

FINAL YEAR THESIS PROJECT

Predicting the Accuracy with Which Upper Air Wind Dynamics can be Measured by the Doppler Tracking of a Pilot Balloon

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And, seriously, the greatest thanks and praise goes to God. For from Him and through Him and to Him are all things. To Him be glory forever.

PLAGIARISM DECLARATION

This thesis is my own work. I have not plagiarised it from any source. I know that plagiarism is a serious form of academic dishonesty. I have referenced all ideas borrowed from others.

Dinè le Roux

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY	5
1.1 INTRODUCTION AND BACKGROUND.....	5
1.2 REVIEW OF LITERATURE.....	6
1.4 IMPLEMENTATION.....	8
1.5 TESTING.....	10
1.6 CONCLUSIONS & RECOMMENDATIONS	12
1.7 FUTURE WORK	14
2 INTRODUCTION AND BACKGROUND	15
2.1 TERMS OF REFERENCE.....	15
2.2 BACKGROUND INFORMATION ON THE PROJECT	15
2.3 A BRIEF OVERVIEW OF THE REPORT.....	18
3 LITERARY REVIEW	19
3.1 USES OF DOPPLER TRACKING	19
3.2 METHODS OF OBTAINING UPPER AIR WIND DATA.....	20
3.3 IMPLEMENTATION OF DOPPLER TRACKING IN VARIOUS SYSTEMS	20
4 THE DESIGN	22
4.1 THE DESIGN SPECIFICATION	22
4.2 CONCEPTUAL DESIGN	23
5 IMPLEMENTATION.....	27
5.1 DETERMINING THE BALLOON'S PATH FROM FREQUENCY READINGS	27
5.2 ERRORS DUE TO VARIATION OF THE TRANSMITTED FREQUENCY	34
5.3 ERRORS DUE TO LINE-OF-SIGHT DROPOUTS	37
5.4 ERRORS ON ACCOUNT OF THE RECEIVER	38
5.5 ERRORS DUE TO ANTENNA POSITIONING	44
5.5 THE REFINED SYSTEM	45
6 TESTING	47
6.1 TEST DATA	47
6.2 TESTING UNDER PERFECT CONDITIONS	48
6.3 TESTING WITH FREQUENCY ERRORS	48
6.4 TESTING WITH MULTIPATH DROPOUTS	60
6.5 TESTING WITH LINE-OF-SIGHT DROPOUTS	63
7 CONCLUSION & RECOMMENDATIONS	65
7.1 THE CORRECTNESS OF THE SOFTWARE SIMULATOR	65
7.2 RECOMMENDATIONS CONCERNING EXTERNAL FACTORS.....	65

7.3 THE EFFECT OF VARIOUS ERRORS ON THE SYSTEM.....	66
7.4 CONCLUSION	67
8 FUTURE WORK.....	68
8.1 IMPLEMENTATION OF A KALMAN FILTER	68
8.2 A METHOD FOR TRACKING THE BALLOON IN THE FIRST STAGE OF ITS FLIGHT.....	68
8.3 A METHOD TO ELIMINATE ERRORS DUE TO CHANGES IN TRANSMISSION FREQUENCY	68
REFERENCES	70
APPENDIX A: NORMAL (GAUSSIAN) DISTRIBUTION.....	73
APPENDIX B: FRESNEL ZONES.....	74

1 EXECUTIVE SUMMARY

1.1 Introduction and Background

Instructions to execute this project were given by Mr Ian Robertson of Tellumat Pty (Ltd) in May 2006, under the guidance of Professor Mike Inggs. The need for the project arose when new ways of tracking weather balloons (otherwise known as pilot balloons) were being investigated by Tellumat on behalf of the South African Weather Services. Mr Robertson's instructions were to:

- Construct software to accurately extract the path of a weather balloon during its ascent, using Doppler tracking.
- Extract wind velocity (speed and direction) information at different altitudes from this data.
- Analyze the accuracy of the system, and thus the accuracy of the velocity data produced.

Twice a day weather balloons are released from weather stations throughout South Africa. By tracking the position of a weather balloon, wind speed and wind direction of upper-air regions can be calculated. This wind information is vital in producing weather forecasts. At present, the South African Weather Service is using a system where balloon positions are recorded by an operator using a theodolite. This method of balloon tracking is highly unreliable, and thus an alternate method of tracking needs to be implemented.

A better option would be to use Doppler tracking to track the balloon. With Doppler tracking however, there are several factors which contribute to the tracking system's inaccuracies. The weather service requires an indication of the extent of the deviation of the calculated path and velocity of the balloon from its actual path and velocity. If the deviation is too great, the Doppler tracking method cannot be used.

The objective of this thesis is to predict the accuracy with which a weather balloon can be tracked using a Doppler tracking technique, and thus predicting the accuracy with which wind velocities (speed and direction) can be measured.

1.2 Review of Literature

Research was done to gain insight into various implementations of Doppler Tracking, as well as various methods of obtaining upper air wind data.

Doppler Tracking has been used to track a variety of moving objects, including precipitation, spacecraft, underwater vehicles, and even sea ice [6]. It is also being used to measure solar gravitational deflection in various studies, such as the Cassini experiment [2]. In the United States, upper air wind data is obtained mostly by various methods using Doppler Weather Radars, such as one described in [21], or by using MST radars [16].

In all the Doppler tracking systems investigated, the moving object either emits a signal or reflects one, which is then received by a stationery receiver. Either the frequency or the phase of the received signal is used to extract velocity information of the object. There are very few papers that describe a simple Doppler Tracking system using omni-directional antennas. Doppler tracking systems are generally extremely sophisticated and complex. Not much useful information was gained from the papers studied, with the exception of the equations for determining radial velocity. We thus approached the problem from first principles.

Towards the end of this project two papers were discovered which proved to be extremely helpful. In a paper entitled “Analysis of a Four-Station Doppler Tracking Method using a simple CW Beacon” [5], the authors describe a process of tracking a continuous-wave beacon using Doppler tracking with three antennas, by the method of the intersection of three spheres. We had then already discovered and implemented this kind of solution (see Section 5.1). Fricke and Watkins noted the necessity of eliminating the transmitter frequency variation. They also present a solution that uses

four receiving stations, where the problem of transmitter frequency variation is eliminated by comparing frequencies to each other.

1.3 Design

The problem that this project addresses is finding the path of a weather balloon during its ascent, and hence its velocity (speed and direction) at different altitudes. The solution must be in the form of software that implements a Doppler Tracking technique.

This system requires a low-cost transmitter to be attached to the balloon. It also requires three or more omni-directional receiving antennas. The antennas will each have a receiver attached which will report on the frequency received. The design of the antennas, receivers and transmitters does not fall under the scope of this project.

The frequencies received by the antennas will have been distorted as a result of the Doppler Effect. The difference in transmitted frequency and received frequency will be reported by the receiver. This difference is called the Doppler Frequency. Given these Doppler frequencies, as well as the launch site of the balloon and the locations of the antennas, the path of the balloon needs to be extracted. Subsequently, the errors associated with the entire system must be analyzed.

The data available at the start of the process is the x-, y- and z- Cartesian coordinates of the three antennas, the x-, y- and z- Cartesian coordinates of the launch site of the balloon and the Doppler frequencies (in Hz) from each antenna. The software consists of several modules:

- **A Relative Velocity Calculator:** This part of the software will use the Doppler equation to obtain the velocity of the transmitter relative to each antenna.
- **A Position Calculator:** This component will calculate the new position of the transmitter after time T, using the current position as well as the velocity from the relative velocity calculator.

- **A Velocity Calculator:** Since the path of the balloon is now known, by differentiation the actual velocity over a certain interval may be calculated.

From the velocity calculator, a list of velocity magnitudes and angles will be produced as output.

1.4 Implementation

1.4.1 Determining the Path of the Balloon

The Relative Velocity Calculator was implemented by converting the Doppler frequencies from the various receivers into velocities, using the Doppler equation. The outcome of this module will be distances traveled by the transmitter over time T , relative to the respective antennas. If the antennas are located at A, B and C, then these distances are d_a , d_b and d_c .

The Position Calculator, which finds the new position of the transmitter after time interval T , was first implemented by adding the three velocity vectors from each antenna to obtain the total velocity. However, this method did not yield the correct results. The problem was then revised as the problem of finding the intersection of three spheres of radii, r_a+d_a , r_b+d_b and r_c+d_c , where d_a , d_b and d_c are the distances mentioned above, and r_a , r_b and r_c are the current distances of the balloon from the antenna. The first implementation of this method worked well, but it was too slow. It was then implemented using the **Solve** function in Matlab, and yielded most satisfactory results.

The Velocity Calculator could now be implemented by simply calculating the velocity over a certain time interval by differentiating the path.

1.4.2 Sources of Errors in the System

The transmitter will have some unpredictable frequency error associated with it due to a variety of factors, particularly the aging of the quartz crystal [8]. It is therefore

suggested that, while the transmitter is stationary, the frequency be recorded and used to adjust readings later.

A problem occurred when it was established that the transmitter's frequency varies with temperature. Fortunately, the transmitting device takes temperature readings for various altitudes, and once all the data has been collected, the transmitted frequency can be corrected according to the temperature. The frequency received must thus be altered using this frequency-temperature curve. If the frequencies cannot be corrected exactly, it will cause an error in the system.

When the balloon is near the ground, at least two of the antennas will not be in its line of sight. For the first few hundred metres of the balloon's ascent, no frequency readings will reach two of the antennas, and thus the path cannot be calculated. As we are not interested in the wind velocities at these low altitudes, all that is of concern is the height of the balloon. We will aim to predict the height traveled by the balloon in this first stage of ascent, and thus have an estimated current position of the balloon when the first frequency readings are recorded. If the height is not predicted correctly, it will cause an error in the system.

Several sources of error are also present in the receiver. This includes an error due to the number of frequency samples taken in the Power Spectral Density, and also errors due to signal fading. Multipath causes signal fading through more than one version of the transmitted signal arriving at the receiver via multiple paths. Multipath is caused mostly by diffraction and ground reflection, and this diffraction can be avoided by obtaining Fresnel zone clearance.

However, even if caution is taken to clear Fresnel zones, it is likely that fading will still occur. This will result in the amplitude of the incoming signal being weakened. When the signal-to-noise ratio becomes too large, it becomes impossible to detect the frequency f , because the signal is too small compared to the noise. It is thus important to analyze the incoming signal and determine the signal-to-noise ratio. If the SNR value is too low, the reading should be discarded. The discarded signal can be predicted using a spline.

1.5 Testing

The software simulation had now been constructed, and the various sources of errors in the system identified. We were able to run tests to see how these errors affect the velocities of the balloon as calculated by the simulator. For each test case, only one source of error was added to the input. This input - with the error added to it - was then entered into the simulator to see how it would affect the calculated velocities of the balloon. In each case, the resulting error in velocity is shown, by subtracting the velocity calculated by the simulation, v , from the correct velocity, v_c . This is done for both magnitude $|v|$ and direction $\angle v$.

1.5.1 Testing under Perfect Conditions

The first tests were run using a set of perfect data. This yielded the exact correct path. We can therefore safely assume that the simulation works correctly when no errors are added to the input.

1.5.1 Testing with Frequency Errors

The second set of tests involved varying the frequency transmitted, and thus the frequency received. The frequencies received by all three stations were given normal distributions with certain standard deviations. This data was entered into the simulator, and the calculated velocities of the balloon were then investigated.

The standard deviation of the transmitted frequency due to temperature is about $\sigma_{fd} = 5.24 \times 10^3$ Hz. No tests were run for this case, as it is obvious that inaccuracies in velocities will be enormous. The standard deviation in frequency due to errors in the receiver is $\sigma_{fd} = 0.42$ Hz. To see what effect this will have on velocities calculated, we ran tests where the input frequencies were given a standard deviation of 0.42 Hz. The input frequencies were also given errors of other standard deviations, in order to gain a better understanding of how frequency errors affect the velocity output.

The resulting velocity magnitudes and angles were subtracted from the correct magnitudes and angles to show the error. These differences are $d_m = |v_c| - |v|$ and $d_a = \angle v_c - \angle v$. They have normal distributions with μ_{dm} , σ_{dm} and μ_{da} , σ_{da} .

It was found that if we crudely impose a constant rate of ascent on the balloon, as well as make use of splines, the results are better.

The table shows how errors in frequency inputs affected resulting velocities.

Standard Deviation Of Frequency (σ_{fd})	Error In Velocity Magnitude		Error In Velocity Angle	
	Mean (μ_{dm})	Standard Deviation (σ_{dm})	Mean (μ_{da})	Standard Deviation (σ_{da})
0.167 Hz	0.0047 m/s	2.73 m/s	0.0572 rad.	0.1565 rad.
0.42 Hz	0.0838 m/s	6.8002 m/s	0.0122 rad.	0.2798 rad.
0.667 Hz	9.25 m/s	50.57 m/s	0.0302 rad.	0.8532 rad.
1.667 Hz	39.05 m/s	65.98 m/s	0.0104 rad.	0.6303 rad.
3.33 Hz	80.40 m/s	135.06 m/s	0.0177 rad.	0.8647 rad.
6.67 Hz	277.32 m/s	449.36 m/s	0.0146 rad.	1.1487 rad.

1.5.2 Testing with Multipath Dropouts

A number of weak signals were entered into the system, which will be discarded, as they will produce poor signal-to-noise ratios. A spline is used to predict the resulting missing positions in the path. For 30 or less dropouts, the difference (d_m) between actual velocity magnitude and perceived velocity magnitude is has a standard deviation (σ_{dm}) of roughly 11 m/s, while the difference (d_a) between the actual velocity angle and perceived velocity angle has a standard deviation (σ_{da}) of roughly 0.14 radians.

1.5.3 Testing with Line-of-Sight Dropouts

This set of tests was run with the balloon being out of line-of-sight of two antennas for the first 120 metres of ascent, and thus no frequencies appearing at two of the receivers. The path was not calculable, and it had to be predicted for the first few seconds. The difference (d_m) between actual velocity magnitude and perceived velocity magnitude for the entire path then has a mean (μ_{dm}) of 57.3932 m/s and a standard deviation (σ_{dm}) of 115.8911 m/s. The difference (d_a) between the actual velocity angle and perceived velocity angle has a mean (μ_{da}) of 0.0058 radians and a standard deviation (σ_{da}) of 0.9018 radians.

1.6 Conclusions & Recommendations

A working piece of simulation software was produced that uses the Doppler frequencies received from the transmitter by three different antennas to track the balloon. When an error-free set of frequencies is used as input to the path simulator, the path calculated, and therefore the velocities calculated, is exactly correct.

Various recommendations were made concerning factors external to the software, in order to minimize errors. These were:

- Ensure that the line-of-sight path between the antennas and the transmitter has first Fresnel zone clearance.
- Ensure that the layout of the antennas does not affect frequency readings negatively.
- Keep the bandwidth of the receiver to a minimum, and discard readings with poor signal-to-noise ratios.
- In the receiver, take as many frequency domain samples as possible

During testing, it was established that using a spline and imposing a constant rate of ascent on the balloon can greatly improve the simulation's calculation of the balloon's path and velocity. Even so, the various errors in the system cause large errors in the calculated velocity of the balloon.

The test results below show the effect of various sources of errors on the accuracy of the calculated velocity, and whether the accuracy obtained is satisfactory or not.

Affecting Factor	Error in Input	Accuracy of Calculated Velocity	Desired Accuracy	Satisfactory? (YES/NO)
None	none	$\sigma_{dm} = 0 \text{ m/s}$ $\sigma_{da} = 0 \text{ rad.}$	$\sigma_{dm} = 1.25 \text{ m/s}$ $\sigma_{da} = 0.0436 \text{ rad}$	YES
Multipath Dropouts	30 or less dropouts	$\sigma_{dm} = 11 \text{ m/s}$ $\sigma_{da} = 0.14 \text{ rad.}$	' '	NO
LOS Dropouts	dropouts for the first 120m of ascent	$\sigma_{dm} = 115.89 \text{ m/s}$ $\sigma_{da} = 0.9018 \text{ rad.}$	' '	NO
Frequency	$\sigma_f = 0.167 \text{ Hz}$	$\sigma_{dm} = 2.73 \text{ m/s}$ $\sigma_{da} = 0.15 \text{ rad.}$	' '	NO
	$\sigma_f = 0.667 \text{ Hz}$	$\sigma_{dml} = 50.55 \text{ m/s}$ $\sigma_{da} = 0.85 \text{ rad.}$	' '	NO

Multipath dropouts and line-of-sight dropouts cause the calculated velocities to be less accurate than permitted. Even small errors in frequency also cause large errors in calculated velocities. Both the frequency error produced by change in temperatures, as well the frequency error in the receiver cause the velocity calculations to be more inaccurate than permitted. It was found that in all cases, when errors were added to the simulation, the error in calculated velocity is larger than permitted. Solutions for dealing with multipath- and line-of-sight dropouts may be developed, but the main concern is the change in transmitter frequency. This simulator requires frequencies to be extremely accurate, and this is not feasible.

It should be noted, however, that the simulator is very crude. Therefore the idea of Doppler tracking balloons should not be discarded at this point. Rather, a more sophisticated simulator is needed which does not require the transmitted frequency to be accurate. Evidence for such a system exists, and is discussed below.

1.7 Future Work

In order to build a software simulator which can accurately determine the path and velocity of a balloon using Doppler tracking, a number of tasks need to be carried out.

When multipath dropouts occur, no new position of the balloon can be calculated. The position therefore needs to be estimated. At present, a spline is used. This is a fairly simplistic method, and a more sophisticated one will ensure better accuracy in calculated velocities. The recommended method for future use is the Kalman filter, which will need to be implemented.

During the first 120 metres of the balloon's ascent, it is not within line-of-sight of two of the antennas. At present, this is solved in the simulator by simply assuming that the balloon moves straight up. However, this method creates large errors in velocities calculated. A better way of either tracking or predicting the path of the balloon during this first stage needs to be invented.

As already mentioned, the main concern in the current simulator is the error due to change in transmitter frequency. This simulator requires transmitted frequencies to be extremely accurate. A more sophisticated simulator is needed which does not require the transmitted frequency to be accurate. A possible method is described in [Fricke, 1961]. This method uses four receiving stations, with one at the origin of the Cartesian coordinate system. The trick is to measure the *difference* in frequency between two stations. By using this method, changes in the transmitter frequency can be completely ignored. It is suggested that an alternate simulator be implemented, using this technique.

2 INTRODUCTION AND BACKGROUND

2.1 Terms of Reference

Instructions to execute this project were given by Mr Ian Robertson of Tellumat Pty (Ltd) in May 2006, under the guidance of Professor Mike Inggs. The need for the project arose when new ways of tracking weather balloons (otherwise known as pilot balloons) were being investigated. His instructions were to:

- Construct software to accurately extract the path of a weather balloon during its ascent, using Doppler Tracking.
- Extract wind velocity (speed and direction) information at different altitudes from this data.
- Analyze the accuracy of the system, and thus the accuracy of the velocity data produced.

2.2 Background Information on the Project

2.2.1 Pilot Weather Balloons

Numerical weather prediction proceeds from initial readings of pressure, wind, temperature, moisture and other data [21]. Some of this data must come from upper-air regions, and can be obtained from weather balloons (also known as pilot balloons). Twice a day weather balloons are released from weather stations throughout South Africa. The balloon flights last around 2 hours. The balloon can drift as far as 200 km away, and rise up to over 30 km into the atmosphere.



Figure 1: The Launch of a Weather Balloon. (Source [1])

Weather balloons, which are made of latex or synthetic rubber, are filled with either hydrogen or helium. The sides are about 0.051 mm thick before release and will be only 0.0025 mm thick at typical bursting altitudes. The balloons, which start out measuring about 1.8 metres wide before release, expand as they rise to about 6.1 metres in diameter. [14]

2.2.2 Weather Sensing Instruments

An instrument called a radiosonde is attached to the balloon. The main component of the radiosonde is a sturdy, lightweight, white cardboard and polystyrene instrument package. Various weather sensing instruments are located within or attached to this package. These include temperature, humidity and air pressure sensors.

