



NTNU – Trondheim
Norwegian University of
Science and Technology

POSITION CONTROL FOR AUTOMATIC LANDING OF UAV IN A NET ON SHIP

Kjetil Hope Sørbø

Submission date: December 2015
Responsible professor: Thor Inge Fossen, Tor Arne Johansen

Norwegian University of Science and Technology
Department of Engineering Cybernetics

Abstract

Automatic landing of a fixed wing Unmanned Aerial Vehicle (UAV) in a net on a ship require a accurate positioning system. To increase availability the system must consist of low-cost components, which exclude the commercial landing system that exist today. Real Time Kinematic GPS (RTK-GPS) can provide centimeter level accuracy with the use of low-cost Global Navigation Satellite System (GNSS) receivers. The accuracy will be reduced in a highly dynamical system like a Unmanned Aerial Vehicle (UAV) due to the processing delay.

This work present software and hardware systems that is used in a navigation system that apply Real Time Kinematic GPS (RTK-GPS). Two different system will be compared against each other, as well as there individual performance. The RTK-GPS system is using single-frequency Global Navigation Satellite System (GNSS) receivers, the Piksi system from Swift Navigation and the open-source Real-Time Kinematic Library (RTKLIB). The RTK-GPS system is implemented in DUNE(DUNE:Unified Navigation Environment)-framework running on the embedded payload computer on-board the UAV. Outdoor lab tests and a flight test was used to check the performance of the navigation system. What is presented in this work:

Keywords: test,teste

Contents

List of Figures	vii
List of Tables	ix
Acronyms	xiii
1 Introduction	1
1.1 Background and motivation	1
1.2 Literature Review	2
1.3 Scope of work	3
1.4 Layout	4
2 Real time kinematic GPS	5
2.1 System layout	5
2.2 Reference frames	7
2.2.1 ECI	7
2.2.2 ECEF	7
2.2.3 Local reference frame	8
2.3 GPS	9
2.3.1 GNSS constellations	9
2.3.2 GPS attributes	9
2.4 Error sources	10
2.4.1 Clock error	10
2.4.2 Ionospheric and Tropospheric Delays	10
2.4.3 Ephemeris Errors	11
2.4.4 Multipath	11
2.5 Dilution of Precision	11
2.6 Differential GPS	11
2.6.1 Integer Ambiguity Resolution Strategy	12
2.6.2 Cycle slip	12
2.6.3 Error mitigation in DGPS	13
2.6.4 RTK GPS	13

3 System Components and implementation	15
3.1 Hardware	15
3.1.1 UAV	15
3.1.2 Embedded Computer	16
3.1.3 GNSS receiver	17
3.1.4 GNSS Antenna	19
3.2 Software	21
3.2.1 LSTS toolchain	21
3.2.2 RTKLIB	22
3.3 Implementation	23
3.3.1 Software implementation	25
3.3.2 Hardware implementation	25
4 Experimental testing	27
4.1 Physical testing	27
4.1.1 Test 1: Test of the RTK-GPS navigation system	27
4.1.2 In-flight test	36
5 Conclusion and recommendation for further work	41
5.1 RTK-GPS lab testing	41
5.2 RTK-GPS in-flight test	42
5.3 Further work	43
References	45
Appendices	
A Rtklib Configuration	47
A.1 str2str	47
A.2 rtkrcv	47

List of Figures

2.1	The structure of the autonomos landing system	6
2.2	The Earth-Centered-Earth Fixed (ECEF) frame. Picture from [I, 2011]	8
2.3	Concept figure of DGPS	12
2.4	The ECEF frame. Picture from http://gpsworld.com/wp-content/uploads/2014/01/I-Fig1.jpg	13
3.1	X8 Skywalker from Skywalker Technologies, Picture from www.campilot.tv/blog/win-x8	16
3.2	BeagleBone Black element 14, Picture from http://www.element14.com	17
3.3	Ublox LEA M8T, Picture from http://www.csgshop.com	18
3.4	Piksi, Picture from www.swiftnav.com	19
3.5	Piksi, Picture from http://sigma.octopart.com/21411362/image/Maxtena-M1227HCT-A-SMA.jpg	20
3.6	Piksi, Picture from http://www.novatel.com/assets/Web-Phase-2-2012/Product-Page-Images/Product-Images-Banner-and-Thumbnail/Antennas/702-L.png	20
3.7	The communication structure of rtklib	22
3.8	Hardware Software	24
3.9	Antenna splitter	26
4.1	A xy plot of the piksi,rtklib real time solution and the rtklib post processed solution	28
4.2	The communication structure of rtklib	29
4.3	The difference between rtklib real time and post processed solution	29
4.4	The communication structure of rtklib	30
4.5	Standard deviation of the difference between rtklib real time and post processed solution	30
4.6	Standard deviation of the difference between piksi real time and rtklib post processed solution	31
4.7	Velocity data from the piksi and rtklib real time solution	31
4.8	Visable statellite for the piksi and rtklib	32

4.9	Visable statellite for the piksi and rtklib	33
4.10	Velocity data from the piksi and rtklib real time solution	33
4.11	Visable statellite for the piksi and rtklib	34
4.12	Visable statellite for the piksi and rtklib	35
4.13	Visable statellite for the piksi and rtklib	35
4.14	Velocity data from the piksi and rtklib real time solution	36
4.15	Velocity data from the piksi and rtklib real time solution	37
4.16	Velocity data from the piksi and rtklib real time solution	37
4.17	Velocity data from the piksi and rtklib real time solution	38
4.18	Velocity data from the piksi and rtklib real time solution	39
4.19	Velocity data from the piksi and rtklib real time solution	39
4.20	Velocity data from the piksi and rtklib real time solution	40
4.21	Velocity data from the piksi and rtklib real time solution	40

List of Tables

3.1	Components in the X8 at the UAVLAB	16
3.2	Rtklib output solution format	24
3.3	The Inter-Module Communication (IMC) message RtkFix	26

Acronyms

DGPS Differential GPS.

DOP Dilution Of Precision.

ECEF Earth-Centered-Earth Fixed.

ECI Earth-Centered-Inertial.

ENU East North Up.

EPO Expanded PolyOlefin.

GLONASS Global Navigation Satellite System.

GNSS Global Navigation Satellite System.

GPS Global Positioning System.

GPST GPS Time.

IMC Inter-Module Communication.

INS Inertial Navigation System.

L1 Link 1.

L2 Link 2.

L5 Link 5.

LAMBDA Least-squares AMBiguity Decorrelation Adjustment.

LSTS Underwater Systems and Technology Laboratory.

NED North East Down.

NTNU Norwegian University of Science and Technology.

RTK-GPS Real Time Kinematic GPS.

RTKLIB Real-Time Kinematic Library.

SHF Super-High Frequency.

SIL Software In the Loop.

TOW Time Of Week.

UAV Unmanned Aerial Vehicle.

UHF Ultra-High Frequency.

UTC Coordinated Universal Time.

WGS-84 World Geodetic System, 1984.

Chapter 1

Introduction

1.1 Background and motivation

In the resent past the development of flying UAVs have seen to provide an attractive alternative to task previously performed by manned alternatives. Typical task which has attracted attention includes inspection, aerial photography, environmental surveillance and search and rescue. Today UAV are mostly operated over land, but in the future this will include the out at sea as well. This will give some challenges that must be overcome. One of these challenges is that the UAV should be able to perform a autonomous landing.

A UAV can provide an attractive alternative for many maritime operation where today only other manned aircraft or satellites are the only solution. In the maritime sector they can be used in iceberg management, monitoring of oil spills, search and rescue and maritime traffic monitoring.

An obvious premise for successfully and safe UAV operation, in particular at sea, is the provision of a robust system for safe landing of the UAV following a complete mission. In order to complete an automatic landing a path planner, guidance system and a accurate position estimation system, in addition to the low level control system in the UAV is required. Such complete system is still subject for development, where only method for achieving the different objectives has been developed, i.e. path planner and guidance system respectively. The path planer and guidance system as basis for this work was developed as previous master thesis work in the UAVLAB by [Marcus, 2015]. The gudiance system is currently under further development in two project thesis. A key component in the guidance system is the position estimation system, which for the guidance referenced was developed by [Amstrup, 2015]. However, this system has been concluded to be in-sufficient with respect to provide means required for automatic landing.

2 1. INTRODUCTION

There exist landing system that can guide the UAV towards a net, but they are expensive and restricted to a few UAVs. A pilot could always land the UAV, but it would be better if the UAV could hit the net by it self. In order to make the UAV able to perform a automatic landing the minimum requirement is that it know where it is at all time. This require a accurate position estimation in real time. A highly accurate position sensor is typically expensive, however it's possible to achieve a accurate solution with low cost sensors. By combining two GNSS receivers it's possible to estimate the relative position of one of the receivers in respect of the other receiver highly accurately. This work will test a new generation of GNSS receiver, and use Global Positioning System (GPS) to find the relative position of the UAV. The demand on the accuracy is that the error must be in decimetres to ensure safe landing in the net.

This work will continue the research done by Spockeli, and introduce a new GNSS receiver that will be used with the open source program, rtklib. The motivation is to have a system with accurate local position estimate, such that in the future a landing can be performed automatic.

The automatic landing system will use RTK-GPS for position estimation. The main motivation for this work is to describe the gaps of the available position system sufficient to scope further work required for closure of such gaps ultimately providing means for position estimating sufficient for completion of automatic landing.

1.2 Literature Review

Automatic landing in a net has privously been successful performed in the NTNU MSc thesis [Robert and Lie, 2014]. They managed to land a UAV in a stationary net using RTK-GPS. Unfortunately a different hardware and software setup at the Uavlab has made the code they used obsolete.

Further research on the automatic landing system at the UAVLAB at NTNU was done in the MSc thesis by [Amstrup, 2015] and [Marcus, 2015]. In the MSc thesis by Spockeli he studied a integrated RTK-GPS/Inertial Navigation System (INS) navigation system with a nonlinear observer. In the MSc thesis by Froelich he create a control and guidance system that in simulation has successfully managed to follow a landing trajectory. He also created a dynamical path generation system that allows the net to move, and re-plan the landing path. The control and guidance system created by Froelich has yet to be integrated with the work done by Spockeli. Froelich never did a physical test of the landing system, and the position estimate used in the system is not based on Real Time Kinematic GPS (RTK-GPS) at this this.

A other successful automatic landing was done in the Stellenbosch University

MSc thesis [Adriaan, 2013] using Differential GPS (DGPS). The MSc thesis give a good descibetion on the control system required to perform a automatic landing, however the system in the thesis require a runway in order to land.

An other low-cost position system that can be used for automatic landing that is vision based landing system. In the paper [Jin et al., 2013] it was proposed a vision based landing system, that would detect the recovery net, and plan a landing path. The system was successfully tested and is a valid alternative for a low-cost autonomous landing system. An other vision based landing system was proposed in [Paul and Michael, 2012]. The paper describe a intelligent vision aided landing system that can detect and generate landing waypoints for a unsurveyed airfield. The drawback with a vision based landing system is that it require much computational power, in addition to the visual line of sight can quickly decrease during a operation.

