

IDENTIFYING AND REDUCING POSITIONAL ERRORS  
IN CESIUM MAGNETOMETER SURVEYS

by

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A senior thesis submitted to the faculty of

Ithaca College

in partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics

Ithaca College

April 2008

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DEPARTMENT APPROVAL

of a senior thesis submitted by

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This thesis has been reviewed by the research advisor, senior thesis instructor,  
and department chair and has been found to be satisfactory.

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## ABSTRACT

### IDENTIFYING AND REDUCING POSITIONAL ERRORS IN CESIUM MAGNETOMETER SURVEYS

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We present the effect of reaction time and speed variations of the operator on alternating positional errors, also known as the “zig-zag” or “zipper” effect, in a bidirectional, magnetic survey conducted on a three meter non-magnetic track. We specifically enumerate the effect of fiduciary marks and automated start and end lines. We find that increasing the speed of the survey has negligible effect on positional errors, but changing speed significantly increases the zipper effect. Use of fiduciary marks decreases the zipper effect significantly, and our data suggests that using accurate end points also contributes to reducing the zipper effect.

## ACKNOWLEDGMENTS

Ithaca College Department of Physics for financial support of this research

Professor Rogers, for supporting and guiding my research this far

Nikolas Batruch, for all of the work he did on this project

Kevin Faehndrich, Kristian Georgiev, and Greg Shear for laying the ground-work that has lead to this research



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# Chapter 1

## Introduction

The field of magnetometry has numerous applications. Often it is used to aid archaeologists in narrowing their search area to only areas containing features of interest. However, magnetometry has several other useful applications. Magnetometer surveys can also be used to detect land mines and unexploded ordinance remotely. It can also be used to find known sites that have been lost where digging might not be appropriate, such as when locating burials or other sensitive historical sites. However, accurate surveys require knowledge of what might affect the survey data, and how the data will be affected.

Magnetometer surveys locate subsurface artifacts and features by recording the small (down to 1 nT) changes in the magnitude of the Earth's local magnetic field, which ranges from 30,000 nT to 60,000 nT. In a cesium magnetometer this is accomplished through a process that is essentially reverse nuclear magnetic resonance. First, an unshielded cell containing cesium 133 vapor is excited using a high radio frequency field. Since the cell is unshielded the energy levels of the cesium are split due to the Zeeman effect because the cell is in an external magnetic field (here the Earth's magnetic field). The radiated light is then passed through a lens, a filter, and

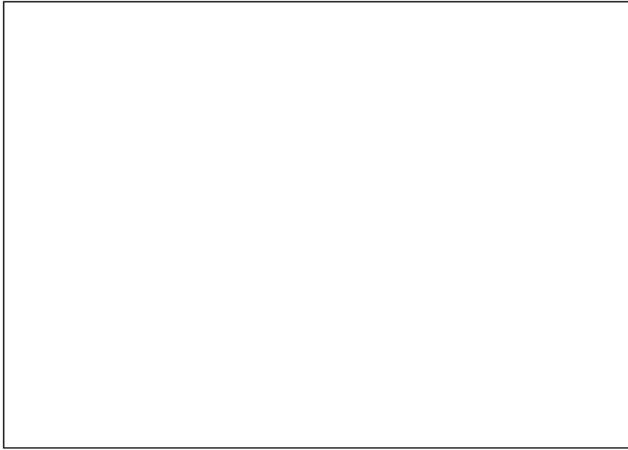


Figure 1.1 A pin diagram for the magnetometer. Taken from the Geometrics G-858 Magnetometer User Manual (<http://www.geometrics.com/858-d.html>).

a circular polarizer. The filter blocks all light with energies matching the antialigned to aligned transition from passing through. The light then passes through a second vaporized cesium cell and lands on a photodetector. The output of the photodetector is read by a circuit which controls a coil of wire that is wrapped around the second cell. An alternating magnetic field is generated by means of this coil. The dipoles of the cesium then lock onto one of the rotating components of this alternating field, and thus the field “pumps” the atoms into the antialigned state. Since the energies of the photons are only for antialigned ground state energy level to antialigned first excited state transitions, the atoms now absorb the photons, and so the transparency of the chamber decreases. When this reaches a maximum, the alternating magnetic field is proportional to the external magnetic field on the first cell, and thus a measurement of the Earth’s local magnetic field can be made. The aligned first excited state to aligned transition is blocked by the nature of the circularly polarized light [1].