The radiosonde thus measures pressure, temperature and relative humidity as it ascends up into the atmosphere. These observed data are transmitted immediately to the ground station by a radio transmitter located within the instrument package [11]. At the end of the flight, the balloon will burst and the radiosonde will fall to the ground.

2.2.3 Measuring Wind Dynamics

The balloons are set up to follow a constant rate of ascent of approximately 6 m/s. By tracking the position of the balloon, wind velocity (speed and direction) can be calculated. This information is vital in producing weather forecasts. At present, the South African Weather Service is using a system where balloon positions are recorded by an operator using a theodolite. The operator records both the horizontal and vertical angles of the balloon using the theodolite. This is known as optical tracking. The path of the balloon can then be calculated.

This method of balloon tracking is highly unreliable, as it requires the balloon to be seen at all times, and it also relies on the operator committing no human errors. As soon as the balloon is behind a cloud, no readings can be taken. An alternate method of tracking thus needs to be implemented.

One solution would be to attach a GPS receiver to the radiosonde and transmit GPS data back to ground at certain intervals. However, GPS receivers are expensive (about US\$40) and since radiosondes are not often recoverable, this is not a feasible option. Another option would be to use a rawinsonde tracked by a radio direction finder, or radio theodolite. This is a ground-based, steerable radio antenna that tracks precisely the angular position (azimuth and elevation) of the rawinsonde [23]. A third, very similar option, would be to use Doppler tracking to track the balloon.

2.2.4 Doppler Tracking

The Doppler Effect is the change in frequency and wavelength of a wave perceived by an observer when the source is moving relative to the observer. This phenomenon can be used in radar to measure the velocity of detected objects. The frequency of the radar reflection is shifted, based on the relative velocity of the target.

An advantage to using Doppler tracking is that the system will not need steering antennas, it can simply use omni-directional ones. In addition, there are inherent advantages that occur when a balloon is tracked with Doppler tracking that help to reduce errors. [21] We will use the Doppler method, since it is easier to implement.]

2.2.5 Objectives of this Project

With Doppler tracking, there are several factors which contribute to the tracking system's inaccuracies. The weather service requires an indication of the extent of the deviation of the calculated path and velocity of the balloon from its actual path and velocity. If the deviation is too great, the Doppler tracking method cannot be used.

The objective of this thesis is to predict the accuracy with which a weather balloon can be tracked using a Doppler radar technique, and thus predicting the accuracy with which wind velocities (speed and direction) can be measured. Currently, the readings are required to be accurate within 2.5 m/s and 5 degrees (0.0872 radians).

2.3 A Brief Overview of the Report

The implementation of Doppler Tracking in various systems was researched and is explained in Chapter Three. Chapter Four explains the design of the simulation software which will calculate the path of the balloon. Chapter Five illustrates in detail the implementation of the software described in Chapter Four. It reports the process followed in order to reach the final solution, and also discusses the various sources of errors encountered in the system. Chapter Six describes tests run to see how these errors affect the velocities of the balloon as calculated by the simulator. In Chapter Seven, the correctness of the software simulator produced is discussed, and various recommendations are made that will reduce sources of errors in the entire system. The effects of the remaining errors in the system are then discussed, and a conclusion regarding the use of Doppler Tracking for pilot balloons is drawn.

3 LITERARY REVIEW

Research was done to gain insight into various implementations of Doppler Tracking. In this chapter, the different uses of Doppler Tracking are first discussed, as well as various methods of obtaining upper air wind data. Lastly, the implementations of Doppler Tracking that may be of use in this project are discussed.

3.1 Uses of Doppler Tracking

Doppler Tracking has been used to track a variety of moving objects, including precipitation, spacecraft, underwater vehicles, and even sea ice [6]. It is also being used to measure solar gravitational deflection in various studies, such as the Cassini experiment [2].

The most common utilization of the Doppler Effect is in Doppler radar, which is used to obtain meteorological information. A radar unit sends out a pulse of microwaves. When the microwaves strike objects, such as falling precipitation, some of the microwaves are reflected back to the radar unit, where they are detected by an antenna and displayed on a screen. Doppler radar can determine wind speed by measuring the speed at which precipitation is moving horizontally toward or away from the radar antenna. It does this by measuring the change in frequency of the returning microwaves. The frequency of the returning waves decreases if the rain is moving away from the radar unit and increases if the rain is moving toward it. [18] The Doppler frequency shifts in Doppler Weather Radars are very small, and for this reason, Doppler radars must employ extremely stable transmitters and receivers.

Doppler tracking with radio waves has also been widely employed to track a number of different objects such as motor vehicles and spacecraft. In [9], Henning discusses the results of tracking a spacecraft – the Trailblazer. Jensen et al. presents a non-coherent spacecraft navigation technique using Doppler Tracking, to provide velocity of a spacecraft. [10]

A form of Doppler tracking which uses acoustic waves is also implemented in some SONAR systems. In [20], Wilcox presents a method for tracking a submarine with respect to N omni-directional sonabuys, by looking at the Doppler shifts in one or more frequencies emitted by the target. In a paper by A.H. Carof [4], a positioning and guidance technique for autonomous underwater vehicles (AUVs), based upon differential delay and a Doppler tracking system is proposed. The system uses a low-cost omni-directional hydrophone mounted on the AUV, and an external dual frequency transmitting subsystem.

3.2 Methods of obtaining Upper Air Wind Data

In the United States, upper air wind data is obtained mostly by various methods which use Doppler Weather Radars, such as one described in [21] where a Doppler Weather Radar and computer-controlled antenna maps winds throughout the lower troposphere. Another common method is using MST radars [16]. An MST radar, or mesosphere–stratosphere–troposphere radar, is a type of wind profiler designed to measure winds and other atmospheric parameters up to altitudes of 100 km or more [1].

3.3 Implementation of Doppler Tracking In Various Systems

In all the systems described in Section 3.1, the moving object either emits a signal or reflects one, which is then received by a stationery receiver. Either the frequency or the phase of the received signal is used to extract velocity information of the object,

by the equations $v_r = \lambda f_d$ or $v_r = \frac{\lambda}{2T_r} \left(\frac{\phi_2 - \phi_1}{2\pi} \right)$ respectively. The path of the object

can then be established.

There are few papers that describe a simple Doppler Tracking system using omni-directional antennas seem to be available. Tracking of point targets is often done with a monopulse feed horn or a conical-scan feed horn [12]. Modern Doppler tracking systems, such as the ones mentioned above, are often extremely sophisticated and complex. Not much useful information was gained from the above sources, with the

exception of the equations for determining radial velocity. We thus approached the problem from first principles.

Towards the end of this project two papers were discovered which proved to be extremely helpful. In a paper entitled “Analysis of a Four-Station Doppler Tracking Method using a simple CW Beacon” [5], the authors describe a process of tracking a continuous-wave beacon using Doppler tracking with three antennas, by the method of the intersection of three spheres. We had then already discovered and implemented this kind of solution (see Section 5.1).

F&W use as data the initial position of the balloon and the Doppler frequencies returned by the receivers, noting that the frequencies have to be extremely accurate. They start off using three antennas and implementing a system almost identical to the one described in Section 5.1 of this report. The radial velocity of the beacon as seen by each antenna is calculated using the equation $v_r = \lambda f_d$, and hence the distances that the beacon moves in relation to all three receiving stations are determined. The new position of the beacon is then calculated by the intersection of three spheres.

Fricke and Watkins noted the necessity of eliminating the transmitter frequency variation. They also present a solution that uses four antennas, where the problem of transmitter frequency variation is eliminated by comparing frequencies to each other. A paper by Henning [9] goes on to give some experimental results for such a system.

Enough information was gained from this literary review to proceed to designing the system in question.

4 THE DESIGN

This section explains the planned design of the software that will calculate the path of the balloon. It describes the specifications for the design, by looking at the problem statement, the scope of the project and the acceptance requirements. It then gives a conceptual overview of what the system will encompass. The implementation of these concepts is discussed in Chapter Five, together with the sources of errors detected in the system.

4.1 The Design Specification

The first step of the design work was to write a brief specification.

4.1.1 Problem Statement

The problem that this project addresses is finding the path of a weather balloon during its ascent, and hence its velocity (speed and direction) at different altitudes. The solution must be in the form of software that implements a Doppler Tracking technique.

This system will have a low-cost transmitter, transmitting a low-power continuous wave signal,

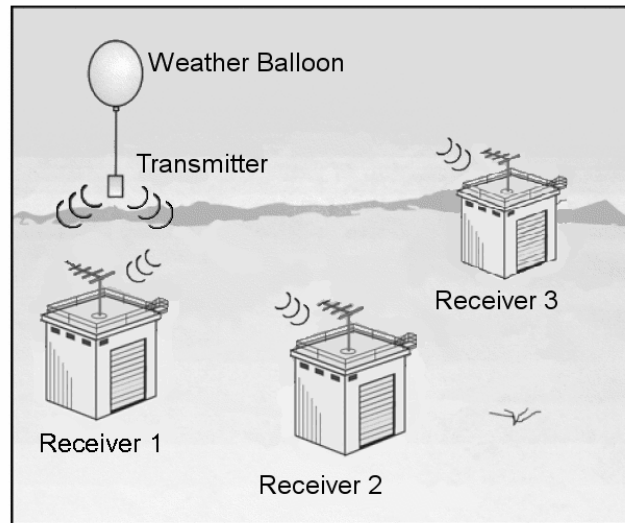


Figure 2: A cartoon drawing of the hardware used.

attached to the balloon. It will also have three or more omni-directional receiving antennas, such as Vertically Stacked Dipole antennas. The antennas will each have a receiver attached to it. The antennas will be placed roughly 50 km apart, and elevated to a height of about 30 m. The exact locations of the antennas are yet to be decided, and suggestions as to a layout will be made.

The frequencies received by the antennas will have been distorted as a result of the Doppler Effect. The difference in transmitted frequency and received frequency will be reported by the receiver. This difference is called the Doppler Frequency f_d . Given these Doppler frequencies, as well as the launch site of the balloon and the locations of the antennas, the path of the balloon needs to be extracted. Subsequently, the errors associated with the entire system must be analyzed.

4.1.2 The Scope of the Project

The scope of this project is to produce a working piece of software that takes the frequencies detected by the receivers and produces data of velocities versus altitude for the balloon. The errors associated with the entire system must be analyzed. However, the design of the antennas, receivers and transmitters does not fall within the scope of this project.

4.1.3 Acceptance Requirements

This project needs to comply with the following acceptance requirements:

- The software must:
 - Receive as input the location of 3 or more receiving antennas and the launch location of the balloon (all in Cartesian coordinates), as well as an array of Doppler frequencies versus time from each receiver.
 - Convert the Doppler frequencies to velocities.
 - Calculate the new position of the balloon after each time interval, and produce the path of the balloon.
 - Differentiate this path to find the velocity (speed and direction) of the balloon.
- The velocity vectors of the balloon versus altitude must be reported.
- The accuracy of this data must be estimated.

4.2 Conceptual Design

Below is a conceptual representation of what the simulation software will comprise. Each component is then discussed. It is assumed at this point that the system is entirely errorless.

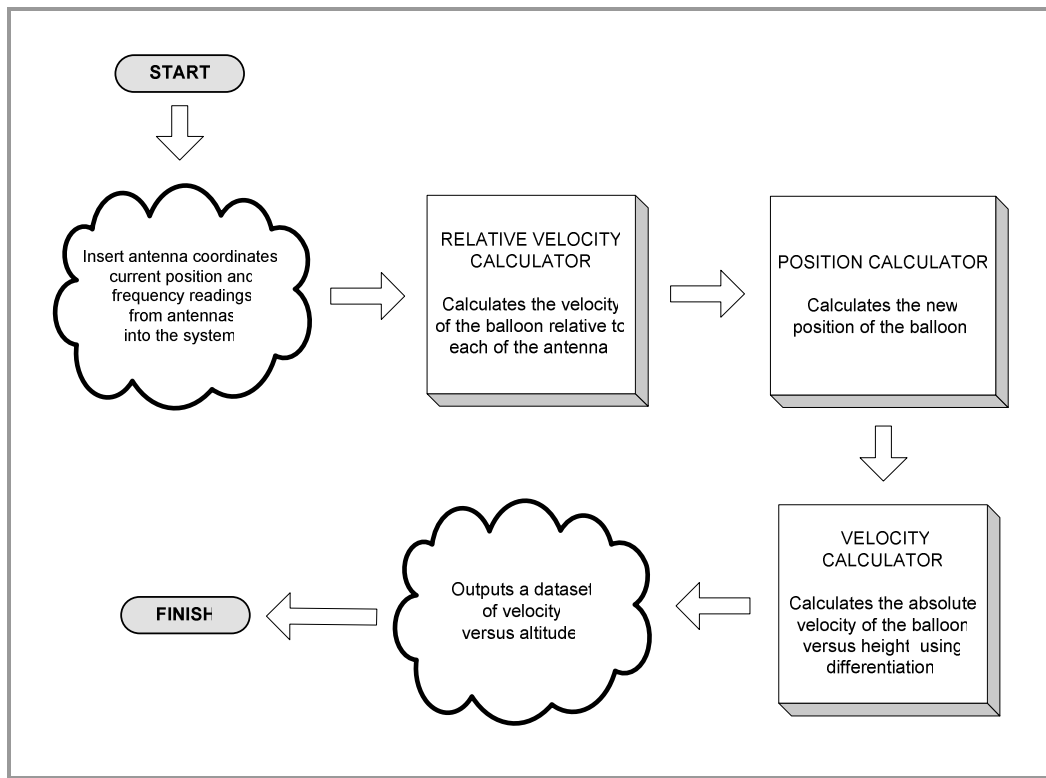


Figure 3: Conceptual Representation of the System.

4.2.1 Input Data

The data available at the start of the process is:

- the x-, y- and z- Cartesian coordinates of the three antennas
- the x-, y- and z- Cartesian coordinates of the launch site of the balloon
- Doppler frequencies (in Hz) from each receiver in the format shown in Figure 4.

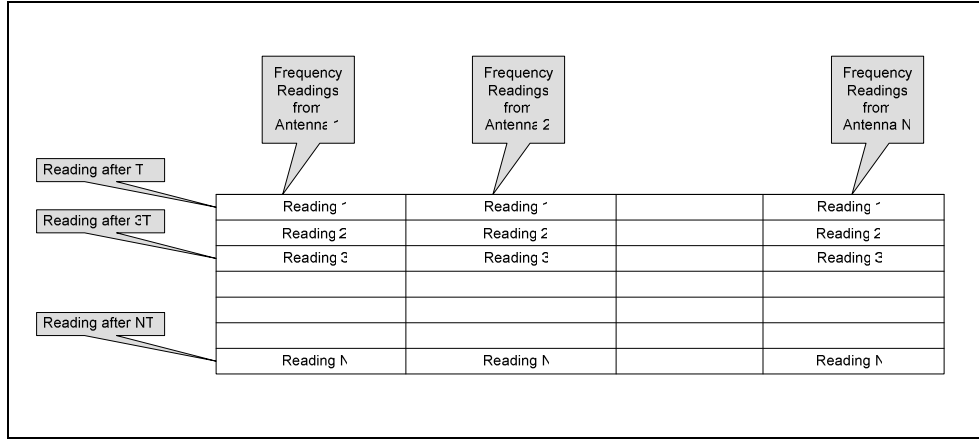


Figure 4: Input Data Format,

4.2.2 Relative Velocity Calculator

This part of the software will go through each row of frequencies received by the antennas, and use the Doppler equation (discussed in the next chapter) to obtain the velocity of the balloon relative to each antenna from the given Doppler frequency. This will be done for a specified time interval T . The actual velocity of the balloon is yet unknown.

4.2.3 Position Calculator

This component will calculate the new position of the transmitter after time T , using the current position of the balloon as well as the velocity from the relative velocity calculator. When this process has been executed for all frequency readings from all antennas, the result will be a list of x - y - and z - Cartesian coordinates of the position of the balloon versus time.

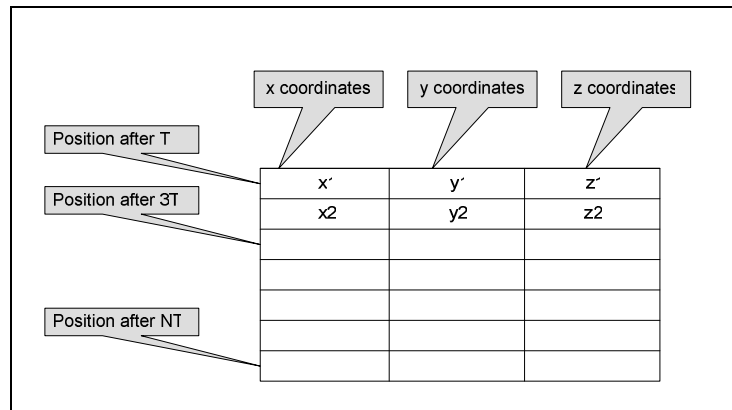


Figure 5: Output of Position Calculator

4.2.4 Velocity Calculator

Since the path of the balloon is now known, by differentiation the actual velocity over a certain interval may be calculated.

4.2.5 Output Data

From the velocity calculator, a list of velocity magnitudes and angles will be produced.

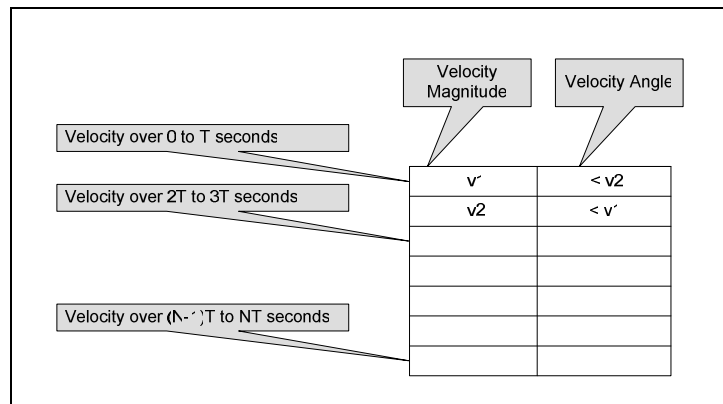


Figure 6: Output of Velocity Calculator

Ways of implementing these concepts will now be discussed.

5 IMPLEMENTATION

This chapter describes in detail the implementation of the software described in Chapter Four. It reports the process followed in order to reach the final solution, and also discusses the various sources of errors encountered in the system. Alterations are made to the software in order to minimize these errors and in conclusion, a conceptual representation of the final altered system is given.

5.1 Determining the Balloon's Path from Frequency Readings

It was decided to use Matlab for programming, as it included most of the necessary mathematical functions needed to implement the simulator. The implementation of the various concepts showed in Figure 3 above is discussed in this section.

5.1.1 The Relative Velocity Calculator

The various Doppler frequencies can easily be converted into velocities, using the Doppler equation.

The Doppler Effect is the change in frequency and wavelength of a wave perceived by an observer when the source is moving relative to the observer. This phenomenon can be used in radar to measure the velocity of detected objects. The frequency of the radar reflection is shifted, based on the relative velocity of the target [18]. The Doppler frequency shift is given by: [12]

$$f_d = \frac{2v_r}{\lambda}, \text{ where } \lambda = \frac{c}{f_0}$$

f_0 is the transmitted frequency, v_r the relative (or radial) velocity of the target with respect to the radar, and c is the velocity of propagation which is 3×10^8 m/s. This can be rearranged to give:

$$v_r = \frac{f_d \lambda}{2}$$

In the case of this particular project, there is no radar reflection, only a distortion of the wave as transmitted directly from the transmitter to the receiver. Hence the factor of 2 is removed to give:

$$v_r = f_d \lambda$$

This then gives the velocity of the transmitter *relative to* each antenna. In this project, only the magnitudes of velocities are obtained, as the antennas are omni-directional. The Doppler frequencies f_{da} , f_{db} and f_{dc} from antennas A, B and C will thus produce velocities v_a , v_b and v_c . By multiplying with time T , the distances traveled by the transmitter over T can be obtained. These are then d_a , d_b and d_c .