Real Time Kinematic GPS (RTK-GPS) apply phase measurement of the GNSS signal for position estimation. In order to get a accurate position estimate the integer ambiguity. An integer ambiguity resolution strategy was proposed in [Geoffrey, 1989], and demonstrated centimeter level accuracy for a baseline up to 2000km. Further studies on integer ambiguity resolution strategies resolved in the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) strategy, which was proposed in [P.J.G., 1994], and further disused in [P.J.G., 1995, Teunissen P.J.G and C.C.J.M., 1995]. The Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) has been wildly used, and has proven a quick strategy to resolve the integer ambiguity, which makes it ideal for RTK-GPS systems.

The use of RTK-GPS for accurate position estimation has been studied in [W., 2013]. The paper proposed how to create a low-cost RTK-GPS system that can accurate measure the position in 3D. They used raw GNSS data from the GNSS receiver and the program library Real-Time Kinematic Library (RTKLIB) to estimate the position of a trolley in real time.

In the paper [W. and M., 2011] it was studied high precision positioning of micro-sized UAV using RTK-GPS. The system used a GNSS receiver that used a ground based augmentation system as a base station. The use of a ground based augmentation system us advantageous if the UAV can communicate with the ground station. For UAV operations where information from a ground based augmentation system is not available a local reference station must be considered.

1.3 Scope of work

The scope of work is to validate the performance of suitable positioning systems by study and testing, and to identify gaps required to be closed for successful

4 1. INTRODUCTION

implementation for a integrated autonomous Guidance, Navigation and Control system which will allow for automatic landing of a UAV at sea. This will include: The

Testing of the performance of Ublox LEA M8T

Compare the performance of Real-Time Kinematic Library (RTKLIB) and Piksi

Compare the real time estimate with the post processed estimate

scope of this work is to test the performance of ublox-LEA M8T GNSS receiver in a real time differential Differential GPS (DGPS) configuration. The RTK-GPS solution will be calculated with the open source program rtklib, which will communicate with a task in DUNE. The solution from rtklib will be compared against the solution from Piksi, and a post processed solution from rtklib. The result from the experiment will be used in the discussion on how to perform a automatic landing.

1.4 Layout

This section is currently not up to date

Chapter 1 Intro

Chapter 2 Theory about coordinate system

Chapter 3 Theory about GNSS system with focus on the GPS

Chapter 4 Hardware and software

Chapter 5 Test and result

Chapter 6 Conclusion, discussion and further work

Chapter 2

Real time kinematic GPS

This chapter will explain Real Time Kinematic GPS (RTK-GPS), as well as how it's used in the automatic landing system. The first section will include a overview of the system, including the state of the current system. The next part will contain different reference frame used in the RTK-GPS module. Then the different Global Navigation Satellite System (GNSS) system will be presented as well as attributes in the Global Positioning System (GPS). Then a quick overview over the different error sources that can affect a GNSS system, before the concept Differential GPS (DGPS) is presented. Lastly the term RTK-GPS will be explained.

In the following the behaviour of a receiver is denoted using terms rover and base station. The term base station means a receiver assumed to have a known position by the other receivers. The term rover means a receiver that is allowed to move, is the main focus for position estimation.

2.1 System layout

An integrated system required for automatic landing will typically consist of four main sub-systems as shown in figure 2.1. Today these systems are individually available or in development; however not integrated into a proven working system allowing for automatic landing of UAVs. The four main systems comprises of the navigation part, guidance part, control part and the user interface, where further validation and development of the first is the main topic for this work.

6 2. REAL TIME KINEMATIC GPS

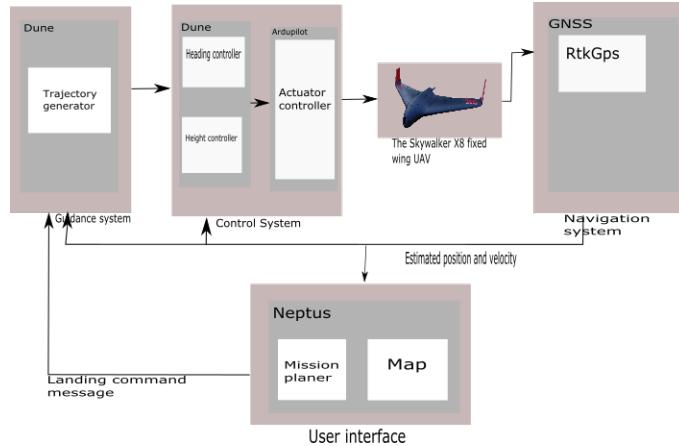


Figure 2.1: The structure of the autonomos landing system

The navigation system will apply RTK-GPS to estimate the relative position of the UAV. More details about what RTK-GPS is, will be given in 2.6.4.

The control and guidance system has currently only been tested in Software In the Loop (SIL) simulations with Ardupilot, which shows promising result likely to be sufficient for automatic landing applications. However this module has not yet been implemented to support the use of RTK-GPS as required for performing automatic landing.

This work will identify and describe the navigation system necessary to allow for automatic landing of UAVs. The RTK-GPS solution will be compute by two different system ,which will be compared against each other. The first system is called Piksi, and is developed by Swift navigation. The second system will is called Rtklib, and is developed by T. Takasu. The latter is indepente on the type of receiver, and thus will be the main focus of this work. More detail about Piksi and Rtklib will be given in 3.1.3 and 3.2.2.

The comparison test will be used to summarize further work required for complete identification of gaps and work required for closure of these gaps such that a control system including provision for automatic landing may be developed and implemented in a integrated UAV control system. The UAV that will be used in the test is a Skywalker X8 Fixed Wing UAV. More details about the X8 will be given in 3.1.1

This work will identify and describe the gaps which will need to be closed on order to develop and implement a solution which will allow for automatic landing of UAVs. Two different system that will be compared against each other. The current state of

the system is that it consist of two parts that has not yet been integrated with each other. The part were which is the main focus of this thesis is the positioning part. The plan is to use RTK-GPS for positioning estimation. The second part is the path and control path. Currently there has only been done simulation of the guidance system. It shows promising results, but is yet to be integrated with RTK-GPS. For more information on the subject please read the MSc thesis by [Marcus, 2015]. Figure 2.1 gives a overview on how the system may look like. Ideas on how the intergration can be acheived will be given in the future work section.

2.2 Reference frames

A GNSS system calculate a position estimated of where on the Earth the receiver is. For the position to have any meaning a reference system has to be defined where a frame can be consider as an inertial frame. From there a reference frame can be fixed to the Earth rotation, but for local navigation if must be referred to surface of the Earth. This section will present the different reference frame used in global navigation systems.

2.2.1 ECI

Earth-Centered-Inertial (ECI) frame is considered a inertial frame for terrestrial navigation. The origin is fixed in the center of the Earth, and the axis is fixed in space. This frame can be considered as a non-accelerating where Newton's laws of motion applies.

2.2.2 ECEF

The ECEF coordinate system is defined in the center of the Earth with it's x-axis point toward the intersection between the Greenwich meridian and Equator (0 deg longitude, 0 deg latitude). The z-axis points along the Earth's rotational axis, and the y-axis complete the right handed orthogonal coordinate system. The ECEF system can be represented in either Cartesian coordinates (xyz) or ellipsoidal coordinates (longitude, latitude and height). The ECEF frame rotate relative to the ECI frame at a angular rate of $\omega_e = 7.2921 \times 10^{-5} rad/s$, where ω_e is the Earth rotation. Due to the relatively low rotation speed some system can consider the ECEF frame as inertial.

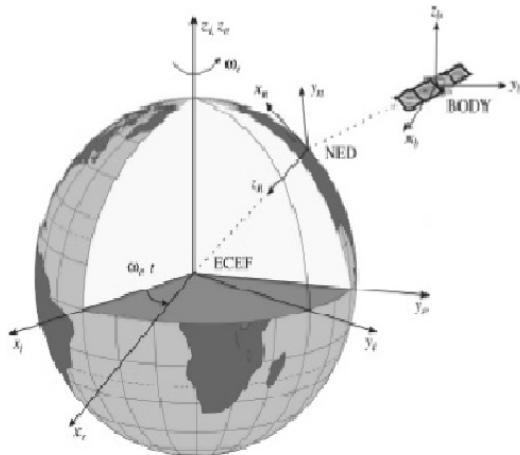


Figure 2.2: The ECEF frame. Picture from [I, 2011]

2.2.3 Local reference frame

The North East Down (NED) and East North Up (ENU) frame is defined as relative to the Earth reference ellipsoid (World Geodetic System, 1984 (WGS-84)). For the NED frame the x axis points in the direction to the true North, y axis towards East while the z axis points downward to completed the right handed orthogonal coordinate system. The ENU has the x and y axis exchange place in respect of the NED frame, and the z axis point upwards instead of downwards.

2.3 GPS

A quick overview of the gps and other gnss systems.

2.3.1 GNSS constellations

There are currently two operation GNSS constellations with global coverage, which is American GPS and Russian Global Navigation Satellite System (GLONASS). Other GNSS constellations that will be operational in the near future is the Chinese BeiDou and European Galileo.

2.3.2 GPS attributes

The GPS satellites transmits continuously using two radio frequencies in the L-band referred to as Link 1 (L1) and l2. The L-band covers frequencies between 1 GHz and 2GHz, and is a subset of the Ultra-High Frequency (UHF) band.

Previously only the L1 signal was intended from civil users, but in the future a new l2 signal as well as the Link 5 (L5) signal will be available for civil users.

GPS uses it's time reference called GPS Time (GPST), which is independent from the Coordinated Universal Time (UTC). Because of this independent the UTC diverge away from the GPST, and to correct this the GPS keeps track of the offset between GPST and UTC. The offset is included in the GPS message as leap seconds to be added to the GPST. GPST can be given as Time Of Week (TOW), which include the number of weeks since 1980-01-06T00:00Z. TOW is given in seconds, and is reset each week when the week number is incremented. More information about the GPS can be found in [Bjørnar, 2014, Pratap and Per, 2011]

The two basic ways to measure the psedurange is code and phase measurement. Phase measurement is the most accurate of the two, but also least reliable. In code measurement the information in signal is used to calculate the psudorange between the receiver and the satellite. In phase measurement the receiver measures the phase of the GNSS satellite and compares it against a receiver generated signal. Then by knowing the phase and the frequency function, as well at the start and end epoch time the geometric range between the receiver and satellite can be estimated. It's phase measurement that is used in RTK-GPS. In phase measurement it's advantgus to know the unknown number of cycles between the satellite and the receiver, referred to as integer ambiguity. Estimation of integer ambiguity is called integer ambiguity resolution and will be more explained in 2.6.1.

The receiver needs at least four satellite to be able to estimate the receiver position. Three of the satellite is used for the position, and the fourth if used to

calculate the receiver clock bias. The position is calculated in the ECEF reference frame.

2.4 Error sources

In order to get high accuracy in the position estimation the different error sources must be identified and removed if possible. This section will identify some of the larger error sources that can affect the GPS signal, and how to remove or mitigate them in the estimation.

2.4.1 Clock error

There is drift in both the satellite clock and the receiver clock. The atomic in the satellites makes the clock drift negligible from the user perspective. The receiver clock tend to drift, and if not taken into account will cause large deviations in the position estimate from the true position. This error is remove by including a fourth satellite in the position computation. The satellite clock error given in the satellite message.