While this leads to very precise measurements of the local magnetic field, there are several effects that can lead to misleading results. Some of these, such as diurnal effects (the magnetic effect of the sun as it passes overhead, causing the local magnetic field to increase before noon and decrease afterwards), are well understood. However, one remains relatively unstudied. The main one we focused our research on was the so called “zipper” or “zig-zag” error. This is a positional error where every other line of data is shifted to either the north or the south in a consistent pattern. Because of this shifting, features that are supposed to be straight lines generate a jagged image, reminiscent of a zipper. Figure 1.2 provides an excellent example of this zipper effect, showing a section of the results of a survey over several drainage pipes. The most common method for correcting this effect is fairly simple, every other line is shifted a certain amount so that local magnetic maxima and minima line up. [2–6].

However, this is not necessarily the best method for resolving this issue. One issue is that one cannot know which set of lines to shift, the odd lines or the even lines. A second is that both sets may need to be shifted, but this then raises the question by how much? Do they both need to be shifted to meet in the middle, closer to the odd lines, or closer to the even lines? It is difficult to answer these questions without knowing the exact source of the zipper effect. Here we attempt to discover the causes of this zig-zag effect, and attempt to develop methods to remove the effect entirely during data collection.

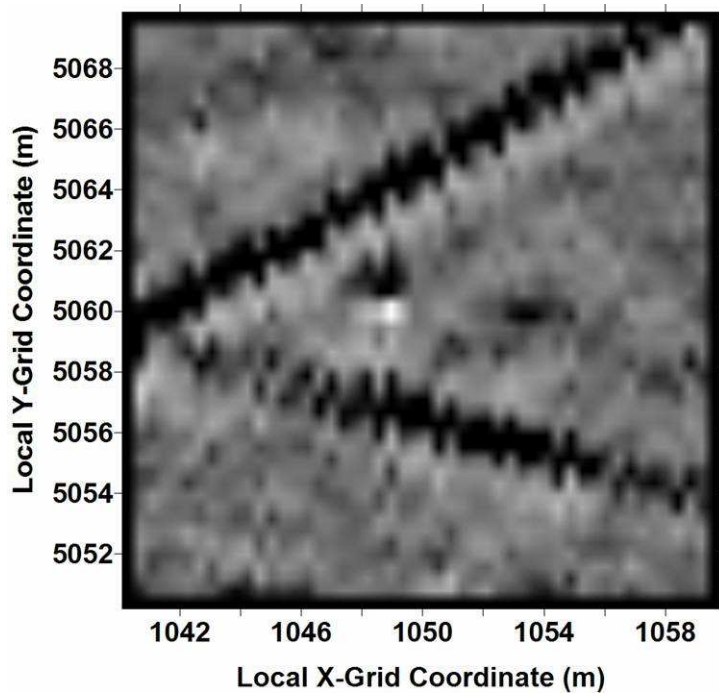


Figure 1.2 An excellent example of the "zipper" effect, taken from a larger survey conducted by Professor Rogers at the Oregon State University Research Dairy [7]. Here the two thick black lines are drainage pipes. These should be straight lines but appear jagged due to the zipper effect.

## Chapter 2

# Survey Method and the Non-Magnetic Track and Cart

The surveys Nik Batruch and I conducted were bidirectional, east-west surveys. Each survey consisted of ten westbound passes and ten eastbound passes using a Geometrics G-858G cesium, optically-pumped magnetometer. We placed a magnetic anomaly, a metal camping spike approximately 1.7 m along the survey path to create a distinct magnetic monopole. Each pass would consist of either an eastward or westward progression. Each run consisted of twenty passes, alternating westward then eastward. The cart was moved by a motor at one end of the track. A string was run from the motor, to the cart, and then around two pulleys at the other end of the track, before attaching back to the motor. This ensured that there was always tension in the string so the cart would maintain a constant speed (Figure 2.1). The speed of the motor was controlled by changing the current flowing to the motor. We did this through the use of a variable resistor connected between the power source and the motor. A device to automatically set fiducial marks was also designed and constructed by Nik Batruch. This consisted of a control box with a lead attached to the magnetometer,