5.1.2 Position Calculator

Once the Doppler frequencies have been converted into velocities and distances, a method is needed to find the new position of the transmitter after time interval T . The current position of the transmitter is known, and is represented as (x, y, z) .

Failed First Attempt

At first, the three velocity vectors from each antenna was added together in order to obtain the total velocity. The three vectors had magnitudes d_a , d_b and d_c , and the direction in each case was taken as the direction of the balloon relative to the antenna. An example is shown in Figure 7 below. The three grey lines are the three velocity vectors, and these were then added to produce the total velocity (the black line.)

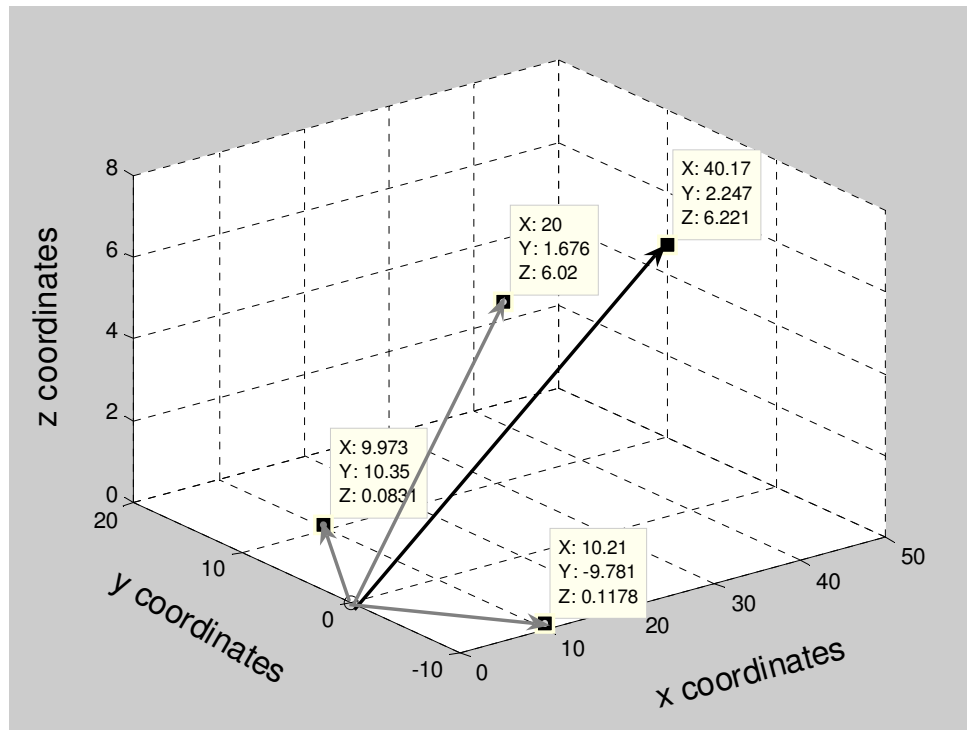


Figure 7: Graphical Illustration of the First Attempt

However, when this method was run continuously to find the path of the balloon, it was apparent that it was incorrect. The calculated path does not represent the actual path at all, as Figure 8 shows.

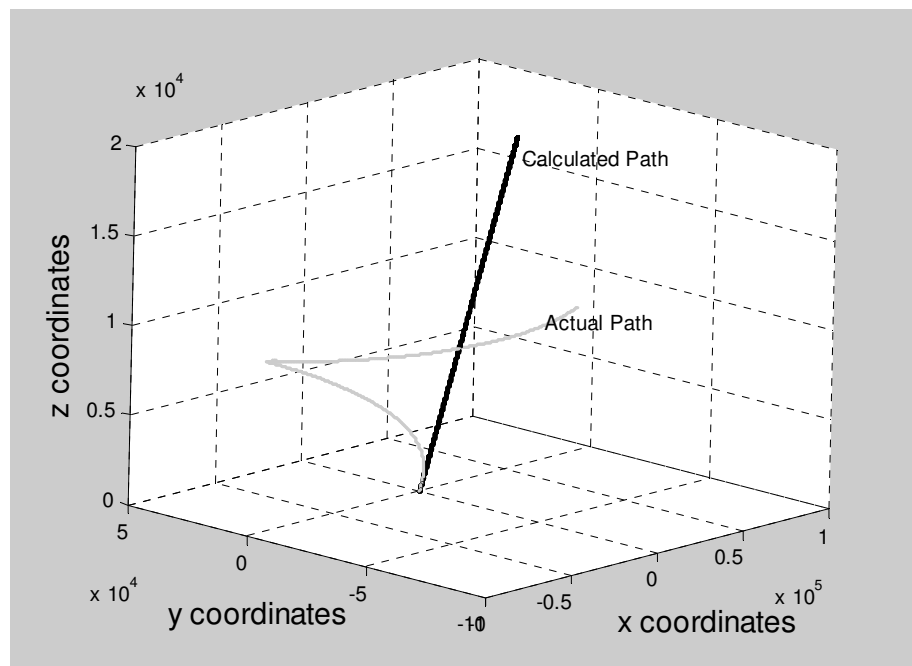


Figure 8: Test results for the First Attempt

It was then thought that simplifying the problem to two dimensions would make it easier.

Intersection of 3 Spheres

The problem was that the relative velocity observed by each antenna is only an indication of *how far away from the antenna the balloon has moved*. If the balloon was r metres away and it then moves another d metres away, it is now $r+d$ metres away. In two dimensions, this gives a circle with the antenna as the centre, and in three dimensions it gives a sphere.

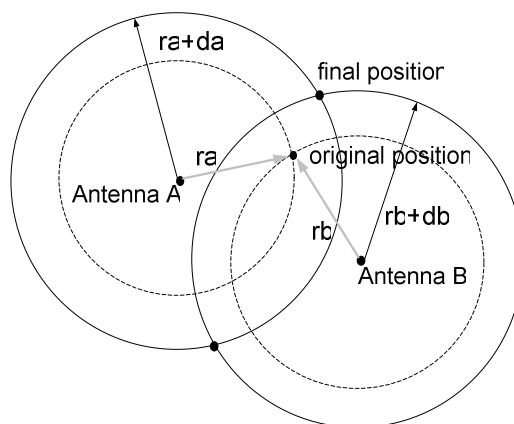


Figure 9: Illustration Of The Tracking Problem In 2D.

If we have two circles of possible points on which the balloon might lie, we can find the position of the balloon by taking the intersection of the two circles (as in Figure 9). Initially, the balloon is r_a metres away from antenna A and r_b metres away from antenna B. It then moves another d_a metres away from antenna A and another d_b metres away from antenna B. The new position is the intersection of the circles of radii r_a+d_a and r_b+d_b . In the case of

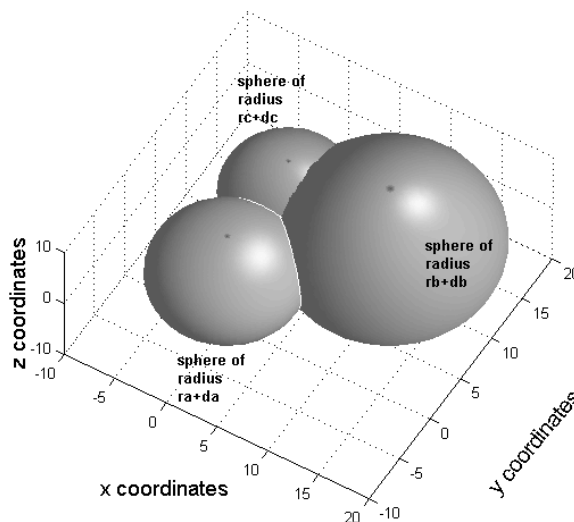


Figure 10: The problem is finding the intersection of three spheres. The white circles show the intersections of the spheres with each other.

this project, there are three antennas (A, B and C) that each report a distance traveled by the balloon (d_a , d_b and d_c) in three dimensions. The problem is thus to find the intersection of three spheres, as is shown in Figure 10.

Code was written that, in three dimensions, calculates first the intersection of sphere A with sphere B. Then it calculates the intersection of sphere A with sphere C (see appendix for details). Both these intersections are circles (the white circles in Figure 10 above). The circles will each have centre p , normal n and radius r , as in Figure 11. The intersection of these 2 circles with each other was calculated, giving the two points of intersection of the 3 spheres. The one point could be ignored, as it would fall below the surface of the earth.

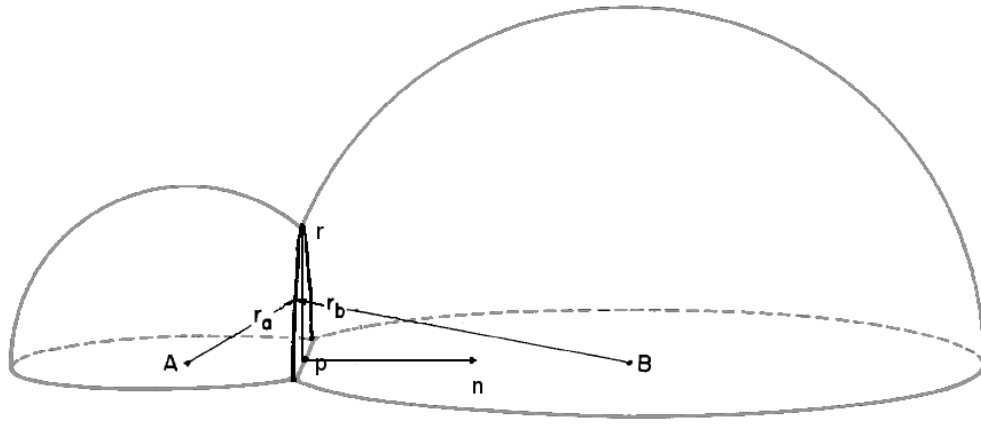


Figure 11: The intersection of 2 spheres.

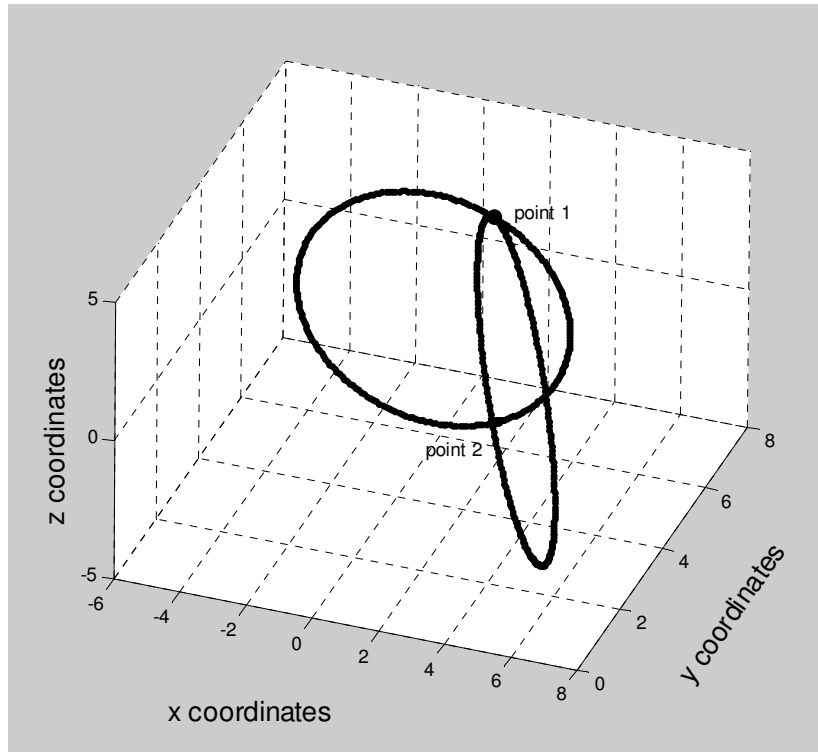


Figure 12: Finding the intersection of 3 spheres by the intersection of 2 circles.

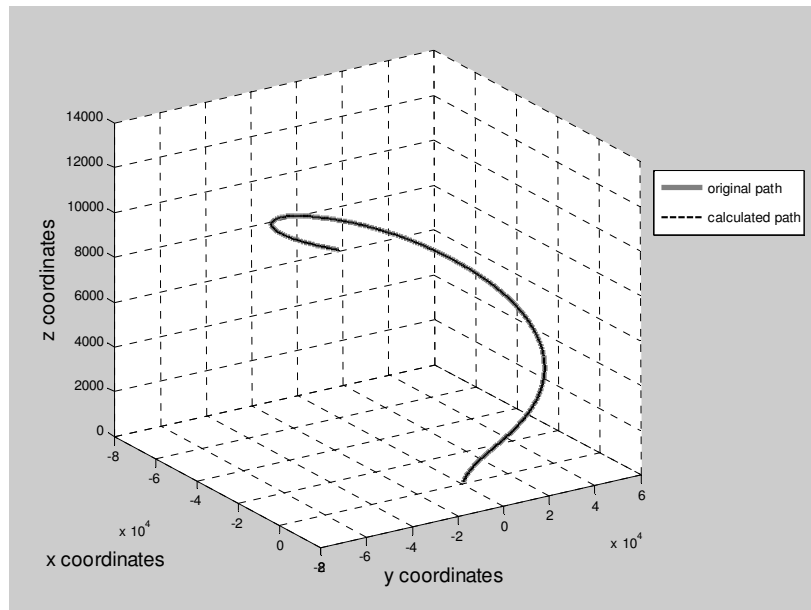


Figure 13: The calculated path versus the actual path.

This program yielded the correct result, as proved by Figure 13, where the actual path and the calculated path fall directly on top of each other. However, it took a very lengthy time to compute.

Improved Intersection of 3 Spheres

The Matlab function **Solve** was then tried to find the intersection of the spheres. This function gives the symbolic solution of to a set of algebraic equations. It was simply used to solve for the x-, y- and z-coordinates of the intersection of the three spheres. The spheres will have centers (x_a, y_a, z_a) , (x_b, y_b, z_b) and (x_c, y_c, z_c) , with radii $(r_a + d_a)$, $(r_b + d_b)$ and $(r_c + d_c)$. Thus the following equations were used:

$$(x - x_a)^2 + (y - y_a)^2 + (z - z_a)^2 - (r_a + d_a)^2 = 0$$

$$(x - x_b)^2 + (y - y_b)^2 + (z - z_b)^2 - (r_b + d_b)^2 = 0$$

$$(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2 - (r_c + d_c)^2 = 0$$

This method was considerably faster, and yielded the same results as in Figure 13 above. It will therefore be the one used in the simulator.

5.1.3 The Velocity Calculator

The velocity over a certain time interval can easily be calculated by simply differentiating the path. (Note that there is a difference between the *Velocity Calculator* and the *Relative Velocity Calculator* above).

A method has been established for finding the path, and hence the velocity of the balloon. The errors in the system will now be evaluated. Note that errors due to inaccuracies in the location of the launch site or in location of antennas are not investigated. It is assumed that these locations can be identified highly accurately using GPS.

5.2 Errors due to Variation of the Transmitted Frequency

Several factors may cause the transmitted frequency to deviate from the specified 1.7 GHz. These are discussed below.

5.2.1 Unpredictable Variation in Frequency

The transmitter will have some frequency error associated with it due to various factors, particularly the aging of the quartz crystal [17]. It is suggested that one of the antennas be located at the launch site, in line-of-sight of the transmitter. While the transmitter is stationary, the frequency can be recorded and used to adjust readings later.

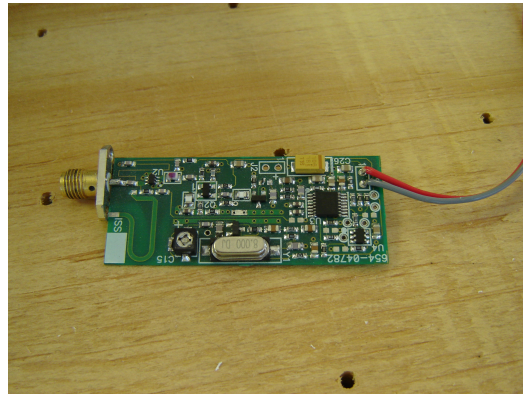


Figure 14: The Transmitter

5.2.2 Variation due to Temperature Changes

A problem occurred when it was established that the transmitter's frequency varies with temperature.

A 4 MHz quartz crystal is used in the transmitter to produce the 1.7 GHz. Quartz crystals' frequencies are known to change with changes in temperature. This relationship of frequency versus temperature follows a third degree curve, the shape of which depends on the theta angle of the crystal's cut. [8]

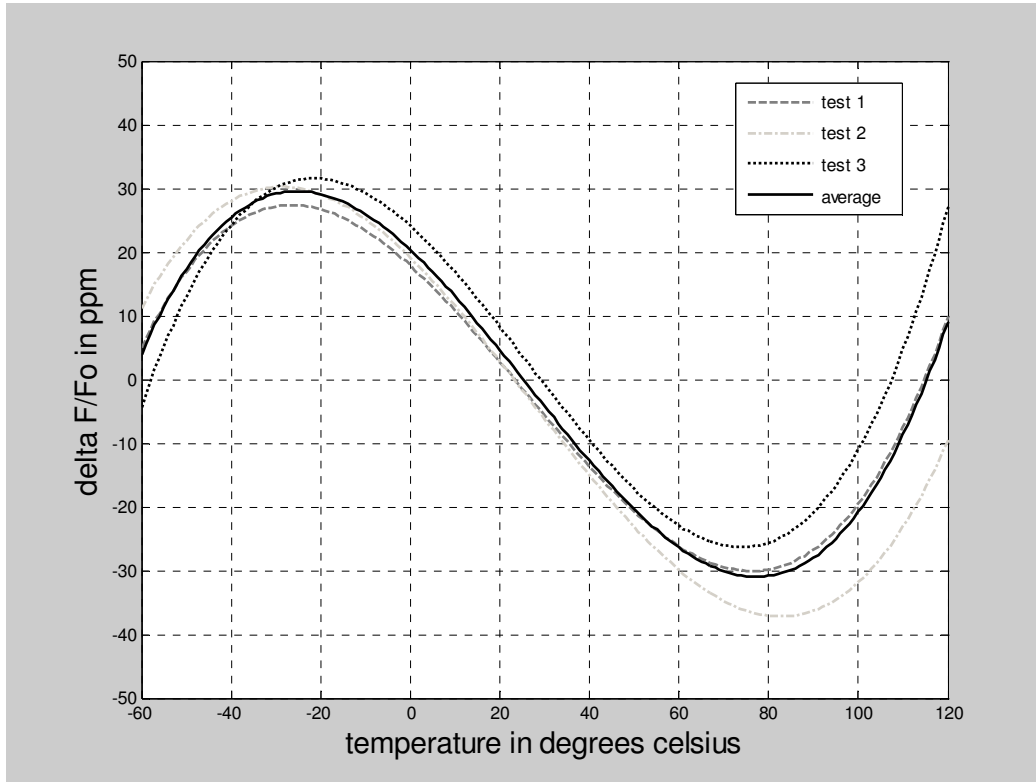


Figure 15: The Frequency-Temperature Curve Of The Crystal In The Transmitter.

As the transmitter will be traveling through a great range of altitudes, the temperature of its surroundings will change considerably, and the frequency will be affected. Fortunately, the transmitting device takes temperature readings for various altitudes, and once all the data has been collected, the transmitted frequency can be corrected according to the temperature. Tests were run on the transmitter to determine its frequency-temperature curve. This was done in an environmental chamber, by setting up both the transmitter and an antenna, varying the temperature in the chamber and taking readings. The tests were run three times, then curve-fitted, and the results are shown in Figure 15. The average curve was calculated, which falls roughly on the curve of test 1.

