentional plane, the issue that came up over and over during ground testing was reliability. Not only was system reliability (percentage of time in RTK Fixed mode) an issue, but when the Piksi RTK system was not in RTK Fixed mode, the data output was inconsistent. There were times during testing that the Piksi RTK system did not put out a single position solution for over 90 seconds! That alone could cause catastrophic failures during flight testing.

Not only by default was the Ublox NEO-M8P (via C94-M8P application board) chosen as the RTK system to integrate, but the Ublox NEO-M8P proved that it is capable of continuous positions solutions. Additionally, the Ublox NEO-M8P consistently put out position solutions with centimeter level accuracy.

Autonomous Flight Test

For full integration into the SUAS, the Ublox NEO-M8P had to be integrated into the flight controller; a 3DR Pixhawk (see Figure 12). A wiring diagram is shown in Figure 48. Figure 49 highlights interfaces on the two subsystems.

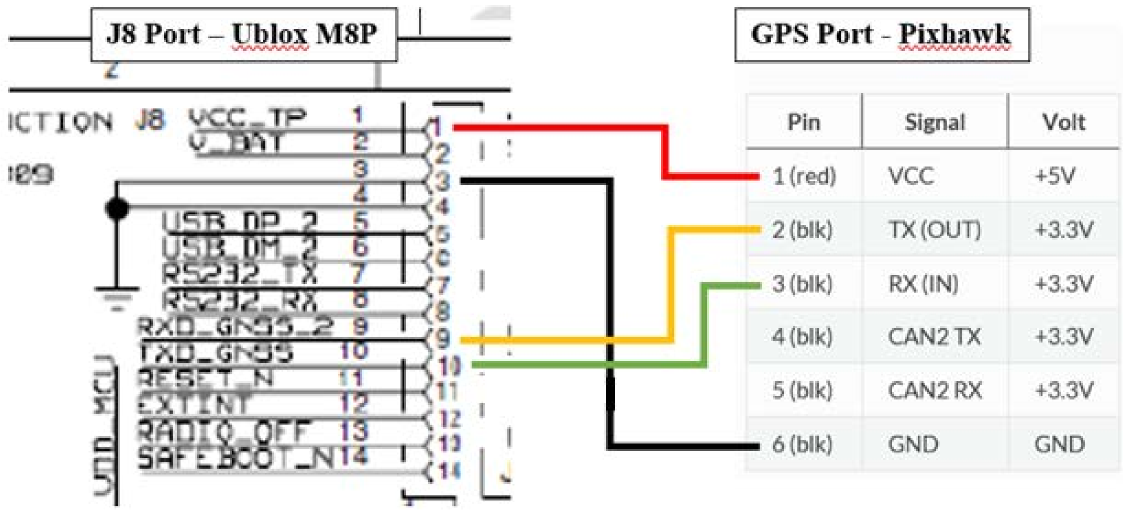

Figure 48. Ublox C94-M8P Integration with 3DR Pixhawk - Wiring Diagram

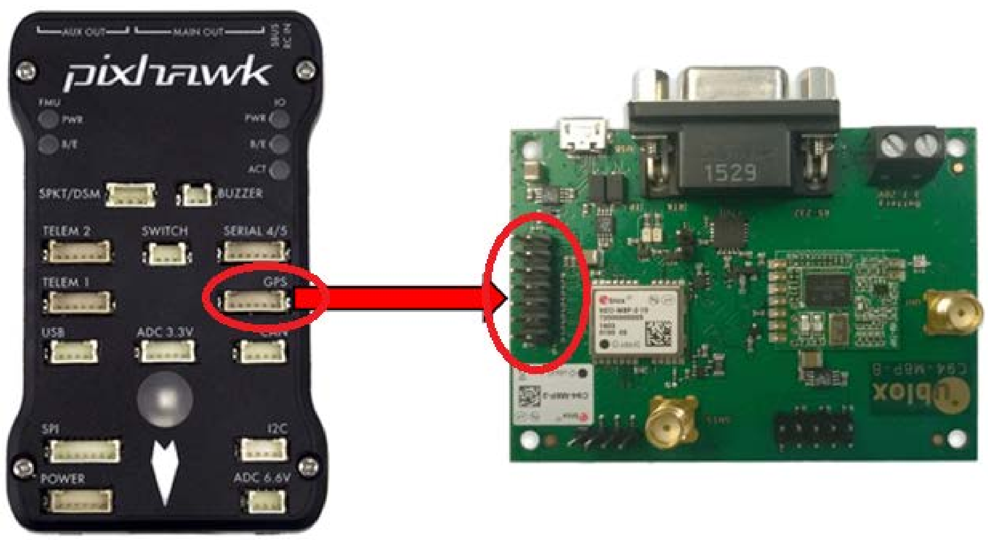

Figure 49. 3DR Pixhawk Flight Controller Integration to Ublox C94-M8P – GPS Port to J8: Test and Integration Port

Flight Test Failure Troubleshoot