2.4.2 Ionospheric and Tropospheric Delays

When the GPS signals travel though the atmosphere there will be a delay caused by the different layers, as further explained in this section.

Ionospheric delay

Gas molecules in the ionosphere becomes ionized by the ultraviolet rays that is emitted by the sun, which release free electrons. These electron can influence electromagnetic wave propagation, such as GNSS signals. The delay that the single get from the ionosphere may cause a error the the order of $1 - 10\text{ meters}$. The error can be mitigated by using a double frequency receiver, or by applying a mathematical model to estimate the delay. Both those cases is with a single receiver, but by having a second receiver the GNSS solution system can assume that both receiver receive signal in the same epoch, which means that the signals have experienced the same delay. More on this in section 2.6.3.

Tropospheric delay

The tropospheric delay is a function of the local temperature, pressure and relative humidity. The delay can vary from 2.4meters to 25 meters depending on the elevation angle of the satellites. The error can be mitigated by applying a mathematical model to estimate the tropospheric delay, and by using a elevation mask can remove all satellites with a elevation angle bellow a certain threshold. Error caused by

tropospheric delay can be removed in the same manners as ionospheric delay when using two or more receivers. More on this in section 2.6.3.

2.4.3 Ephemeris Errors

A satellite isn't able to perfectly follow a given orbit, and therefore there will be a deviation between satellite position given to the receiver and the true position of the satellite. This is called the ephemeris error. The true position of a satellite is monitored and corrected by the owner of the GNSS constellation, but error between each correction can be expected.

2.4.4 Multipath

One of the primary source of error in in a GNSS receiver is multipath. Multipath happens when the satellite signal is reflected by a nearby surface before if reach the antenna. The delay introduced in the signal can make the receiver believe that its position is several meters away form its true position. The easiest way to mitigated multipath is to place the antenna at a location with open skies, and not tall structures nearby.

2.5 Dilution of Precision

The geometry of the GNSS constellation affect the accuracy of the position solution. Pore geometry will also enhance the effect that different error sources has on the position solution.

2.6 Differential GPS

Differential GPS consist of at least two receivers, where one is called a base station and the rest rovers. The two receivers are within range of a communication channel over which they are communicating. Figure 2.3 gives an example on DGPS. The base station has a known position, and the rover estimate the baseline from itself to the base station.

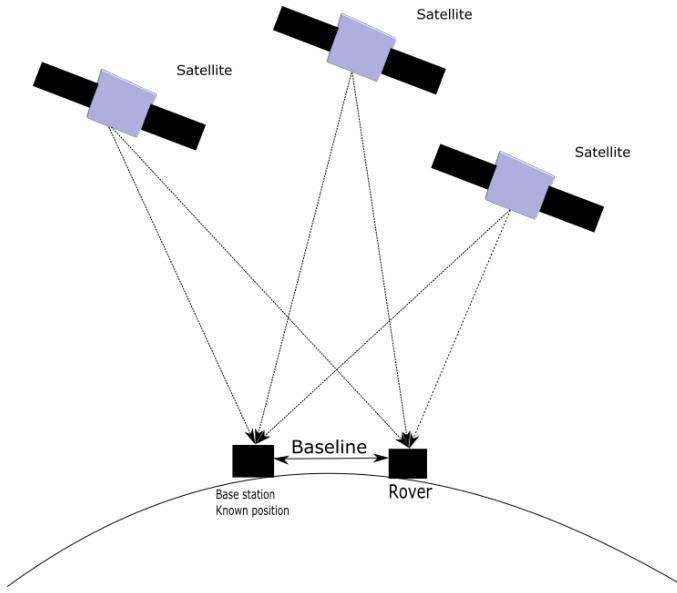


Figure 2.3: Concept figure of DGPS

2.6.1 Integer Ambiguity Resolution Strategy

The problem with precise relative positioning with phase measurement is problem of estimation of integer ambiguities.

There are several strategies on how to resolve the integer ambiguity. A well used strategy is the LAMBDA method. LAMBDA starts by reducing the integer search space by decorrelation adjustment. The LAMBDA method has two types of outputs. One is called the fixed solution, and the other is called the float solution. The float solution is the first solution given by the LAMBDA method and is used to find the fixed solution. When the right fixed solution is reached the position estimation from a DGPS can be considered highly accurate. The solution program can calculate the wrong fixed solution, or experience a cycle slip (2.4). In order to reduce the possibility of letting a wrong solution become the fixed solution the program need a good integer ambiguity validation strategy. One validation strategy is to check if the ratio between the best ambiguity estimate and the second best estimate is greater than a certain threshold. High Dilution Of Precision (DOP) will effect the time the LAMBDA method needs to find a fixed solution.

2.6.2 Cycle slip

When the integer number of cycles experience a sudden jump in value due to loss of lock of a receiver phase lock it's called cycle slip. The effect of cycle slip is a bias in

the measurement large enough to make navigation difficult. The effect of cycle slip will appear as seen in figure 2.4.

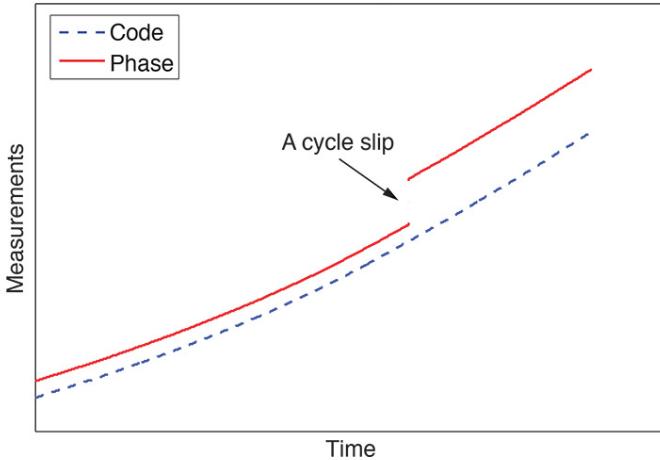


Figure 2.4: The ECEF frame. Picture from <http://gpsworld.com/wp-content/uploads/2014/01/I-Fig1.jpg>

2.6.3 Error mitigation in DGPS

The advantage with DGPS is that two or more receivers can share the same error sources. This enable the solution system almost completely remove them. In the case of a moving baseline situation the GNSS system assumes that the rover is close enough to the base station such that they share the same atmospheric conditions. If this assumption holds the system should be able to almost remove the error caused by atmospheric delay.

2.6.4 RTK GPS

RTK-GPS provide accurate baseline position estimation in real time. Can either have a kinematic setting or a moving baseline setting. The difference between the two is that in kinematic the base station has a known stationary position, while in moving baseline the base station position is unknown and allowed to move. The advantage with the moving baseline configuration is that RTK-GPS can be used to find the relative position between two dynamical system using GNSS in real time. This will be the case in automatic ship landing system, where the base station must be allowed to move. Also to determine the exact position of a base station require a long measurement period. The advantage with kinematic mode is that it can give a more accurate position estimate.

14 2. REAL TIME KINEMATIC GPS

RTK-GPS systems needs to calculate the position estimate quicker then a standard system. This is done by sacrificing the correctness of the solution, however in the resent time efficient software and hardware has reduced the this factor.

In a RTK-GPS set-up the rover assumes that it's receive the GNSS signals at the same time as the base station, and thus the two receivers receive the same signal without it having been altered any more disturbance, except local disturbance like multipath. This puts a restriction on the the range of the baseline. The assumption that the two receiver share the same disturbance is valid for a baseline up to $2km$. The relative position of the rover can be given in either the NED or enu frame.

Chapter 3

System Components and implementation

This chapter will present the different software and hardware components used in this work, in addition to how they are implemented and connected to each other. The two first sections in this chapter will present the hardware and software components respectfully. This is followed by a overview over the components in the UAV and base station that is used to create the RTK-GPS system. The two last chapters will explain how the software and hardware implementation respectfully.

3.1 Hardware

The different hardware used in this work is a UAV, payload computer, GNSS receiver and antenna.

3.1.1 UAV

The Skywalker X8, see 3.1, is a fixed wing UAV that is moulded out of Expanded PolyOlefin (EPO), which makes it a cheap and robust platform for prototype testing. The large space within the fuselage makes it ideal for experimental payload and projects with modest requirements.



Figure 3.1: X8 Skywalker from Skywalker Technologies, Picture from www.campilot.tv/blog/win-x8

The X8 has a wingspan of 2120mm which allow for a Maximum Take-Off Weight of 4.2kg, including 1kg for the payload. The X8 used in this work is outfitted in according to the specification given in [Zolich A. P. and K., 2015]. The components that is used in the X8 at the UAVLAB is given in table 3.1.

Sensors	3DR ublox GPS with Compass Kit Pixhawk Airspeed Sensor Kit
Servo	Hitec HS-5125MG
Motor	Hacker A40
ECU	Jeti Master Spin 66 Pro
Main Battery	1 Zippy Compact 4S 5000 mAh
Autopilot	3DR Pixhawk
Primary digital data link	Ubiquiti Rocket M5

Table 3.1: Components in the X8 at the UAVLAB

3.1.2 Embedded Computer

The embedded computer chosen as payload in the X8 is a Beaglebone Black, shown in figure 3.2. The Beaglebone was chosen because of its sufficient computation power, low energy consumption and variety of communication interfaces. For ease interface access the the Uavlab at NTNU has developed an extension board called "CAPE".

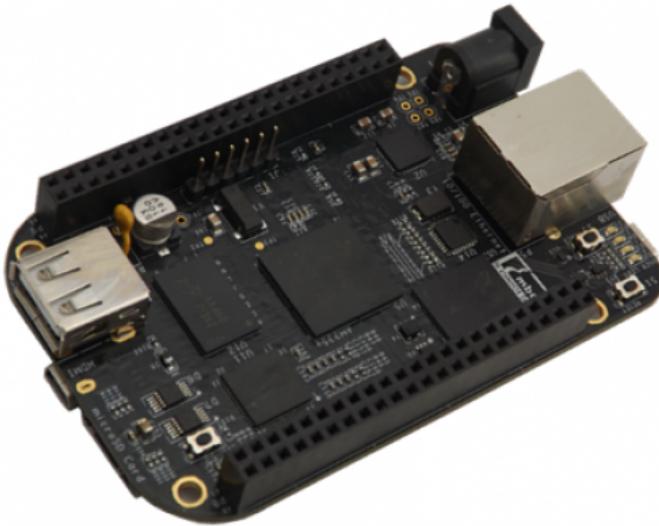


Figure 3.2: BeagleBone Black element 14, Picture from <http://www.element14.com>

The Beaglebone black supports linux operation systems, and is compatiable with the Underwater Systems and Technology Laboratory (LSTS) toolchain, which will be return to in 3.2.

3.1.3 GNSS receiver

The system will use two types of GNSS receivers, namely the Ublox LEA M8T and the Piksi system.

Ublox LEA M8T

The Ublox LEA M8T is a new generation of low-cost GNSS receiver from ublox. The receiver support sending out raw GNSS data from both GPS and GLONASS in the same configuration. The receiver have great performance in acquisition and tracking sensitivity of GNSS satellites. More technical detail can be found in [Ubl, a,b]. Write about the Ublox LEA M8T gnss receiver. Also include that it support sending GPS and GLONASS data at the same time. Need to be configured. A receiver were prepare and mounted in the x8.