The frequency received must thus be altered using this curve. However, it is clear that there will be a possible error in the adjusted frequency, as there is variation of the frequency-temperature curve. This error is displayed on the graph below. In the case of a 1.7 GHz transmitter:

$$\Delta f = (1.7 \times 10^9) \cdot (\text{error})$$

So when the worst case error occurs:

$$\sigma_{\Delta f} = (1.7 \times 10^9)(4.5 \times 10^{-6}) = 7.65 \times 10^3 \text{ Hz}$$

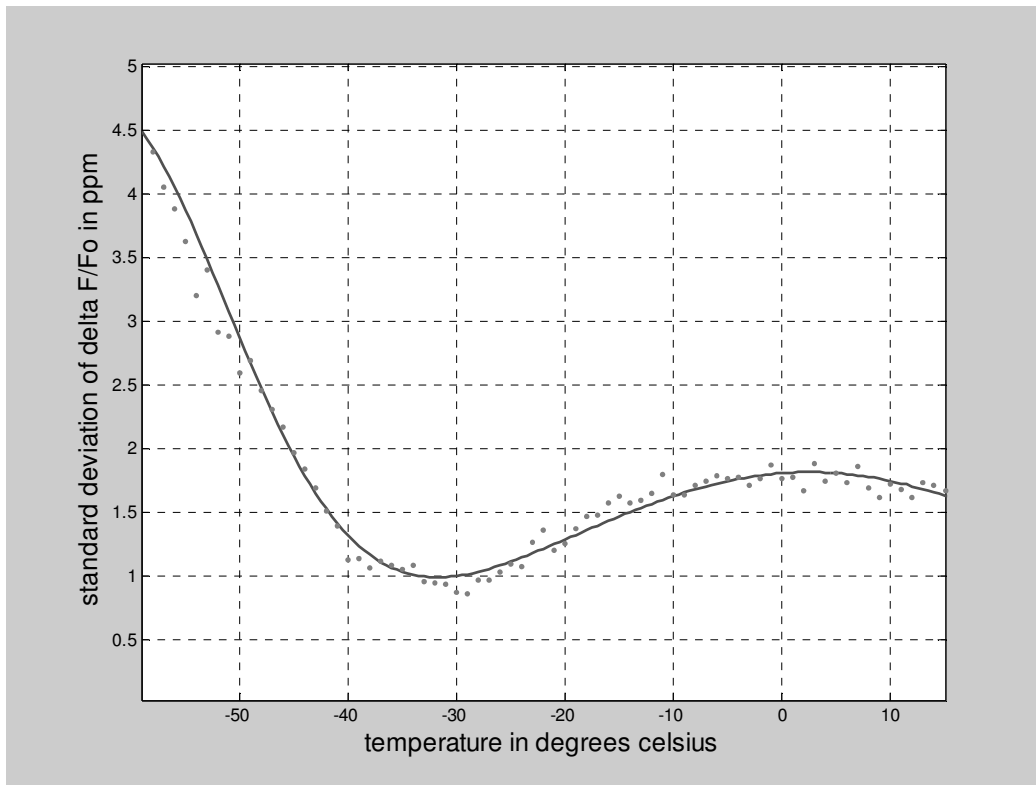


Figure 16: The Standard Deviation Of Frequency Versus Temperature.

However, the temperature in the atmosphere varies roughly according to the graph shown in Figure 17. The average standard deviation of received frequency can thus be calculated to be

$$\begin{aligned} \sigma_f &= (1.7 \times 10^9)(3.085 \times 10^{-6}) \\ &= 5.24 \times 10^3 \text{ Hz} \end{aligned}$$

This is remarkably large, and is expected to cause large errors in velocity readings.

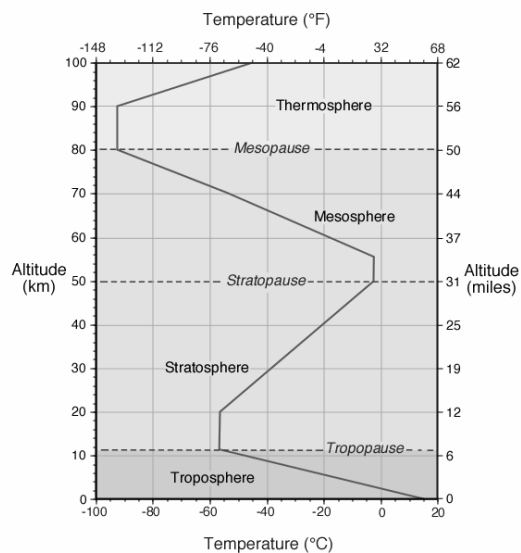


Figure 17: Vertical change in average global atmospheric temperature. Source: www.physicalgeography.net

5.3 Errors due to Line-of-Sight Dropouts

When the balloon is near the ground, at least two of the antennas will not be in its line of sight. This is due to the fact that the earth is “in the way”. If two points on the globe are about 50 km apart, the “height” of the earth will be about 50m at the midpoint between them.

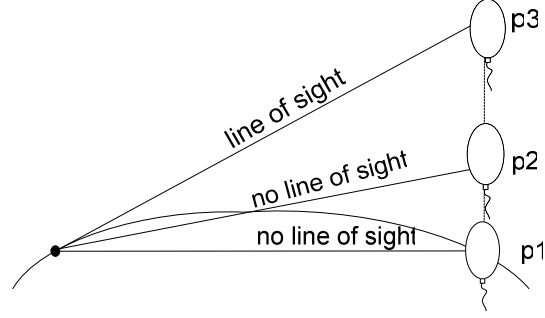


Figure 18: An illustration of the line of sight problem.

According to the line-of-sight equation, the height of the transmitter above the earth needs to be h metres in order to be in line-of-sight of the antenna, where

$$h = \left(\frac{d}{3.57} \right)^2 \cdot \left(\frac{1}{K} \right) - h_a$$

and d is the distance between transmitter and receiver in kilometres, K is the constant $\frac{4}{3}$, h_a is the height of the antenna above ground. [12]

In this case $d = 50$ km and $h_a = 30$ m, so $h = 117.12$ m. Therefore, for the first 117m of the balloon’s ascent, no frequency readings will reach two of the antennas and thus the path cannot be calculated. As we are not interested in the wind velocities at these low altitudes, all that is of concern is the height of the balloon, as we need to have accurate height in order to accurately report wind speeds versus height. We will aim to predict the height traveled by the balloon in these first 117 m, and thus have an estimated current position of the balloon when the first frequency readings are recorded.

The balloon has been set up to ascend at a constant speed of 6m/s on average. In a paper by W.R Gregg [7] he observed that in cases where the surface wind is changing

during an ascent, there are large variations in the rates of ascent of balloons. B.J. Sherry states in [13] that near the surface of the earth the rate of apparently similar balloons will sometimes differ as much as fifty percent, and the balloons usually ascend faster than formulas indicate they should. After the balloons reach an altitude of approximately 1,000 metres, the rates of ascent are usually much more uniform and there is better agreement in the observed rates with the rates indicated by the formulas.

Sherry suggests that to compensate for the increase of rate in the lower levels, certain corrections may be introduced in the computations of the altitude of the balloon during the first five minutes of ascent. He states that computed altitudes of the balloons agree best with the actual altitudes if the rate of ascent is increased by 20 percent for the first 300 metres.

We will thus assume the balloon to be rising at $6 \times 1.2 = 7.2$ m/s for the first 150 metres. Since this is only an estimation, it is likely to cause errors in velocity calculated.

5.4 Errors on account of the Receiver

A number of frequency errors also occur in the receiver. The receiver will first be examined briefly.

5.4.1 Brief overview of the Receiver

Figure 19 below gives an idea of what the receiver accomplishes. The incoming signal will be somewhere in the range of between $1.7 \times 10^9 - 450$ Hz and $1.7 \times 10^9 + 150$ Hz. The bandwidth we are interested in consequently has a magnitude of $600 \times 2 = 1200$ Hz. The incoming signal needs to pass through a bandpass filter which will preserve only the 1200 Hz in which we are interested. Then a frequency converter must translate this spectrum to a lower frequency where it is more convenient to work with. It does this by multiplying all spectral components by a sinusoid of fixed frequency

[15]. Lastly, the receiver will perform a peak pick, and thus identify the frequency we are interested in.

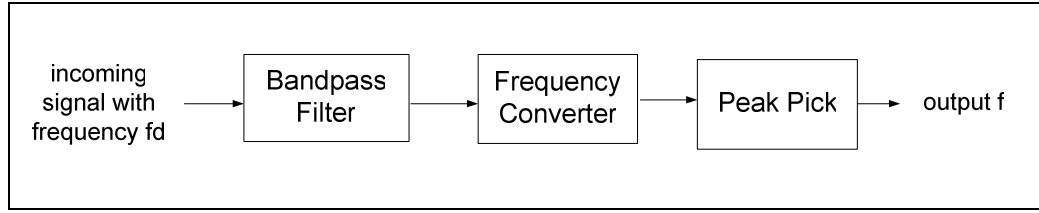


Figure 19: A Crude Representation of the Receiver

To sample at the Nyquist rate, the sampling period has to satisfy the condition:

$$T < \frac{1}{2B}$$

$$\therefore T < \frac{1}{2 \times (1200)}$$

Taking a Fourier transform over a bandwidth of 1200 Hz, if we want the frequency resolution to be 0.5 Hz, then we need to make the number of points $N = \frac{f_s}{\Delta f} = \frac{1200}{0.5} = 4800$. Then, inherently the receiver will have a possible error of anything between 0 and 0.5 Hz. This is illustrated in the figures below. Figure 20 shows a power spectrum of a signal of 300 Hz. Figure 21 shows a close up of a portion of the spectrum. The bin size can be seen to be 0.5. Therefore, if a signal has a frequency that falls in between two samples, it can have an error of up to 0.5 Hz. The standard deviation of the frequency produced due to this error is discussed in Section 5.4.2.

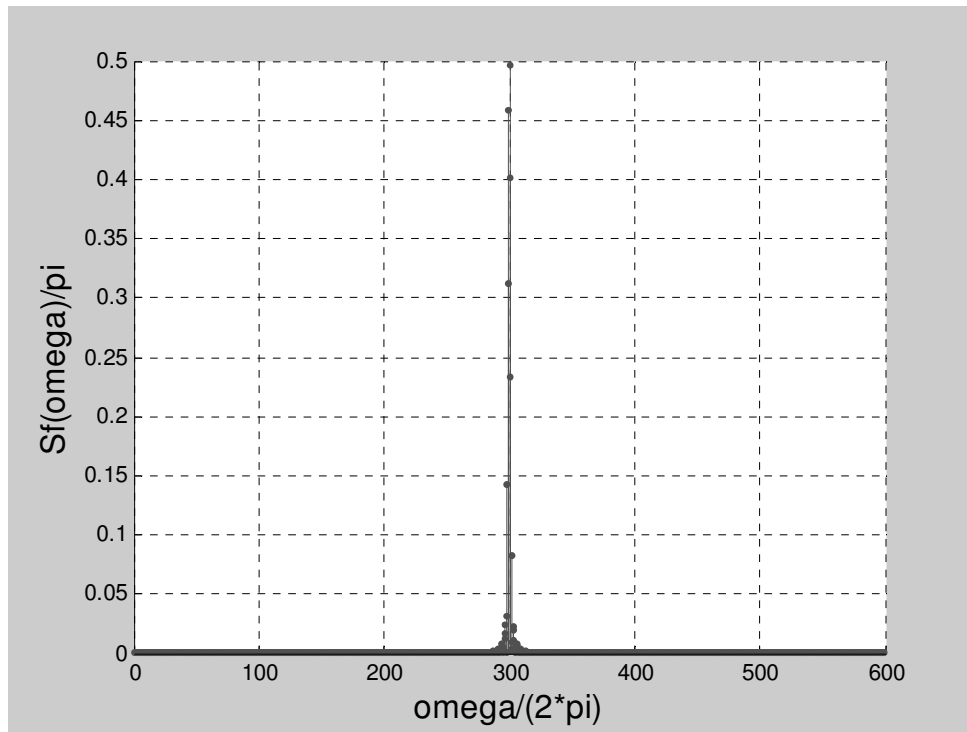


Figure 20: The spectral density of a signal with frequency 300 Hz. SNR = 164 dB.

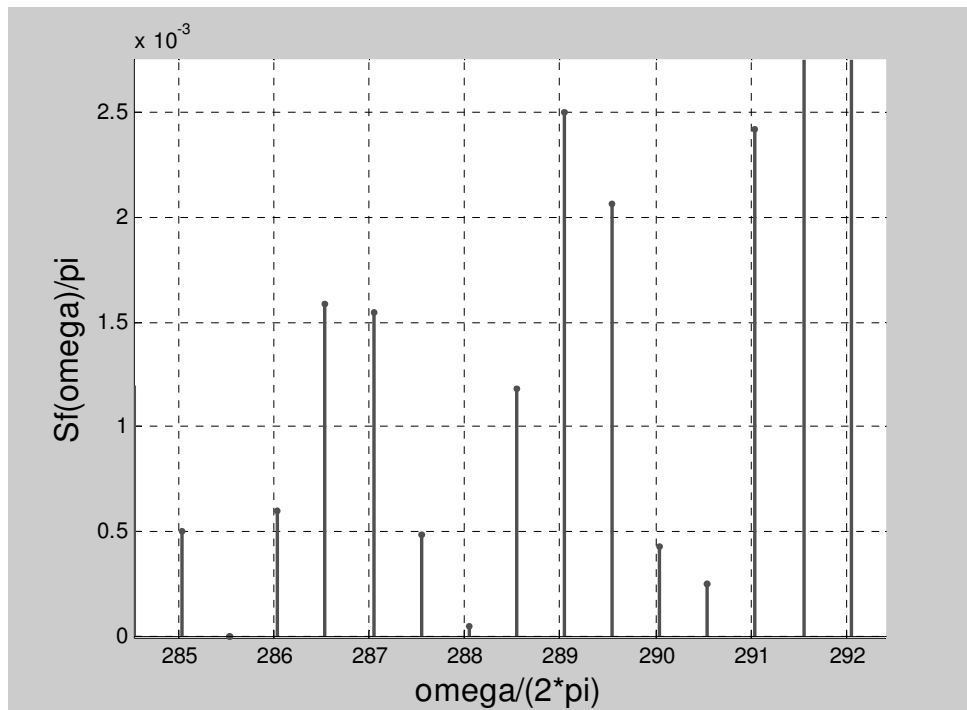


Figure 21: Δf is 0.5 Hz, which is then the maximum possible error in the detected frequency.

5.4.2 Errors due to Signal Fading

Frequency readings can also be distorted as a result of the phenomenon of Multipath.

Multipath causes signal *fading* through more than one version of the transmitted signal arriving at the receiver via multiple paths. These replicas are delayed. Fading is caused by destructive interference of two or more versions of the transmitted signal arriving at the receiver at slightly different times (with different phases). [3] This causes the signal strength at the receiver to vary, and sometimes it is very weak. When it is very weak, it is impossible to extract the right frequency, due to noise interference. Hence erroneous frequency readings are made.

Multipath is caused mostly by diffraction and ground reflection. Diffraction can be avoided by obtaining Fresnel zone clearance. However, a LOS path may have adequate Fresnel zone clearance, and yet still have a path loss due to reflections.

A Fresnel zone is an ellipsoid through which the radio waves travel from transmitter to receiver. If this zone is penetrated by any obstacles, they will cause diffraction to occur, and thus signal fading could take place. A radio path has first Fresnel zone clearance if no objects penetrate the first Fresnel zone. In fact, it is sufficient to have 60% of first

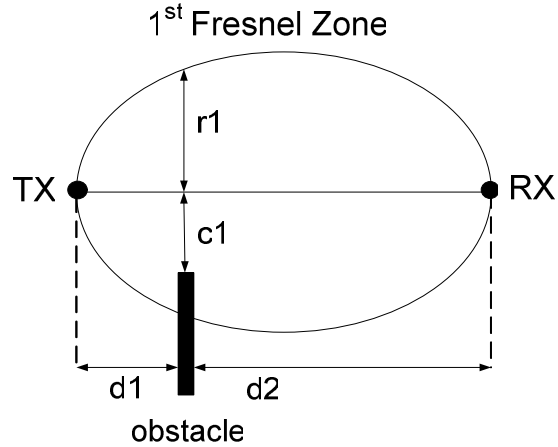


Figure 22: A graphical illustration of fresnel clearance.
For clearance, c_1 needs to be larger than 60% of r_1 .

Fresnel clearance [22]. The radius of the Fresnel zone is calculated by [19].

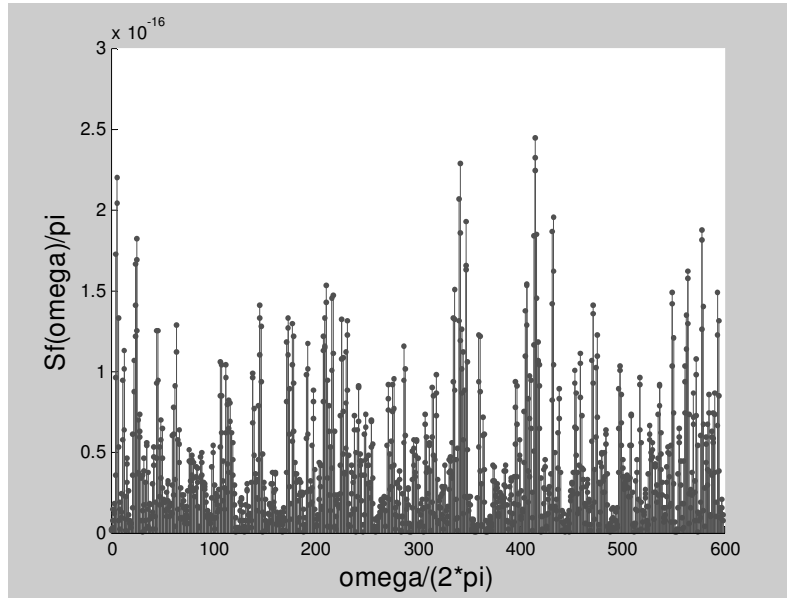
$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

where n is the number of the Fresnel zone, λ the wavelength of the transmitted signal, d_1 the distance of the obstacle from the transmitter and d_2 the distance of the obstacle from the receiver. Figure 22 illustrates the concept of a Fresnel zone. For clearance, c_1 needs to be larger than 60% of r_1 . (For more on Fresnel clearance, see Appendix B).

However, even if caution is taken to clear Fresnel zones, it is likely that fading will still occur. This will result in the amplitude A of the incoming signal being weakened. The signal-to-noise ratio in the receiver can be calculated by [15]

$$SNR = \frac{\overline{s^2(t)}}{\overline{n^2(t)}} = \frac{\frac{1}{2}A^2}{kT_e B}$$

where $B = 1200\text{Hz}$, $k = 1.38 \times 10^{-23}$ and $T_e = 1000$, which are all characteristic of the receiver. A is the amplitude of the input signal of which the value at any given moment is unknown. When the signal-to-noise ratio becomes too large, it becomes impossible to detect the frequency f . This is illustrated in the figures below. In Figure 20, it is easy to see what the frequency of the signal is. Here A is large, and SNR is 164 dB. In Figure 23 below, it is impossible to detect the frequency, due to A being small – not much larger than the amplitude of the noise. Here SNR is only 11.78 Db.



**Figure 23: The PSD of a spectrum with poor SNR.
It is impossible to detect the frequency of the signal. SNR is 11.78 dB.**

By running many signals of different frequencies and signal strengths through the simulator, we could form an idea of how the signal-to-noise ratio affects the frequency. This can be seen in the graph of inverse standard deviation versus SNR below (Figure 24).

