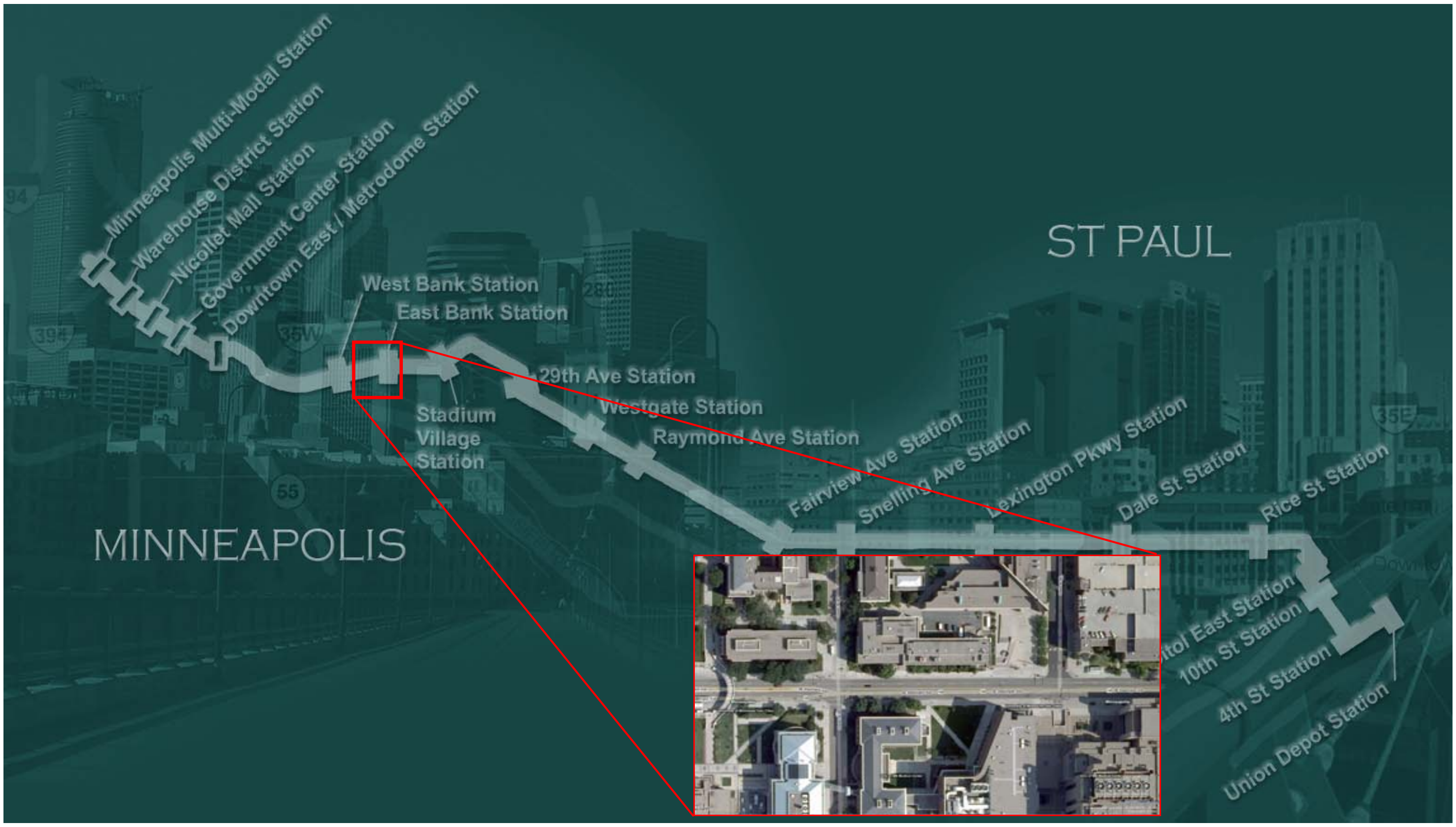
# APPENDIX J2

# ELECTROMAGNETIC FIELDS AND INTERFERENCE




# Electromagnetic Interference

# Measurement and Assessment

May 2008

Prepared for:
**Metropolitan Council**
**St. Paul, MN**

# Electromagnetic Interference

# Measurement and Assessment

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Reviewed By: Jim Alexander

May 2008

# Contents



# Illustrations

The following Appendices contain illustrations that accompany the text:

# 1 Background and Purpose

The Central Corridor Light Rail Transit (CCLRT) alignment extends along Washington Avenue through the University of Minnesota East Bank campus. As part of the environmental documentation process, the Central Corridor Project Office (CCPO) was made aware in February and March 2008 of several superconducting Nuclear Magnetic Resonating spectrometers (NMR) that are operated in University of Minnesota research facilities located in close proximity to the planned CCLRT alignment along Washington Avenue.

