Lucerne University of
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Localization of a Sounding Rocket via GPS

Bachelor Thesis

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Classification: Access

May 22, 2018

Declaration

I hereby declare and confirm that this thesis is entirely the result of my own original work. Where other sources of information have been used, they have been indicated as such and properly acknowledged. I further declare that this or similar work has not been submitted for credit elsewhere.

Horw May 22, 2018

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Abstract

Contents

Chapter 1

Introduction

Global Navigation Satellite Systems, GNSS for short, are uesd in a wide variety of applications nowadays. The most prominent and oldest system is GPS. It started as a military and maritime navigation aid, but is now used extensively in civil applications. This thesis evaluates the use of GPS for the localization of a sounding rocket.

1.1 Framework

The need for such a project originated form ARIS, the Swiss Space Initiative or Akademische Raumfahrt Initiative Schweiz in german. ARIS was founded in 2017 by students from the ETH Zürich and HSLU. Now, over 50 students from the ETH Zürich and the universities of applied sciences in Luzern (HSLU) and Zürich (ZHAW) work on its inaugural project which is called TELL. The goal of project TELL is to build a sounding rocket to compete in the 2018 Spaceport America Cup in New Mexico. More than 100 student teams compete there to launch a 4kg payload with a sounding rocket to a target altitude of 10000 feet or about 3km. [1]

Figure 1.1: Project Tell

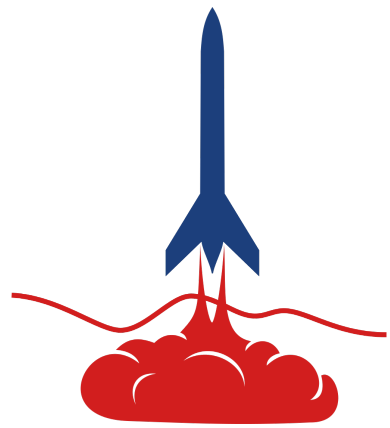

Figure 1.2: Spaceport America Cup

A jury distributes points for achievements in the competition itself and the planning, engineering and documentation that went into the project. A maximum score of 1000 points can be reached. The points are distributed as follows:

- Delivery of Entry Form: 60 points - 6%
- Technical Report: 200 points - 20%
- Design Implementation: 240 points - 24%
- Flight Performance: 500 points - 50%

Points for flight performance are split between reached apogee relative to the target apogee (350 points) and successful recovery (150 points). The points for apogee precision are calculated with this formula:

$$Points = 350 - \left(\frac{350}{0.3 \times Apogee_{Target}}\right) \times |Apogee_{Target} - Apogee_{Actual}|$$

$$\text{with } Apogee_{Target} = 3048m(10000feet)$$

With that equation, a deviation of about 9 meters from the target apogee results in a loss of 1% (3.5 points) of possible points for a correct apogee. [2]

For project TELL, the rocket motor is dimensioned to overshoot the target apogee and airbrakes are used to reduce the apogee to the target. A controll loop is implemented to controll the position of the airbrakes during the accent. The position and velocity data for the loop is fused from on-board pressure and acceleration sensors. Although GPS is implemented in the rocket, it is only used to locate and recover the rocket after it landed. This is because standalone GPS has a vertical error of less than 15 meters for 95% of the time. [3] This is not accurate enouth to be beneficial for the sensor fusion. A vertical error of less than 1 meter for 95% of the time would be needed for it to be feasable. With such an accuracy improvement, the GPS position could be fused together with the pressure and accelerometer. The addition of GPS would especcialy help in reducing the drift introduced by the accelerometer. This is the origin of this bachelor thesis.

1.2 Task Decsription

In short, the feasability of GPS for the localization of a sounding rocket should be evaluated. This should be done in multiple steps. First, it has to be determined which internal and external error sources could limit the GPS accuracy. This means errors that degrade the GPS signal before it enters the antenna, as well as errors that come from the signal processing. A focus should be on potential error sources that are specific to the application in a sounding rocket.