Figure 3.3: Ublox LEA M8T, Picture from <http://www.csgshop.com>

Piksi

Piksi, see figure 3.4, is a low cost, high performance GPS receiver with RTK-GPS functionality with capability for centimeter level relative positioning accuracy developed by Swift Navigation. Piksi is ideal for autonomous vehicles because of its small form factor, fast position solution update rate and low power consumption. More detailed information about Piksi can be found in [Pik]

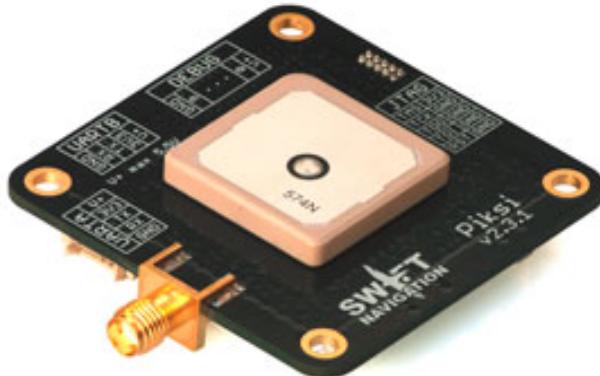


Figure 3.4: Piksi, Picture from www.swiftnav.com

3.1.4 GNSS Antenna

The navigation system will use two GNSS antenna, one for the UAV and the other for the base station. The main criteria for the UAV antenna is that it's small, compact and have a light weight.

The M1227HTC-A-SMA, seen in figure 3.5 has been used in other UAV setups at the UAVLAB with good results. The antenna is small, compact and with a light weight of 17g. It's design for L1/L2 gps/glonass bands. Further information or specification can be found in [max]

The base station do not have any restriction on size, weight or aerodynamic. The important factor for a base station antenna is that it has good multipath rejection. Also the base station position should be calculated as accurate as possible which impose further restriction on interference handling, phase center stability and noise rejection.

The Novatel GPS-701-GG, seen i figure 3.6, was chosen as the base station antenna. The antenna has excellent multipath rejection whit a highly stable phase center. It has reception for both GPS and GLONASS L1 signals..Further information or specification can be found in [nov].



Figure 3.5: Piksi, Picture from <http://sigma.octopart.com/21411362/image/Maxtena-M1227HCT-A-SMA.jpg>



Figure 3.6: Piksi, Picture from <http://www.novatel.com/assets/Web-Phase-2-2012/Product-Page-Images/Product-Images-Banner-and-Thumbnail/Antennas/702-L.png>

3.2 Software

This section contain the different software that is used in the x8 system. The following sections contain the operating system that runs on the base station and rover, the middleware used to connect the different tasks, the messages protocol, the missionplaner program and rtklib which will have the main focus.

3.2.1 LSTS toolchain

The Underwater Systems and Technology Laboratory (LSTS) toolchain is a flexible, scalable, open-source software that supports integration and control of various types of unmanned vehicles [Pinto et al., 2013]. The toolchain includes a operating system, runtime environment, message protocol and a command and control for operations. The following program is included in the toolchain

GLUED

Glued is a minimal Linux distribution, and design with embedded system in mind. It is platform independent, easy to configure and contain only the necessary packages to run on a embedded system. This makes GLUED a light and fast distribution. GLUED is configured through a single configuration file that which can be created for a specific system.

Dune

Dune (DUNE Uniform Navigation Environment) is a runtime environment for un-manned systems. DUNE is operating system independent and can run on-board the embedded computer. It can interact with the sensors, actuators and payload. It can also be used for tasks like communication, navigation, control, manoeuvring, plan execution and supervision.

Dune works by setting up individual task that can dispatch and subscribe to different IMC messages. The IMC messages will be explained in 3.2.1.

IMC

The Inter-Module Communication (IMC) protocol is build to interconnect systems of vehicles,sensors and human operators. The protocol is a messages-oriented protocol that enable exchange of real-time information about the environment and updated objectives, such that the participant in the communication can pursue a common goal cooperatively. IMC has a standard way of dispatching and consuming messages, which abstracts hardware configuration from the software.

Neptus

Neptus is an open source command and control software that can be used for a single or fleet of unmanned vehicles with different types of sensors. The operator can observe real time data from a vehicle, review previous missions and plan future mission. In this work Neptus has been used to extract data logged by Dune during a defined mission, and to monitor the integer ambiguity solution from rtklib and piksi.

3.2.2 RTKLIB

Rtklib is a open source program package for standard and precise positioning with GNSS developed by T. Takasu. Rtklib can use raw GNSS data to estimate the position of the rover. Rtklib can be configured to give a position solution in real time in differential mode. Figure 3.7 shows how rtklib can be used in a RTKGNS mode. The two main moduels here is str2str and rtkrcv. Both will be explalined more closely in the following sections. More information about rtklib can be found in [Rtk].

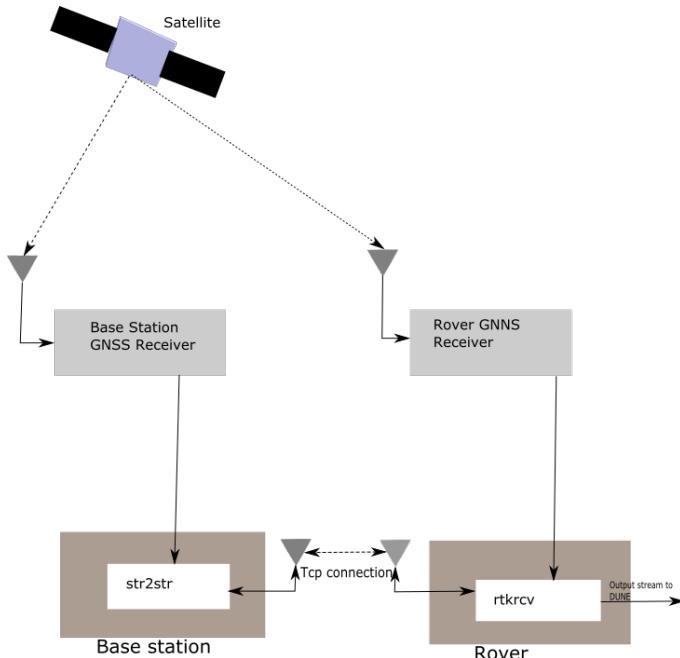


Figure 3.7: The communication structure of rtklib

rtkrcv

Rtkrcv is the app program that calculate the position of the rover. Rtkrcv can be configured to have two output streams. The structure of the output stream is given the rtklib manual, however there has been done some alteration in the structure of the output. It's desired in a automatic landing system that have that velocity solution. This was not provided in the newest version of rtklib, and therefore the source code was altered to send out the velocity data. A quick note here is that it is only available in the output solution is in a enu format. The format of the output is given in table 3.2.

When set configured as a differential GPS rtkrcv uses the LAMBDA method to resolve the integer ambiguity. The solution is considered fixed if the ration between the best estimate and the second best estimate is above a certain threshold. The position solution is calculated with a Extended Kalman Filter, that can have different structure depending on how rtkrcv is configured

str2str

Str2str is the app program that retrieve the ublox signal from the gps and sends over tcp to the rtkrcv app. The str2str is setup to either send RMTC 3 messages, or whatever is send in from the GPS. Since the str2str do not support to send ublox signal directly. How to write that the user should not specify the input format or the output format.

3.3 Implementation

This section explain how the implementation was done for the RTK-GPS navigation system. Figure 3.8 gives an overview on how the system is connected. The implementation includes both a software and a hardware part.

24 3. SYSTEM COMPONENTS AND IMPLEMENTATION

Header	Content
1 Time	The epoch time of the solution indicate the true receiver signal reception time. Can have the following format: yyyy/mm/dd HH:MM:SS.SSS: Calender time in GPST, UTC or JST. WWWW SSSSSSS.SSS: GPS week and TOW in seconds
2 Receiver Position	The rover receive antenna position
3 Quality flag (Q)	The flag which indicates the solution quality. 1:Fixed 2:Float 5:Single
4 Number of valid satellites (ns)	The number of valid satellites for solution estimation.
5 Standard deviation	The estimated standard deviation of the solution assuming a priori error model and error parameters by the positioning options
6 Age of differential	The time difference between the observation data epochs of the rover receiver and base station in second.
7 Ratio factor	The ratio factor of "ratio-test" for standard integer ambiguity validation strategy
8 Receiver velocity	The velocity of the rover. Given only when output is in enu format

Table 3.2: Rtklib output solution format

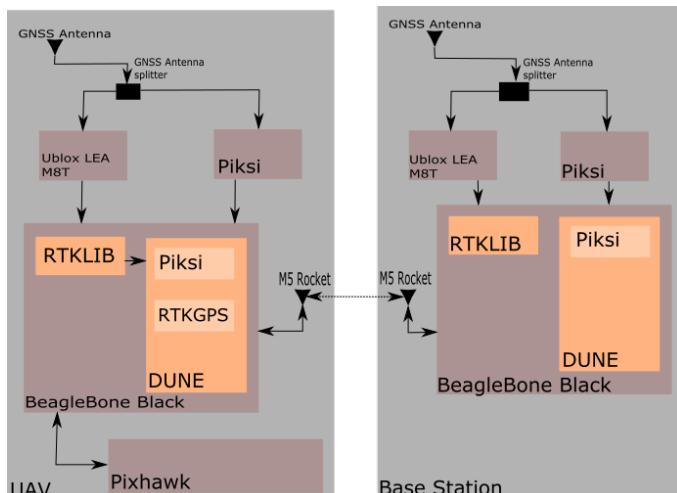


Figure 3.8: Hardware Software

3.3.1 Software implementation

The software implementation consist mainly of rtklib and dune. Piksi is also used in the experiment, however it's rtklib and the Dune task RTKGPS that will be discussed thoroughly. It should be noted that the rtklib that is used is an altered version from the latest stable version. The alteration was done in the ENU output setting where the ENU velocity variables was included. The new structure is given in 3.2

Rtkgps

The RTK-GPS module in the navigation system consist of three parts. That is rtklib, and the two Dune tasks RTKGPS and Piksi. The RTKGPS task is connected to rtklib through a virtual connection, and the Piksi task has a physical connection to the Piksi receiver.

Rtklib is separated into the base station and the rover. The base station implementation runs the str2str program were it communicate with the Ublox over a uart cable, and start up a tcp server.

The rover uses the rtkrcv program from rtklib to estimate the position of the rover. Rtkrcv connect itself as a tcp client to the tcp server that str2str create. Rtkrcv is configured in a moving baseline configuration to simulate the behaviour that is expected during a landing on a ship. The configuration file is included in A

The output from the Dune tasks is a IMC message called RtkFix, see table 3.3, which include the relative position of the UAV as well as the velocity, type of integer solution and the GPS TOW.

3.3.2 Hardware implementation

The base station configuration was already finish by the time this work began. The only hardware that was included was the Ublox and the GPS antenna splitter. On the UAV a the payload computer had to be prepared.