CCPO understands that the facilities housing NMRs along Washington Avenue include Hasselmo Hall, Smith/Kolthoff Halls, Weaver Densford Hall, Phillips-Wangensteen Hall, and the 717 Delaware Hall. Based on discussions with University of Minnesota staff and its major NMR supplier, Varian, CCPO understands that Hasselmo Hall houses the most sensitive NMR equipment. While all of the NMRs on the University campus are of concern, it is the 800MHz NMR at Hasselmo Hall that is the most sensitive because of its low tolerance to magnetic interference of no more than 2 milligauss (mG) immediately outside of the device and its close proximity to the planned track alignment. Hasselmo Hall houses six other NMRs. Based on this, the 800Mhz NMR has been the primary focus as it is considered to be the governing device in terms of mitigation requirements.

See map in Appendix A for locations of the affected facilities along Washington Avenue.

LRT produces electromagnetic interference (EMI) that may impact the operation of the NMRs.

Magnetic perturbations from light rail are generated by two means:

- Strong magnetic fields generated due to current flowing through conductors.

  Any change in an electrical field creates an associated, varying magnetic field. The electrical or magnetic field variations can cause interference to various types of equipment. The currents flowing through the overhead contact and the at-grade rails generate strong magnetic fields that vary with the position of trains.

- Magnetic distortions of the earth's magnetic field due to large, moving ferromagnetic masses.

  Any large mass of ferromagnetic material (e.g., iron, steel…) has a distorting effect on the earth's magnetic field. Stationary objects pose no problem, however objects in motion "perturb" the field in a time-varying way. These geomagnetic perturbations are a function of mass and can be significant in magnitude.

In order to understand the potential impacts to NMRs from the CCLRT and to develop possible mitigation measures, the CCPO conducted a testing program to identify magnetic disturbances caused by LRT on the Hiawatha LRT (HLRT) line. Background testing was also conducted along Washington Avenue on the East bank campus in the vicinity of Hasselmo Hall.

The CCPO team involved in the testing and mitigation design includes LTK, David Fugate of ERM and Dr. Luciano Zaffanella of Enertech. Mr. Fugate with the assistance of LTK conducted the testing and Dr. Zaffanella conducted the mitigation analysis.

This report summarizes the testing activities performed to assess the impact of the CCLRT on the known NMRs on the University of Minnesota campus and where required, provides mitigation measures to reduce the impact of the EMI on affected NMRs to within acceptable levels.

# 2 Magnetic Field Testing

The first stage of testing was designed to measure the electrically induced magnetic fields resulting from the operation of the HLRT, to characterize magnetic field transients produced by the operation of LRT and to mimic, as close as possible, conditions that will be expected on the CCLRT. The CCLRT will initially use 2-car trains, however, it is anticipated that ridership demand will eventually require the use of 3-car trains. As such, the testing program included both 2- and 3-car trains.

The program included recording magnetic field measurements at test locations along the HLRT using a data acquisition system. The location of interest was at the Government Plaza Station due to the similar design and operational characteristics planned along Washington Avenue on the East Bank campus.

The CCLRT includes the East Bank Station, which will be located on either side of Union Street on Washington Avenue approximately 150 to 200 feet east of Hasselmo Hall. Trains may simultaneously leave the station presenting a worst-case electrical load that this segment of the CCLRT will be subjected to. This high draw of current will result in a strong magnetic field emanating from both the rails and the overhead conductors.

The planned power distribution substations at West Bank and Stadium Village are almost equidistant from Hasselmo Hall; the Government Plaza test site was chosen to replicate this anticipated substation spacing on CCLRT along Washington Avenue.

The vehicles for the CCLRT will be limited to 1,000 amps (A) per car. A pair of trains, one in each direction and three-cars in length, with each car demanding 1,000 A will present a peak load of 6,000 A to the electrical system. It should be noted that normal operation will generally not result in electrical currents this high, however the testing program included a number of tests using this electrical load to record system-wide, worst-case scenario measurements. Due to substation placement (equidistant at the test site), the currents will be split equally with 3000 A being provided by each substation.