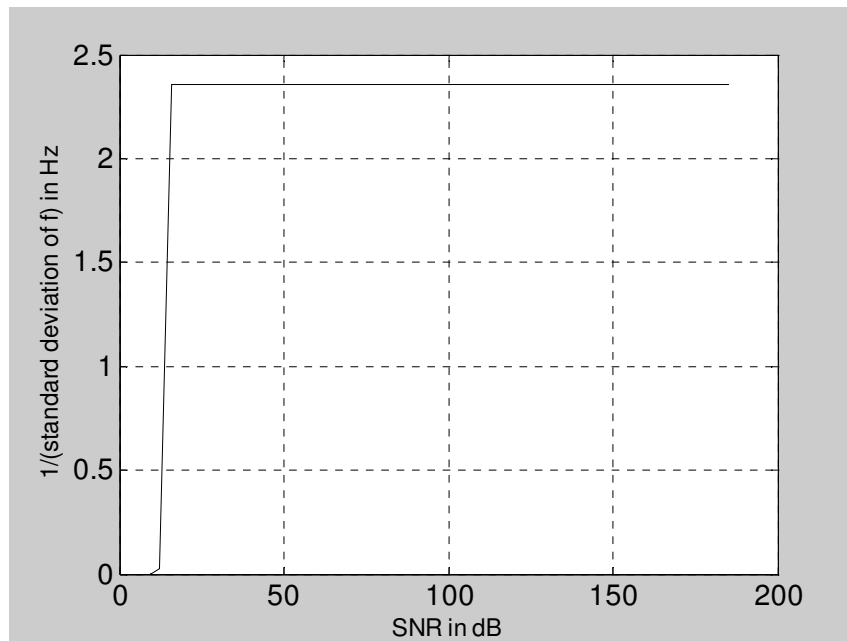


Figure 24: Graph of standard deviation of frequency versus signal-to-noise ratio.

For signal-to-noise ratios of less than 16dB, the standard deviation of the frequency is large (up to about 400Hz), but for signal-to-noise ratios of more than 16dB the standard deviation settles down to about 0.42 Hz . (This deviation is due to the error caused by the bin size, as discussed in Section 5.4.1). It is thus important to analyze the incoming signal, determine a signal-to-noise ratio, and if the SNR value is too low, the reading should be discarded. The discarded signal can be predicted using a spline.

A spline in mathematics is a special function defined piecewise by polynomials. It is used in interpolating data. A set of points may be piecewise defined as a function (which is the spline) and this function is then used to predict the next point in the set. If the set of data is highly non-linear (as in our case), it is advisable to only use the most recent points in order to get the best prediction. However, if a number of succeeding points are missing and need to be predicted, using only the last few points may cause a problem. A trade-off needs to be established. In this case, it was found best to use only the last six points.

5.5 Errors due to Antenna Positioning

It should be noted that when the balloon moves on a circle with the antenna as its centre, the balloon is not moving away from or towards the antenna, and therefore no change in frequency will occur. When the antennas are too close together, this can cause errors in the path calculated. Keep in mind that the balloon may drift as far as 200 km, and placing antennas only 10 km apart is relatively close together. Consider Figure 25 (a). When the balloon moves from point P1 to point P2, the path falls on the circles of all three antennas. Little or no change in frequency is reported, and it appears that the balloon is not moving at all.

Contrast this with the situation in Figure 25 (b). Here the balloon again moves on the circle of antenna C, but since antennas are further apart, the balloon is moving further away from antennas B and C. This will yield much more accurate results. Therefore, care needs to be taken to place the antenna sufficiently far apart.

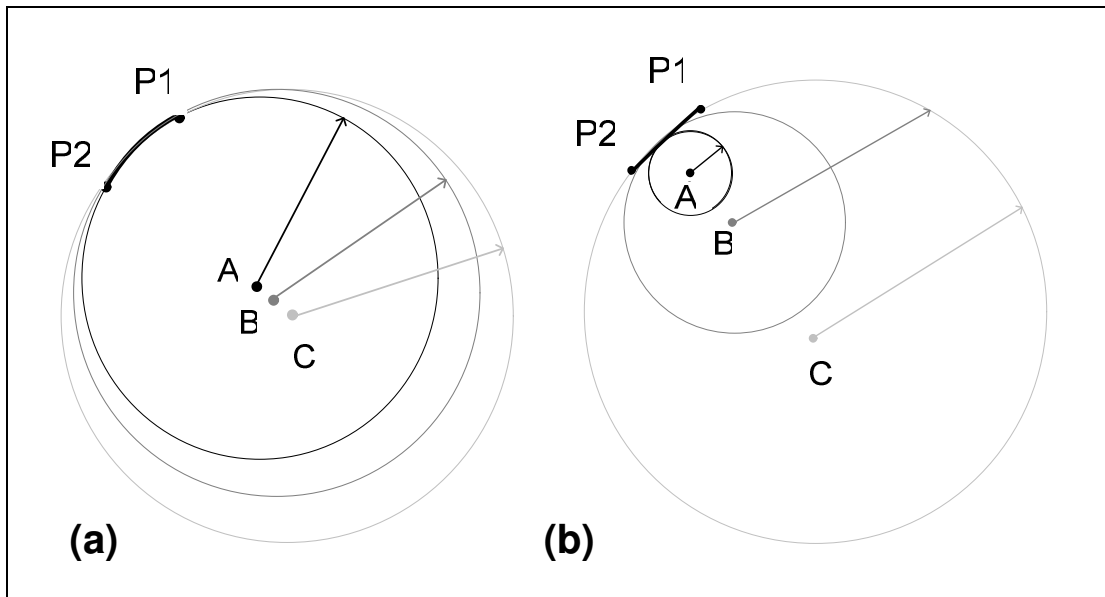


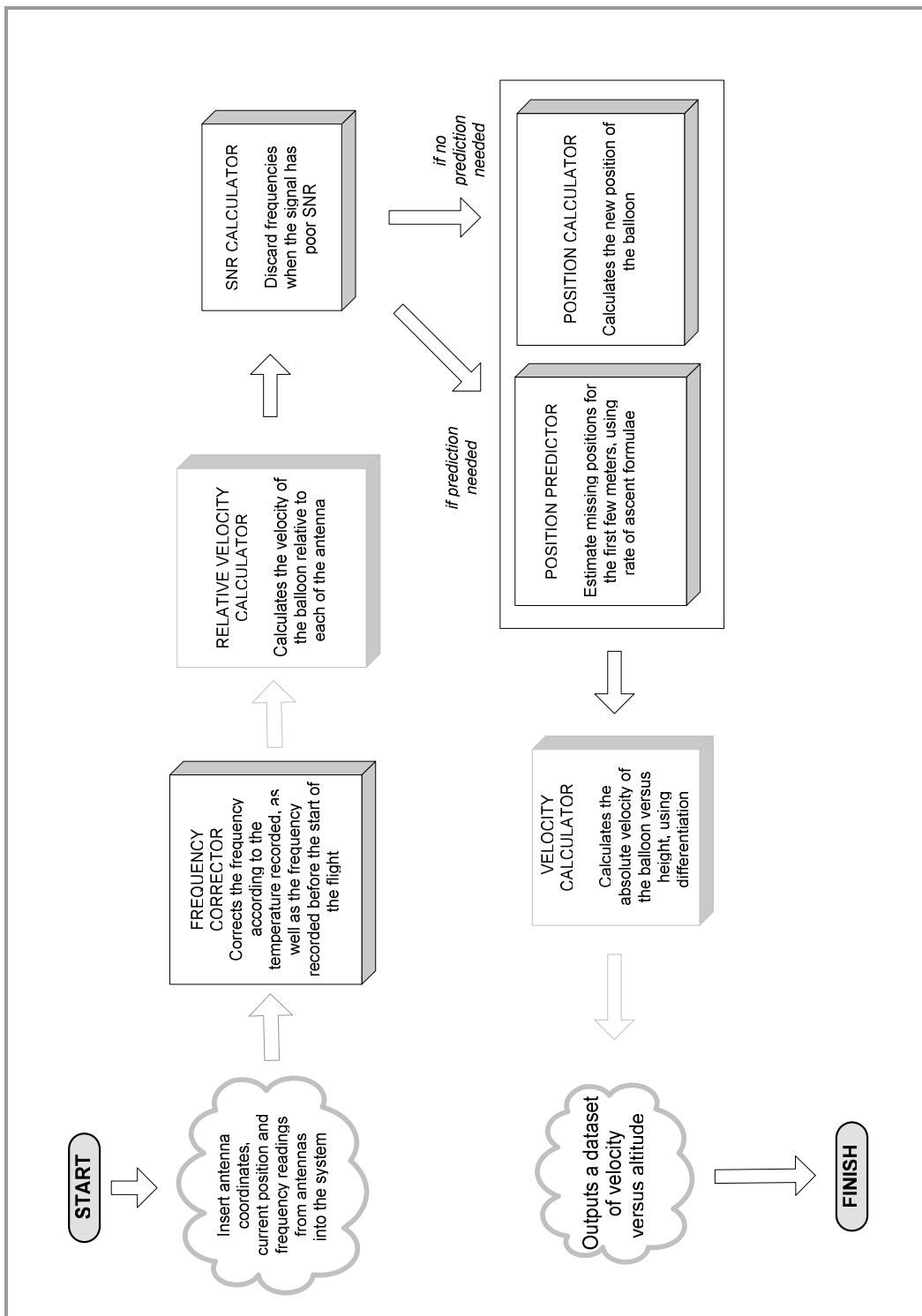
Figure 25: How positioning of antennas affect the velocity calculated. Antennas are located at A, B and C.

5.5 The Refined System

As various errors were uncovered, a number of modules had to be added to the system in order to minimize these errors. These alterations include:

- A frequency corrector that corrects frequencies distorted by temperature, as well as adjusts frequencies according to the frequency measured before the start of the flight.
- A SNR calculator to calculate SNR in the receiver and discard frequencies obtained from signals with a poor SNR.
- A Position predictor to fill in positions when they are not otherwise calculable.

These fit into the system as shown on the next page.



6 TESTING

Once the software simulation had been constructed, and the various sources of errors in the system identified, we could run tests to see how these errors affect the velocities of the balloon as calculated by the simulator. The main component of input to the simulator is the matrix of Doppler frequencies (see Section 4.1.2 for more details). This is also the component of input which will be affected by the various sources of errors. For each test case, only one source of error was added to the Doppler frequencies. This input - with the error added to it - was then entered into the simulator to see how it would affect the calculated velocity of the balloon.

First, the ideal case was tested (i.e. no errors in the input), which was followed by a set of tests with inputs of noisy frequencies. Tests were then run with inputs with faded signals, and finally inputs with line-of-sight dropouts.

In each case, the resulting error in velocity is shown, by subtracting the velocity predicted by the simulation, v , from the correct velocity, v_c . This is done for both magnitude $|v|$ and direction $\angle v$.

6.1 Test Data

The test data used is a set of 2025 frequencies which, if processed correctly, shows the balloon travelling in a perfect spiral, as in Figure 26 below.

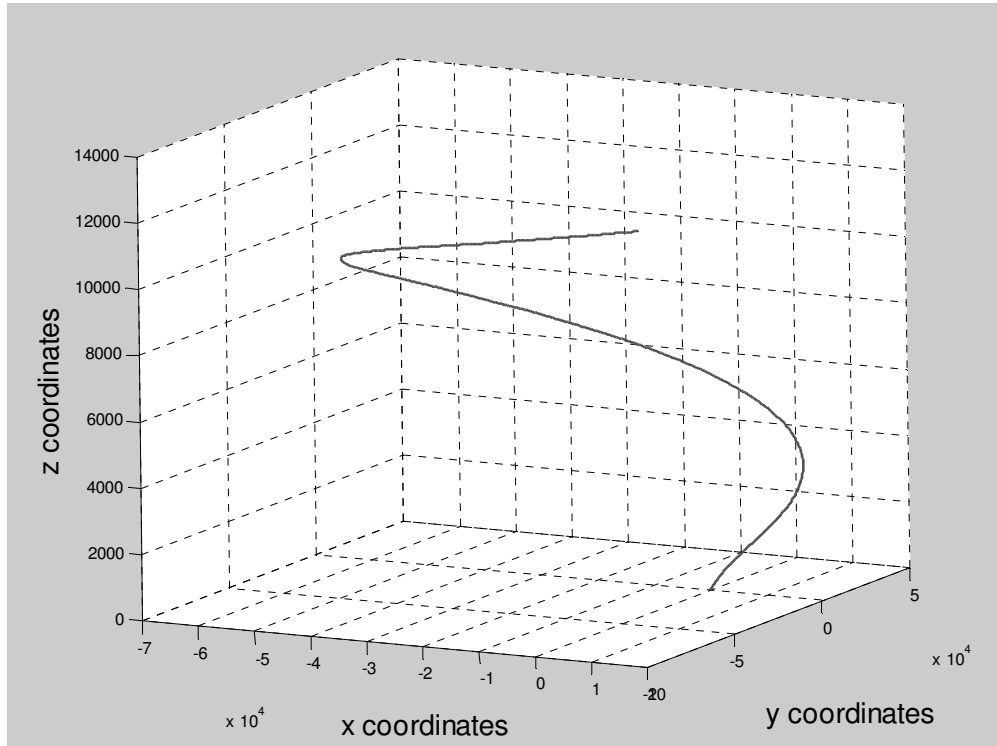


Figure 26: The path obtained from the ideal test Data.

6.2 Testing Under Perfect Conditions

The first tests were run using a set of perfect data. This yielded the exact correct path (as in Figure 26 above). Therefore we can safely assume that the simulation works correctly when no errors are added to the input.

6.3 Testing With Frequency Errors

The second set of tests involved varying the frequency transmitted, and thus the frequency received. The frequencies received at all three stations were given normal distributions with certain standard deviations. This data was entered into the simulator, and the calculated velocities of the balloon were then investigated. (For a review of the concepts of normal distributions, see Appendix A.)

We will first examine the effect of frequency errors due to temperature and frequency errors due to the receiver on the calculated velocity. We will then give the input

frequencies errors with other standard deviations, in order to gain a better understanding of how frequency errors affect the velocity output.

6.3.1 Frequency Errors due to Temperature

The standard deviation of the received frequency due to temperature is about $\sigma_{fd} = 5.24 \times 10^3$ Hz. No tests were run for this case, as it is obvious that inaccuracies in velocities will be enormous.

6.3.2 Frequency Errors due to the Receiver

We stated previously that the standard deviation in received frequency due to errors in the receiver is $\sigma_{fd} = 0.42$ Hz. To see what effect this will have on velocities calculated, we ran tests where the input frequencies were given a standard deviation of 0.42 Hz. The path of the balloon predicted by the simulator is shown in Figure 27, together with the correct path.

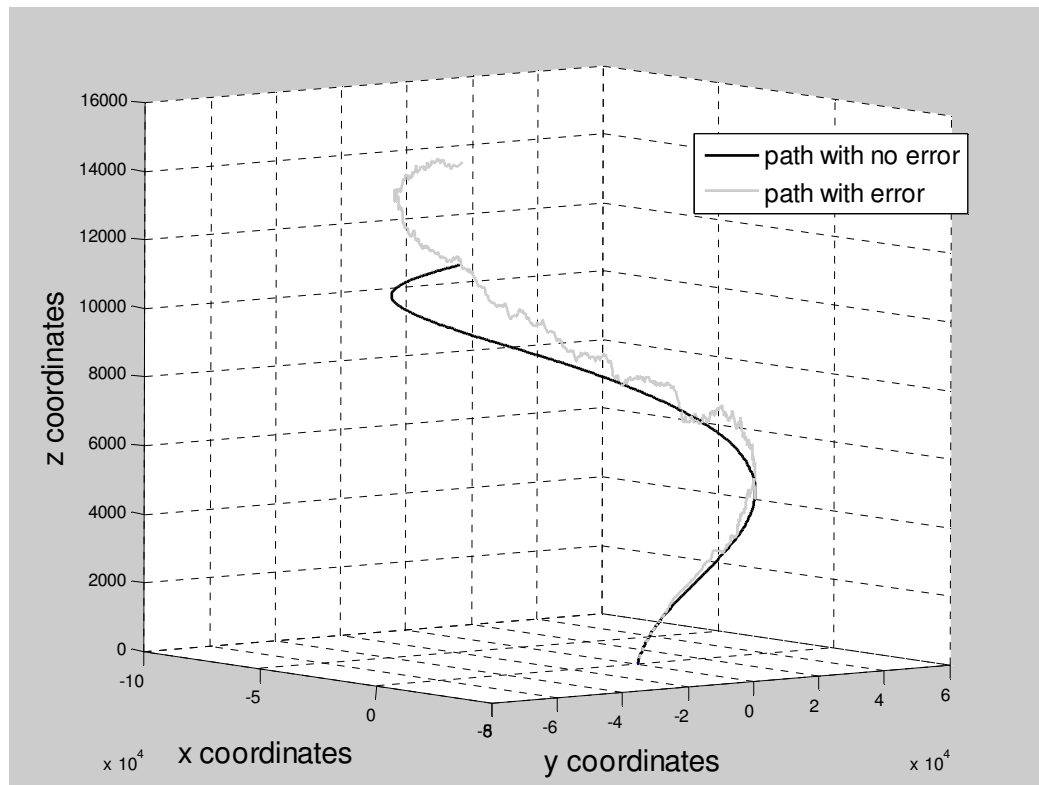


Figure 27: The resulting path when $\sigma_{fd} = 0.42$ Hz.

The resulting velocity magnitudes and angles were subtracted from the correct magnitudes and angles, and the difference between the two is graphed in Figure 28. v_c is the correct voltage and v is the calculated velocity.

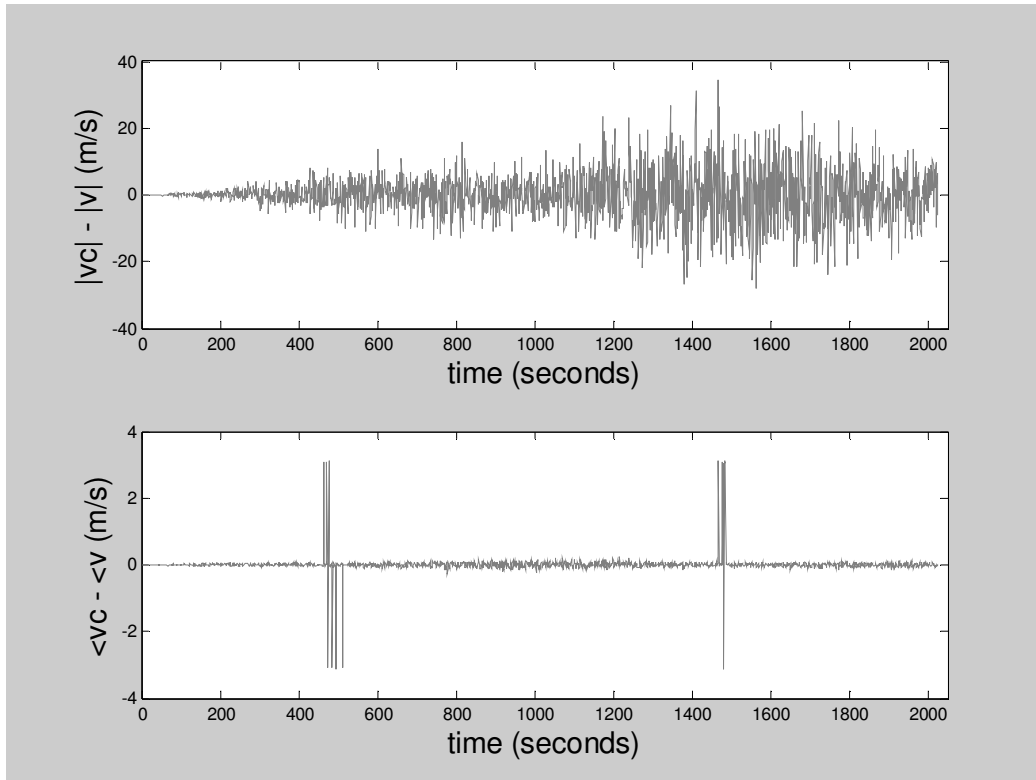


Figure 28: The difference between the resulting velocity magnitudes and angles and the correct magnitudes and angles.