The embedded computer uses GLUED as its operating system, and on it runs both Dune and rtklib. The Piksi and Ublox is connected to the BeagleBone over uart cables.

The primary data-link to the UAV is done with shf Ubiquiti AirMax radios, that is based on a Ubiquity Rocket M5

The two RTK-GPS system is connected to a antenna splitter , figure 3.9, such that both system receive the same GNSS signals. This is done to easy the comparison of the two RTK-GPS system, and to remove the antenna as a source of error.

26 3. SYSTEM COMPONENTS AND IMPLEMENTATION

Header	Content
tow	Gps time of Week
n	Baseline North coordinate
e	Baseline East coordinate
d	Baseline Down coordinate
v_n	Velocity North coordinate
v_e	Velocity East coordinate
v_d	Velocity Down coordinate
iar_hyp	Number of hypotheses in the Integer Ambiguity Resolution
iar_ratio	Quality ratio of Integer Ambiguity Resolution
type	Type of fix: None = No solution, but RTK task is running Obs = No solution, but receiving observations Float = Floating point solution of Integer Ambiguity Resolution Fix = Fixed(single) solution of Integer Ambiguity Resolution

Table 3.3: The IMC message RtkFix

More information on the hardware setup used in the X8 and the Base station is given in [Zolich A. P. and K., 2015]



Figure 3.9: Antenna splitter

Chapter 4

Experimental testing

This chapter contain the result from the test that were performed. The goal with these test was to evaluate the ublox receiver against the pixi receiver, and to get a impression on the accuracy to the rtklib solution with ublox. The comparison test was performed with the pixi and ublox connected to the same antenna at both the rover and the base station. Then the deviation in the position estimate can only come from the receivers. The accuracy test of the ublox was tested by performing the same manoeuvre several times. All position and velocity data is given in the NED frame.

4.1 Physical testing

The experimental test was split in two independent test, one where the X8 UAV was carried around on a open field to test the performance of the RTK-GPS system in a more controlled environment. The goal of the first was to log data from both RTK-GPS system in optimal condition for the navigation system. The second test was perform in a more realistic environment for a navigation system.

4.1.1 Test 1: Test of the RTK-GPS navigation system

In this part two sessions of navigation data will be presented. Both sessions were performed on the same day, which was cloudless and at a time with low DOP. The raw data from the Ublox receiver was post processed with rtklib, and is should be more accurate than it's real time counter part. Therefore a error was defined as:

$$e(t) = p_r(t) - p_p(t) \quad (4.1)$$

where $p_r(t)$ and $p_p(t)$ is defined as the position solution from the real time system and the position solution from the post processed solution respectfully. It should be noted that in order to compare the different time-series the position data was

synchronized with each other. From the error the cumulative standard deviation for the error was calculated using the matlab function "std".

First session

As expected both systems provided a position estimate with fixed integer solution that followed the true path, and further confirms that both system performed in a similar manner. Therefore both systems are suitable for further comparison of position estimation in a flying test. Figure 4.1 shows a North East plot of how the walk was. The plot contain only the fixed solution from both the piksi and rtklib.

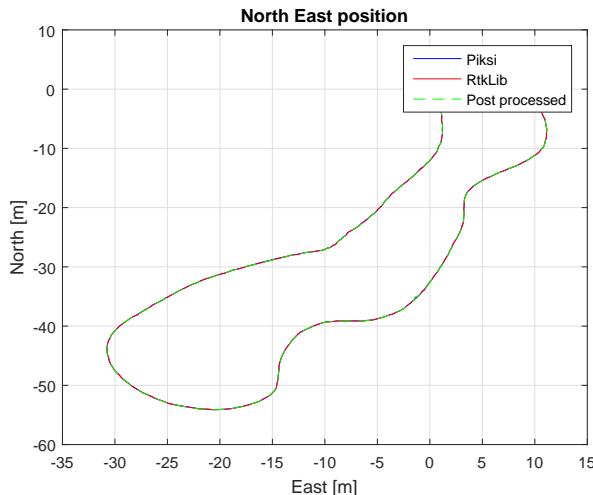


Figure 4.1: A xy plot of the piksi,rtklib real time solution and the rtklib post processed solution

Figure 4.2 shows the down position, as well as how the integer ambiguity solution was during the experiment. As seen in the figure both the Piksi and Rtklib manage to keep there fixed solution. The position solution from both the Piksi and Rtklib agrees with the post processed solution.

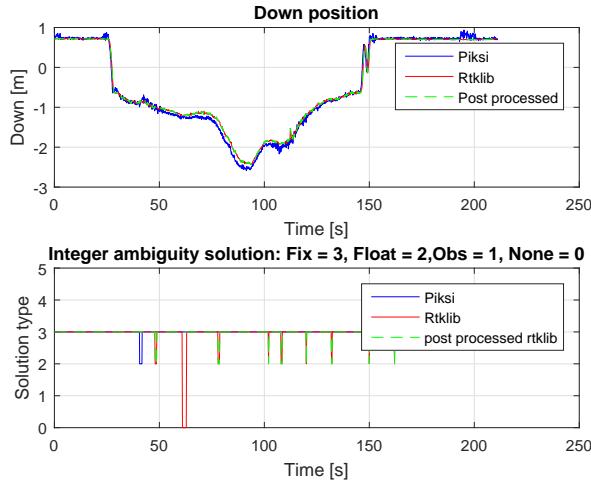


Figure 4.2: The communication structure of rtklib

As seen in figure 4.1 the difference between the different solution appear to be small, which is confirmed in the error plot shown in figure 4.3 and 4.4

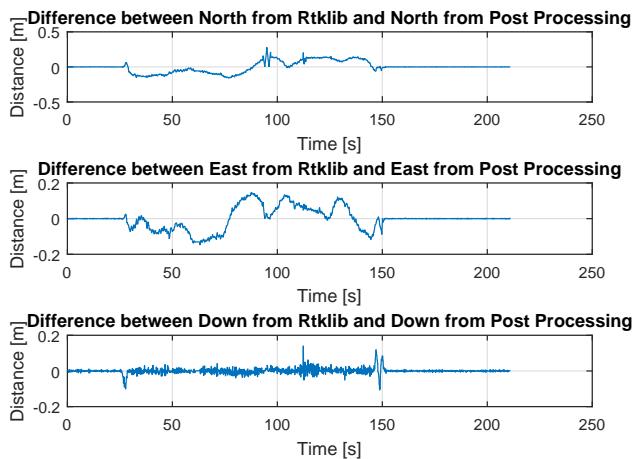


Figure 4.3: The difference between rtklib real time and post processed solution

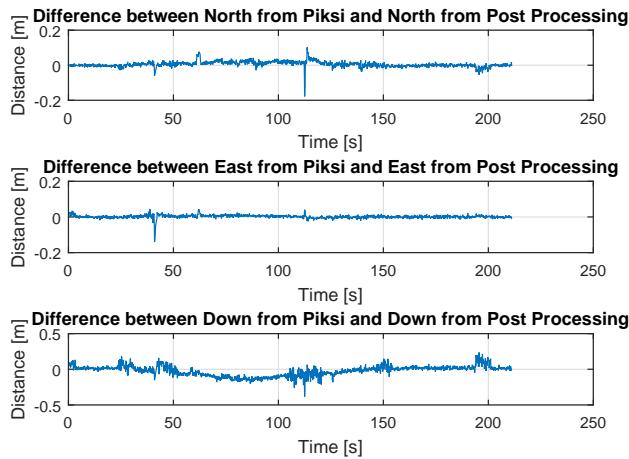


Figure 4.4: The communication structure of rtklib

The small variation in the position error can be seen in figure 4.6 and 4.5.

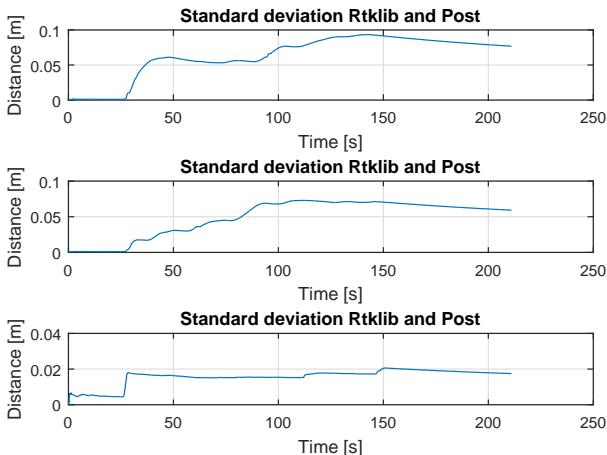


Figure 4.5: Standard deviation of the difference between rtklib real time and post processed solution

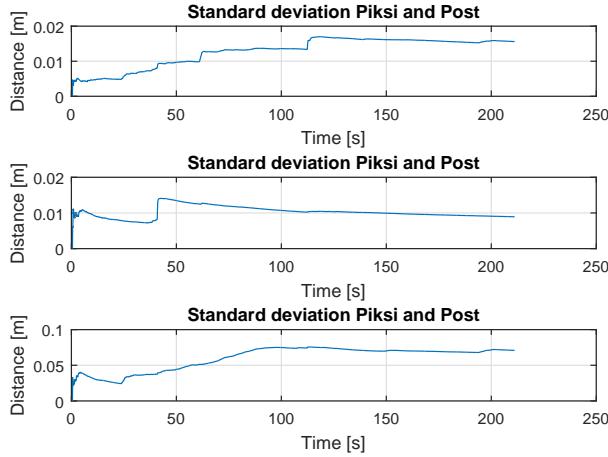


Figure 4.6: Standard deviation of the difference between piksi real time and rtklib post processed solution

Both the Piksi and RTKLIB appear to be able to correctly estimate the North and East velocity, as seen in figure 4.7. However the Down velocity from RTKLIB is more noisy than the Piksi.

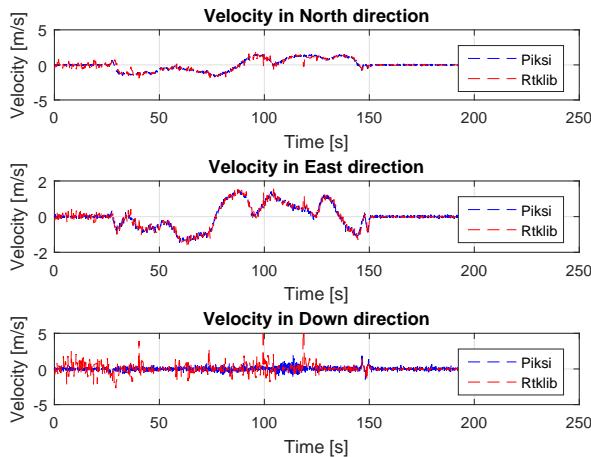


Figure 4.7: Velocity data from the piksi and rtklib real time solution

The different receiver used in Rtklib and Piksi was not able to track the same satellites at all time. Figure 4.8 shows that the Ublox LEA M8T receiver connected to Rtklib managed to track more satellite then the receiver used in Piksi. Figure

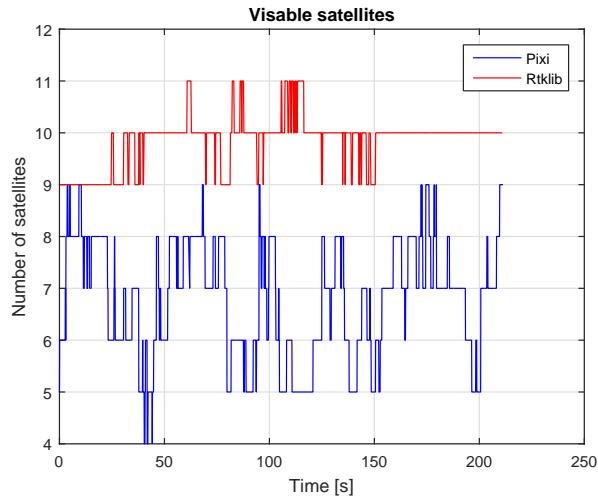


Figure 4.8: Visable statellite for the piksi and rtklib

The position estimate of the rover is a relative position in reference to the base station. Due to the fact that the position of the base station is calculated with a single receiver with one frequency, there will be introduced a bias in the position estimate. Figure 4.9 shows the North, East position of the the first walk. The true position is exactly the same, but in the figure it appear that the distance is approximately 5cm. The distance from the base station to the estimated start and stop position was calculated to be 3.29m and 3.26 respectfully. The measured distance was approximately 3.3m. That gives an initial error off 0.04m. This gives an accuracy level at centimeter level at stationary condition.