Testing details are provided in the following sections.

## 2.1 Electrically Induced Magnetic Field Testing

Testing was conducted at two locations on the HRLT to measure electrically induced magnetic fields created by the operation of the LRT. The two locations included Government Center Plaza and immediately north of 42$^{nd}$ Street East on the HLRT. The Government Center Plaza location was chosen because of the similar characteristics to Hasselmo Hall on Washington Avenue. The second test site, 42$^{nd}$ Street East was chosen to measure maximum electromagnetic interferences (system-wide, worst-case scenario) that could be caused by LRT. It should be noted that the physical and operational characteristics at the 42$^{nd}$ Street test site are not representative of Washington Avenue and should only be considered an upper bound for LRT.

The magnetic field at both HLRT test locations was measured at distances parallel to the track of 20, 40, 80, 120, and 160 feet.

### 2.1.1 Testing on Hiawatha LRT at Government Plaza Station

Testing at this location was conducted from 2:20 AM to 3:40 AM on April 9, 2008. The test site was located on the south side of Government Plaza Station. Appendix B-1 includes a map of the test site.

This test location was selected primarily because the physical and operational characteristics of the HLRT system at this location are representative of those planned for the CCLRT along Washington Avenue including:

- Overhead contact configuration consisting of contact wire with supplemental feeders buried in the street.
- Embedded track
- LRT operational speeds

Additionally, the test site is located approximately equidistant between substations, which is similar to the location adjacent to Hasselmo Hall.

The testing at the HRLT Government Plaza location consisted of a set of runs using two, 3-car trains accelerating away from each other from a dead stop. Accelerations were at maximum propulsion and at typical acceleration.

Two test runs were made at full acceleration and two at normal acceleration. Since the maximum allowable speed in this area is 25 miles per hour (mph), the trains were accelerated until they reached 25mph, then they were braked.

- Under full acceleration the current recorded onboard the vehicles totaled over 6,500 A.
- Under typical acceleration the current recorded onboard the vehicles totaled over 3,700 A.

See Appendix B-2 for the Test Data.

### 2.1.2 Testing on Hiawatha LRT at 42nd Street East

Testing at this location was conducted from 2:20 AM to 3:40 AM on April 8, 2008. The test site was located immediately north of 42nd Street East and south of the HLRT tracks. Appendix C-1 includes a map of the test site.

This test location was selected for the following reasons:

- Maximize electromagnetic interference (system-wide, worst-case scenario).
- The overhead contact configuration along this segment (contact wire and messenger) produces the highest EMI.
- Relative remoteness and straight, flat track allowed for uninhibited maximum propulsion of the Light Rail Vehicles.

**Note:** *This configuration **is not** representative of the physical and operational characteristics planned along Washington Avenue and the test results should only be considered as an upper bound for LRT.*

Measurements were recorded at this location for two runs at full acceleration and two runs at normal (operating) acceleration.

- Under full acceleration the current recorded onboard the vehicles totaled over 6,500 A.

- Under typical acceleration the current recorded onboard the vehicles totaled over 3,900 A.

See Appendix C-2 for the Test Data.

## 2.2 Geomagnetic Perturbation Testing

### 2.2.1 Testing on the Planned Central Corridor LRT Alignment at Washington Ave

Testing was performed on the north side of Hasselmo Hall to assess a baseline for geomagnetic perturbations. The purpose of this phase of testing was to measure the amount of geomagnetic perturbation created by existing traffic on Washington Avenue as the roadway currently accommodates several hundred buses a day as well as truck and automobile traffic. The testing was also conducted to measure the amount of decay in the magnetic field caused by the existing vehicle traffic on Washington Avenue as the distance from the magnetic source (i.e., vehicles) increases.

Testing at this location was conducted from 3:45 pm to 4:30 PM on April 8, 2008. Measurements were recorded at twice per second for 15 minute periods at three locations: near the southern curb of Washington Avenue at a distance of 44 feet from the center of the planned trackway; near the northern building face of Hasselmo Hall, approximately 86 feet from the center of the planned trackway; and near the southern curb of Washington Avenue about 200 feet east of Hasselmo Hall. The sensors were located as such to determine the degree of decay of magnetic fields generated by vehicle traffic on Washington Avenue. Appendix D-1 includes a map of the test site.