Based on that, methods to mitigate those errors should be found. These methods should be feasable to implement in a sounding rocket and enhance the accuracy of the GPS positioning to a level where it is usable for the rocket controll. The fasability of one of the methods should be shown with a proof of concept. That could be a simulation or a prototype depending on the approach.

1.3 Requirements

There are two different classes of requirements. One is to define the performance the system should achieve. The other is to make it possible to integrate the system into the rocket in terms of interfaces and infrastructure.

The main parameter to rate the performance of a positioning system is the accuracy. The accuracy consists of two components, the variance and the bias. Two metrics that are used often are the 95th precentile and the root-mean-square error (RMSE).

The accuracy reqirement for the sounding rocket GPS is:

$$RMSE \leq 1m$$

Another metric is the integrity of the system. This could be a problem especially during the burn of the rocket because of the high acceleration. For the GPS system to be useful for the competition, it is not vital to have a GPS fix during the burn. But the rocket should have a fix soon after the burnout to have enough time to correct the flight path before the apogee is reached. The requirement is:

GPS fix max. 2 seconds after burnout

In project Tell, a telemetry link is implemented. This link is mainly a downlink from the rocket to the ground station, but there is the option to add an uplink without much effort. Such an uplink could potentially be used by the GPS system. The limitation of the uplink bandwidth for a GPS system is:

Uplink bandwidth max. 2kbit/s

Chapter 2

GPS Concept and Error Sources

Along with earlier navigation systems, this chapter explains the positioning concept of GPS and modern Global Navigation Satellite Systems in general. The error sources that impact the accuracy of GPS are listed and split into categories that determine in which segment those errors occur.

2.1 Predecessors

Before there was GPS, other radionavigation systems were used. They were mostly ground based and limited to a certan area or time.

One of the early examples is the U.S. system *Loran*. It works with multiple transmission stations with a distance of about 1000km to each other. They send out pulse signals in all directions. With the difference in time-of-arrival of those pulses, a receiver can triangulate its position. This method is one variant of hyperbolic positioning. Only a 2D fix can be acieved with such systems. The height, if needed, has so be determined with a different method. The development of *Loran-A* was started during World War II. *Loran-C* is the latest version and still in use today It has a rms positioning accuracy of about 250m.

Another hyperpolic positioning system was *Omega*. It was the first global radionavigation system and operational from 1970 to 1997. But rather than measuring the time differene of pulses, the phase difference of sinusoidal signals was measured. This method resulted in a rms postitoning accuracy of 2-4km. The lower accuracy can be explained with the much wider area it had to cover.

Apart from those ground based systems, there was a working satellite navigation system that came even before *Omega*. It is called *Transit* and was operational from 1964 to 1996. A doppler based systen that was launched by the U.S. Navy. In doppler positioning, a 2D position can be determined from the time the doppler of the satellite signal changes from high to low and the sharpnes of the change. At the moment the doppler changes, the satellite is the closest to the receiver on its orbit. The distance from the projected orbit can then be determined by how sharp the doppler changes. When the receiver is directly on the projected orbit, the doppler changes the fastest. In contrast to modern GNSS, *Transit* satellites had polar orbits with a low altitude of 1100km. Only one satellite was visible at a time with a wait time of up to 100 minutes between them. This made positioning a relatively long process, but the rms positioning accuracy was much better with 25m.

A range of counterparts from Russia and Eurpoe existed to those U.S. systems. *Gee* was a hyperbolic system from Great Britain similar to Loran. It was used by the Royal Air Force during World War II. Doppler positioning was already used in reverse to determine the orbit of *Sputnik I* from a ground station with a known location. The idea to measure the postiton on earth came from this application. The Soviet Union had two dopple based system similar to *Transit* called *Parus* and *Tsikada*. [4]