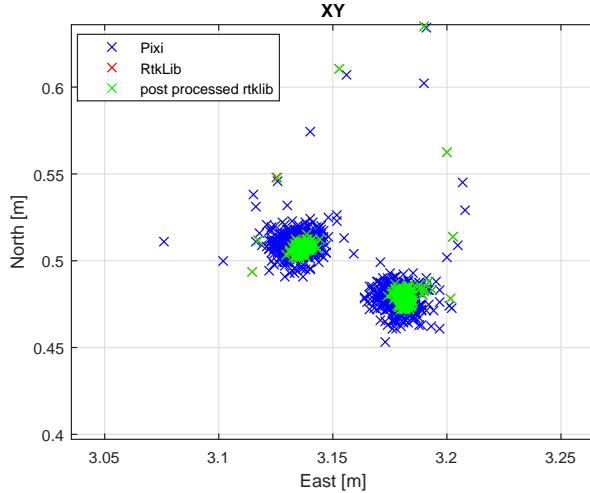


Figure 4.9: Visable statellite for the piksi and rtklib

The position estimate from RTKLIB appear to be delay in comparison to the solution from the Piksi. Figure 4.10 shows that both the post processed solution and the real time solution is delay by 0.5 seconds compared to the Piksi. This could be how RTKLIB resolve the millisecond in Time Of Week (TOW), and will not be seen as an extra delay seen from the control systems perspective.

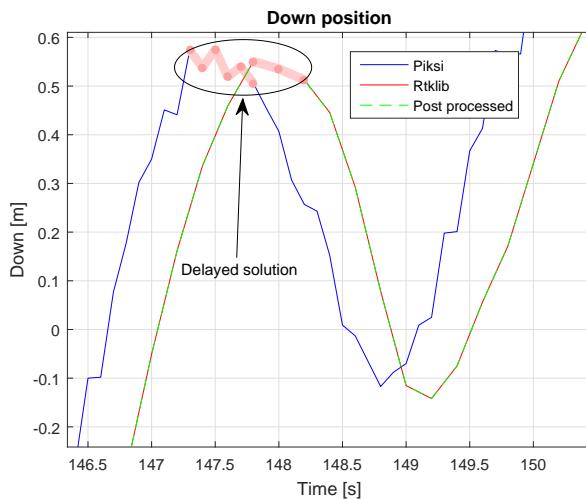


Figure 4.10: Velocity data from the piksi and rtklib real time solution

Given that the error given in figure 4.4 and 4.3 is never has a greater absolute value then $0.2m$ it's possible to assume that the true error will be bellow $1m$ which was given as an evasion criterion in the MSc thesis by [Marcus, 2015], if the RTK-GPS system has a fixed integer solution.

Second session

The second session was perform few minutes after the first, whit the same weather condition. During the second session the Piksi lost its fixed integer solution, while Rtklib managed to keep its fixed integer solution as seen in figure 4.11 and 4.12.

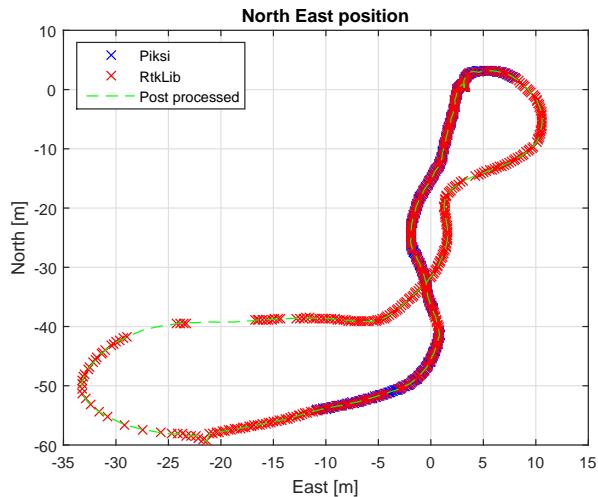


Figure 4.11: Visable statellite for the piksi and rtklib

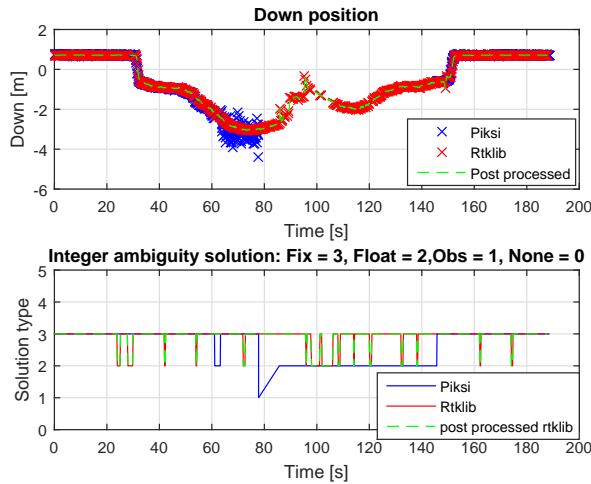


Figure 4.12: Visable statellite for the piksi and rtklib

The reason for why the Piksi lost its fixed solution might be because it lost track of several satellite, as seen in figure 4.13. Since both receive share the same antenna it can be concluded that the satellite tracing performance in the Ublox is superior to the Piksi. Even when the Piksi managed to regain track of the satellite it lost, it took 60 seconds before it regain a fixed integer solution.

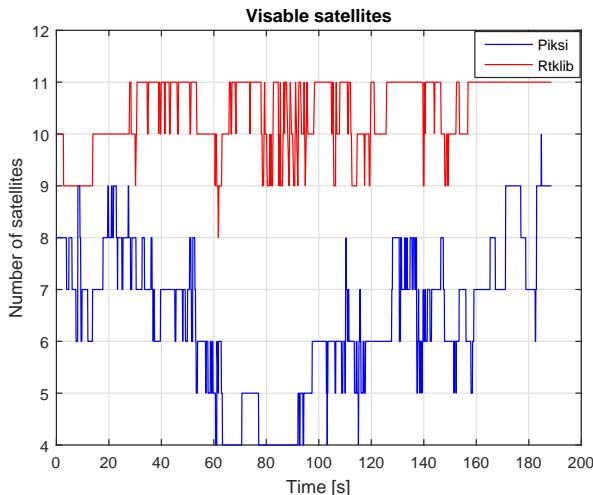


Figure 4.13: Visable statellite for the piksi and rtklib

4.1.2 In-flight test

A flight test with the UAV was performed at Udduvoll. Because of bad weather they were only performed one flight, and before the flight started only the Rtklib had a fixed solution. That is why in this part only performance from the Rtklib is considered, as a fixed solution is a must for a automatic landing system.

During the flight test the integer ambiguity solution were more float then fixed as seen in figure 4.15 and 4.14, which affected the measurement. The same behavior will be seen during the landing, however if the float solution is accurate enough the system should be able to perform a automatic landing.

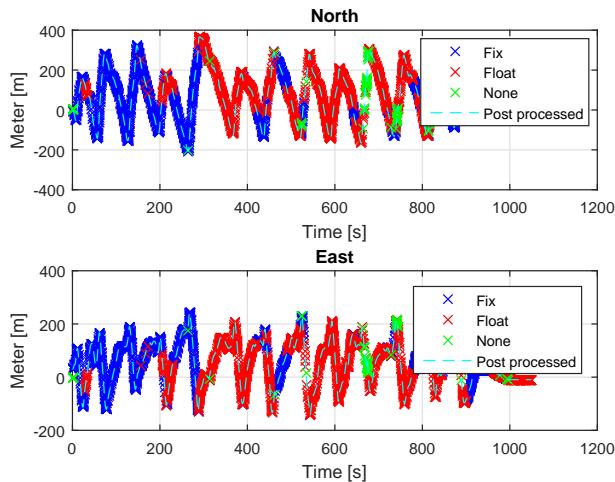


Figure 4.14: Velocity data from the piksi and rtklib real time solution

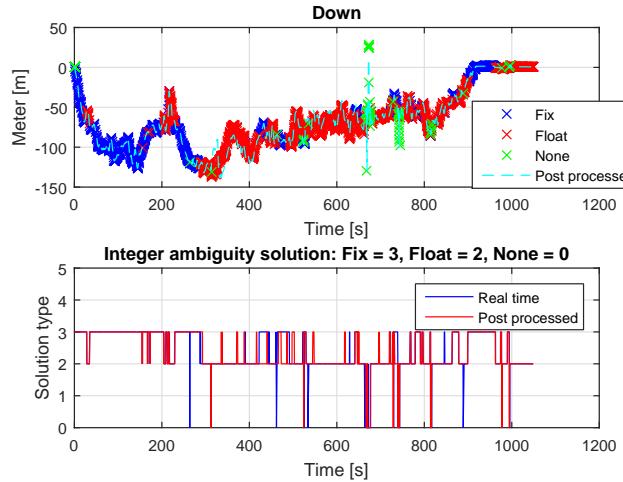


Figure 4.15: Velocity data from the piksi and rtklib real time solution

The main reason for this behaviour is because of the number of valid satellite the receiver can track experience large variation, as seen i figure 4.16. A problem that was experienced during the flight is that the dynamic behaviour of the UAV blocks the antennas view of different satellites. That is a problem that can be solved by setting restriccion on the dynamical behavior of the UAV expesially befor and during landing.

