Flight Testing of a Pseudolite Navigation System on a UAV

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BIOGRAPHY

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ABSTRACT

Due to an increasing reliance on navigation as an assumed infrastructure in many systems, there is an increasing need to develop non-GNSS based navigation systems that work in situations where GNSS systems are not available. One good example is a flight reference system, which is used to test navigation systems in a variety of environments. If a flight reference system's accuracy is fundamentally dependent on precision DGPS (as is often the case), then that system will not be appropriate for conducting testing in the presence of GPS jamming. One promising approach to solve this problem is the use of non-GNSS navigation beacons (sometimes referred to as pseudolites).

This paper describes flight testing of a new pseudolite navigation system built by Locata that operates in the 2.4 GHz ISM band. Up to now, the Locata system has been used almost exclusively on the ground, where it has demonstrated positioning accuracy at the 3-5 cm level compared to kinematic carrier-phase DGPS. This paper describes a series of UAV flight tests of the Locata system conducted at the Advanced Navigation Technology center at the Air Force Institute of Technology. Previous research has developed methods to characterize geometry effects for pseudolite applications as well as methods, such as primary component analysis, that can be used to mitigate situations where there is poor measurement geometry.

The flight test is described in detail, including the hardware configuration of the ANT Center UAV, which simultaneously flew a Locata receiver, a NovAtel GPS receiver, and a radio datalink system. The results indicate that there is strong agreement between the GPS and Locata solutions when there is good measurement geometry for Locata.

INTRODUCTION

Despite the future increase in the number of available GNSS systems being developed, there is a need for alternative methods of precision navigation. All satellite based navigation systems have the same problem of weak signal strengths and, therefore, poor availability in situations where buildings or natural obstacles attenuate their signals. For the same reason, these systems are susceptible to hostile jamming.

One form of alternative navigation is through the use of ground-based transmitters. These transmitters use a signal that is very similar to the GPS signal, thus the term pseudo-satellites or pseudolites has been associated with these navigation beacons. While some of the limitations of a satellite based system are avoided with pseudolites, there are different difficulties and implementation issues that must be addressed when using ground based transmitters.

The ANT center has been working to understand and overcome the difficulties associated with pseudolite systems, and has moved from simulation to real implementation. This paper will highlight the design, setup, and testing of a pseudolite system on an unmanned air vehicle (UAV).

BACKGROUND

Working with pseudolites solves some of the problems that are associated with satellite based systems. In an environment where satellite visibility is an issue, the possibility of launching a satellite for the purpose of attaining the desired geometry is not an option. Pseudolites have been used in the past to augment GPS. By placing a pseudolite transmitting a GPS signal of its own in a location to provide the needed measurement geometry the users have a cost effective solution to their problem. This is a solution for a problem of visibility that is encountered many times in an open pit mining and urban canyon environment. In this example the pseudolite is augmenting GPS and operates at the same L1 frequency as GPS. Other situations require specialized pseudolites, with their own signal structure and different carrier frequency. An example is when a system must operate in the presence of GPS jamming by either friendly or hostile design.

A flight test reference system is used to provide the reference trajectory during the testing of various flight systems. For accurate comparison, the referenced system must have a level of precision at least an order of magnitude better than that of the system under test. As flight systems are becoming more reliant on precision navigation systems, protecting these systems from jamming has also become more important. Testing systems under GPS jamming has drawbacks. By nature, testing in this environment denies the very GPS signal used by the reference system. In the past, this type of testing was accomplished by jamming one of the two available GPS frequencies and allowing the reference system to use the other. For more rigorous testing dual frequency jamming is required. In this situation the degradation in the flight test reference system could render the results invalid. Pseudolites operating on a frequency other than GPS could provide the test reference system that is needed.

Past work has addressed many of the issues that prevented the creation of a precise pseudolite-based system. The well known near-far problem has been handled by various pulsing schemes. The ANT center has focused at characterizing and mitigating additional issues facing pseudolites.