2.2 Global Navigation Satellite Systems

From the knowledege gained from *Tansit*, a new class of space based navigation systems emerged. The first one beeing the NAVSTAR Global Positioning System (GPS) developed by the U.S. Government. The first GPS satellite was launched in 1978 and the system became fully operantional in 1993. To be independent from the U.S. when it comes to navigation and improve local positioning, other nations started to launch their own systems. The generic term for such systems is Global Navigation Satellite Systems (GNSS). The fisrt addition to the group was the former Soviet and now Russian system GLONASS. It is very similar to GPS in terms of use case and architecture. Both were mainly developed for military use and designed to cover the whole globe with a full constellation of 24 satellites in medium earth orbit. [4]

A newer addition is the european system GALILEO. It is similar in terms of system architecture to GPS and GLONASS, but it is the first GNSS that is under civilian controll. This guarantees that civil receivers can get the highest precission possible. The GALILEO constellation is not yet complete with 14 usable satellites at the moment, but it is said to improve the accuracy to the centimeter level in normal operation. [5]

Beside global navigation systems, there are also local programs which improve the regional accuracy. They consist of satellites in geostationary or geosynchronous orbits. This gives them a constant location above the earth or within a few degreees of longitude. Such systems are the Japanese QZSS and the Indian IRNSS. The Chinese BeiDou system is a combination of global and regional. It started with just geostationary and geosynchronous satellites over China, but now has three operational global satellites with more to come.

2.3 GPS

This section closer explains the system architecture, functional principle and performance of GPS. The difference to the ohter GNSS is minor. Orbits, frequencys and signal modulation are slightly different between the systems, but the basic architecture is the same.

2.4 System Architecture

The GPS system can be split into three segments. The Space Segment includes the satellites, the Control Segment is the ground equipment that manages the satellites and the User Segment are the receivers.

Space Segment

A full GPS constellation consists of 24 satellites as shown in figure 2.1. Currently, there are 31 GPS satellites in operation. They are in medium earth orbit at an altitude of about 20'200km with each satellite circling the earth twice a day. About 8 satellites are visible to a user at a time. These satellites are constantly beeing replaced by newer ones with new features. The different generations of satellites are divided into Blocks. Starting with the first generation of satellites launched from 1978 until 1995 called Block I. Block II satellites had a series of incremental improvements and added new signals over the time they were launced from 1989 until 2016. The separate satellite series of the Block II generation were called II, IIA, IIR, IIR-M and IIF. The first Block III launch is scheduled for 2018. The third generation adds even more signals and trinsmitts at higher power levels.

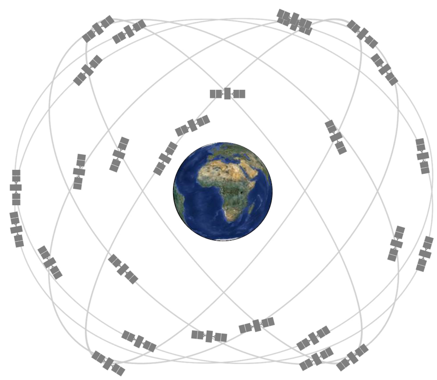

Figure 2.1: GPS satellite constellation [6]

Control Segment

To ensure an accurate positioning service for GPS users, the satellites have to be constantely monitored and maintained. This is the job of the Control Segment. It monitors satellite orbits and time to predict satellite ephemerides and clock parameters. It then updates the satellite navigation data, which is later sent from the satellite to the user. If neccesary, the Control Segment can order the satellites to performe maneuvers to maintain a correct orbit or to relocate to another orbit. The Control Segment comprises of a network of ground based stations spread arround the globe. This network is coordinated by the Master Controll Station in the U.S. state of Colorado.

User Segment

Finally, the User Segment is where the satellite signals are picked up and the position of the user is calcuated. Unlike the other segments, the User Segment is not developed by the U.S. Government, apart from military receivers. The design of civil GPS receivers is left to market forces. The size of those receivers droped dramatically during the lifetime of GPS from the size of a backpack, to the size of a single microchip.