Upon completion of wiring integration (Figure 48 and Figure 49), ground testing was conducted with the full SUAS system. During system ground testing, there was a configuration issue in which the flight controller kept auto-configuring the rover GPS unit.

After troubleshooting the radio, flight controller, and base station subsystems, the problem was localized to a communication issue on the port (UART1 port) configuration. The correct protocol configuration is shown Figure 50 and Figure 51 (and in Appendix A – Ublox C94-M8P User's Guide); for the base and rover unit, respectively.

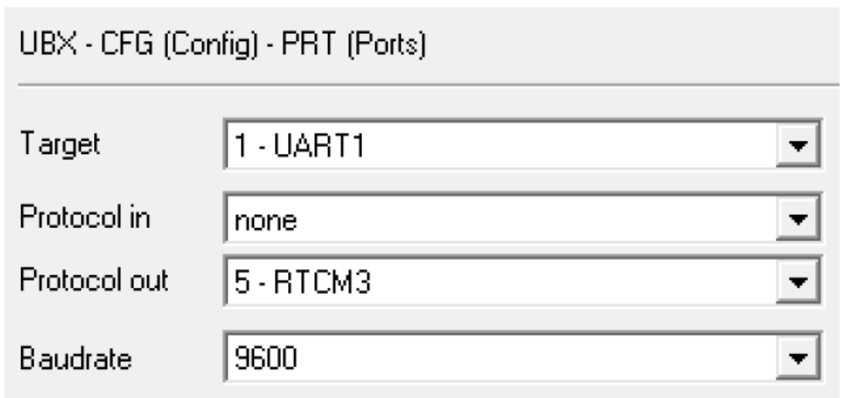

Figure 50. Radio Configuration for Ublox C94-M8P Base Unit in Ublox Ucenter

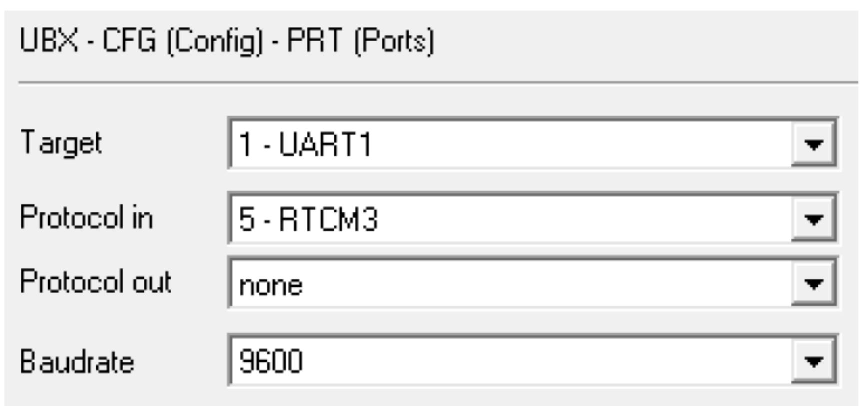

Figure 51. Radio Configuration for Ublox C94-M8P Rover Unit in Ublox Ucenter

During system testing, after the rover unit had been set to the correct settings, the rover unit was connected to the Pixhawk via configuration shown in Figure 49 above. After a few seconds, the Pixhawk automatically re-configured the rover unit in a way that it no longer communicated via UART1 with the base unit. The ‘Protocol In’ was turned to UBX + NMEA, and the ‘Protocol Out’ was changed to UBX. The baudrate was set to 38400. It was also discovered that the ‘Rate’ and ‘Nav5’ setting were changed to 5 Hz and Airborne < 4g, respectively.