In order to see what the impact of the difference shown above is, we can plot histograms to see how many of the readings are badly affected.

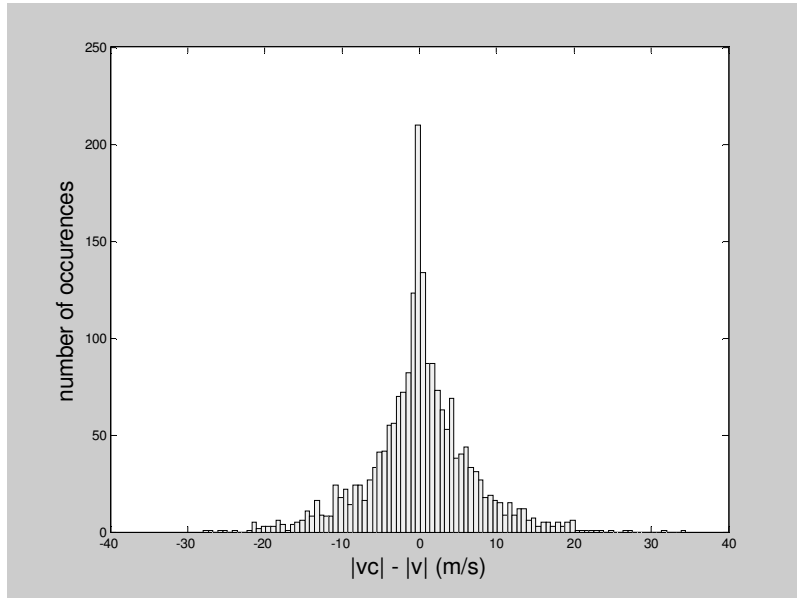


Figure 29: Histogram of the difference in velocity magnitudes.

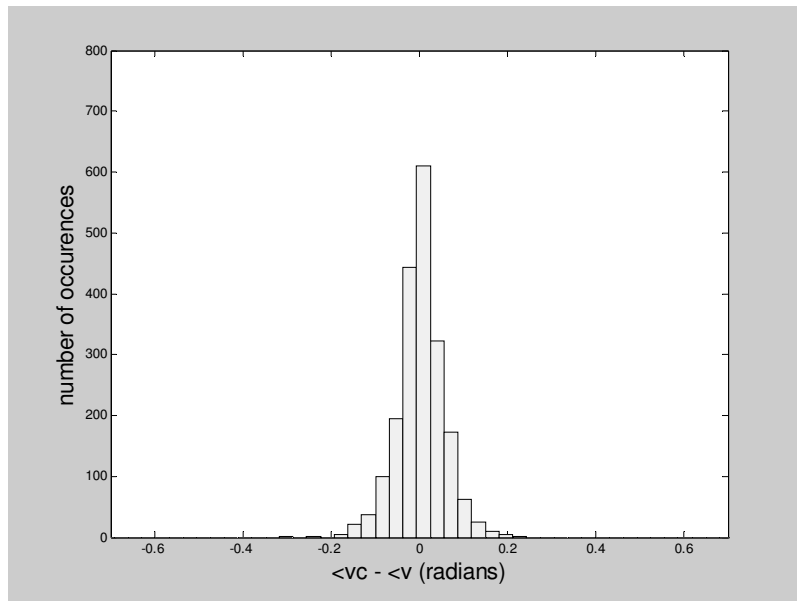


Figure 30: Histogram of the difference in velocity angles.

Both graphs show a normal distribution. The difference between the correct velocity magnitude and perceived velocity magnitude has a mean of 0.0838 m/s and a standard deviation of 6.8002 m/s. The difference between the correct velocity angle and perceived velocity angle has a mean of 0.0122 radians and a standard deviation of 0.2798 radians.

6.3.3 General Frequency Errors

The input frequencies were also given errors of other standard deviation, in order to gain a better understanding of how frequency errors affect the velocity output.

Test 1: $\sigma_{fd} = 0.167$ Hz

For this test, the frequency recorded at all three stations was given a standard deviation of 0.167 Hz. The resulting predicted path is shown below. It varies slightly from the original path.

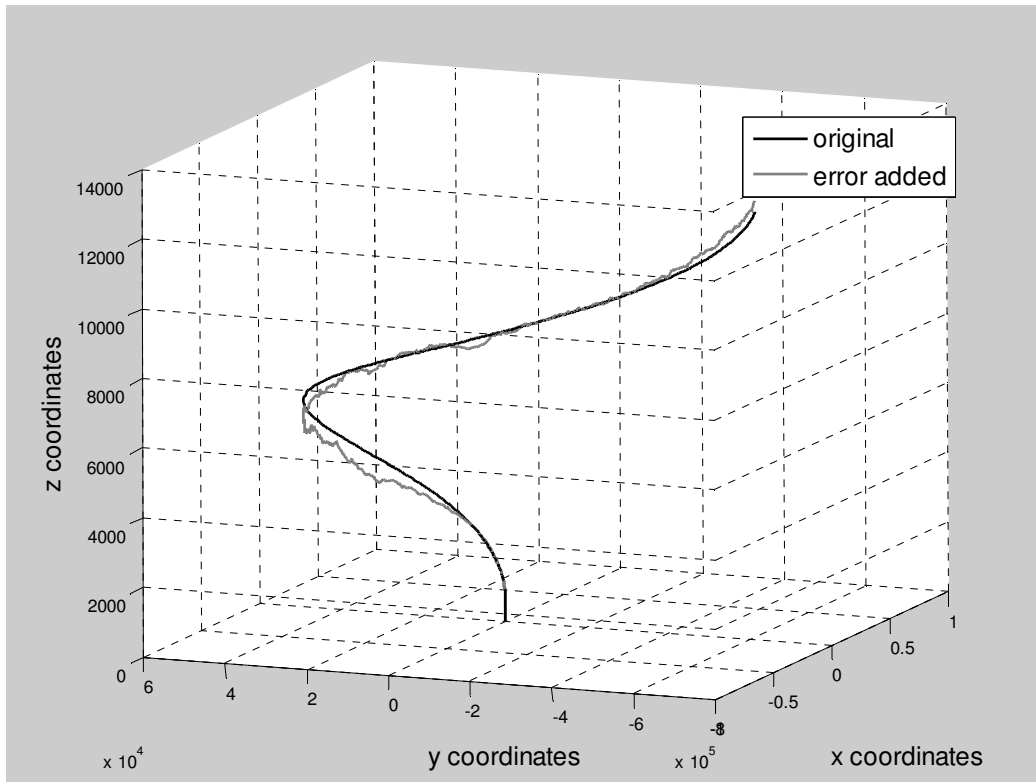


Figure 31: The resulting Path when $\sigma_{fd} = 0.167$ Hz

The difference between the velocity magnitudes has a mean of 0.0047 m/s and a standard deviation of 2.7372 m/s. The difference between the velocity angles has a mean of 0.0572 radians and a standard deviation of 0.1565 radians. These differences are shown in Figure 32 below.

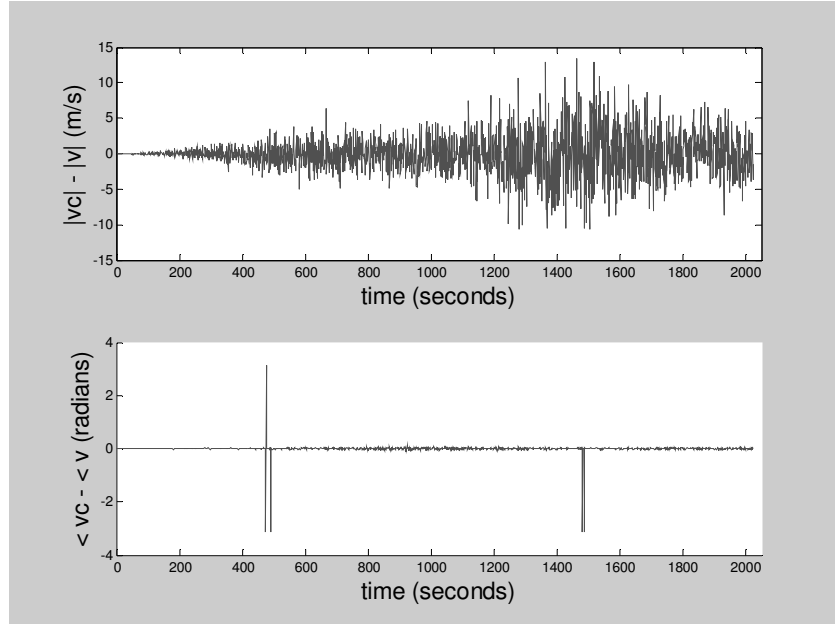


Figure 32: Difference in calculated velocity and correct velocity when $\sigma_{fd} = 0.167$ Hz

Test 2: $\sigma_{fd} = 0.667$ Hz

For this test, the frequencies at all three stations were given errors of standard deviation 0.667 Hz. The resulting path is shown below. It compares poorly to the correct path.

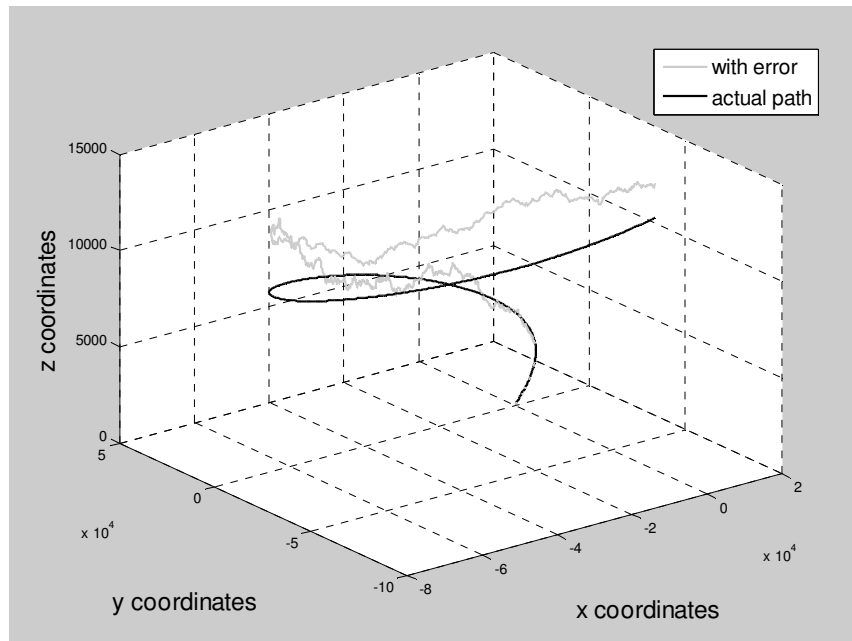


Figure 33: The resulting path when $\sigma_{fd} = 0.667$ Hz

The difference between the correct velocity magnitude and perceived velocity magnitude then has a mean of 13.8758 m/s and a standard deviation of 61.0117 m/s. The difference between the correct velocity angle and the perceived velocity angle has a mean of 0.0317 radians and a standard deviation of 0.8552 radians. The differences are illustrated in the Figure 34 below.

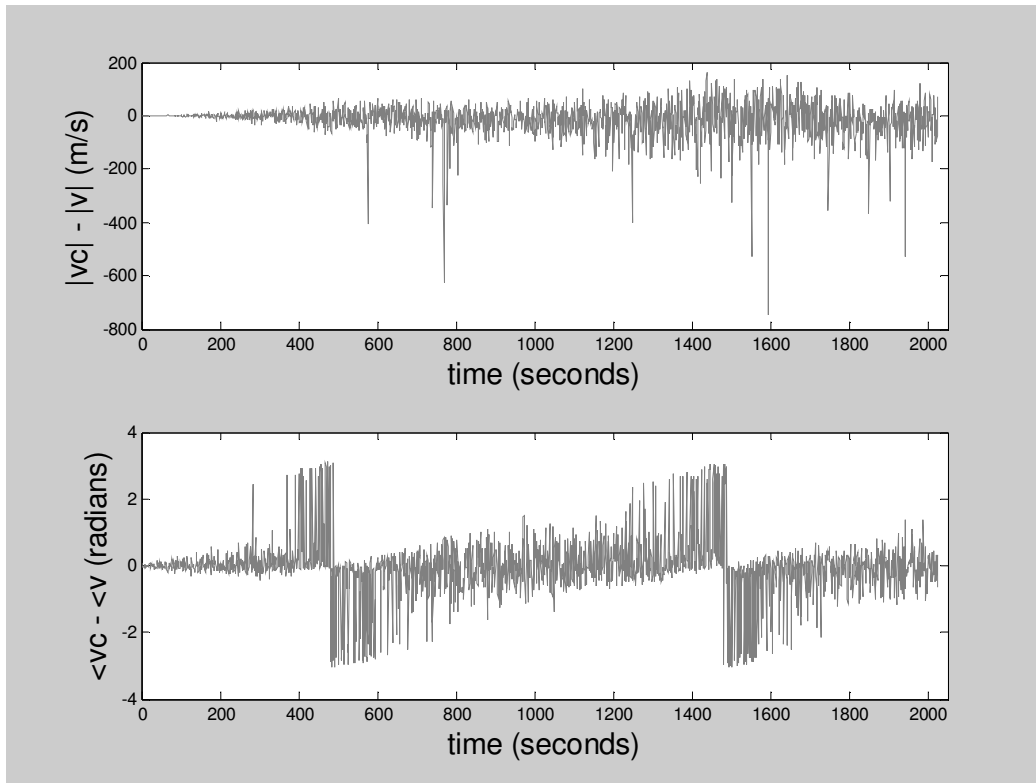


Figure 34: The difference in calculated velocity and correct velocity when $\sigma_{fd} = 0.667$ Hz

Imposing a Constant Rate of Ascent on Data

We know that the balloon has, on average, a constant rate of ascent of 6 m/s. In the path obtained in Figure 33 above, the balloon is calculated to move down at times. If we crudely impose a constant rate of ascent on the balloon (i.e. increase the z-axis in a constant manner), results are better. The dark grey line in the figure below represents the path when a constant rate of ascent is enforced.

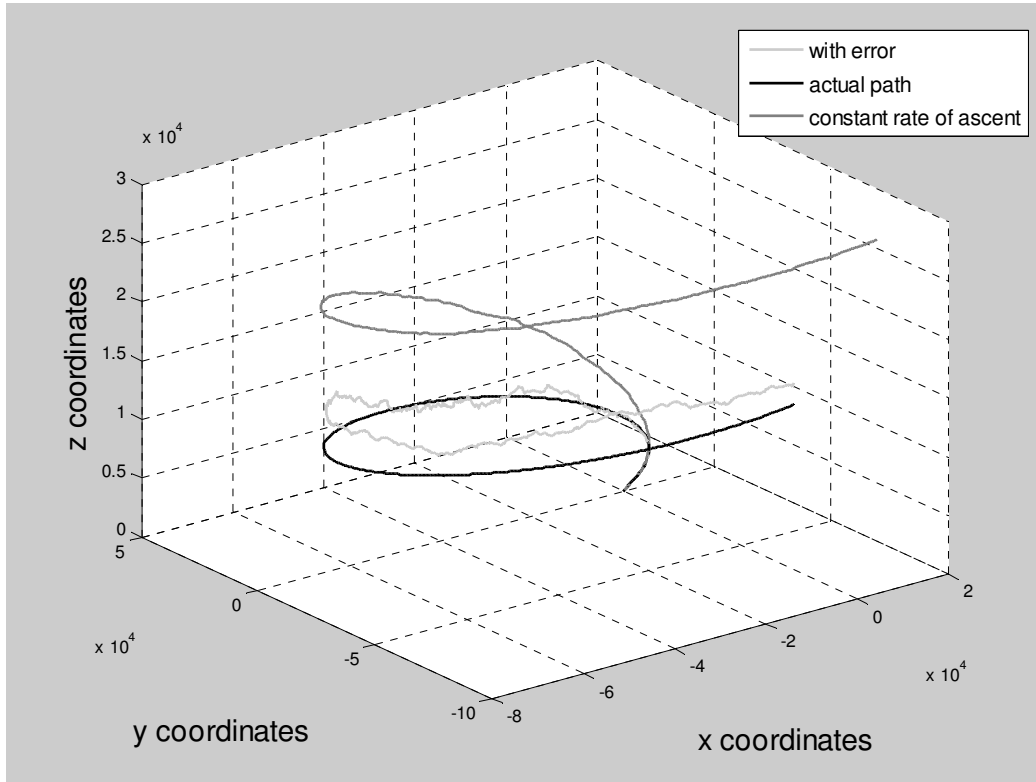


Figure 35: The path when a constant rate of ascent is imposed.

The difference between the correct velocity magnitude and perceived velocity magnitude then has a mean of 11.7808 m/s and a standard deviation of 25.8880 m/s. The difference between the correct velocity angle and the perceived velocity angle has a mean of 0.0010 radians and a standard deviation of 0.3992 radians. This is illustrated in the Figure 36 below.

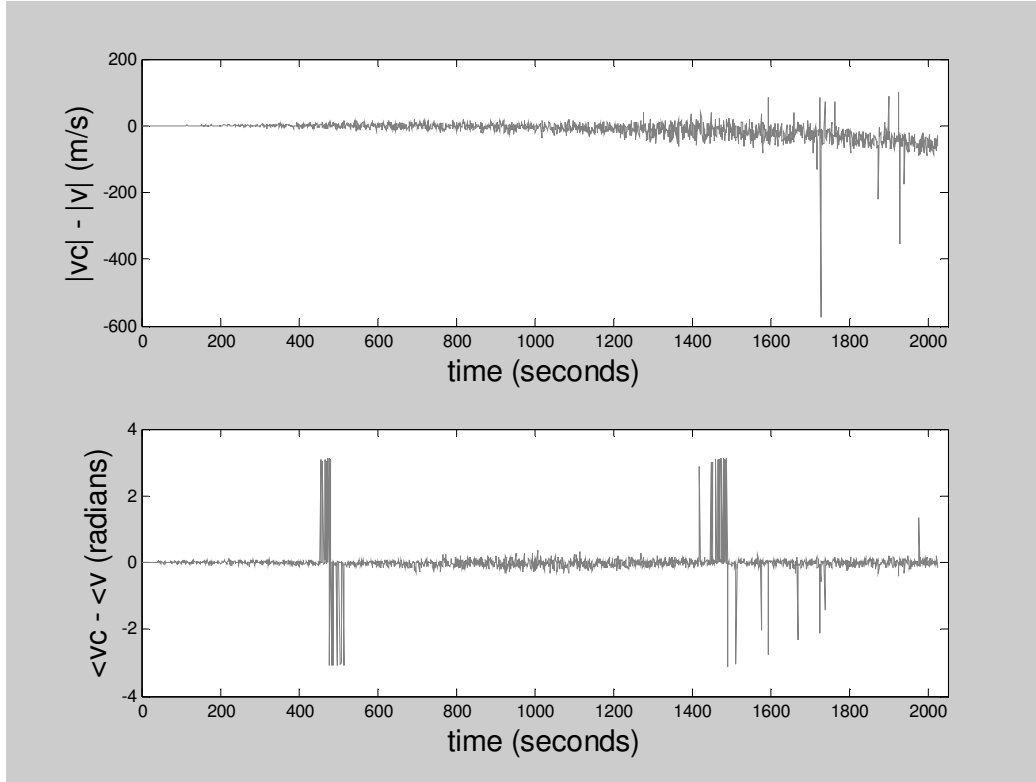


Figure 36: The differences in velocities when a constant rate of ascent is imposed.

Test 3: $\sigma_{fd} = 1.667$

For this test, all the received frequencies were given a standard deviation of 1.667 Hz. A crude constant rate of ascent was also enforced in the simulator.

The path had some zero readings, as the point of intersection between the three spheres could not always be found (cf. Section 5.1.2). The test was run again, this time using a spline to fill in missing readings. A plot of the x-coordinates of the path is shown in Figure 37 below. Notice how the spline smoothes out the path by predicting readings in place of the zero readings.