See Appendix D-2 for the Test Data

### 2.2.2 Testing on the Hiawatha LRT Near the Mall of America

Testing at this location was conducted from 2:20 AM to 3:40 AM on May 10, 2008. The test site was located on the HLRT east of the Mall of America adjacent to Old Shakopee Road. Appendix E-1 includes a map of the test site.

The purpose of this testing was to measure the geomagnetic perturbations from the light rail vehicles. The geomagnetic perturbation from the vehicles was isolated by shutting down all train operations and powering down nearby substations to eliminate the possibility of any other perturbation sources.

Testing was first performed on a single 2-car train. Then a second 2-car train was pulled parallel and tested. A third test was then performed with a single 3-car train. Measurements were also recorded to show the decay as trains moved away for both 2-car and 3-car train consists. Data was collected after trains were moved in 50 foot increments down the track.

See Appendix E-2 for the Test Data

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# 3 Mitigation

## 3.1 SUMMARY

The operation of CCLRT may interfere with some of the NMRs located along Washington Avenue on the University of Minnesota East Bank campus without proper mitigation. The NMRs require an extremely stable DC magnetic field, such as the geomagnetic field. A change of magnetic field of even a few mG, if not constant, will affect NMR performance. The currents required by the LRT will flow into overhead wires and rails and will produce magnetic field perturbations. The level of magnetic field perturbation decreases with the distance from the tracks. Calculations were made for distances in the range of those between existing NMR machines and the track of the proposed route. It was found that, if the track section along Washington Avenue on the East Bank campus were designed as the rest of the LRT system, these perturbations would be relatively large and could impact some of the NMRs.

For instance, operation with two 3-car trains operating at their maximum current (1000 A per car) may cause magnetic field perturbations outside the NMR machines up to 38.3 mG at 80 feet from the center of the track and up to 9.4 mG at 160 feet from the tracks. The perturbations of the vertical component of the magnetic field outside the machine would be 13.4 mG at 80 feet and 1.7 mG at 160 feet. Magnetic field perturbations of these levels inside the machine may be unacceptable for the type of scientific research performed at the University.

A mitigation design has been developed that will considerably reduce the interference caused by the LRT electrical system to the NMRs. The proposed design is based on the experience gained during the development of a similar system for the extension of the Metrolink LRT near the Washington University campus located in St. Louis, Missouri. The mitigation applied to Metrolink is called a “split power-supply” system because the power supply current was divided among two wires: the contact wire and a much larger cable positioned in a selected location under the rails in the center of the tracks. Because NMRs at the University of Minnesota are closer to train tracks than the NMRs at Washington University, a more efficient mitigation system is proposed for the CCLRT. It consists of placing two (instead of one) large size cables at two different selected locations below the rail. For reference, in this report a system with only one buried cable is called the “single-split” and that with two buried cables is called the “double-split” power supply system. The effectiveness of the single-split system was successfully verified at the Washington University with a series of tests conducted in July 2006 after the construction was completed.

The single-split mitigation system implemented on the Metrolink LRT reduced the magnetic field perturbations outside the NMRs to 3.6 mG at 80 feet and 0.5 mG at 160 feet (compared to the 38.3 mG for 80 feet and 9.4 mG for 160 feet without mitigation). The perturbations of the vertical component of the magnetic field were reduced to 3.6 mG at 80 feet and 0.5 mG at 160 feet outside the machine (compared to 13.4 mG at 80 feet and 1.7 mG at 160 feet without mitigation).

The double-split power supply system envisioned for CCLRT along Washington Avenue will reduce the magnetic field perturbations even further. When 3-car trains drawing the maximum current (1000 A per car) are not in proximity to the measuring location the magnetic field perturbation at 80 feet would be 0.6 mG outside an NMR machine and the vertical component would be 0.11 mG. However, with the double-split mitigation system the worst-case condition may occur when two trains pass simultaneously at the measuring location drawing the maximum current all from one side. The magnetic field perturbations outside the NMR machines would be 3.5 mG at 80 feet and 1.0 mG at 160 feet. The perturbations of the vertical component of the magnetic field would be 0.6 mG at 80 feet and 0.15 mG at 160 feet. For vertical NMR machines the magnetic field of interest is the vertical component of the magnetic field inside the machine. Fortunately, this perturbation lasts a short amount of time because trains drawing the maximum amount of current occurs at speeds of 12 to 20 mph within the affected area. An NMR machine responds to an external field with a long time constant. This fact effectively reduces the potential interference.