These changes caused a loss in communication between the base and rover units; this communication is what enables the RTK function to work. Due to the fact that the two units were not able to send corrections back and forth, the rover unit essentially became a standalone single GPS receiver. Flight testing ensued with the rover unit in standalone GPS status.

An additional test was performed in order to isolate the error to the flight controller. Instead of a 3DR Pixhawk, an ArduPilot (APM 2.6) was used as the flight controller. The result was found to be the same as in the case of the 3DR Pixhawk. Further, it was determined that the Ardupilot could only use earlier firmware which did not support the RTK GPS mode.

Flight Test Data Analysis

Due to the fact that the Ublox NEO-M8P was still able to function as a standalone GPS unit, the location hold test was performed. The SUAS was commanded via Mission Planner to go to a set arbitrary (surveyed) location and maintain that location. A camera was set at the location pointing upwards to capture the SUAS flying above (see Figure 52 and Figure 53).

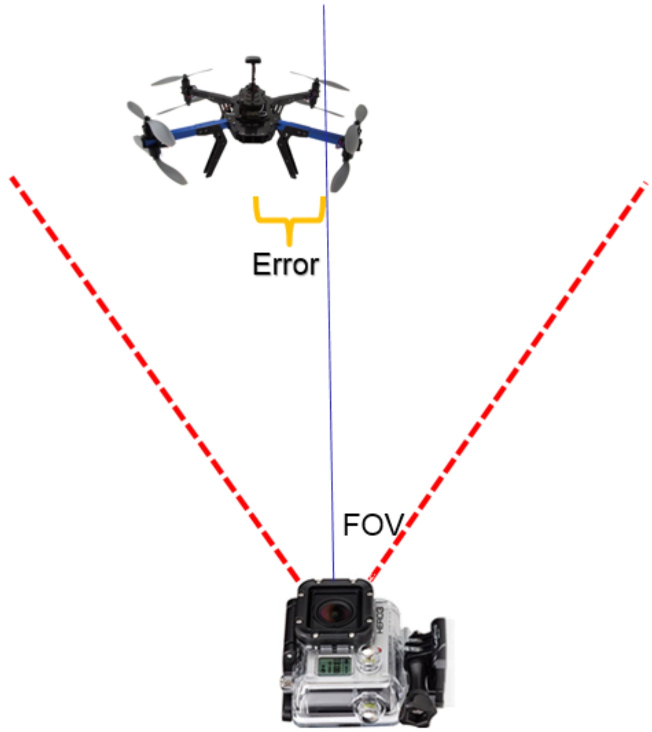

Figure 52. Simplified Setup for Position Hold Flight Scenario Capture

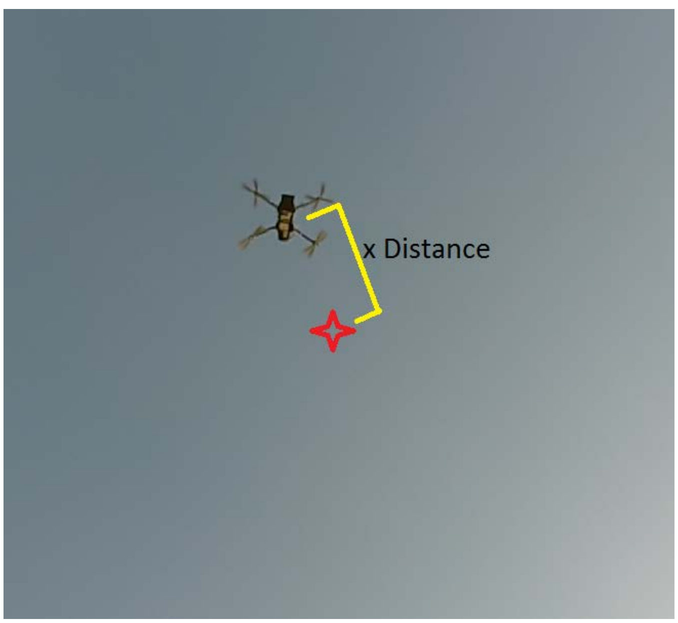

Figure 53. SUAS System Integration Flight Test – Camera View of Hold Location – Distance Analysis Example