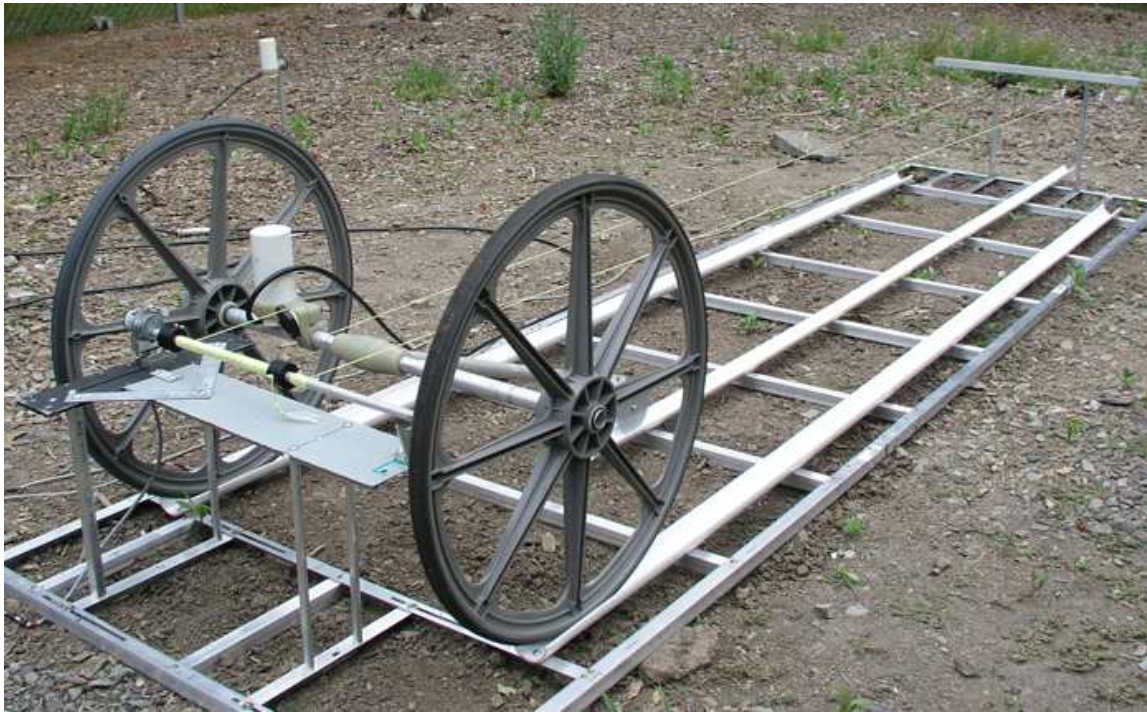


Figure 2.1 An image of the non-magnetic cart and track built [8]. The track is approximately three meters long with a metal stake at approximately two meters. A motor attached at one end wound a string which ensured a constant speed of the cart. and two fiber optic cables running to a holder placed on the magnetometer. A red laser was shone into one fiber optic cable, which terminated directly opposite the second fiber optic cable. The second fiber optic cable then ran to a photodetector inside the control box. Aluminum fins were fitted to the axle of the cart between the two fiber optic cables, with the spacing between the leading edge of each being 50 cm. Each time a fin interrupted the beam, the photodetector would signal the control circuit, which would trigger a fiduciary mark.

## 2.1 Non-Magnetic Cart

Professor Rogers designed the cart to minimize sources of magnetic noise. The wheels, axel, handle and fastenings were all constructed of either plastic or aluminum, both magnetically unresponsive materials. The tires were made of nylon bearing rubber, and likewise magnetically unresponsive. The handle was designed to be of sufficient length, approximately one meter, to distance the magnetometer sensor from the operator so that the magnetic field of the operator would have as little effect as possible on the survey.

## 2.2 Non-Magnetic Track

Nik Batruch also designed the track to have a minimal magnetic profile. The track was located outside of the Clinton Ford Observatory at Ithaca College. The observatory is located far away from any other buildings, with only a single dirt service road approaching it, thus eliminating any effects from nearby traffic. The track itself was built primarily of aluminum, with brass screws to hold pieces together. The entire track was approximately four meters long. Three PVC guides were fastened to the top of the track, two guides to hold the wheels, and a third guide to keep the cart centered and to prevent twisting of the cart, Figure 2.1. At the east end, the motor was attached to a platform. Two different motors were used. One was a motor originally for a car's power windows, and the second was a generic electric motor that turned at 1.8 rpm. We also installed two electronic switches on the southern wheel guide. When triggered, these would automatically start and stop the survey lines. The second magnetometer sensor was placed approximately 1.5 meters away, acting as a remote base station so the background magnetic field of the area could be removed from the final data. It also served to remove any large scale magnetic

anomalies occurring in the area, such as solar effects. The two control boxes, one for the sensor itself and one for the motor and switches, were placed approximately one meter away from both sensors. The power source, two twelve volt car batteries, for both the control boxes and the magnetic sensors was located directly against the observatory, approximately three meters away.

# Chapter 3

## Constant Speed

### 3.1 Data Collection

Data collection began with several surveys at constant speed. The first surveys were done using a 1.8 rpm motor. The magnetometer was put in “continuous” mode, meaning that a measurement of the earth’s local magnetic field was taken ten times every second. Data were collected for thirty minutes, resulting in approximately 18,000 data points (See superslow plot in Fig. 4.1). Several surveys were then conducted at faster, but continuous, speeds(Fig. 3.1). The speed was controlled by using integer settings between zero and five ohms on the variable resistor wired in series with the motor.