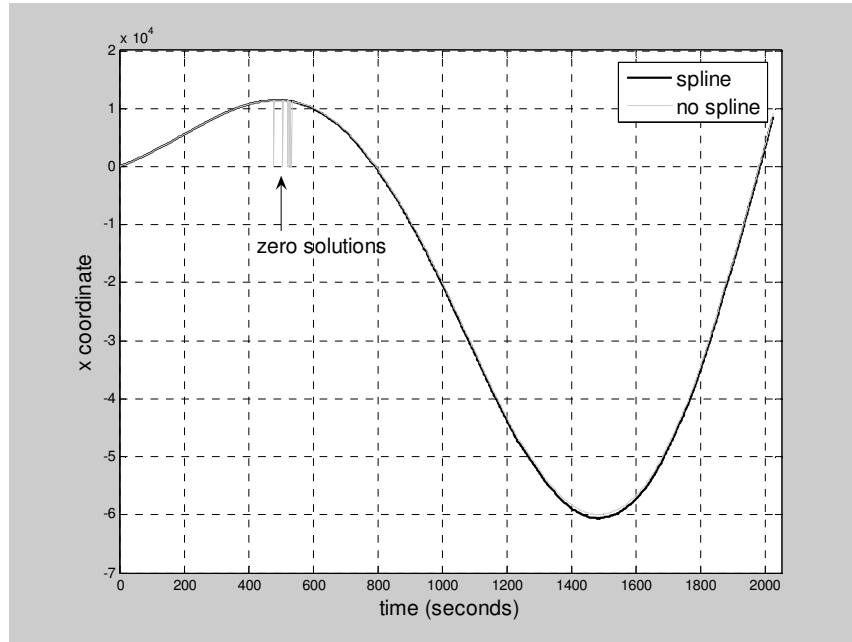


Figure 37: The effect of a spline.

The difference between correct velocity magnitude and perceived velocity magnitude for this test has a mean of 39.0590 m/s and a standard deviation of 65.9816 m/s. The difference between correct velocity angle and perceived velocity angle has a mean of 0.0104 radians and a standard deviation of 0.6303 radians. The plot of velocity differences is shown below.

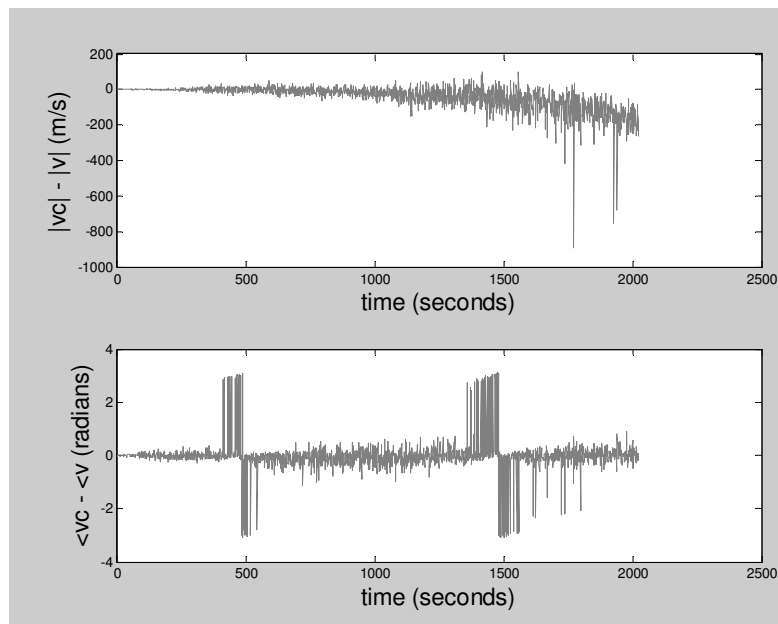


Figure 38: The velocity differences when a spline is used.

Tests with no Spline Used

The graphs shown in Figure 39 below show the differences in velocity when no spline is used. The difference between correct velocity magnitude and perceived velocity magnitude now has a mean of 104.91 m/s and a standard deviation of 1.4563×10^3 m/s, while the difference between correct velocity angle and perceived velocity angle does not have a normal distribution.

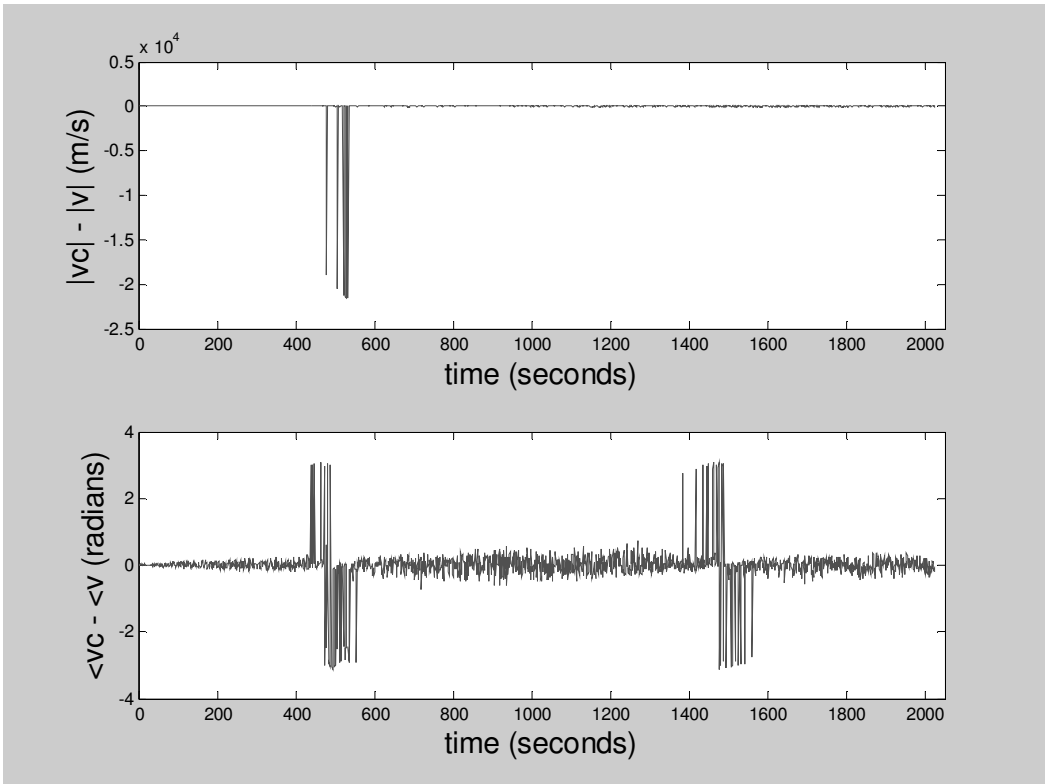


Figure 39: The velocity differences when no spline is used.

Subsequent Tests

More tests were run in the same manner as above, and the table shows how errors in frequency inputs affected resulting velocities. With some tests, the difference is shown with and without a spline and a constant rate of ascent.

Standard Deviation Of Frequency (σ_{fd})	Error In Velocity Magnitude			Error In Velocity Angle	
		Mean (μ_{dm})	Standard Deviation (σ_{dm})	Mean (μ_{da})	Standard Deviation (σ_{da})
0.167 Hz	Spline and Constant ROS	0.0047 m/s	2.73 m/s	0.0572 rad.	0.1565 rad.
0.42 Hz	Spline and Constant ROS	0.0838 m/s	6.8002 m/s	0.0122 rad.	0.2798 rad.
0.667 Hz	No spline	208.59 m/s	2.59×10^3 m/s	not calculable	not calculable
	Spline	13.87 m/s	61.01 m/s	0.0317 rad.	0.8552 rad.
	Spline and Constant ROS	9.25 m/s	50.57 m/s	0.0302 rad.	0.8532 rad.
1.667 Hz	No spline	104.91 m/s	1.45×10^3 m/s	not calculable	not calculable
	Spline	51.64 m/s	317.68 m/s	0.0269 rad.	0.6402 rad.
	Spline and Constant ROS	39.05 m/s	65.98 m/s	0.0104 rad.	0.6303 rad.
3.33 Hz	No spline	733.37 m/s	6.21×10^3 m/s	not calculable	not calculable
	Spline	101.27 m/s	350.55 m/s	0.0278 rad.	0.9077 rad.
	Spline and Constant ROS	80.40 m/s	135.06 m/s	0.0177 rad.	0.8647 rad.
6.67 Hz	Spline and Constant ROS	277.32 m/s	449.36 m/s	0.0146 rad.	1.1487 rad.

6.4 Testing With Multipath Dropouts

In this section, we discuss tests run with signal fading. A number of weak signals were entered into the system, which are discarded, as they will have poor SNR. A spline is then used to predict missing positions due to these missing frequencies.

6.4.1 Ten Dropouts in Frequencies

When 10 dropouts were entered into the system, the path shown in Figure 40 was obtained. It is smooth, and does not appear to differ greatly from the original.

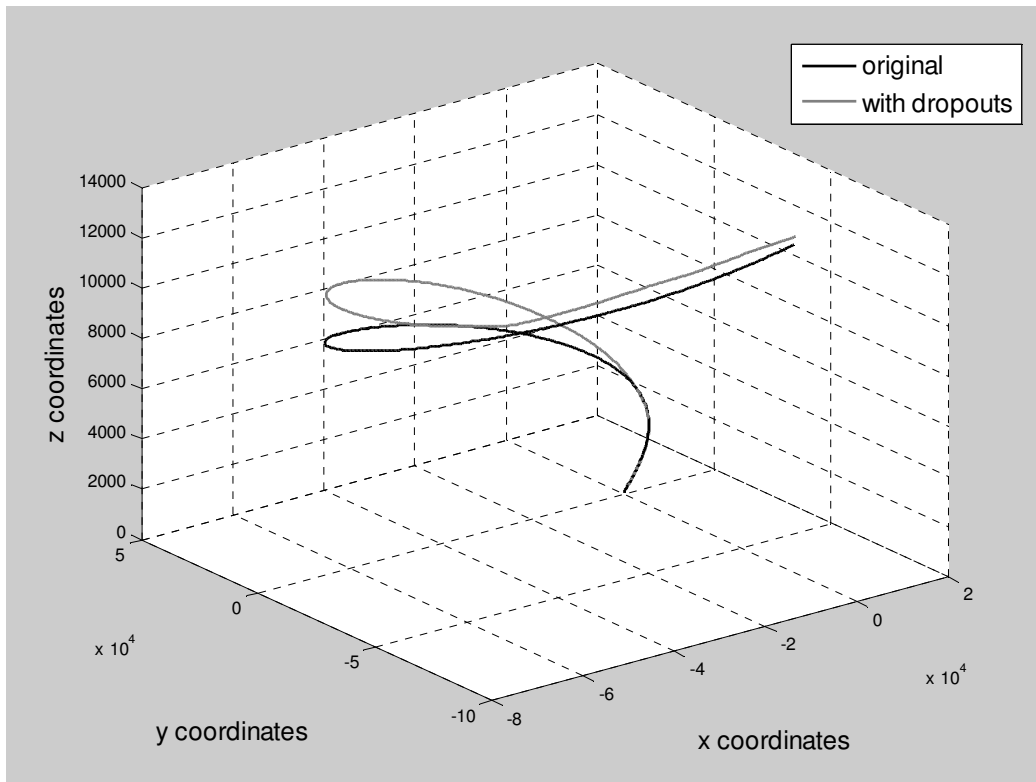


Figure 40: The path obtained with 10 multipath dropouts in the system.

The difference in velocity compared to the correct velocity was then calculated and graphed. It is shown in Figure 41 below.

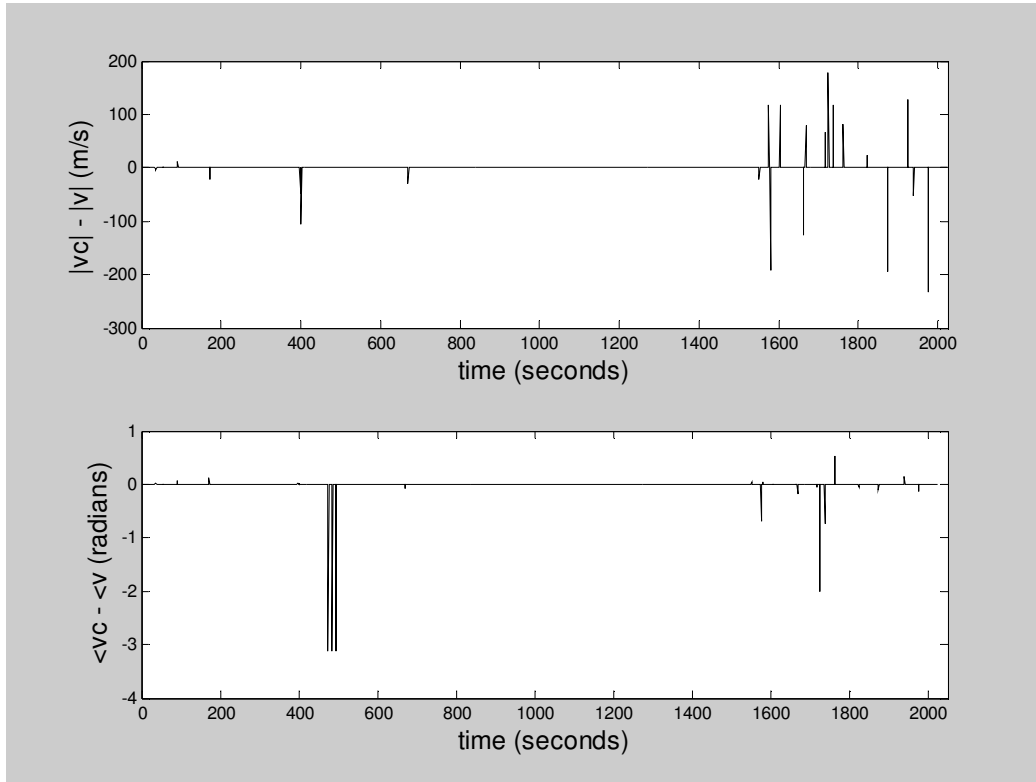


Figure 41: The difference in calculated velocity and correct velocity with ten multipath dropouts in the system.

The difference between actual velocity magnitude and perceived velocity magnitude has a mean of 0.2209 m/s and a standard deviation of 11.5621 m/s. The difference between the actual velocity angle and perceived velocity angle has a mean of 0.0055 radians and a standard deviation of 0.1313 radians.

6.4.2 Twenty Dropouts in Frequencies

For a set of frequencies with 20 dropouts, the path is shown in Figure 42 below, and the difference in velocity in Figure 43.

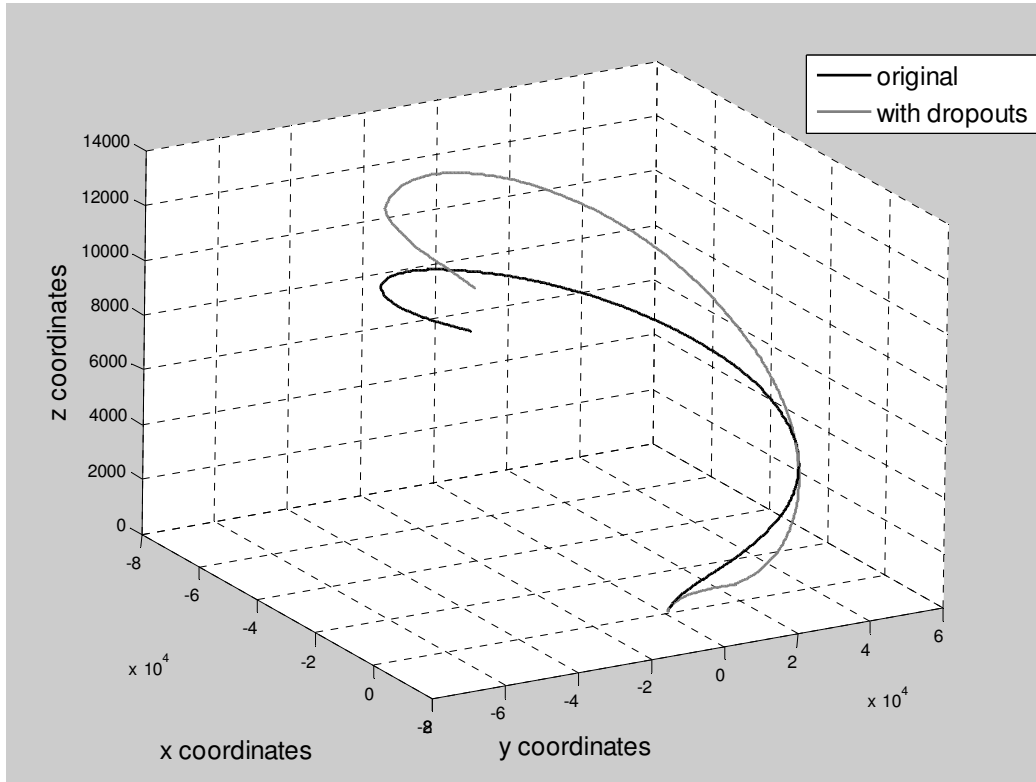


Figure 42: The path obtained with twenty multipath dropouts in the system.

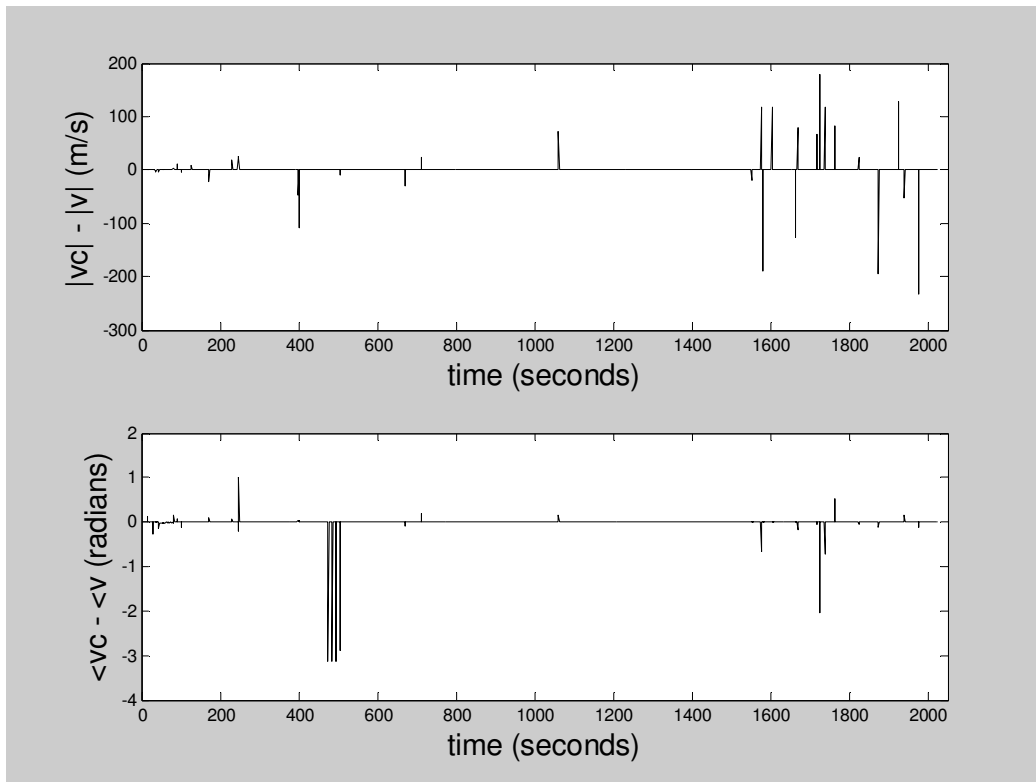


Figure 43: The difference in calculated velocity and correct velocity with twenty multipath dropouts in the system.