The concept on which the double-split method is based is similar to that of the single-split method. The single-split power supply eliminates electrical dipoles (two parallel wires carrying opposite currents form a dipole) and reduces the current carrying wires to a quadrupole (two equal but opposite dipoles), which produces much less field than the dipoles. The double-split power supply eliminates the electrical quadrupole and reduces the current carrying wires system to a higher order multi-pole (two equal but opposite quadrupoles), which produces much less field than the quadrupole.

The calculations whose results are reported here are for a preliminary design and were performed primarily with the purpose of finding out whether a satisfactory mitigation system can be constructed. The final design of the electrical system will require optimization of the system parameters compatibly with all other non-electrical aspects of the light rail system design. In particular the optimum size and location of all electrical wires and the optimum distance between vertical poles along the track should be reviewed and refined.

## 3.2 PROPOSED MITIGATION

The proposed mitigation needs not to be applied to the entire length of the corridor, but only between approximate stationing 1243+00 (East side of the Washington Avenue Bridge) and approximate stationing 1274+00 (intersection with Ontario Street). This 3100 ft section shall be called the “Mitigation Zone”.

The proposed design of the power supply cables in the Mitigation Zone is shown in Figure 1.

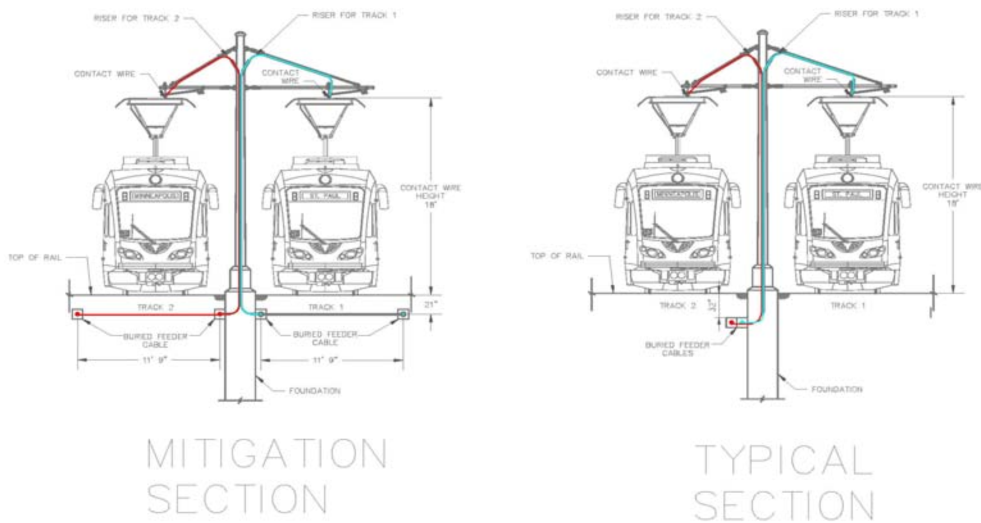



**Figure 1 Layout of Power Supply Wires in the Mitigation Section**

(Left) and in a Typical Section (Right)

The buried feeder for each track consists of two equal cables electrically connected in parallel and located symmetrically with respect to the center of the track at approximately 6 feet from the center of the track one on one side and the other on the other side. The feeder cables are located about 2 feet below the top of the rails. Each buried cable must have a much lower resistance (about 6.3 times lower) than the resistance of the contact wire so that the currents will divide between the contact wire and the buried wire in inverse proportion to the vertical distance from the center of the rails.

The proposed arrangement of the power supply cables is extremely effective in reducing the magnetic field perturbation when the trains are at a certain distance (500 feet or more) from the measuring location.

In order to obtain an effective reduction of the magnetic field perturbation when one or both trains transit at or near the measuring location, the buried feeders of a track are frequently connected to each other and to the contact wire of that track as shown in Figure 2.

