Lucerne University of
Applied Sciences and Arts

ARIS - Localization of a Sounding Rocket via GPS

Bachelor Thesis

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Classification: Access

May 8, 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 8, 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

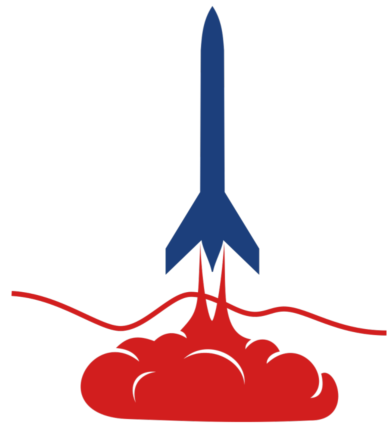

Figure 1.2: Spaceport America Cup

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

To make it possible to integrate the approach into the rocket, a set of requirements is defined. Also requirements for the performance of the system are given.

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 real 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.

2.2.1 Functional Principle

All modern GNSS work with the principle of trilateration. For this method of positioning, the distance to three known lacations is needed to calculate the own position in three dimensions. With radio waves, the distance to a transmitting station can be measured trough the propagation time of the wave. The distance is calculated when the propagation speed is divided by the propagation time. Ground based systems can only solve for the position on a two dimensional plane because they are limited in transmitter height above the surface of the earth. A space-based system can also solve for height with transmitters distributed in all three dimensions.

GNSS achieve this with satellites as transmission stations. GPS satellites are in medium earth orbit at an altitude of about 20'200km with each satellite circling the earth twice a day. The orbits of GLONASS are a bit lower and GALILEO a bit higher.

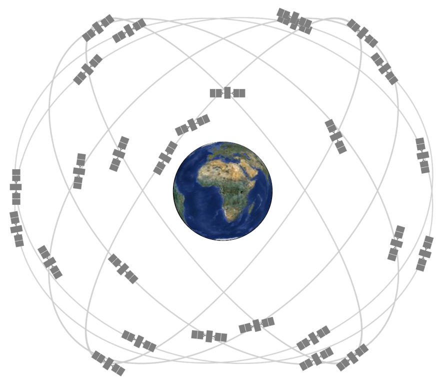

Figure 2.1: GPS satellite constellation [6]

2.2.2 Signals

2.2.3 Performance

2.3 Error Sources

2.3.1 Satellite Errors

2.3.2 Signal Propagation Errors

2.3.3 Receiver Errors

Chapter 3

Accuracy Enhancement Systems

3.1 Carrier-Phase Measurements

3.2 Differential GPS

3.3 Real Time Kinematic

3.4 Satellite-Based Augmentation Systems (SBAS)

3.5 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 [7]. 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