The difference between actual velocity magnitude and perceived velocity magnitude has a mean of 0.4578 m/s and a standard deviation of 11.7087 m/s. The difference between the actual velocity angle and perceived velocity angle has a mean of 0.0049 radians and a standard deviation of 0.1482 radians.

6.4.3 Subsequent Tests

More tests with various numbers of dropouts were run. The table shows how various numbers of dropouts affected resulting velocities.

Number of Dropouts	Difference In Velocity Magnitude		Difference In Velocity Angle	
	Mean (μ_{dm})	Standard Deviation (σ_{dm})	Mean (μ_{da})	Standard Deviation (σ_{da})
10	0.2209 m/s	11.5621 m/s	0.0055 rad	0.1313 rad
20	0.4578 m/s	11.7087 m/s	0.0049 rad	0.1482 rad
30	0.4411 m/s	11.7553 m/s	0.0055 rad	0.1486 rad
40	2.1655×10^7 m/s	1.3385×10^8 m/s	0.0828 rad	0.6714 rad

6.5 Testing with Line-of-Sight Dropouts

This set of tests was run with the balloon being out of line-of-sight of two antennas for the first 120 metres of its ascent, and thus no frequencies appearing at two of the receivers. The path thus was not calculable, and it had to be predicted for the first few seconds. Figure 44 below shows the estimated path of the balloon. It is very different from the original.

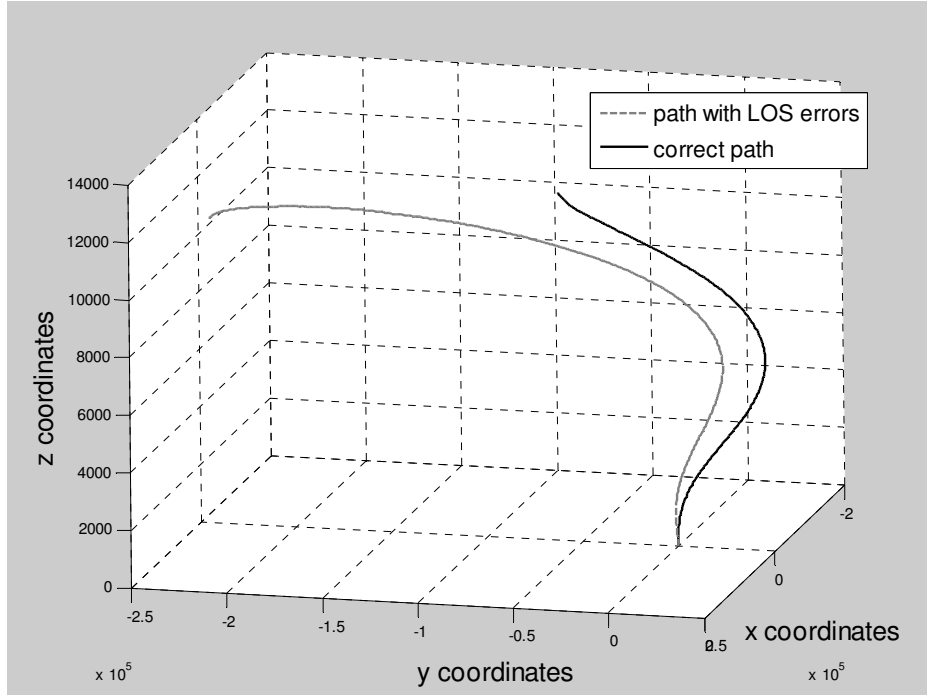


Figure 44: The path obtained with LOS dropouts.

The difference between actual velocity magnitude and perceived velocity magnitude for this test has a mean of 57.3932 m/s and a standard deviation of 115.8911 m/s. The difference between the actual velocity angle and perceived velocity angle has a mean of 0.0058 radians and a standard deviation of 0.9018 radians.

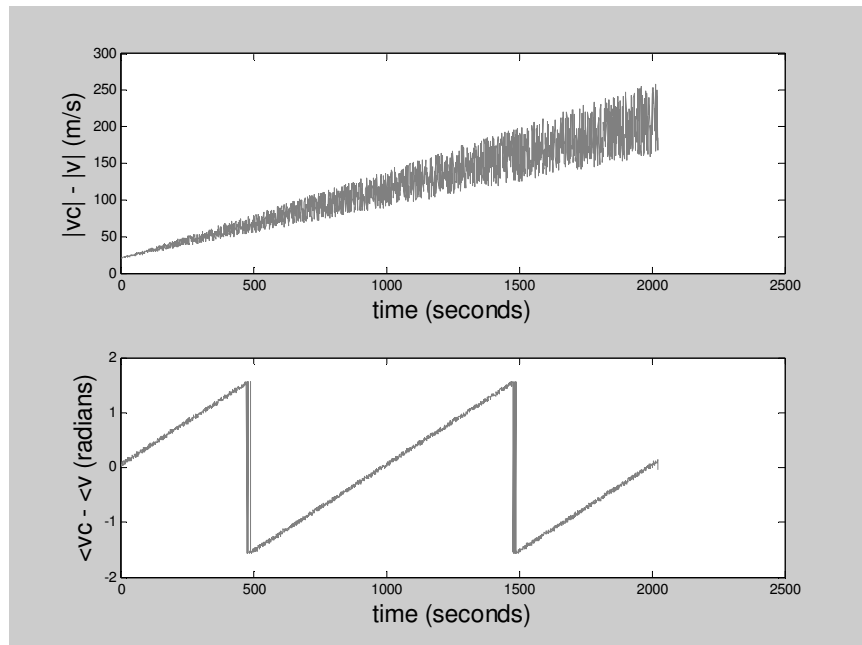


Figure 45: The difference in calculated velocity when LOS dropouts are present.

7 CONCLUSION & RECOMMENDATIONS

In this section, the correctness of the software simulator produced is discussed, and various recommendations made that will reduce sources of errors in the system. The effects of the remaining errors in the system are then discussed, and a conclusion regarding the use of Doppler Tracking for pilot balloons is drawn.

7.1 The Correctness of the Software Simulator

A working piece of simulation software was produced that uses the Doppler frequencies received from the transmitter by three different antennas to track the balloon. Once the path of the balloon had been established, velocity readings for different altitudes could be extracted by the simulation.

When an error-free set of frequencies is used as input to the path simulator, the path calculated, and therefore the velocities calculated, is exactly correct. However, it should be noted that the simulator is very crude and leaves much room for improvement. This is discussed in Section 7.4.

7.2 Recommendations Concerning External Factors

Various recommendations were made concerning factors external to the software, in order to minimize errors. These were:

- Ensure that the line-of-sight path between the antennas and the transmitter has first Fresnel zone clearance.
- Ensure that the layout of the antennas does not affect frequency readings negatively.
- Keep the bandwidth of the receiver to a minimum, and discard readings with poor signal-to-noise ratios.
- In the receiver, take as many frequency domain samples as possible.

7.3 The Effect of Various Errors on the System

During testing, it was established that using a spline and imposing a constant rate of ascent on the balloon can greatly improve the simulation's prediction of the path of the balloon. Even so, the various errors in the system cause large errors in the calculated velocity of the balloon.

The test results below show the effect of various sources of errors on the accuracy of the calculated velocity, and whether the accuracy obtained is satisfactory or not.

Affecting Factor	Error in Input	Accuracy of Calculated Velocity	Desired Accuracy	Satisfactory? (YES/NO)
None	none	$\sigma_{ v } = 0 \text{ m/s}$ $\sigma_{<v} = 0 \text{ rad.}$	$\sigma_{ v } = 1.25 \text{ m/s}$ $\sigma_{<v} = 0.0436 \text{ rad}$	YES
Multipath Dropouts	30 or less dropouts	$\sigma_{ v } = 11 \text{ m/s}$ $\sigma_{<v} = 0.14 \text{ rad.}$	' '	NO
LOS Dropouts	dropouts for the first 120m of ascent	$\sigma_{ v } = 115.89 \text{ m/s}$ $\sigma_{<v} = 0.9018 \text{ rad.}$	' '	NO
Frequency	$\sigma_f = 0.167 \text{ Hz}$	$\sigma_{ v } = 2.73 \text{ m/s}$ $\sigma_{<v} = 0.15 \text{ rad.}$	' '	NO
	$\sigma_f = 0.667 \text{ Hz}$	$\sigma_{ v } = 50.55 \text{ m/s}$ $\sigma_{<v} = 0.85 \text{ rad.}$	' '	NO

Multipath Dropouts cause the calculated velocities to be less accurate than desired, and thus a method of position prediction more sophisticated than a spline is necessary. Line-of-sight dropouts also affect the calculated velocities more than is authorized. A better method of predicting the balloon's path over the first few seconds is necessary.

Finally, even small errors in frequency cause large errors in calculated velocities. This is because in the method of position calculation used, each new position calculated depends on the frequencies received at *all three* antennas, as well as all the previous

positions. It is easy to see how seemingly small errors will accumulate quickly and cause large errors toward the end of the flight. Both the frequency error produced by change in temperatures, as well the frequency error in the receiver cause the velocity calculations to be much less accurate than desired.

7.4 Conclusion

The sources of errors in the system were identified, and the simulation software was used to establish the effect these have on the velocities of the balloon calculated. When the input to the simulator has no errors, the velocities calculated were perfectly correct. However, it was found that in all cases, when errors were added to the simulation, the error in calculated velocity is much larger than permitted.

Ways of avoiding errors due to Multipath dropouts and Line-of-Sight dropouts could be incorporated in the simulator. The error in the receiver can also be improved. However, the main concern is the change in transmitter frequency. The simulator requires frequencies to be extremely accurate, which is not feasible.

It should be noted that the simulator is very crude. Therefore the idea of Doppler tracking the balloons should not be discarded at this point. Rather, a more sophisticated simulator is needed which does not require the transmitted frequency to be extremely accurate. Such a system is discussed in Chapter Eight. There is evidence here that with a better simulator, balloons can indeed be tracked using the Doppler Method.

8 FUTURE WORK

In order to build a software simulator which can accurately determine the path and velocity of a balloon using Doppler tracking, a number of tasks need to be carried out.

8.1 Implementation of a Kalman Filter

When multipath dropouts occur, no new position of the balloon can be calculated. The position therefore needs to be estimated. At present, a spline is being used. This is a fairly simplistic method, and a more sophisticated one will ensure better accuracy in calculated velocities. The recommended method for future use is the Kalman filter. The Kalman filter is an efficient recursive filter which estimates the state of a dynamic system from a series of incomplete and noisy measurements. Only the estimated state from the previous time step and the current measurement is needed to compute the estimate for the current state. In contrast to batch estimation techniques, no history of observations and/or estimates is required. This would be a very appropriate method to predict missing positions in the path.

8.2 A Method for Tracking the Balloon in the First Stage of Its Flight

During the first 120 metres of the balloon's ascent, it is not within line-of-sight of two of the antennas. At present, this solution is solved in the simulator by simply assuming that the balloon moves straight up. However, this method creates large errors in velocities calculated. A better way of either tracking or predicting the path of the balloon during this first stage needs to be invented.

8.3 A Method to Eliminate Errors Due To Changes in Transmission Frequency

As already mentioned, the main concern in the current simulator is the error due to change in transmitter frequency. This simulator requires frequencies to be extremely

accurate. A more sophisticated simulator is needed which does not require the transmitted frequency to be accurate. A possible method is described in [ref].

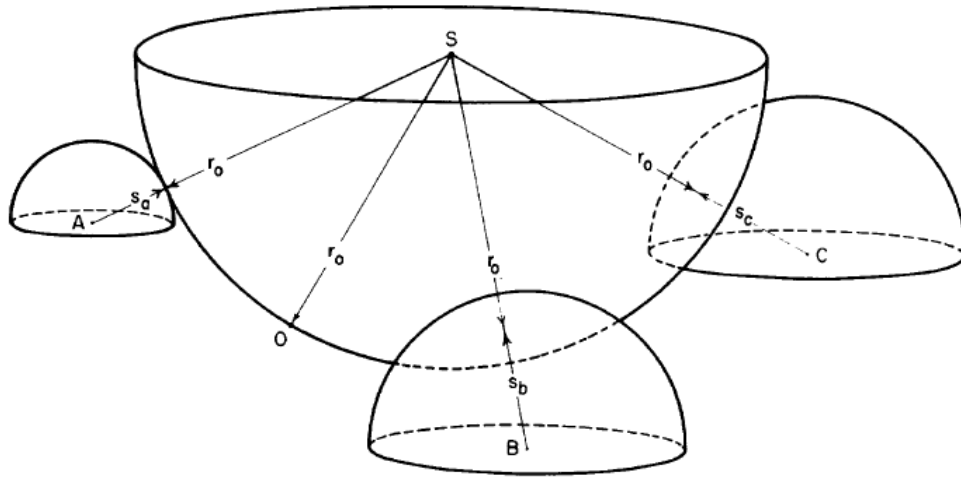


Figure 46: The four station solution that eliminated the problem of transmitter frequency inaccuracies.

This method uses four receiving stations, with one at the origin of the Cartesian coordinate system. The trick is to measure the *difference* in frequency between two stations. Receiving stations are at A, B, C and O in Figure 46. The distance from each antenna to the source is r_a , r_b , r_c and r_o . The transmitter is located at S. Three spheres exist with centers A, B, C and radii

$$s_a = r_a - r_o$$

$$s_b = r_b - r_o$$

$$s_c = r_c - r_o$$

r_a , r_b , r_c and r_o are all obtainable, and the source can be located at the centre of the sphere which is tangent to the spheres A, B and C and goes through the point O. By using this method, changes in transmitter frequency can be completely ignored. It is suggested that an alternate simulator be implemented, using this technique.

REFERENCES

- [1] AMS Glossary of Meteorology. MST Radar.
<<http://amsglossary.allenpress.com/glossary/search?id=MSTRadar>>
[Accessed 1 October 2006]
- [2] Atkinson, D. H., J. B. Pollack, A Seiff. Measurement Of A Zonal Wind Profile On Titan By Doppler Tracking Of The Cassini Entry Probe in *Radio Science* Vol. 25. Sept 1990. pg 865-881.
- [3] Bose, Ranjan. Lecture slides on Mobile Radio Channels. Indian Institute of Technology, Delhi. 2006.
- [4] Carof, A.H. Acoustic Differential Delay And Doppler Tracking System For Longrange AUV Positioning And Guidance in *Proceedings of the Symposium on Autonomous Underwater Vehicle Technology*. July 1994. pg 370-375.
- [5] Fricke, Clifford L., and Carl W. L. Watkins. Analysis Of A Four-Station Doppler Tracking Method Using A Simple CW Beacon. NASA TN D-748. April 1961.
- [6] Galloway, James L., and Humfrey Melling. Tracking the Motion of Sea Ice by Correlation Sonar in *Journal of Atmospheric and Oceanic Technology* Vol 14. June 1997. pg 617-629.
- [7] Gregg, W. R. Some Recent Papers On The Rate Of Ascent Of Pilot Balloons in *Monthly Weather Review*. December 1920. pg 694 – 696.
- [8] Gufflet, Dr. N. Quartz Crystal Resonators.
- [9] Henning, Allen B. Some Experimental Results For A Doppler Tracking Method Using A Simple CW Beacon. NASA TN D-2188. March 1964.

- [10] Jensen, J.R., and R.S. Bokulic. Highly accurate, non-coherent technique for spacecraft Doppler tracking in *IEEE Transactions on Aerospace and Electronic Systems* Vol. 35. Issue 3. July 1999. pg 963-973.
- [11] NOAA. Weather Balloons. <<http://www.srh.noaa.gov/epz/kids/kidswx.shtml>> [Accessed August 2006]
- [12] Scholnik, M. I. Introduction to Radar Systems. First Edition, McGraw-Hill Publishers, United States of America, 1962. pg 72-106 and pg 164-196.
- [13] Sherry, Capt. B. J. The Rate of Ascent of Pilot Balloons in *Monthly Weather Review*. December 1920. pg 692 - 694.
- [14] *South African Weather Service*. Meteorological Observations And Instrumentation. <<http://www.weathersa.co.za>> [Accessed August 2006]
- [15] Stremler, F. G. Introduction to Communication Systems. Third Edition, Addison-Wesley Publishers, University of Wisconsin, 1992.
- [16] Tadeka, S., T Nakamura and T Tsuda. An Improvement Of Wind Velocity Estimation From Radar Doppler Spectra In The Upper Mesosphere in *Annales Geophysicae*. 2001. pg 837–843.
- [17] *TXC Corporation*. Quartz Crystals. <http://www.txc.com.tw/english/in04/in4_01.html#P01> [Accessed 15 September 2006]
- [18] *Wikipedia*. Doppler Radar. <http://en.wikipedia.org/wiki/Doppler_Radar> [Accessed 3 October 2006]
- [19] *Wikipedia*. Fresnel Zones. <http://en.wikipedia.org/wiki/Fresnel_Zones> [Accessed October 2006]

- [20] Wilcox, Ronal E. Underwater Doppler Tracking Using Optimization Techniques in *Journal of the Acoustic Society of America* Vol. 63, No. 3. March 1978. pg 870 – 875.

- [21] Zrnic, Dusan S., and Dale Sirmans, Edwin Kessler. Determination of Winds from Balloon Tracking with a Doppler Radar in *Journal of Atmospheric and Oceanic Technology* Vol. 5. June 1988. pg 442 – 449.

- [22] Zytrax.com. Fresnel Zones and their Effect.
<<http://www.zytrax.com/tech/wireless/fresnel.htm>> [Accessed October 2006].

- [23] Dabberdt, W. F., and R Shellhorn. Radiosondes.

APPENDIX A: Normal (Gaussian) Distribution

The normal distribution, also called Gaussian distribution is a distribution of values that forms a bell curve, as shown in the graph in Figure 47 below. This graph has two parameters: the mean ("average") and standard deviation ("variability"). Assume that 66.6% of the values on the graph fall inside the shaded region, and the other 33.3% outside the shaded region. The mean of the graph (μ) is then zero, and the standard deviation (σ) is 1.

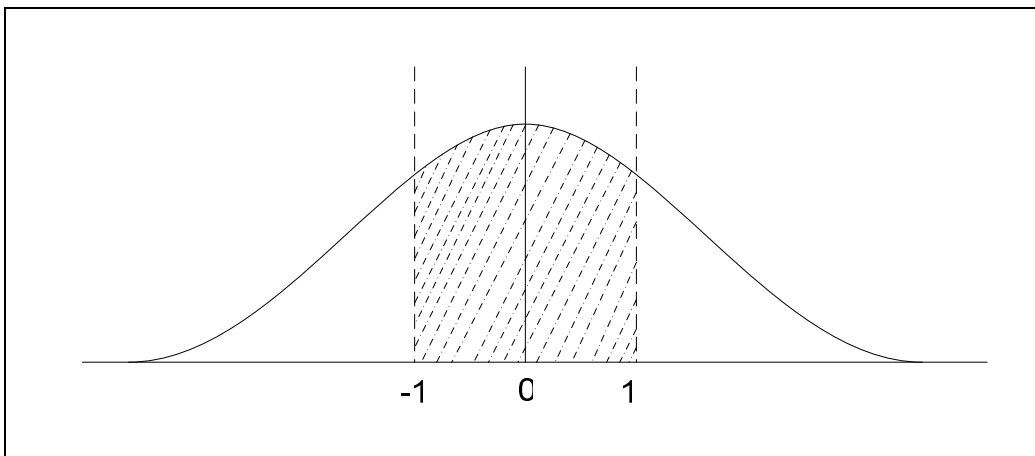


Figure 47: Illustration of a Normal Distribution.

APPENDIX B: Fresnel Zones

In order to make sure First Fresnel Zone clearance is obtained in a system, the specific geography of the area must be studied. Specialised software exists to do this. The following pages show the analysis of a path between Cape Town International and Tellumat Radio Tower. Diffraction losses (together with other losses) can be calculated using a program called Pathloss. By using such software, it can be ensured that the antennas are placed in places where the first Fresnel zone between the antenna and balloon is as clear as possible.