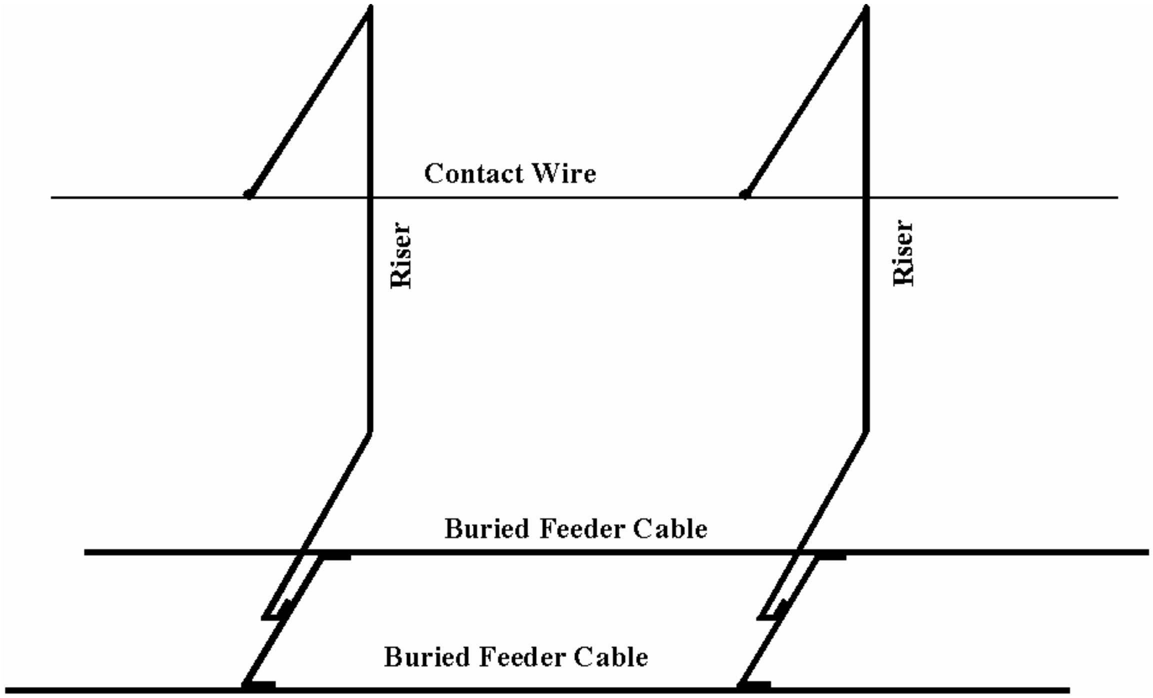



**Figure 2 Connections between Buried Cables and Contact Wire**

Each buried feeder cable must be as continuous as possible (without junctions) in the Mitigation Zone, compatible with the maximum length of a cable that can be transported with one reel. Junctions, if any, should be at the same location for the two buried cables of one track.

The junction between the two buried feeder cables is made using a separate cable. Another separate cable connects the center of this junction to the contact wire. This arrangement will insure that the resistances between the feeder cables and the contact wires will be the same.

It is important that all junctions between cables be made in the best possible way that can minimize contact resistances.

The vertical portion of the cable connecting the buried feeder cables to the contact wire (riser) may be housed inside the columns that support the contact wires.

The distance between risers affects the magnetic field perturbation at a measuring location when a train transits near it. The situation that creates the largest magnetic field perturbation outside NMR machines is when two trains cross each other right at the measuring location. This is not the case for the single-split power-supply mitigation method for which the largest field perturbations are caused when the trains are at some distance from the measuring location. Using the distance of 100 feet between risers, the maximum magnetic field perturbation at 80 feet from the center of the two tracks calculated in the worst case (two trains transiting simultaneously at the measuring location, each drawing 3000 A) is about 3.5 mG. The vertical component of the field (which is the component that counts for a vertical NMR machine) is 0.85 mG. The field will remain at this level for a brief period of time, much shorter than the time constant of the NMR machine.

At the two ends of the Mitigation Zone crossbonds between the rails of the two tracks must be installed and the power supply wires of the two tracks must be tied together as well. Figure 3 shows the electrical layout of the track starting from power substation CC-2 (on the West side of the Mitigation Zone) and into the Mitigation Zone. The electrical wire layout on the East side is similar. There are approximately 2100 feet between CC-2 and the start of the Mitigation Zone, the Mitigation Zone is about 3100 foot long, and there are approximately 1100 feet between the end of the Mitigation Zone and power station CC-3.