2.4.1 Functional Principle

GPS works with the principle of trilateration. For this method of postitoning, the distance to three known lacations is needed to calculate the own position in three dimensions. This works with basic vector geometry. The euclidean distance between two points in three-dimensional space can be calculated with equation 2.1.

$$r^{(k)} = \sqrt{(x^{(k)} - x)^2 + (y^{(k)} - y)^2 + (z^{(k)} - z)^2} = ||\mathbf{x}^{(k)} - \mathbf{x}|| \tag{2.1}$$

For GPS, the two points are the user position $[x, y, z]$ and the satellite position $[x^{(k)}, y^{(k)}, z^{(k)}]$ and the true distance between them is called $r^{(k)}$. The satellites are distinguished with the superscript $^{(k)}$ where k stands for the k-th satellite in view. In theory, with the position and distance of three satellites, a system of equations could be constructed and the three variables of the user position $[x, y, z]$ could be estimated. But in practice, a gps receiver needs at least four satellites to estimate its position. This is because a fourth variable needs to be estimated called δt_u. This is the difference between GPS time and user time.

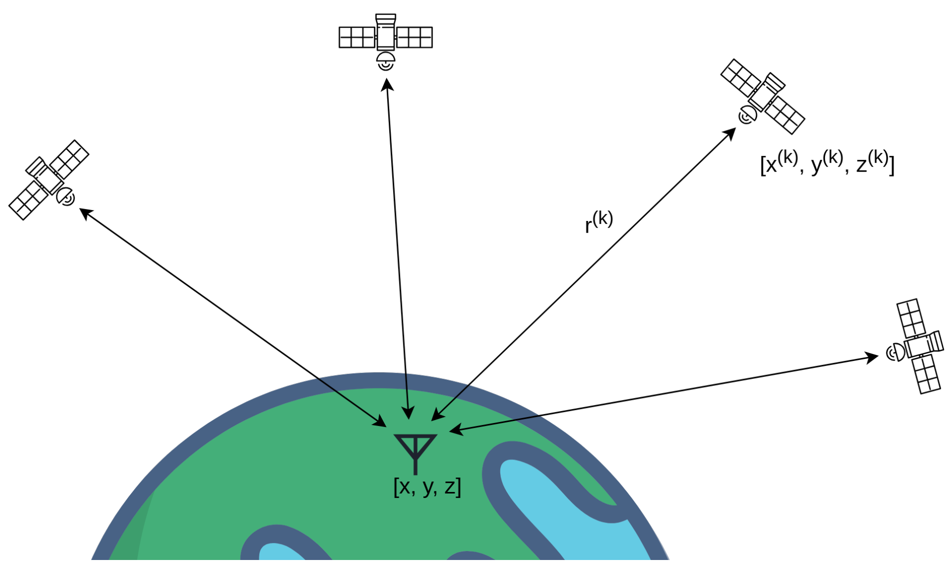

Figure 2.2: GPS triangulation

GPS uses the propagation time of radio waves to determine the distance between satellite and user. The measured transmision time is multiplied by the speed of light to get the distance in meters. This is not the true distance $r^{(k)}$. Insted, the so called pseudorange $\rho^{(k)}$ is measured, which contains the true range and a set of errors. The relation is shown in equation 2.2. The pseudorange contains the clock errors $c[\delta t_u - \delta t^{(k)}]$, the atmospheric errors $I^{(k)} + T^{(k)}$ and the remaining errors $\epsilon^{(k)}$. What they mean is closer explained in section 2.5.

$$\rho^{(k)} = r^{(k)} + c[\delta t_u - \delta t^{(k)}] + I^{(k)} + T^{(k)} + \epsilon^{(k)} \tag{2.2}$$

Important here is the user clock error δt_u. The reason for this error is the unprecise clock in the receiver. The satellites have atomic clocks which are synchorinized to GPS time. It is not feasable to build an atomic clocks into every receiver and keep it synchorinized to GPS time. Insted, the difference between receiver time and GPS time is estimatet with the measurement from a fourth satellite. This is possible because the user clock error is common in the pseudoranges from all satellites. The estimation of the four variables $[x, y, z, \delta t_u]$ is either done iteratively with the Least Square method or with a Kalman filter.