By using laws of proportions, post analysis was performed on the camera footage. Only 2-dimenstional analysis was performed due to the horizontal nature of the camera footage. Variations in position were noted and analyzed. It was determined that the 2-dimentional accuracy of the SUAS to maintain a location was 41.3 cm and a precision of 19.0 cm. Positional variations were not just limited to GPS error; they also included wind, and control system error.

Additional Testing – Drotek Tiny RTK

Due to the limitations exposed during the integration of the Ublox C94-M8P application board to the Pixhawk flight controller, another alternative using the Ublox NEO-M8P was explored; the Drotek Tiny RTK GNSS system. With claims of being a ‘plug and play’ technology as well as being “the smallest high precision GNSS RTK (real time kinematic) module available” for “the Ublox NEO-M8P”, Drotek’s Tiny RTK was the logical next option to examine (Perin, 2016). A simplified diagram of functionality for the Drotek Tiny RTK GNSS system is shown in Figure 54.

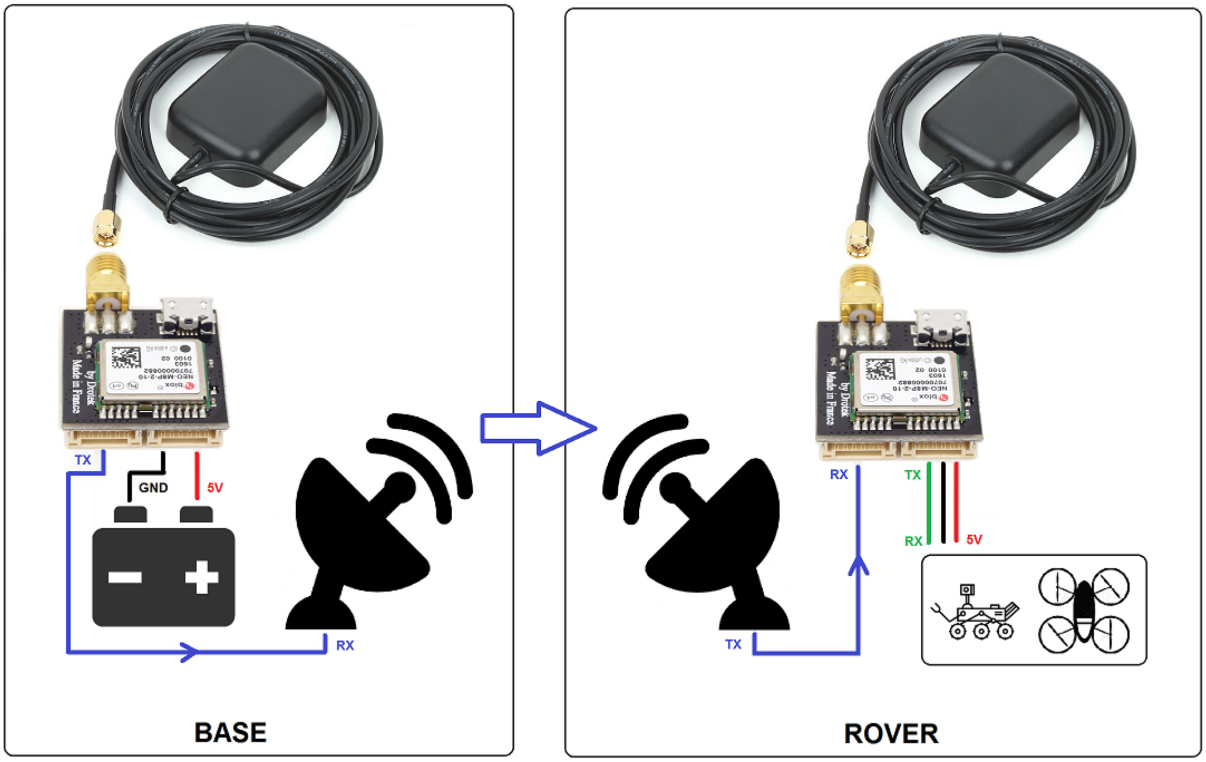

Figure 54. Simplified Diagram of Base and Rover – Drotek Tiny RTK GNSS System

The Drotek Tiny RTK GNSS system, referred to as Drotek RTK system for the rest of this document, was configured as outlined in Appendix C – Drotek Tiny RTK GNSS System User Guide. There are two ways outlined in the Drotek documentation to configure the Drotek Tiny RTK systems: by a 'dedicated telemetry link' or by 'Injecting GPS data'. For the dedicated telemetry link setup, each unit has its own dedicated 915 Hz radio that communicates by sending corrections to each other. This is the same approach used by the Ublox C94-M8P units. The inject GPS configuration has the base unit connected to the ground station (laptop) via USB. The base unit then sends its encapsulated raw data to the rover unit over the telemetry link set up via Mission Planner.

This research explored both configuration options to determine if it was feasible to integrate these RTK systems onto a SUAS. In both configurations, the rover unit was able to produce a 3D GPS Fix. However, both never transitioned into a DGPS Fix as outlined in the Drotek documentation. Although they appeared to maintain location well, the rover unit seemed to act as a single receiver instead of an RTK system.