### 3.2 Analysis

The raw data was first first moved from the magnetometer onto a computer. The data was then imported into the Geometrics MagMapper software, packaged with the magnetometer. The data was then imported into Microsoft Excel. The “MAX”

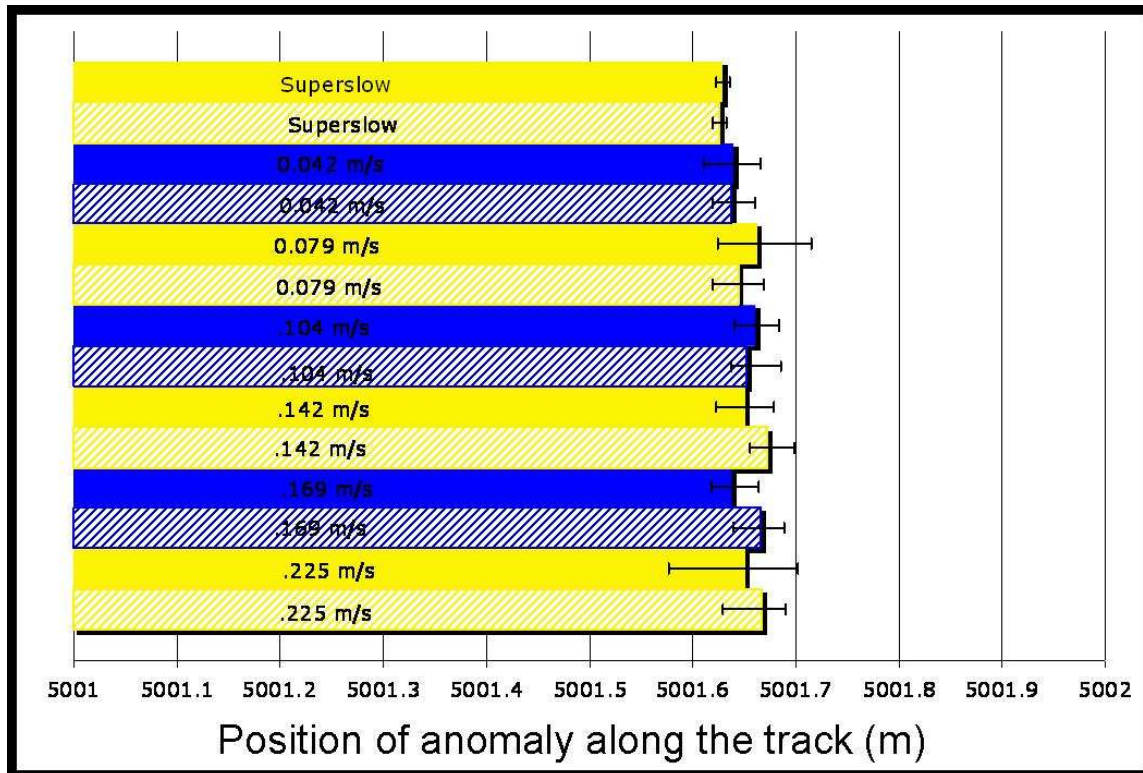


Figure 3.1 Results from surveys at constant speed. Speed is measured in ohms, with higher resistance indicating a slower speed. Solid bars are westbound runs while striped bars are the eastbound runs. Error bars represent the maximum and minimum of the set.

function was used to find the maximum of the data set, discounting the end nearest the motor. Due to the size of the data sets, the superslow runs were instead imported into ProFit and the maxima found manually. The average maxima position was then graphed for eastbound and westbound. Error bars on the graphs were generated by taking the maximum and minimum of the location of the maxima.

### 3.3 Results

The results of the constant speed surveys is fairly clear. Nearly all of these surveys yield a constant position for the magnetic peak. Further, the error bars show that the small zipper effect that is present is not significant. These errors likely result more from the experimental setup than an actual effect. We suspect that this arises from the fact that when going in one direction the motor is directly pulling on the cart through the string, but in the other direction the string passes through two pulleys before pulling on the cart.



# Chapter 4

## Variable Speed

### 4.1 Data Collection

After completing the constant speed surveys, the 1.8 rpm motor was removed and a car window motor was installed to take advantage of the greater torque provided by that motor. Marks were then placed one-third and two-thirds of the way along the track. The operator used these marks to determine when to change the resistance on the variable resistor, and thus change the speed of the magnetometer. The first survey was a changing speed westbound and a constant speed eastbound. The changing speed was very simple, from two ohms to one ohm to zero ohms (resulting in an increasing speed). The eastbound return was done at zero ohms. The next survey was done using the same westbound speed pattern, but the eastbound pattern was changed to the opposite of the westbound pattern so that the magnetometer was going the same speed in the same third of the track. The final survey was done to determine the extremes. The westbound speed was five ohms for the first two-thirds and zero ohms for the last. The eastbound was opposite the westbound pattern.