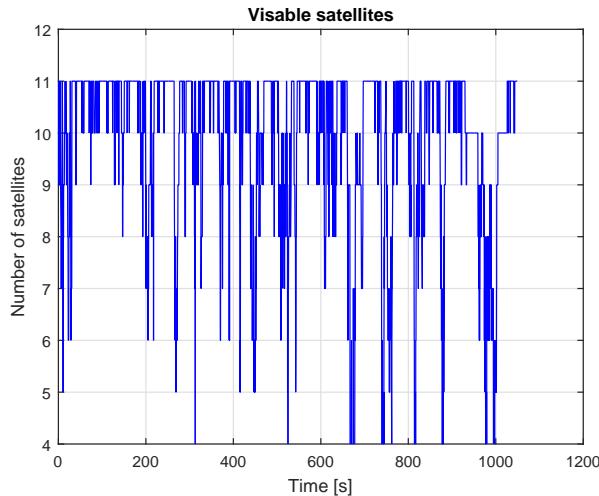


Figure 4.16: Velocity data from the piksi and rtklib real time solution

Landing

As expected the RTK-GPS system had problem with keeping it's fixed integer solution. The RTK-GPS position estimate of the landing path is shown in figure 4.17. The system kept changing between float and fixed solution during the landing phase. Figure 4.18 shown the North East position during the landing with the type of solution. The Down position as well as the integer ambiguity solution is for the landing phase is seen in 4.19. The RTK-GPS system was unable to maintain a fixed solution, however it did maintain a float solution. Further test with a control system is required in order to test if also the float solution is accurate enough to perform a automatic landing.

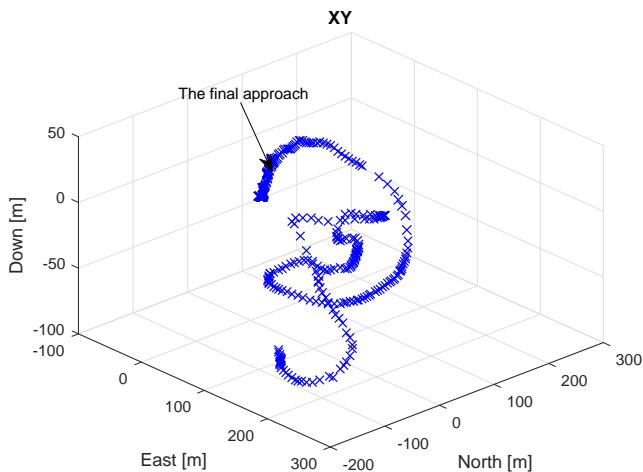


Figure 4.17: Velocity data from the piksi and rtklib real time solution

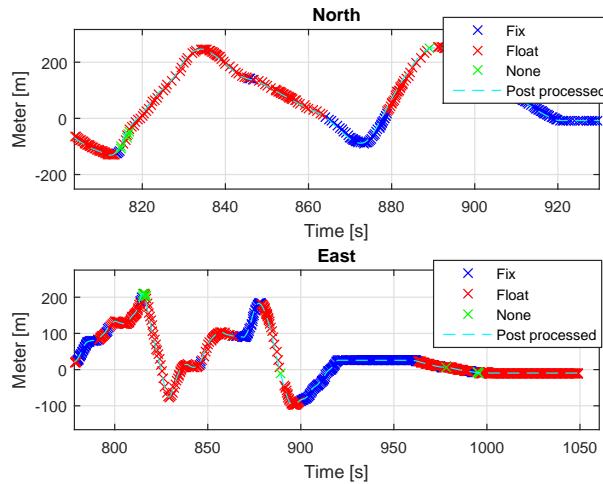


Figure 4.18: Velocity data from the piksi and rtklib real time solution

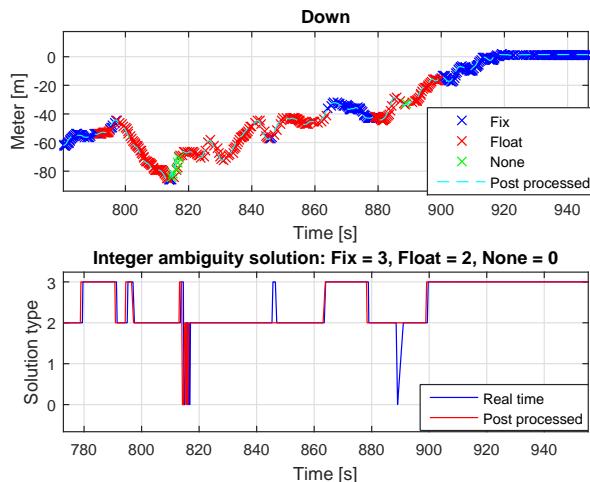


Figure 4.19: Velocity data from the piksi and rtklib real time solution

From the error plot seen in figure 4.20 it appear that to be able to estimate it's own position with an error bellow 1 meter most of the time. However this is compared to the post processed estimate, which also will diverge from the true value.

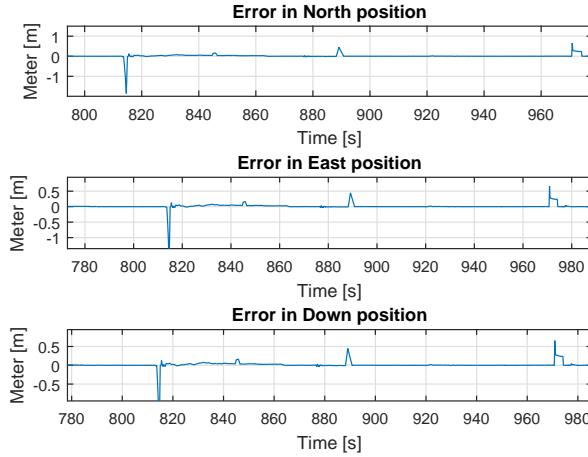


Figure 4.20: Velocity data from the piksi and rtklib real time solution

The landing velocity seen in 4.21 confirms the trend see in the first session. The North and East velocity seams to get a nice estimate, however that is not the case with the Down velocity. The Down velocity estimate appear noisy, and not suited for input into a control system.

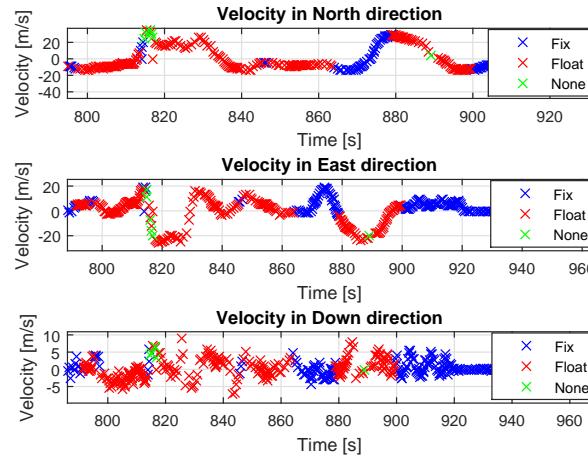


Figure 4.21: Velocity data from the piksi and rtklib real time solution

Chapter 5

Conclusion and recommendation for further work

This chapter will discuss the result from the field tests, which will be used to conclude the performance of the individual RTK-GPS system. The last part of this chapter will include suggestion for further work regarding the design of a automatic landing system.

5.1 RTK-GPS lab testing

It was seen in the lab testing that both the Piksi and RTKLIB was able to get a fixed solution, although the RTKLIB was faster. In the first test were the UAV was carried both system gave similar result during the first session UAV, however during the second the Piksi lost its fixed solution. Rtklib had also problem during this session, but unlike the Piksi managed to find a fixed solution again. The ability for the navigation system to quickly recover its integer solution is critical in a automatic landing system.

The estimated position is accurate when the UAV isn't moving down to centimeter level accuracy. When the UAV is in motion this will decrease down to decimeter accuracy, and due to the precision in the position estimate it could be concluded that the accuracy is not worse then decimeter level accuracy. That should be good enough in a navigation system for a automatic landing system.

The velocity estimate from Piksi and RTKLIB have similar estimate for the North and East component, but differ in the Down component. The velocity output from RTKLIB appear to affect by to much noise to be at any use for a control system. It could be used if sent through a low-pass filter.

The tracking performance from the two receiver type indicate that the Ublox is superior to the Piksi. It always manage to track more satellites, and did not easily loose track of them.

5.2 RTK-GPS in-flight test

The flight test showed that keeping the fixed integer solution during a flight is difficult, most likely because of the dynamic behaviour of the UAV. The landing phase of the UAV operation should be kept independent from the rest of the operation. Therefore landing specific constraint cannot be imposed on the UAV behaviour. In order to then get a best relative position estimate the RTK-GPS must be able to recover it's fixed integer solution as quickly as possible while the UAV is in flight.

Before the take-off the piksi had yet solved its integer ambiguity, while RTKLIB had. That might be because of it kept track of fever satellites. However the navigation system must be able to resolve its integer ambiguity quickly to increase the probability of performing a safe and successfully automatic landing.

During the flight the Ublox lost track of more satellite then during the GPS lab tests. The antenna follows the orientation of the UAV and therefore some satellite will be blocked by the fuselage. This must be consider when designing a guidance system for automatic landing. To ensure that the antenna has a clear view of the sky, the UAV should try to have a maximum roll when the automatic landing system is engaged.

DO NOT INCLUDE WHAT IS BELOW BEFORE FURTHER WORK

It might be that the float position estimate is good enough to perform a automatic landing. Further test are required.

Rtklib managed to keep float/fixed solution during the landing.

The rtklib was the only system able to get a fixed solution. Discuss the performance of rtklib, whit the ublox receiver.

What can be concluded:

Rtklib is able to faster find a fixed solution. Can be because of better receiver, better integer ambiguity resolution strategy, poorer validation of ambiguity, more efficient algorithm. Based on how many satellites the ublox receiver manage to track I will say that the receiver had a large part in shortening the time.

When fixed there is not a large deviation between the two solutions. One difference that might cause problem in a guidance system is that it appear that the solution

from rtklib is delayed. The TOW that's given with the solution do not include the millisecond value.

The Piksi is faster to calculate the position, but slower to resolve the integer ambiguity.

The conclusion of the different system. Piksi has better and more efficient solution software, however rtklib can use a superior GNSS receiver.

Both system has a good estimation of the North and East velocity, however it appear that rtklib has problem estimating the vertical velocity.

5.3 Further work

The Ublox receiver and the GNSS antennas are able to receive both GPS and GLONASS L1 signals, which should be exploited to increase the number of valid satellite available for the RTK-GPS system. This could also give better constellation geometry, and help the system resolve its integer ambiguity faster.

The RTK-GPS system must be integrated with the existing control and guidance system, and a test landing in a stationary net must be performed.

A RTK-GPS system can use both the Piksi and Rtklib such that the automatic landing system has redundancy in position, and velocity estimation. A validation task must then be design to choose which of the system should send the rtkfix IMC message to the rest of the system.

A RTK-GPS/glsins integration navigation system can be implemented in the automatic landing system. A RTK-GPS/glsins integration was proposed in [Amstrup, 2015], which can be used.

A position estimation system that can accurately predict were the UAV will be a few seconds ahead of time, such that the UAV can better know were it is instead of were if was.

Setting constraints on the path such that the antenna has a clear view of the satellites at all time during the landing phase.

References

Piksi Datasheet ver. 2.3.1.

RTKLIB ver. 2.4.2 Manual.

NEO/LEA-M8T u-blox M8 concurrent GNSS timing modules, Data Sheet, a.

U-blox M8 Receiver Description Including Protocol Specification, b.

M1227HCT-A-SMA L1/L2 GPS-GLONASS Active Antenna, Data Sheet.

Novatel, GPS-701-GG and GPS-702-GG, Data Sheet.