When in the 'inject GPS' configuration, the HDOP got as low as 0.62; however, when in the 'dedicated telemetry link' configuration, the HDOP was 99.99 (which is as high as it can go), and was triggering a HDOP warning on Mission Planner. Although the HDOP was reading high, the stationary performance of the GPS unit did not appear any different than the other configuration. Both configuration appeared to have an accuracy on the sub-meter level, consistent with the earlier measurements with the UBlox C94-M8P application boards.

Summary

This chapter started out with a brief dive into hobbyist GPS standards via previous AFIT student Captain Kevin Hendricks research. What followed was a slew of ground testing results (see Table 2) that covered the two RTK GPS systems: Swift Navigation's Piksi and Ublox's NEO-M8P. This chapter ended with flight testing data and analysis.

As a single standalone receiver, the Ublox NEO-M8P (via Ublox C94-M8P application board), proved to be even more precise than the standard hobbyist units; a DRMS of 1.08m and 1.58m for NEO-M8P and hobbyist standard, respectively. That is a difference of half a meter and is a significant difference for a singular GPS receiver.

Ground testing on Ublox's NEO-M8P RTK GPS system was done through Ublox's C94-M8P application board. The ground tests (#1-#8) varied antenna choice, static and dynamic movement, and relative vs. absolute testing. It was determined that multi-path error effected the position solution accuracy in tests #1-#4. Additionally, data points to the Novatel antenna proved to be the better performing antenna amongst test configuration, both static and dynamic. Highlights for tests #1-8 can be seen in Table 15.

Table 15. Testing Summary for Tests #1-#8 --Reliability and DRMS (Fixed Mode)

Test #	Reliability (%)	Fixed Mode DRMS (cm)
1	64.5	1.6
2	30.2	4.0
3	0.0	13.8*
4	8.3	56.0
Test #	Reliability (%)	Fixed Mode MRSE (cm)
5	73.7	0.6
6	35.8	6.1
7	97.9	n/a
8	59.1	n/a

*overall DRMS – test #3 never achieved Fix Mode

Ground testing on Swift Navigation's Piksi RTK GPS system (test #9-14) proved to be very important, in particular because it unveiled a disconcerting issue: the position solutions for the Piksi system were not being output at a consistent rate. Due to the irregular data output, test #10 and tests #12-16 were aborted. Regardless of the inconsistent data output, a statistical analysis was performed on the results of the test #9 and test #11; the test setups for these were that of a Novatel pinwheel antenna and in static and dynamic testing fashion, respectively. For each test, the data for RTK Fixed mode was strictly analyzed. With a reliability of 48.5%, in static testing, this setup achieved a DRMS of 5.4 cm. With a reliability of 36.7%, in dynamic testing, this setup achieved a DRMS of 3.4 cm.