Since pseudolites are ground based their signals do not travel through the ionosphere, but primarily through the troposphere. In many cases the accuracy of the pseudolite system can be aided by further estimation of the residual tropospheric delay. This residual delay is present after normal methods of removing the delay caused by the troposphere have been exercised. Work by Bouska [1, 2] and Shockley [3] shows the results of simulation and ground testing when estimating this delay. Additionally, Shockley investigated the estimation of pseudolite survey errors.

Since pseudolites are ground based, their geometry to the receiver is different than normally encountered with GPS. Many times the observability of the vertical direction is poor due to the coplanar nature of the receivers and beacons. Ground tests were run with the goal of finding ways to intelligently constrain the position solution using knowledge of the surface being traveled on. Work done by Amt [4], investigates many methods for constraining the solution using this information. In this testing it is important to note that the solution achieved agreement with carrier-phase differential GPS to within 9 cm. Thus the capability of the pseudolite system used has been validated for ground based navigation.

To try and characterize the effects of geometry on pseudolite systems, simulations were conducted using various pseudolite configurations. The research by Crawford [5] primarily investigates the geometry effects using the scenario of a landing aircraft. While the aircraft is flying at altitude, there is likely no observability problem. As the aircraft approaches the ground and becomes closer to the same plane as the beacons the simulation shows the expected breakdown of the vertical observability. Finding the optimal elevation angle that a transmitter needs to become effective at aiding the vertical estimation was acheived. Another scenario placed numerous beacons along the runway so that at any time the aircraft would be ‘over’ a transmitter and thus attaining good measurement of the vertical. This type of scenario used an overly large number of beacons before becoming useful. An interesting solution that was simulated placed a transmitter and receiver on an orbiting aircraft at a high altitude. This orbiting pseudolite could provide the needed geometry to the landing aircraft.

This previous work has led to the testing that has recently occurred and will continue to occur at the ANT center. To validate the use of pseudolites as a flight test reference system it is essential that flight tests be conducted. The ANT center has worked in cooperation with the Locata Corp. to create its own pseudolite test network. The following sections describe the equipment used, the setup of the test, and the results attained so far.

EQUIPMENT

The pseudolites used in this test were developed by Locata Corp. The functionality of the pseudolites is described in [6]. The Locata pseudolites ‘locatalites’ operate at 2.4 GHz, which allows them to transmit unaffected by GPS jamming. Additionally, the pseudolites are able to self-synchronize their clocks to a uniform time. This ability to synchronize eliminates the need for a base receiver to estimate the individual transmitter clock biases. Figure 1 shows a picture of a locatalite.

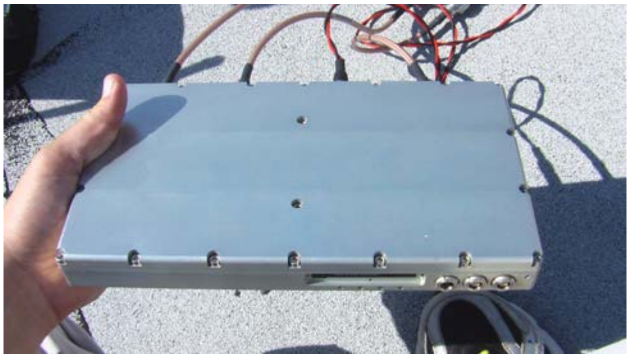

Figure 1: *Picture of a Locata Transmitter*

Each locatalite has a single receive antenna and two transmit antennas. The receive antenna is used in the synchronization process. In the system a locatalite is designated as the master pseudolite. All other pseudolites detect the signal from the master and synchronize to it in a process developed by the manufacturer called TimeLoc. The two transmit antennas allow each locatalite to transmit two PRN codes from the same clock. This allows for a unique method of multipath mitigation discussed later in this paper. The locatalite transmitters form a LocataNet. Once this is formed a roving transmitter in the UAV can create pseudorange and carrier-phase measurements for each PRN.