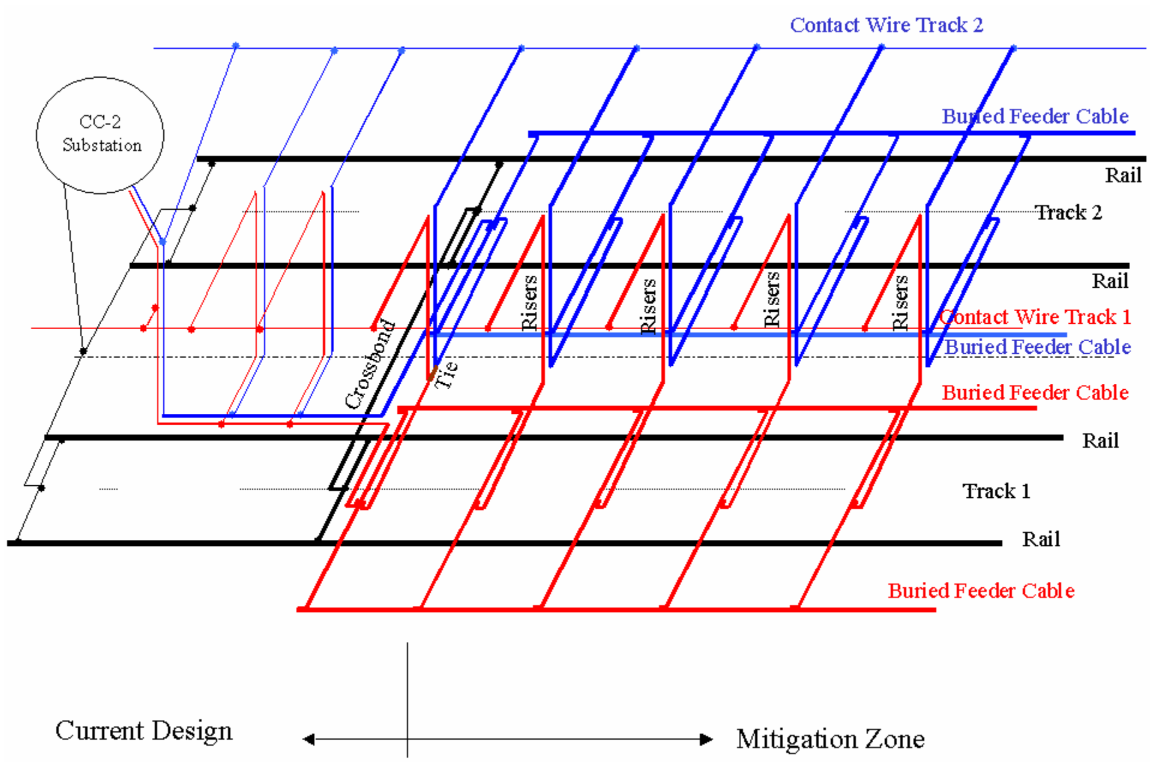



**Figure 3 Layout of Electrical Wires**

**SUMMARY TABLE**

Magnetic Field Perturbation at Different Distances from the Middle of the Tracks with Different Designs of the Electrical System and Different Operating Conditions

| | | Case | Distance = 80', Rail Height | | | | Distance = 160', Rail Height | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Hor. Parall. | Hor. Perpen | Vert. | Res. | Hor. Parall. | Hor. Perpen. | Vert. | Res. |
| | | | Bx (mG) | By (mG) | Bz (mG) | B (mG | Bx (mG) | By (mG) | Bz (mG) | B (mG) |
| No Mitigation | One 3-Car Train | (a) | 0 | 21.5 | 18.1 | 28.1 | 0 | 5.1 | 3.4 | 6.1 |
| | Two 3-Car Trains | (b) | 0 | 35.9 | 13.4 | 38.3 | 0 | 9.2 | 1.7 | 9.4 |
| Single-Split Power Supply | One 3-Car Train | (c) | 0 | 0.4 | 2.0 | 2.1 | 0 | 0.02 | 0.23 | 0.23 |
| | Two 3-Car Trains | (d) | 0 | 0.14 | 3.6 | 3.6 | 0 | 0.06 | 0.46 | 0.46 |
| Double-Split Power Supply | One 3-Car Train | (e) | 2.5 | 0.9 | 0.5 | 2.7 | 0.7 | 0.04 | 0.08 | 0.7 |
| | Two 3-Car Trains | (f) | 3.2 | 0.4 | 0.6 | 3.3 | 1.0 | 0.3 | 0.15 | 1.0 |
| Double-Split Power Supply | One 3-Car Train | (g) | 0 | 0.37 | 0.08 | 0.4 | 0 | 0.02 | 0.01 | 0.02 |
| | Two 3-Car Trains | (h) | 0 | 0.56 | 0.11 | 0.6 | 0 | 0.03 | 0.01 | 0.03 |

(a) Worst case. Nearest track. All train current (3000 A) flows at measuring location.
(b) Worst case. Both train current (3000 A + 3000 A) flow at measuring location.
(c) Worst case. Nearest track. All train current (3000 A) flows at measuring location.
(d) Worst case. Both train current (3000 A + 3000 A) flow at measuring location.
(e) Worst case. Train transits at measuring location. Train current (3000 A) all drawn from one side. 100 ft between risers.
(f) Worst case. Trains cross at measuring location. Train currents (3000 A + 3000 A) all drawn from one side. 100 ft between risers.
(g) Train on nearest track. All train current (3000 A) flows at measuring location.
(h) Both train current (3000 A + 3000 A) flow at measuring location.