2.4.2 Signals

A GPS receiver can work with only the information included in the signals from the satellites. This means the information for distance and satellite position have to be transmitted with those signals. GPS solves this problem with a three-layered signals like the one in figure 2.3.

The carrier is a sinusoidal signal in the L band. Most civil GPS receivers work with the L1 signal at 1575.42MHz. GPS satellites also send on L2 at 1227.6 MHz and newer satellites on L5 at 1176.45 MHz too. A variety of civil and encrypted military signals are modulated onto those carriers. The main signal for civil applications is the C/A-code on L1. It consists of the C/A-code itself and a data stream. The C/A-code and the data stream are both binary sequences. They are first XORed together and then modulated onto the carrier using *binary phase shift keying* (BPSK).

The C/A-code is a sequence of 1023 bits, which repeats every millisecond and is unique to each satellite. The lenght of each bit, or chip in this context, is about $1\mu s$. This code is used to measure the signal transmission time. The received signal is demodulated and correlated with local copies of the C/A-codes on separate channels. The local copy is shifted in time until an autocorrelation peak emerges. This timeshift

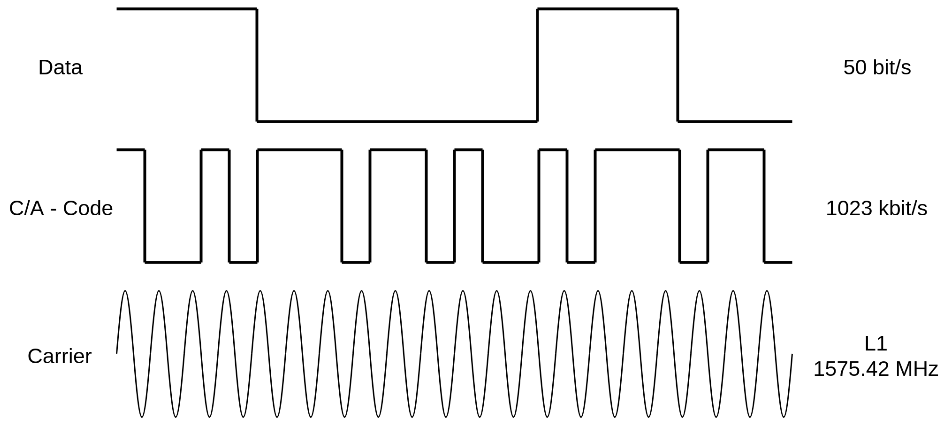

Figure 2.3: C/A-code signal structure (not to scale)

determines the signal transmission time.

Besides the C/A-code is the data stream that contains the navigation message. It has information about the satellite orbit and the satellite clock error. The obit data is called ephemeris data. With it, the position of the satellite can be calculates at the desired time. The satellite clock error information is used to correct the pseudorange for the term $\delta t^{(k)}$.

2.4.3 Performance

To evaluate the performance of GPS, a number of metrics can be used. The most prominent one is of course the accuracy. This was already addressed in 1.3, where the requirements were defined. Accuracy can be explained with the two errors variance and bias. In GPS, the two errors are often not given separately when the accuracy of the whole system is described. Accuracy simply describes how close the measurement matches the real position. The two most used metrics to described GPS postitoning accuracy are the 95th precentile and the root-mean-square error (RMSE). The 95th precentile describes the border in meters, where 95% of errors are smaller and 5% are larger. The RMSE equals the variance of 1σ, as long as the mean error is zero. A mean error is a bias, that is considered in the RMSE but does not impact the variance.

RMSE is calculated with:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} ||\mathbf{x}_{real} - \mathbf{x}_{meas}||^2}{n}} \tag{2.3}$$

Accuracy can be further divided into horizontal and vertical error. The GPS SPS(Standard Positioning Service) Performance Standard defines an average $\leq$9m 95% horizontal error and a $\leq$15m 95% vertical error [3].