The Ublox NEO-M8P (C94-M8P Application Board) was chosen as the RTK system to integrate into the SUAS. During ground test for integrated SUAS, it was determined that the Ublox C94-M8P was being autoconfigured by the Pixhawk. This rendered the RTK system inactive; the roving unit on the SUAS then acted as a single GPS receiver. Flight testing ensued; the SUAS was commanded to stay at a fixed location. It did this with a 2-dimensional accuracy of 41.3 cm and a precision of 19.0 cm.

Additional effort was put forth to determine if the Drotek Tiny RTK system (utilizing the Ublox NEO-M8P) would fair any better than the Ublox C94-M8P. The Drotek was supposed to be put into two different configurations in order to deliver cm-level performance. The two configurations were investigated and it was determined that neither was able to deliver RTK performance with the Pixhawk autopilot.

The next chapter will use the results found in this chapter to answer the investigative questions found in Chapter 1 as well as point to potential future research.

V. Conclusions and Recommendations

Overview

This Chapter addresses the investigative questions pushed forth in Chapter 1. Additionally, this chapter will provide recommended areas for future research.

Investigative Questions Reexamined

After briefly introducing readers to the topic of GPS and SUAS, Chapter 1 presented a series of investigative questions. This section addresses each investigative question, in order, and provides insight into how this research relevantly answered each question.

<u>What is the current achievable accuracy of stock GPS equipment?</u>

Although this research did not perform tests on this actual question, the results of this investigative question are paramount to the RTK system research found in this thesis as a both a baseline and point of reference. For the answer to this first question, readers can turn to previous AFIT student Captain Kevin Hendricks' thesis research in 2016.

Hendricks writes, "Although there is documentation regarding the accuracy and precision of the uBlox receiver integrated into the 3DR kit, information regarding how well the kit performs with the integrated antenna had not been completed. The results of the data collection showed that accuracy of the 3DR GPS receiver kit has DRMS of 1.58 meters and MRSE of 3.08 meters. This research specifically investigated the accuracy and precision of the 3DR GPS receiver kit" (Hendricks, 2016).

It is important to note that there is a transition to the Ublox NEO-M8 as the new standard GPS Unit. This unit is what can be found in the new 3DR GPS Kits. This transition makes sense; as shown in single receiver testing in Chapter 4, the Ublox NEO-M8P performs significantly better than the old Ublox LEA-6 model.

How accurate and precise are the low-cost RTK systems; specifically, the Ublox's NEO-M8P and Swift Navigation's Piksi RTK system?

This question is specifically geared toward the two RTK systems analyzed: Swift Navigation's Piksi and Ublox's NEO-M8P RTK GPS systems. This question should be caveated by the term 'while outputting a consistent data stream'. For this research, the Piksi can effectively be taken off of the answer to this question because it did not continuously put out a position solution; there were times where a position solution was missing for up to 90 seconds at a time.

Looking strictly at the Ublox NEO-M8P RTK system, there were several tests where antenna choice, movement, and truth sources were varied. Of all the tests, test #1 (Novatel Pinwheel antenna in static testing environment) was shown to have the greatest accuracy and precision, a DRMS of 1.6 cm and a MRSE of 10.1 cm, respectively. The reliability of test #1 was that of 64.5%; the reasons of the reliability issues are discussed in the next investigative question answer.

What are the limiting factors associated with the low-cost RTK system versus the traditional RTK systems?

As alluded to in the previous investigative question answer, there were several issues with system reliability. System reliability was defined by the percentage of time the RTK system was in 'RTK Fixed mode' throughout the whole testing lifespan. There were several factors that contributed to lower reliability.

One noted limitation of the RTK system is performance in proximity to structures. Tests #1-#4, were performed within 50 meters of building 640, 642, and 644 on the AFIT campus and produced relatively low reliability numbers. With an inkling that the structures may, in fact, be an issue (causing multi-path errors and signal blockage issues) to the system reliability, tests #7 and #8 were performed. To test the theory of signal interference of the AFIT structures, tests #7 and #8 were conducted far from any structures (Figure 40). These tests showed an increase of reliability from 30.2% to 97.9% and 0% to 59.1% for static and dynamic tests, respectively of the same test setup.