A UAV was chosen to provide a cost-effective and easily controlled test platform. For initial testing, a full-sized aircraft would not have been able to fly in the restricted test range and would have proved difficult to alter the flight pattern for unforeseen events. With a remote controlled (RC) UAV a ground pilot could easily fly the vehicle with the ability to make quick accommodations. The UAV used is shown in Figure 2. The plane is a SIG Rascal 110. It measures 110 inches wingtip to wingtip and is 76 inches nose to tail. With a 1.2 cubic inch, 3.1hp, 2 cycle motor the plane is able to carry a payload weighing 15 to 20 lbs. The RC plane was controlled via a 75 MHz transmitter.

Figure 2: *Picture of the UAV. A SIG Rascal 110.*

To create a reference trajectory for the test a differential GPS solution was obtained from a NovAtel OEM IV FlexPak. A GPS base station was setup nearby at a surveyed location. From the base station, differential corrections were transmitted to the GPS unit on board the UAV using a FreeWave 900 MHz spread-spectrum data modem.

TEST SETUP

This section will provide a detailed description of how this flight test was setup. The goal of this initial flight test was to not only attempt to validate the use of a pseudolite based reference system for flight, but to investigate issues that must be addressed in future tests.

A nearby runway, which has been used for RC airplane testing by the ANT center, was the location at which the tests were conducted. The area around the runway is relatively flat, which made it difficult to place any locatalites at any significant height. This situation is most likely representative of many runways, since large structures or landmarks are dangerous for landing aircraft.

Figure 3 shows an overhead view of the pseudolite placement. The stars mark the location of the locatalites, while the trajectory and approximate location of the runway are shown in the middle of the double cross pseudolite layout. The locations were chosen to attain the best coverage possible in the limited test area.

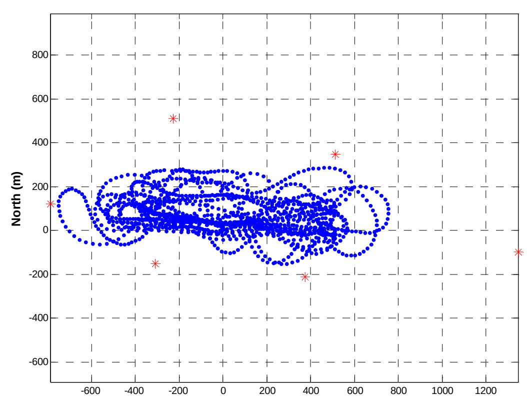

Figure 3: *Horizontal view of the test area.*

Six locatalites appear in Figure 3. As previously stated each pseudolite has the ability to transmit two separate navigation signals. This translates into a total of 12 PRNs that can be tracked by the receiver. Figure 4 shows a picture of how the locatalites were mounted. To create a makeshift tower, ladders were used to anchor metal masting. Once this metal masting was adjusted so that it was plumb, three patch antennas were attached. The arrangement for each pair of PRNs is nearly identical at each location. The highest antenna is designated as the first transmitter. Immediately below the top antenna is the receive antenna. The third antenna and lowest on the mast is the second transmitter. It is important to note the two PRNs that are transmitted from the same locatalite are offset vertically. This vertical separation has been found to aid in some cases of multipath.