Other than accuracy, availability and integrity are two other important metrics. The availability is the likelihood a user anywhere on earth can get a GPS fix. The GPS SPS Performance Standard defines an average $\geq$99% locational availability [3]. Integrity is how trustworthy the information of the system is. This is especially important for safety-of-life applications like airplane navigation. GPS constantly monitors itself and informs the user if the data does not meet the requirements. This is done with satellite self-monitoring, cross-monitoring between satellites, and ground based monitoring.

2.5 Error Sources

The error in the GPS position is determined by two Factors. The reason there is a position error at all are the errors in the measured distances to the satellites called User Range Error (URE). These errors are further divided into three groups depending on where they occure. Errors in the parameters broadcasted by the satellites are here called satellite errors. Errors that occure in the signal path from the satellite to the receiver are called signal propagation errors. Finally, errors that are caused by unprecise measurenents of the signals by the receiver are called measurement errors. All three types are discussed later in this section.

The other factor is the satellite geometry. It determines how much the URE impacts the positioning accuracy. An optimal geometry would be stellites evenly distributed in all three dimensions. This is not possible because a receiver on the surface of the earth can not receive signals from satellites blocked by the earth. A metric to determine the geometry quality is the Dilution of Precision (DOP). Different versions of DOP can be determined like the Horizontal DOP (HDOP), Vertical DOP (VDOP), 3-D Position DOP (PDOP) and Time DOP (TDOP). The RMS position error can then be calculated with the variance of the URE (σ^2), and the corresponding DOP. For example, the horizontal RMS position error can be calcuated with:

$$RMS(\text{horizontal position error}) = \sigma \cdot HDOP \tag{2.4}$$

2.5.1 Satellite Errors

2.5.2 Signal Propagation Errors

2.5.3 Measurement Errors

Chapter 3

Error Correction Methods

Since GPS became operational, a range of methodes emerged to improve its positioning accuracy, which were not planned by the inventors of GPS. These methodes are designed to mitigate the effects of specific errors described in 2.5. Three of the most prominent ones are evaluated in this chapter. They are rated by how effective they are at improving the accuracy and how well they can be implemented on a sounding rocket.

3.1 Dual Frequency Measurements

A relatively new method of error mitigation for civil GPS users are Dual Frequency Measurements. This only became possible with the launch of Block IIR-M and IIF satellites. They transmit a second civilian signal on the L2 frequency called L2C. The benefit of measuring both the L1 C/A and L2C signal is that the ionospheric delay can be determined. The ionosphere slows down and radio waves, and thus adds a delay to the measured pseudoranges. This delay depends on the frequency of the radio wave. With the difference from pseudorange measurement received on different carrier frequencys, the total ionospheric delay can be calculated.

Dual Frequency Measurements can mitigate the ionospheric error, which is one of the biggest error sources, to a large degree. This error would otherwise have to be modeled with parameter transmitted by the GPS satellites. The modeled correction only reduces the error by about 50%. Used to implement the dual frequency measurements method are a dual frequency receiver and antenna. [7]

3.2 Carrier-Phase Measurements

3.3 Differential GPS

3.4 Summary

Chapter 4

GPS Concept for a Sounding Rocket

The challenge of reaching a GPS accuracy of 1 meter on a sounding rocket consists mainly of two parts. First, the GPS receiver on the rocket has to be able to get a position fix. This is not a given because of the extreme conditions the receiver experiences during the flight. Section 4.1 investigates this challenge. Secondly, the GPS accuracy has to be improved. The important part here is the vertical accuracy, because this is the value used by the controll to reach the right apogee. Standard GPS is only accurate to 15 meters for 95% of the time in the vertical axis. A significant improvement is needed to satisfie the accuracy reqiurement of 1 meter stated in section 1.3.

4.1 Special Conditions

The conditions on a rocket are unlike anything most GPS receivers will ever experience. The acceleration, velocity and height are the three main parameter that could exceed the operating range of a COTS receiver. There could either be a technical or legal limit to those parameters. A receiver as to be picked or tested for these requirements.