## 4.2 Analysis

The raw data was first first moved from the magnetometer onto a computer. The data was then imported into the Geometrics MagMapper software, packaged with the magnetometer. The data was then imported into Microsoft Excel. The "MAX" function was used to find the maximum of the data set, discounting the end nearest the motor. Due to the size of the data sets, the superslow runs were instead imported into ProFit and the maxima found manually. The average maxima position was then graphed for eastbound and westbound. Error bars on the graphs were generated by taking the maximum and minimum of the location of the maxima.

## 4.3 Results

The results of this data is quite straightforward. The super slow survey shows virtually no zipper effect, and has very high precision. However, when one increases speed in one direction while staying constant in the other, the zipper effect appears. This zipper is approximately 50 cm. When the speed change is mirrored, increasing in one direction and decreasing the same amount in the other, the zipper effect increase to approximately 70 cm. If the speed change is very extreme, going from very slow to very fast, and mirrored, the zipper effect become quite significant, approximately 1m. This change is significantly larger than any error that results from going at a constant speed, and therefore cannot be a result of that. Due to the magnitude of the zipper effect seen in the surveys, we concluded that the variable speed is a major source of positional error that results in the zipper effect.

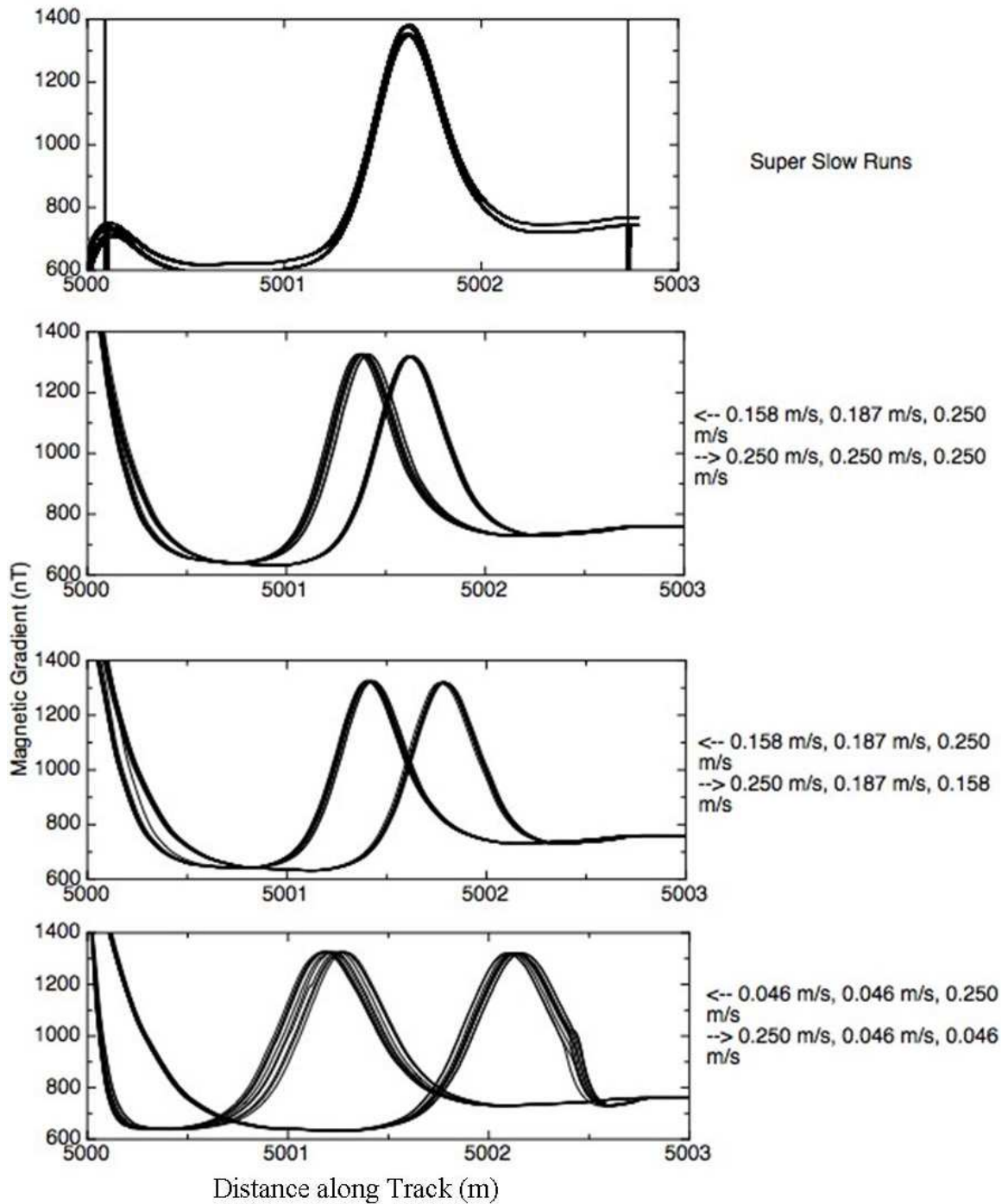