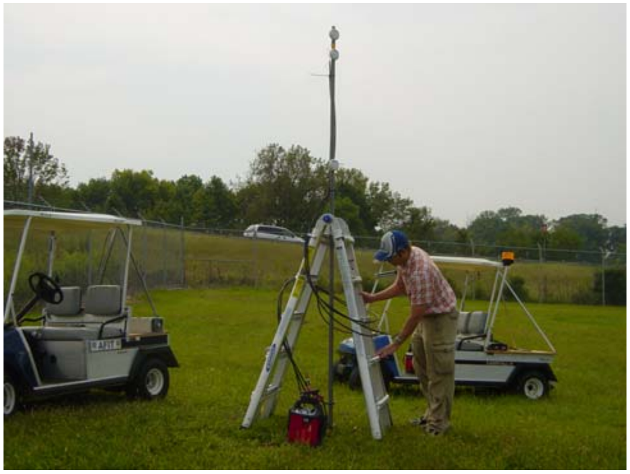

Figure 4: *Picture of pseudolite antenna setup.*

In ground testing the slant or glance angle between the pseudolite transmitter and receiver can be very shallow. This can lead to cases where a multipath signal interferes destructively with the original signal and causes a loss of signal lock. When working with a small number of transmitters, a loss of lock on a pseudolite can cause significant loss of needed geometry. The vertical separation of two signals from the same horizontal position can allow a larger chance of maintaining favorable geometry at a given location. This is due to the different slant angles caused by the varied height of the transmitters, which can cause the destructive multipath to occur in different locations. While the receiver may be in a spot at which the signal from PRN X is weak, due to multipath interference, the signal from PRN Y, which is in the same horizontal location as PRN X, is strong and unaffected by multipath.

The patch antennas that are associated with the transmission of PRN signals are angled to point into the test area, while the receive antennas are all angled to point at whichever pseudolite has been deemed the master. This allows the ‘slave’ pseudolites to track the master signal.

Part of setting up each locatalite involves a precise survey and measurement of the antenna locations. To attain an accurate navigation solution the receiver must have knowledge of the location of each transmitter. A significant error source depends on the accuracy of the transmitter position survey. In this test a GPS antenna was placed on top of each mast. A carrier-phase differential GPS solution was attained for the top of the mast. To calculate the position of the transmit antennas the vertical offset was then measured from this point.

Once the network of pseudolites was arranged, the base station for the UAV was set up. The base station for the UAV served two purposes. First, the station would send differential corrections over the wireless data modem to the GPS receiver onboard the UAV. Secondly, the base station would receive and record the calculated DGPS position being transmitted from the UAV. This was required since there was no way of recording the reference trajectory on the plane itself. Due to restrictions and interference, the reference position was only updated at a 1 Hz rate. Luckily, the Locata receiver was capable of recording its measurements internally to a compact flash card for later retrieval.

It can be seen that many components were required to be onboard the UAV. Figure 5 shows a picture of the payload compartment of the SIG Rascal after modification.

Figure 5: *Interior payload compartment of the UAV.*

The components are arranged along the left side of the picture from top to bottom. The nose of the aircraft extends to the right of the image and the tail to the left. The device at the top is the NovAtel receiver, in the middle is the Locata receiver, and to the bottom is the FreeWave modem. Not seen are the numerous batteries that were required to power all of the above mention devices. Care was taken to add weight to the nose of the plane to adjust the UAV’s center of gravity to an ideal location under the wings.

Four antennas were used on the aircraft. A 75 MHz antenna was used for RC communication with the pilot. Along the bottom of the aircraft were located the 900 MHz antenna for the FreeWave datalink and the 2.4 GHz Locata antenna. The dual frequency GPS antenna was located on the top of the aircraft.

POSITION CALCULATION

Once all the data was collected, a navigation solution was calculated. To attain a precise solution, carrier-phase measurements had to be used. This involves the estimation of the carrier-phase ambiguity terms. Due to the nature of the current pseudolites, the integer ambiguities were not solved for, but instead were estimated as floating point values. In the future, advanced techniques will be used to solve for the unique set of integer ambiguities.

To eliminate the need for estimating the receiver clock error, single differenced measurements were used. A solution was then found using a method similar to that used in past ground testing [4]. Several steps are taken to achieve the solution.

First, a code solution is found using the method of least squares at each epoch. Initially, estimation in three dimensions is attempted. If this does not begin to converge or a direction is seen to be unobservable, a constraint is applied to hold the problematic dimension to the must recent value. This allows a rough trajectory to be attained.

After the code solution is done a batch process is used to estimate the ambiguities. This batch process calculates all the positions and ambiguities for the entire flight history using both the code and carrier-phase measurements from each epoch. In this manner all the data is being used to appropriately estimate the ambiguities which are constant over many epochs. In the ground testing, this step involved many of the methods for height constraint. In the case of UAV flight there is no set surface the vehicle is traveling upon. This will inhibit the use of these methods for now.