An additional limitation was the antenna choice. The two antennas tested were the native antennas of the RTK system and the upgraded Novatel antennas. It was shown that the Novatel antennas performed much better than the native antennas; this was most likely, in part, due to the multi-path rejection feature and more consistent reception pattern.

<u>How reliable are low-cost RTK systems?</u>

As specified during the previous investigative question answer, there was an issue with reliability, especially concerning the Swift Navigation Piksi RTK system. There are many factors that produce reliability (as prior defined). In this research, it was concluded that proximity to structures was an issue for reliability of these RTK systems. However, when tested in an open field, away from buildings, the Ublox NEO-M8P obtained a stationary reliability of 97.9% and a dynamic reliability of 59.1%. The topic of reliability is very important and should be investigated further. Contributing factors to reliability include, motion, antenna choice, shock/vibration, temperature, power supply statbility, RF interference, and proximity to structures amongst other things.

What are the limitation of these COTS RTK systems being integrated into autonomous flight scenarios?

As proven in flight test results in chapter 4, the NEO-M8P (via Ublox C94-M8P application board) was integrated into a 3DR X-8 Octocopter; the 3DR Pixhawk was the flight controller used. However, as described in results, the NEO-M8P was only able to be integrated as a single receiver and not in its RTK paired mode due to configuration issues. The integration proves that the two subsystems (NEO-M8P and Pixhawk) are compatible, but the configuration to bring out the best geo-location accuracy potential needs to be researched further.

Recommendations for Future Research

In keeping with consistent environments when conducting tests, the recommendation is made to take position solutions when the satellite constellation is the same overhead. In order to do this, data collection needs to be started at the same time every day (minus four minutes); in doing so, the satellite constellation will be as close to a constant as possible, thus eliminating it as a variable for tests. An additional annotation that accompany each test is dilution of precision (DOP). With DOP being annotated, the relative geometry of satellite signals will be known relative to each test.

The single largest recommendation for future research is to integrate the Ublox NEO-M8P onto a SUAS while in RTK mode. If this can be uncovered, it could have significant application improvement for day to day projects involving geolocation. Having centimeter (and sometimes even millimeter) level precision would be monumental. Research into reliability issue mitigation needs to be investigated further as well.

Another area of interest for future work would be to investigate other application packages for the Ublox NEO-M8P. In this research the C94-M8P application board was heavily investigated as well as a quick overview of the Drotek Tiny RTK; both using the Ublox NEO-M8P as the GNSS board. There will soon be more application uses for the NEO-M8P; hopefully they will have better user interfaces. As more research and development is put forth into these boards, they will become less expensive and smaller.

At the time of this writing, Swift Navigation released a new version of the Piksi RTK system called Piksi Multi GNSS Module. This release essentially negates the original Piksi and makes it obsolete with the new claims of 2 cm accuracy, "RTK convergence in seconds" (instead of minutes), and reliability that is "robust in both open sky and mixed environments with challenging conditions" (Piksi, 2017). It is worth a look into this emerging product.

Additionally, in lieu of obtaining a COTS RTK unit, it is recommended there be a future look into making our own "in-house" solution. This can be done by using Ublox NEO-M8T boards that AFIT owns and integrating with a RTK algorithm (either proprietary or RTKLIB). This way, all internal data exchanges and interfaces are known and can be controlled to inject a GPS position solution into the flight controller.

Appendix A – Ublox C94-M8P User's Guide

https://www.u-blox.com/sites/default/files/C94-M8P-AppBoard_UserGuide_(UBX-15031066).pdf

POSITIONING

C94-M8P

u-blox RTK Application Board Package

User Guide

Abstract

This document describes the structure and use of the C94-M8P RTK application board package and provides information for evaluating and testing the u-blox NEO-M8P high precision positioning modules.

www.u-blox.com

UBX-15031066 - R04

Appendix B – Swift Navigation User's Guide

http://docs.swiftnav.com/wiki/Piksi_User_Getting_Started_Guide#Installing_the_Piksi_Console

Piksi User Getting Started Guide

From Swift Navigation Wiki

Welcome to the Getting Started Guide for the Swift Navigation Piksi™ RTK GPS Receiver! This guide is intended for first time Piksi users and provides an overview of how to install the required software, connect to and configure Piksi and acquire position solutions.