Figure 4.1 Data taken from several variable speed runs. This illustrates that variation of speed contributes to the zipper effect, with the contribution proportional to the change in speed.



# Chapter 5

## Fiduciary Marks

### 5.1 Data Collection

Once finished with the variable speed surveys, Nik's fiduciary mark system was installed on the cart. A survey was then conducted at roughly half a normal walking pace (referred to as "superfast"). This was done with fiduciary marks automatically set every 50 cm. The motor was then removed. The remainder of the surveys were completed with a human operator. Surveys were conducted first without fiduciary marks, and then with the fiduciary marks placed by Nik's system.

### 5.2 Analysis

The raw data was first first moved from the magnetometer onto a computer. The data was then imported into the Geometrics MagMapper software, packaged with the magnetometer. The data was then imported into Microsoft Excel. The "MAX" function was used to find the maximum of the data set, discounting the end nearest the motor. Due to the size of the data sets, the superslow runs were instead imported

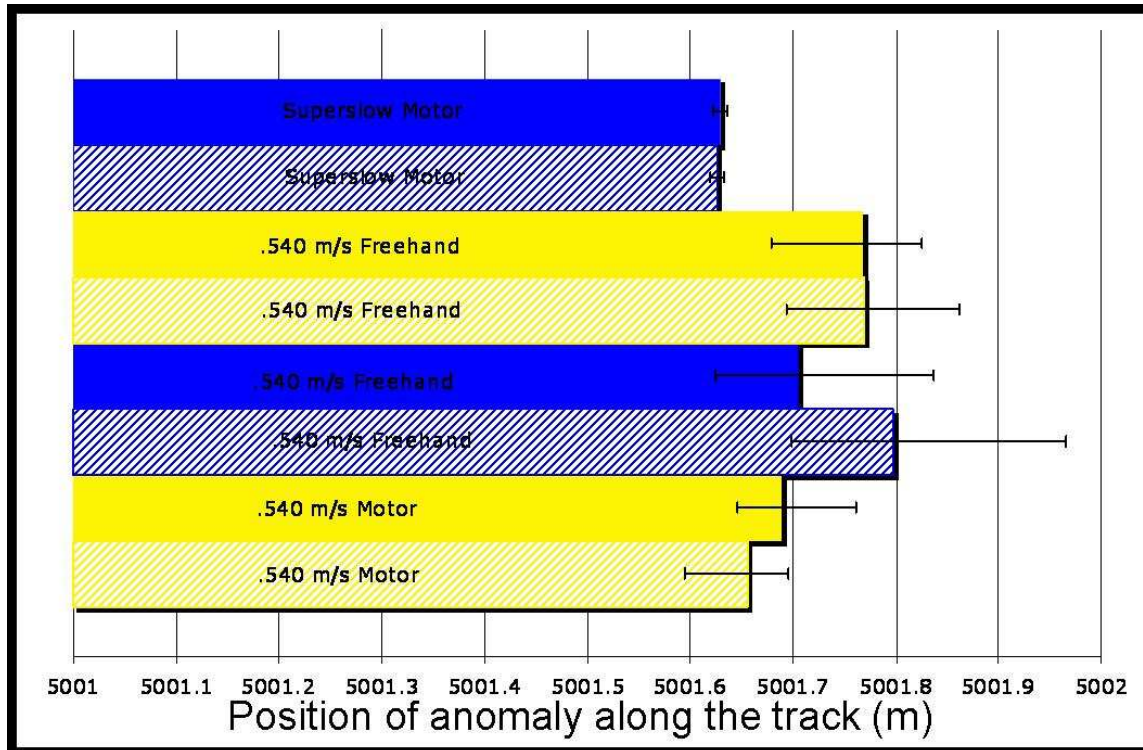


Figure 5.1 Results from tests of the fiduciary marks. The dark blue indicates surveys without fiduciary marks, while the light yellow shows surveys with fiduciary marks. Solid bars are westbound runs while striped bars are the eastbound runs. Error bars represent the maximum and minimum of the set.

into ProFit and the maxima found manually. The average maxima position was then graphed for eastbound and westbound. Error bars on the graphs were generated by taking the maximum and minimum of the location of the maxima.