Once the ambiguities have been estimated in the batch process, a final estimation scheme is done using the carrier-phase measurements. With the ambiguities already estimated the carrier-phase measurements are treated much like the code measurements and a simple least squares algorithm can be used to calculate the position at each time epoch. It is now almost possible to compare the pseudolite based trajectory with the DGPS reference trajectory. The last missing step required is to align the two different trajectories in time. The pseudolite network time is synchronized among the transmitters, but is not aligned with GPS time. This process will be described along with the results of the flight test.

TEST RESULTS

This section will highlight a portion of the UAV flight. First, a short discussion will show how the GPS and pseudolite trajectories are aligned in time. Then, the comparison and results of the flight will be presented.

To accurately compare the GPS and pseudolite trajectories they must be properly aligned in time. Since the pseudolite time is the most arbitrary it will be shifted to match GPS time. A method to get an initial estimate of the offset is to simply plot the trajectories together. Figure 6 shows such a plot, with the GPS trajectory in green and the pseudolite trajectory in red. A simple bias is added to the pseudolite time vector until it closely matches the GPS track.

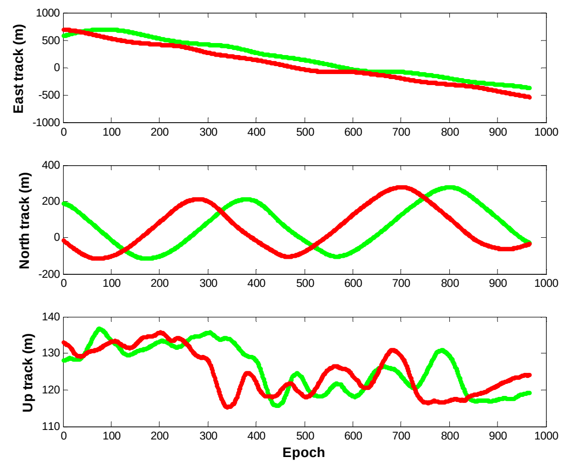

Figure 6: *GPS and pseudolite trajectory components showing a misalignment of roughly 10 seconds.*

Once a coarse time alignment has been accomplished, finer adjustments can be calculated in another ad-hoc method. Plotting the receiver velocity against the error will illustrate time shifts. If there is a time difference between the trajectories there will be a larger error when the receiver is traveling faster. Below in Figure 7 a small time misalignment of a tenth of a second is present. The diagonal skew shows how the error is predominately related in a linear fashion to the speed of the receiver.

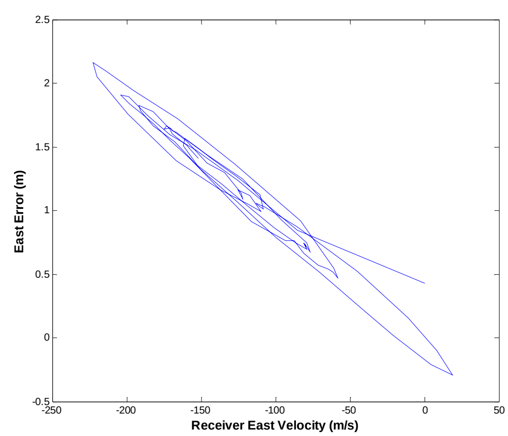

Figure 7: *Velocity vs. Error plot showing a misalignment of 0.10 seconds.*

Once the times have been aligned the error is no longer correlated strongly with the velocity. Figure 8 shows the same flight trajectory as seen in Figure 7, but the time has been properly aligned.

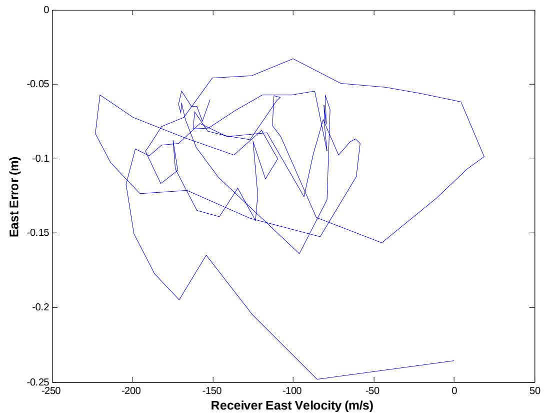

Figure 8: *Velocity vs. Error plot with proper time alignment.*

In both cases the East error and East velocity are used since the most motion is along the East axis. This method is definitely ad-hoc and requires time consuming analysis to perform. It is important to note that in the future the master Locatalite time will be force to align with GPS and thus the slave devices will also be aligned with GPS, making this misalignment correction unnecessary.