Apart from that, there is also vibration and rotation present on the rocket. Vibration should not be a problen for a GPS receiver apart from the mechanical stress on the electronics. Sounding rockets often have a spin during accent to stabilize the flight path. This rotation can have an effect on how the receiver antenna receives a signal. There is a problem called the wind-up effect, where an error occures when the receiver antenna is rotated relative to the satellite antenna. This error only affects carrier phase measurements and not pseudoranges. One full rotation results in an error in the phase measurement of one wavelength, which is about 20cm for the GPS L1 carrier [8]. So only system with carrier phase measurements would need to correct for this error if the rotation reults in a too large error. Apart from that, the receiver could experience fading of the GPS signals because of rotation. This could happen if a satellite elevation relative to the antenna changes during the rotation and the antenna gain is not constant in this area. It will have to be tested how a receiver behaves in such a situation.

Another problem could come from internal interference. Especially from the telemetry transmitter with its relatively high power. The GPS signal, when it reaches the surface of the earth, has a signal strength of about -125dBm. To pick up such a weak signal, GPS antennas need a high gain and the receivers a high sensitivity. This increases the risk of interference from a transmitter close by even if it transmitts on a different frequency band. Interference can cause the *carrier-to-noise densitiy* to shrink to the point that tracking of the GPS signals is lost. Tests are needed to evaluate the influence of other elecrtonical components in the rocket on the GPS antenna and receiver. The influence of relatively high power sources like the telemetry transmitter should first be calculated as far as possible to minimize the risk of damaging the GPS receiver.

4.2 Accuray Enhancement Concept

4.3 System Overview

4.4 Data Flow

4.5 Potential Problems

Setup:

- Two M8T modules in the nosecone and one at the ground station.
- RF-uplink from ground station to rocket.

Procedure:

- Ground station averages position measurements over a longer time to get reference position. This might not be the exact position, but this only results in a constant bias in the rockets absolute position. Reference position stays fixed when sending of differential correntions starts.
- Ground station calculates distance to each visible GPS satellite from reference position and ephemeris data.
- The differnce between the calculated distance and the measuren pseudorange is calculated for each satellite.
- RTCM 2.3 meassage 1 and 3 are created with the pseudorenge corrections.
- The RTCM messages are sent to the rocket over the RF-link. The update rate of the corrections could be about 1Hz.
- On the rocket, the messages are fed into the UART interface of the GPS receiver which includes them in the position estimation.
- Tropospheric corrections could be added to the pseudorange corrections at the ground station or in the rocket.
- The first correction is sent when the rocket is still on the launch pad. One or more corrected measurements at the launch pad serve as the zero point of the trajectory.
- The position estimations during the flight can be differnced with the launch pad zero point to get the relative position to the launch pad. With this the reference position bias cancels out. For the rocket controll and the post processing, the relative position to the launchpad is more relevant. The absolute position, where the reference positon bias is still present, is only needed for the recovery of the rocket where accuracy is not as important.

Chapter 5

Implementation

Chapter 6

Testing and Validaton

6.1 Testing Setup

Two receivers, with and without correction message input. Both can log data. Reference station with antenna pole, GPS receiver, laptop and XBee module. Software to visualize data.

6.2 Static Accuracy Test

Compare GPS positioning accuracy with and without correction messages to see if the accuracy is improved. The reference receiver measures the reference position over some hours. The rover is at a fixed and though Google Maps known location. The variance and bias are observed in both cases.

Is the bias improved? Is the variance improved?

6.3 Mobile Accuracy Test

Two receivers test while the rover is moving. A route is walked which was predetermined with Google Maps.

How accurate is the system when the rover is moving?

6.4 Distance Test

Two receiver test with a horizontal distance of about 3km between rover and reference station.

Does DGPS still improve the accuracy if the rover is 3km away from the reference station?

6.5 Height Difference Test

Two receiver test with the rover on a mountain which is about 3km higher than the reference station in the valley.

How much impact does the tropospheric height effect have on the DGPS accuracy?

6.6 Telemetry Antenna Interference Calculation

6.7 Antenna Rotation

6.8 Correction Message Interruption

6.9 Rocket Test

Chapter 7

Conclusion

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Appendices