Smit Samuel Jacobus Adriaan. Autonomous landing of a fixed-wing unmanned aerial vehicle using differential gps. Master's thesis, Stellenbosch: Stellenbosch University, 2013.

Spockeli Bjørn Amstrup. Integration of rtk gps and imu for accurate uav positioning. Master's thesis, Norwegian University of Science and Technology, NTNU, 2015.

Vik Bjørnar. *Integrated Satellite and Inertial Navigation Systems*. Department of Engineering Cybernetics, NTNU, 2014.

Blewitt Geoffrey. Carrier phase ambiguity resolution for the global positioning system applied to geodetic baselines up to 2000 km. *Journal of Geophysical Research*, 94(B8):10,187–10,203, 1989.

Fossen Thor I. *Handbook of marine craft hydrodynamics and motion control*. John Wiley & Sons, 2011.

Kim H Jin, Kim Mingu, Lim Hyon, Park Chulwoo, Yoon Seungho, Lee Daewon, Choi Hyunjin, Oh Gyeongtaek, Park Jongho, and Kim Youdan. Fully autonomous vision-based net-recovery landing system for a fixed-wing uav. *Mechatronics, IEEE/ASME Transactions on*, 18(4):1320–1333, 2013.

Frølich Marcus. Automatic ship landing system for fixed-wing uav. Master's thesis, Norwegian University of Science and Technology, NTNU, 2015.

- Williams Paul and Crump Michael. Intelligent landing system for landing uavs at unsurveyed airfields. In *28th International Congress of the Aeronautical Sciences*, 2012.
- Joel Pinto, Paulo S Dias, Rui P Martins, Joao Fortuna, Eduardo Marques, and Joao Sousa. The lsts toolchain for networked vehicle systems. In *OCEANS-Bergen, 2013 MTS/IEEE*, pages 1–9. IEEE, 2013.
- Teunissen P.J.G. A new method for fast carrier phase ambiguity estimation. *IEEE*, pages 562–573, 1994.
- Teunissen P.J.G. The least-squares ambiguity decorrelation adjustment: a method for fast gps integer ambiguity estimation. *Journal of Geodesy*, 70:65–82, 1995.
- Misra Pratap and Enge Per. *Global Positioning System Signals, Measurements and Performance Revised Second Edition*. Ganga-Jamuna Press, 2011.
- Skulstad Robert and Syversen Christoffer Lie. Low-cost instrumentation system for recovery of fixed-wing uav in a net. Master's thesis, Norwegian University of Science and Technology, NTNU, 2014.
- de Jonge P.J. Teunissen P.J.G and Tiberius C.C.J.M. The lambda-method for fast gps surveying. Presented at the International Symposium "GPS Technology Applications" Bucharest,Romania, 1995.
- Stempfhuber W. 3d-rtk capability of single gnss receivers. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2013.
- Stempfhuber W. and Buchholz M. A precise, low-cost rtk gnss system for uav applications. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2011.
- Cisek K. P. Zolich A. P., Johansen T. A. and Klausen K. Unmanned aerial system architecture for maritime missions. design and hardware description. In *Education and Development of Unmanned Aerial Systems (RED-UAS)*, 2015.

Appendix A

Rtklib Configuration

A.1 str2str

Need start commando and rate configuration of the ublox

A.2 rtkrcv

Configuration given bellow. Summarize the important parts of the configuration.

```
# RTKNAVI options (2015/10/30 13:05:07, v.2.4.2)
```

```
pos1-posmode      =movingbase # (0:single,1:dgps,2:kinematic,3:static,4:movingbas
pos1-frequency    =l1        # (1:l1,2:l1+l2,3:l1+l2+l5,4:l1+l2+l5+l6,5:l1+l2+l5
pos1-soltype      =forward   # (0:forward,1:backward,2:combined)
pos1-elmask       =10       # (deg)
pos1-snrmask_r    =off       # (0:off,1:on)
pos1-snrmask_b    =off       # (0:off,1:on)
pos1-snrmask_L1   =0,0,0,0,0,0,0,0
pos1-snrmask_L2   =0,0,0,0,0,0,0,0
pos1-snrmask_L5   =0,0,0,0,0,0,0,0
pos1-dynamics     =on        # (0:off,1:on)
pos1-tidecorr     =off       # (0:off,1:on,2:otl)
pos1-ionoopt      =brdc      # (0:off,1:brdc,2:sbas,3:dual-freq,4:est-stec,5:ion
pos1-tropopt      =saas      # (0:off,1:saas,2:sbas,3:est-ztd,4:est-ztdgrad)
pos1-sateph       =brdc      # (0:brdc,1:precise,2:brdc+sbas,3:brdc+ssrapc,4:brd
pos1-posopt1      =off       # (0:off,1:on)
pos1-posopt2      =off       # (0:off,1:on)
pos1-posopt3      =off       # (0:off,1:on)
```

```

pos1-posopt4      =off       # (0:off,1:on)
pos1-posopt5      =off       # (0:off,1:on)
pos1-exclsats     =
pos1-navsys       =1         # (1:gps+2:sbas+4:glo+8:gal+16:qzs+32:comp)
pos2-armode        =fix-and-hold # (0:off,1:continuous,2:instantaneous,3:fix-and-ho
pos2-gloarmode    =off       # (0:off,1:on,2:autocal)
pos2-bdsarmode    =off       # (0:off,1:on)
pos2-arthres      =3
pos2-arlockcnt    =0
pos2-arelmask     =0         # (deg)
pos2-arminfix     =10
pos2-elmaskhold   =0         # (deg)
pos2-aoutcnt      =5
pos2-maxage       =30         # (s)
pos2-syncsol      =on         # (0:off,1:on)
pos2-slipthres    =0.05      # (m)
pos2-rejionno     =30         # (m)
pos2-rejgdop      =30
pos2-niter         =1
pos2-baselен      =0         # (m)
pos2-basesig      =0         # (m)
out-solformat     =llh       # (0:llh,1:xyz,2:enu,3:nmea)
out-outhead       =off       # (0:off,1:on)
out-outopt        =off       # (0:off,1:on)
out-timesys       =gpst      # (0:gpst,1:utc,2:jst)
out-timeform      =tow       # (0:tow,1:hms)
out-timendec      =3
out-degform       =deg       # (0:deg,1:dms)
out-fieldsep      =
out-height        =ellipsoidal # (0:ellipsoidal,1:geodetic)
out-geoid          =internal  # (0:internal,1:egm96,2:egm08_2.5,3:egm08_1,4:gsi200
out-solstatic     =all       # (0:all,1:single)
out-nmeaintv1     =0         # (s)
out-nmeaintv2     =0         # (s)
out-outstat       =state     # (0:off,1:state,2:residual)
stats-eratio1     =100
stats-eratio2     =100
stats-errphase    =0.003     # (m)
stats-errphaseel  =0.003     # (m)
stats-errphasebl  =0         # (m/10km)
stats-errdoppler  =1         # (Hz)

```

```

stats-stdbias      =30          # (m)
stats-stdiono     =0.03        # (m)
stats-stdtrop     =0.3         # (m)
stats-prnaccelh   =10          # (m/s^2)
stats-prnaccelv   =10          # (m/s^2)
stats-prnbias     =0.0001      # (m)
stats-prniono     =0.001       # (m)
stats-prntrp      =0.0001      # (m)
stats-clkstab     =5e-12        # (s/s)
anti-postype      =llh         # (0:llh,1:xyz,2:single,3:posfile,4:rinexhead,5:rtc
anti-pos1         =90          # (deg|m)
anti-pos2         =0           # (deg|m)
anti-pos3         ==-6335367.6285 # (m|m)
anti-anttype      =
anti-antdele     =0           # (m)
anti-antdeln     =0           # (m)
anti-antdelu     =0           # (m)
ant2-postype      =llh         # (0:llh,1:xyz,2:single,3:posfile,4:rinexhead,5:rtc
ant2-pos1         =90          # (deg|m)
ant2-pos2         =0           # (deg|m)
ant2-pos3         ==-6335367.6285 # (m|m)
ant2-anttype      =
ant2-antdele     =0           # (m)
ant2-antdeln     =0           # (m)
ant2-antdelu     =0           # (m)
misc-timeinterp   =off         # (0:off,1:on)
misc-sbasatsel   =0           # (0:all)
misc-rnxopt1      =
misc-rnxopt2      =
file-satantfile  =
file-rcvantfile  =
file-staposfile  =
file-geoidfile   =
file-ionofile    =
file-dcbfile     =
file-eopfile     =
file-blqfile     =
file-tempdir     =/tmp/
file-geexefile   =
file-solstatfile =
file-tracefile   =

```

#

```

inpstr1-type      =serial      # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,7:ntripcl
inpstr2-type      =tcpcli     # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,7:ntripcl
inpstr3-type      =off        # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,7:ntripcl
inpstr1-path      =uart/2:115200:8:n:1:off
inpstr2-path      =:@10.0.60.51:50022:/
inpstr3-path      =
inpstr1-format    =ubx        # (0:rtcm2,1:rtcm3,2:oem4,3:oem3,4:ubx,5:ss2,6:hemis
inpstr2-format    =ubx        # (0:rtcm2,1:rtcm3,2:oem4,3:oem3,4:ubx,5:ss2,6:hemis
inpstr3-format    =rtcm2      # (0:rtcm2,1:rtcm3,2:oem4,3:oem3,4:ubx,5:ss2,6:hemis
inpstr2-nmeareq   =off        # (0:off,1:latlon,2:single)
inpstr2-nmealat   =0          # (deg)
inpstr2-nmealon   =0          # (deg)
outstr1-type      =serial      # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,6:ntri
outstr2-type      =file       # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,6:ntrips
outstr1-path      =../tmp/ttyV0:115200:8:n:1:off
outstr2-path      =/opt/lsts/rtklib/log/rtklib_output%Y%m%d%h%M.pos
outstr1-format    =enu        # (0:llh,1:xyz,2:enu,3:nmea)
outstr2-format    =enu        # (0:llh,1:xyz,2:enu,3:nmea)
logstr1-type      =file       # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,6:ntrips
logstr2-type      =file       # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,6:ntrips
logstr3-type      =off        # (0:off,1:serial,2:file,3:tcpsvr,4:tcpcli,6:ntrips
logstr1-path      =/opt/lsts/rtklib/log/rtklib_ubxstream_x8_log%Y%m%d%h%M.ubx
logstr2-path      =/opt/lsts/rtklib/log/rtklib_ubxstream_base_log%Y%m%d%h%M.ubx
logstr3-path      =
misc-svrcycle     =50         # (ms)
misc-timeout       =30000     # (ms)
misc-reconnect    =30000     # (ms)
misc-nmeacycle    =5000      # (ms)
misc-buffsize     =32768     # (bytes)
misc-navmsgsel    =all        # (0:all,1:rover,2:base,3:corr)
misc-proxyaddr    =
misc-fswapmargin  =30         # (s)
#misc-startcmd =./rtkstart.sh
#misc.startcmd =./rtkshut.sh
file-cmdfile1    =/etc/rtklib/data/ubx_raw_10hz.cmd
file-cmdfile2    =/etc/rtklib/data/ubx_raw_10hz.cmd

```