With the trajectories aligned in time it is now possible to accurately compare the two. The trajectory that is being presented is a short, two minute track, which maintains an altitude of roughly 100 meters and travels west. This trajectory was chosen, because it was devoid of many test problems that arose during other portions of the overall test. A plot of the trajectory on the horizontal plane is shown below. The locations of the transmitters are included.

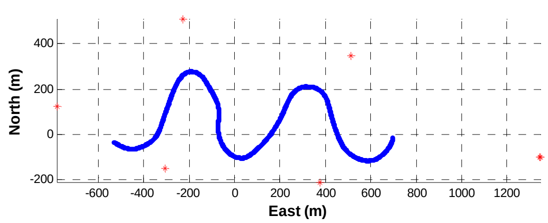

Figure 9: *Horizontal plot of the flight trajectory.*

The position component errors and the 3D position errors are shown in Figures 10 and 11, respectively. The first thing that is noticed is the magnitude of the error. It is much larger than what is expected and desired, since the ground testing has previously achieved better than 9 cm agreement with DGPS. The bottom plot in Figure 10 shows that the vertical error is larger than the horizontal errors. It might initially be decided that the vertical observability is still a problem. Comparing the trends seen in the position component errors with the dilution-of-precision (DOP) plots will show if this is true. Figure 12 shows the east, north, and vertical components of DOP.

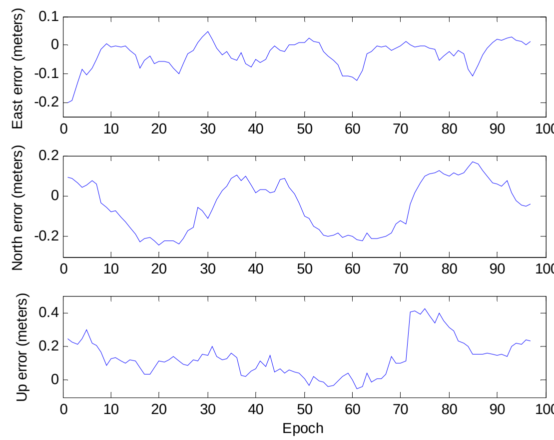

Figure 10: *Position component errors*

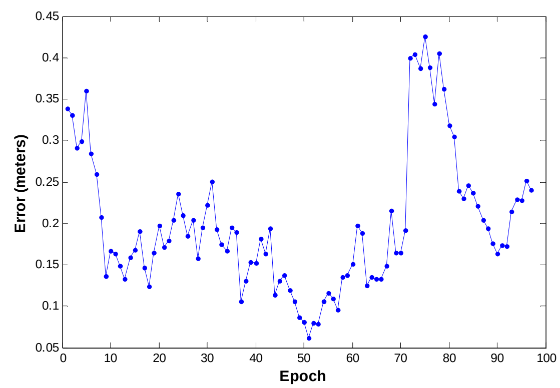

Figure 11: *3D position error.*

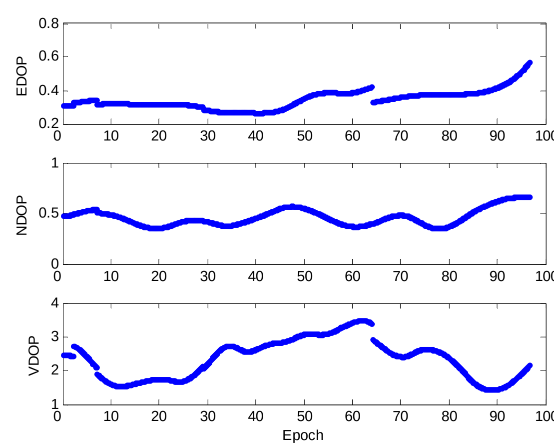

Figure 12: *Dilution of Precision plots.*

Comparing the shape of the DOP plots with the shape of the position component error plots does not show much similarity. This contradicts the assumption that the errors seen are geometry based. Several other factors can be contributing to the increased level of errors in these results.