### 5.3 Results

The results obtained in these surveys is very distinct. The data shows that the fiduciary marks significantly reduce positional errors. Further, the size of the error bars on the superfast motor with fiduciary marks indicates that the difference between the

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east and westbound runs is not significant. The feature that was most unexpected was a bulk shift of the position of the peaks. Both freehand runs are shifted approximately 15 cm. We suspect that this shift is due to misalignment of the initial fiduciary mark, which would lead to a systematic error across all runs. Also, the small zipper effect that is present in the surveys with the fiduciary marks is actually “negative,” the westbound passes produce a maxima at a further position than the eastbound passes (the opposite of surveys without the fiduciary marks). We are still uncertain of the cause of this “peak flipping.”



# Chapter 6

## Reaction Time

### 6.1 Data Collection

After finishing the fiduciary marks surveys, the electronic end switches were disabled, leaving the operator to end the lines manually. The surveys without end switches were done with fiduciary marks every 50 cm, and then repeated without the fiduciary marks.

### 6.2 Analysis

The raw data was first first moved from the magnetometer onto a computer. The data was then imported into the Geometrics MagMapper software, packaged with the magnetometer. The data was then imported into Microsoft Excel. The "MAX" function was used to find the maximum of the data set, discounting the end nearest the motor. Due to the size of the data sets, the superslow runs were instead imported into ProFit and the maxima found manually. The average maxima position was then graphed for eastbound and westbound. Error bars on the graphs were generated by

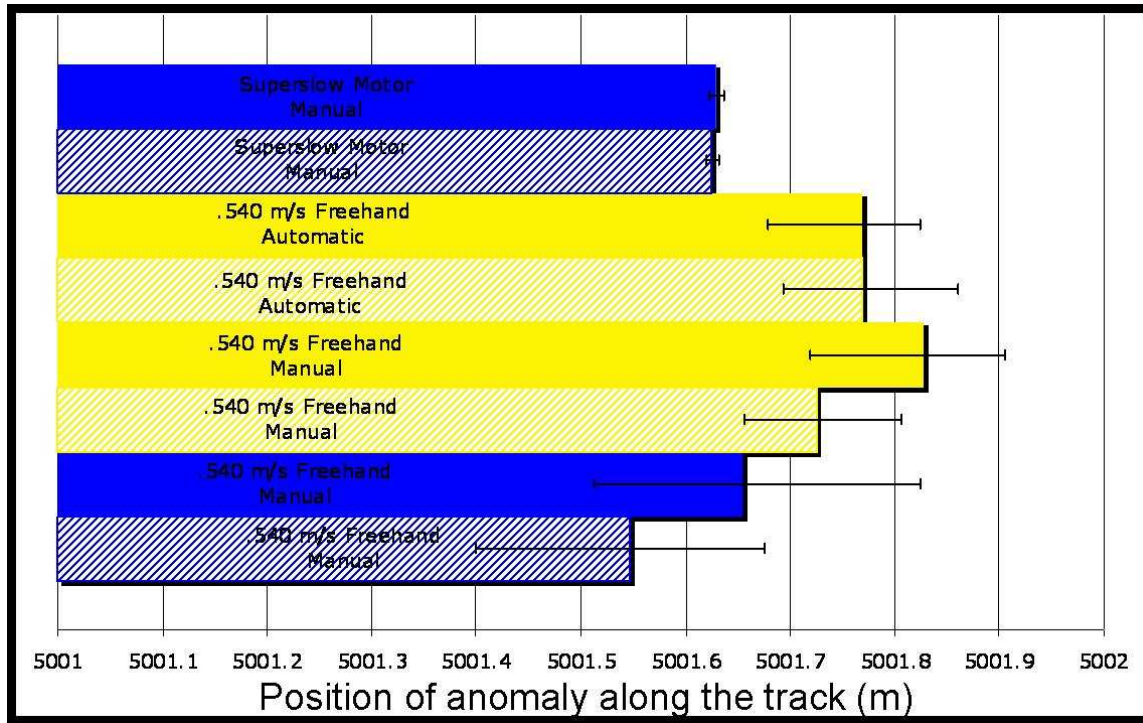


Figure 6.1 Results from tests of the effect of electronic end switches. Bars labeled automatic used the end switches, while manual ones had the ends inputted manually. The dark blue indicates surveys without fiduciary marks, while the light yellow shows surveys with fiduciary marks. Solid bars are westbound runs while striped bars are the eastbound runs. Error bars represent the maximum and minimum of the set.

taking the maximum and minimum of the location of the maxima.