By the end of this guide, you will be able to acquire a fixed RTK solution using two Piksi receivers. The steps in this guide should take you about two hours in total, and the last two steps need to be performed outdoors.

Note: This guide was tested on:

- Windows 7 and 10
- OS X (10.8.5)
- Ubuntu Linux (12.10 32-bit, kernel version 3.5.0-17)

Guide Content:

It is useful to start by watching the 5 minute Getting Started Video that covers the topics in this guide at a high level. If anything in this guide is incorrect or unclear, please contact us (https://www.swiftnav.com/contact-us) and give us your feedback!

Note: The following additional equipment is recommended for the outdoor exercises:

- Tripod for the base station antenna
- Tripod or monopod for the rover antenna
- Battery pack with USB connector to power the base station
- Small table and chair

Piksi RTK Kit Contents

The items listed below are included in the Piksi RTK Kit.

Note: Two kits are available: 915 MHz and 433 MHz. They use different radios.

Appendix C – Drotek Tiny RTK GNSS System User Guide

https://drotek.com/en/tiny-rtk-documentation/

(https://drotek.com/shop/en/home/791-tiny-rtk-gps-neo-m8p.html)

TINY RTK

Author: Jerome Perin
Version: 1.0
En date du : 15 Sep 2016

1. What is RTK?

First, let's understand what **RTK** really stands for! **Real Time Kinematics** is a GNSS technology that allows to partially remove signal errors due to propagation in the atmosphere. These errors are numerous:

- Atomic clocks biases
- Receiver's noise
- Antenna's phase center variation
- Multipath
- Troposphere propagation
- Ionosphere propagation

Ionosphere propagation is the most important effect. The ionization of the propagating medium causes reflections and refractions of the electromagnetic waves. The propagation time measurement time performed by the receiver is therefore false.

Another important effect that cannot be modeled is **multipath**. It corresponds to wave reflection on obstacles near the receiver (trees, buildings…) that retard or duplicate signals. It can be strongly attenuated with a good hardware.

RTK requires consequently two GNSS receivers, a "base" station, generally motionless and whose position is perfectly known, and a "rover" mobile receiver. The base sends correction data to the rover (raw data) so that the rover can compute the double-difference RTK algorithm. This means that pseudoranges and carrier phases from the base will be "substracted" (it is a bit more complicated though) from those from the rover. **RTKLIB** is used to perform those calculations, that can lead to a centimeter-level accuracy.

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14. ABSTRACT

The focus of this research is investigating the utility of two small, low-cost, commercial-off-the-shelf (COTS), real time kinematic (RTK) GPS systems. The intent was to comprehend if current low-cost COTS technology performed as well as expensive high-end technology; as well as integrate a RTK system into autonomous flight scenarios. The RTK systems were characterized by test via static and dynamic scenarios, in parallel to a truth source. The results show that overall, in the Ublox NEO-M8P (via C94-M8P) performed better than the Swift Navigation Piksi (original). The Ublox NEO-M8P RTK System obtained a maximum DRMS (Distance Root Mean Square) of 1.6 centimeters, and a MRSE (Mean Radial Spherical Error) of 10.1 centimeters. The Piksi RTK system output an inconsistent data stream, and was therefore disregarded for flight test integration.

During the integration of the Ublox NEO-M8P and the 3DR Pixhawk (flight controller), an issue of autoconfiguration arose between the 3DR and Ublox. A Drotek Tiny RTK was also attempted to configure with the 3DR Pixhawk, with the same configuration issues. System reliability issues were evident throughout this research; including, but not limited to, signal blockage and multipath errors. It is recommended that research continue to investigate the use of RTK GPS systems.

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