During these flight tests there was no way to measure the attitude of the aircraft. With no knowledge of the attitude only an approximation of the vertical offset between the GPS antenna and the pseudolite antenna can be corrected. The actual lever arm cannot be rigorously corrected until some measure of the attitude is made. The magnitude of the lever arm is on the order of roughly 30 cm. Since, most of the lever arm is in the vertical direction, and this flight is relatively level, this can only account for at most 5 – 7 cm of difference.

The most likely cause of this magnitude of error is faulty cycle slip detection. During the estimation process, cycle slips must be accurately detected so ambiguity states can be properly associated with the measurements and estimated. When a cycle slip occurs, the associated ambiguity is invalid and a new ambiguity is estimated for the remaining epochs. If a cycle slip is not detected, it will improperly be associated with measurements. Since the ambiguities and measurements are all related, a single error will cause errors in all the ambiguity estimates, and will cause large errors in the final solution.

Cycle slips in GPS measurements are usually very easy to identify and are many times can be seen as large discontinuities in the raw phase measurements. Unfortunately, the behavior is different when working with the set of pseudolites under test. The phase measurements have been observed to slip instead of jump. This makes it very difficult to determine a cycle slip from vehicle motion in the raw phase measurements.

A method for determining if such errors are occurring in cycle slip detection is to generate simulated, single difference measurements from the reference trajectory and difference them with the actual single differenced measurements. In this paper, this type of analysis will generate what will be called *true measurement residuals*. This differencing effectively removes the effects of the vehicle geometry. If the cycle slips have been handled properly, the true measurement residuals should be on the order of a cycle or less.

Looking at the true measurement residuals for this test trajectory shows the probable cause of the large solution errors. Figures 13, 14, and 15 are samples of several true measurement residual plots from this test trajectory. All of the true measurement residuals are like these examples and have a range of several tens of cycles. It is apparent that there are several places that cycle slips are not being correctly identified.

Detecting these in a more rigorous fashion will be investigated in future tests. For now there is nothing that can be done other than to arbitrarily declare cycle slips at various locations to try and improve the solution accuracy. This is a tedious method and will not be entertained in this paper.