### 6.3 Results

These surveys show similar results to the others. Here again we observe the bulk shifting that was associated with the fiduciary marks. Similarly, this is likely due to misalignment of the initial fiduciary mark. However, it also becomes apparent that the electronic end switches do reduced zipper effect. There is some uncertainty in the survey with both fiduciary marks and the manual endlines, as the fiduciary marks

should isolate the endlines from the peak since the peak is over a meter away from the ends.



# Chapter 7

## Conclusions

The zipper effect is very pervasive in magnetometer surveys. It appears in virtually all surveys done, but thus far there has been very little research into its causes. To investigate the causes of this effect, we constructed a track and cart system that would completely isolate any possible sources of error except the ones we were testing. Our results show that increasing the speed of the survey does not have a significant effect on positional errors. However, varying the speed while surveying creates a significant positional error. By using fiduciary marks, this error can be reduced, however, our results show a bulk shift that we suspect is a result of improper alignment of the first fiduciary mark. Use of electronic end switches to accurately mark the end of the lines also seems to decrease the zipper effect, but more study is needed. Currently, we are in the process of extending our three meter track to twenty meters, the standard distance used in our field surveys. We plan to conduct further tests on this track, with and without fiduciary marks. These test will increase our data set on variable speed, especially over more realistic lengths and will increase the speeds tested to average walking speeds. We will also test extreme speeds such as a surveyor sprinting. These tests should also help to clarify the results regarding the end switches.

Table 7.1 The results of the surveys at constant speed. The average peak is the total average of both eastbound and westbound passes. The  $\Delta$ Peak is the eastbound average minus the westbound average.

Speed	Average Peak Location	West Peak	East Peak	$\Delta$ Peak
Superslow	5001.628 m	5001.630 m	5001.625 m	-0.005 m
0.0042 m/s	5001.638 m	5001.640 m	5001.637 m	-0.003 m
0.0079 m/s	5001.653 m	5001.662 m	5001.645 m	-0.017 m
0.104 m/s	5001.657 m	5001.661 m	5001.652 m	-0.009 m
0.142 m/s	5001.662 m	5001.651 m	5001.673 m	0.022 m
0.169 m/s	5001.651 m	5001.637 m	5001.665 m	0.028 m
0.225 m/s	5001.659 m	5001.651 m	5001.668 m	0.017 m

Table 7.2 The results of the surveys using fiduciary marks and manual endlines. All surveys were done at 0.540 m/s. The average peak is the total average of both eastbound and westbound passes. The  $\Delta$ Peak is the eastbound average minus the westbound average.

Variables Tested	Average Peak Location	West Peak	East Peak	$\Delta$ Peak
Superfast with Fiduciary Marks and automatic endlines	5001.769 m	5001.768 m	5001.769 m	0.001 m
Superfast without Fiduciary Marks and automatic endlines	5001.751 m	5001.705 m	5001.797 m	0.092 m
Superfast with Fiduciary Marks, automatic endlines, and motor	5001.672 m	5001.689 m	5001.656 m	-0.033 m
Superfast with Fiduciary Marks and manual endlines	5001.777 m	5001.828 m	5001.726 m	-0.102 m
Superfast without Fiduciary Marks and manual endlines	5001.601 m	5001.655 m	5001.546 m	-0.109 m



# Bibliography

- [1] I. Scollar, A. Tabbagh, A. Hesse, I. Herzog. Archaeological Prospecting and Remote Sensing, 461-465. Cambridge University Press, 1990.
- [2] W. Neubauer and A. Eder-Hinterleitner. "3D Interpretation of Postprocessed Archaeological Magnetic Prospection Data." *Archaeological Prospection* 4, 191-205 (1997).
- [3] H. Odah, T.F. Abdallatif, I.A. El-Hemaly, E. Abd El-All. "Gradiometer Survey to Locate the Ancient Remains Distributed to the Northeast of the Zoser Pyramid, Saqqara, Giza, Egypt." *Archaeological Prospection* 12,61-68 (2005).
- [4] A. Eder-Hinterleitner, W. Neubauer, P. Melichar. "Restoring Magnetic Anomalies." *Archaeological Prospection* 3, 185-197 (1996).
- [5] M. Ciminale, M. Loddo. "Aspects of Magnetic Data Processing". *Archaeological Prospection* 8, 239-246 (2001).
- [6] M. Ciminale. "A High-resolution Magnetic Mosaic at the Kyme Archaeological Site". *Archaeological Prospection* 10,119-130 (2003).

- [7] M. Rogers, J. Baham, M. Dragila. "Soil Iron Content Effects on the Ability of Magnetometer Surveying to Locate Buried Agricultural Drainage Pipes". *Applied Engineering in Agriculture* 22(5), 701-704 (2006).
- [8] Photo courtesy of Nikolas Batruch.