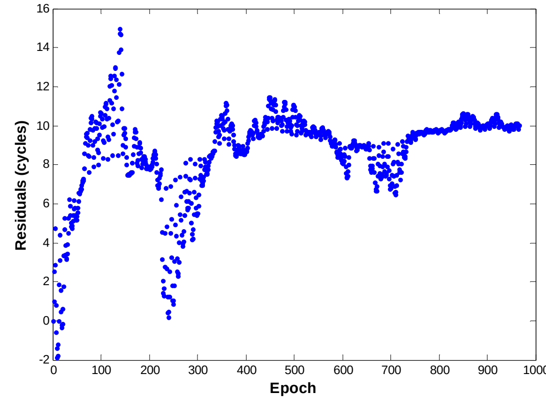

Figure 13: *True measurement residuals for PRN 1 - 3*

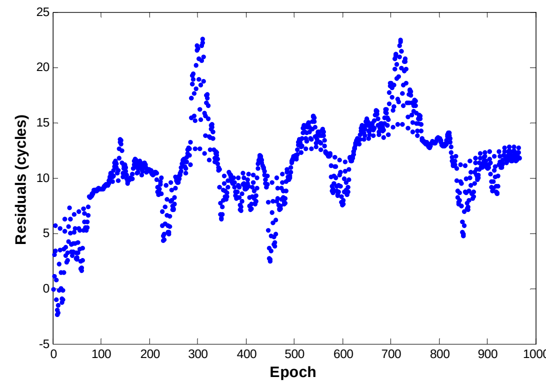

Figure 14: *True measurement residuals for PRN 1 - 10*

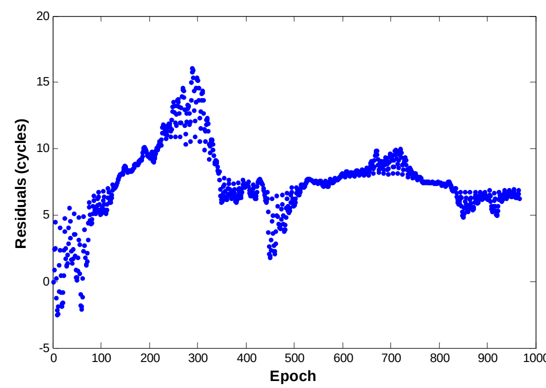

Figure 15: *True measurement residuals for PRN 1 - 12*

TESTING ISSUES

A large part of any initial testing is identifying the pitfalls to be overcome in future work. This test was a definite success in finding some of these preliminary issues.

An example already discussed is the measuring of the UAV flight data. The attitude data could prove vital in attaining the desired level of accuracy. Additionally, having a simple barometer would allow the solution to be constrained to the barometric height during a landing scenario.

One of the reasons that only a portion of the flight data could be analyzed in this paper was the poor transmission and reception of the differential corrections. Many epochs had to be thrown out due to a lack of sufficient GPS accuracy. The best solution that can be obtained with the current system is a narrow integer solution. With inconsistent reception of the differential corrections, the GPS solution would drop into a less accurate solution mode. One could record measurements at the GPS base station and transmit the UAV's GPS measurements to the ground for recording. This would allow a differential solution to be calculated in a post process manner. Unfortunately, the data modem was sporadic in both transmission and reception, and didn't allow the UAV's measurements to be recorded for many epochs.

A draw back of flying an RC plane to simulate the use of the pseudolite network is that the maneuverability between a real sized aircraft and a small RC plane is vastly different. Many times a quick stunt to set up a new test run could very well cause a loss of GPS and pseudolite tracking. These problems would not arise in the same manner during normal operation as a flight test reference system with normal sized aircraft. The planes would not be able to make the same maneuvers that are easily done in an RC plane. For the initial testing some of the trajectories were somewhat farfetched. For example, a knife edge flight or continuous barrel roll would not be a normal test condition. If a test required more aggressive maneuvers, a specific test setup may be needed to make sure the receiver can track enough pseudolites for an accurate position solution.

More robust mounting can be used to attach the pseudolite antennas to the towers. Some error can be attributed to poor surveying of the pseudolite locations, but without rigid mounting and an assurance that the transmitter antennas are directly underneath the survey point, ultra-precise surveying is a largely wasted effort.

Finally, there were many interference issues when operating so many transmitters and power sources in close proximity. Interference seemed to occur mostly when the UAV was close to the runway, which is dangerous for takeoff and landing. In several cases the RC control became sluggish and unresponsive due to interference. Moving the 75 MHz antenna to the outside of the aircraft body did help, but elimination of unneeded transmissions would be key in cutting down on clutter in the plane and interference outside the plane.

FUTURE TESTING

Future testing looks extremely promising. New methods of cycle slip detection and solution processing with these pseudolites is developing, which will bring the solution accuracy to its desired level.

To address the problems with the data modem, future UAV's will carry a GumStix mini processor which will act as an onboard datalogger. With this setup, the DGPS trajectory will be calculated after testing has occurred. This will completely eliminate the need for the data modem and will also allow for a faster measurement rate. Without the data modem there will not only be less clutter in the plane but less interference as well.

Future UAV's will also carry air data sensors to help estimate the aircraft's attitude and barometric height. This information can be used to correctly account for the lever arm between antennas, and the height can be used as a constraint to the solution. Future work will investigate the possibility of using the barometric height in conjunction with the knowledge of the surface topography to make it feasible to use the ground based methods of height constraint that have been developed at the ANT center.

A major test that will be conducted in the future will be creating an orbiting pseudolite scenario. Many technical hurdles must be overcome to accomplish this task, but it may be the best solution to achieving the desired geometry and level of accuracy.

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DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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