## 3.3 EFFECT OF TRAIN MOVEMENT IN THE GEOMAGNETIC FIELD

The movement of trains in the earth's magnetic field may affect the magnetic field at the location of sensitive instrumentation inside the University of Minnesota buildings. This occurs because the trains are made of steel, which distorts the geomagnetic field. The perturbation may be very small relative to the value of the earth's field, which is approximately 580 mG in Minneapolis. In absolute terms, however, the perturbation may be comparable with the perturbations produced by the electrical system and it should be assessed.

The geomagnetic field perturbation depends on the position of the trains relative to the measuring location, on the number of cars in a train, and on the orientation of the tracks. The perturbation is also a function of the amount of steel in each car, on the shapes of the various steel members, and on the way the train cars are connected to each other. For these reasons reliable calculations are practically impossible.

However, an assessment of the effect of train movement in the geomagnetic field can be based on tests performed with 2- and 3-car trains at a location with the same East-West orientation of the tracks as that of the proposed section through the University of Minnesota campus. Magnetic field sensors were placed at different distances from the center of the tracks and trains were moved at different locations without electric power (see Section 2.2.2).

Test Results

| Configuration of Train | Distance (feet) | Vertical Axis Field Perturbation (mG) |
|---|---|---|
| Single Two-car train | 75 | 1.0 |
| Double Two-car train | 75 | 1.37 |
| Single Three-car Train | 75 | 1.16 |
| Double Three-car Train (calculated values) | 75 | 1.85 |

## 3.4 EFFECT OF VARIATIONS OF CURRENTS WITH TIME

The magnetic field perturbation that actually interferes with the operation of an NMR spectrometer is the magnetic field perturbation inside the machine, not the one outside the machine. It is particularly the component of the perturbation that is parallel to the axis of the machine. For vertical NMR machines, which are the most common NMR machines, the magnetic field of interest is the vertical component of the magnetic field inside the machine.

The machine itself causes an attenuation of the magnetic field and, furthermore, any external magnetic field perturbation is sensed inside the machine with a delay characterized by a time constant. Measurements and calculations performed by scientists at Washington University in St. Louis have indicated a conservative value of 5 for the attenuation constant and a time constant of 12 seconds or greater.

Trains draw the largest amount of current when they accelerate after reaching speeds of 12 to 20 mph. At these speeds, however, there will be a short amount of time when the magnetic field perturbation outside an NMR machine installed at a given location will remain at or near the largest calculated field levels. Therefore, the field perturbation inside the machine will be much lower than that calculated on the basis of external field and attenuation factor alone.

Accurate estimates of the field perturbation inside the machines require detailed calculations of variations of train currents, train location, and magnetic field versus time. The results depend on the train operating conditions, such as different number of cars, different train loads, different operating conditions of the power substations, different locations where trains going in different directions cross each other, different maximum speeds allowed in each section of the track route, and different locations where a train may stop and restart.

The preliminary calculations performed for this report use worst-case assumptions such as 3-car trains drawing the maximum allowed current (1000 A per car). The vertical component of the magnetic field inside an NMR machine is much less than the vertical component calculated outside the machine. For example, the reduction factors calculated for the Metrolink LRT in St. Louis was about 7 for trains that are not near the measuring location and about 30 for trains moving simultaneously (in opposite directions) at full speed at the measuring location.

# 4 Conclusions

The testing performed by Dr. Fugate of ERM in conjunction with the analysis by Dr. Zaffanella of Enertech provides the following conclusions:

- The geomagnetic perturbations, in the vertical direction should be within the 2mG limit at a distance of 77 feet. This value considers two 3-car trains operating on Washington Avenue in the proximity of the lab.

- The propulsion perturbations can be limited to below the 2mG limit at a distance of 77 feet by use of the double-split power supply design mitigation.

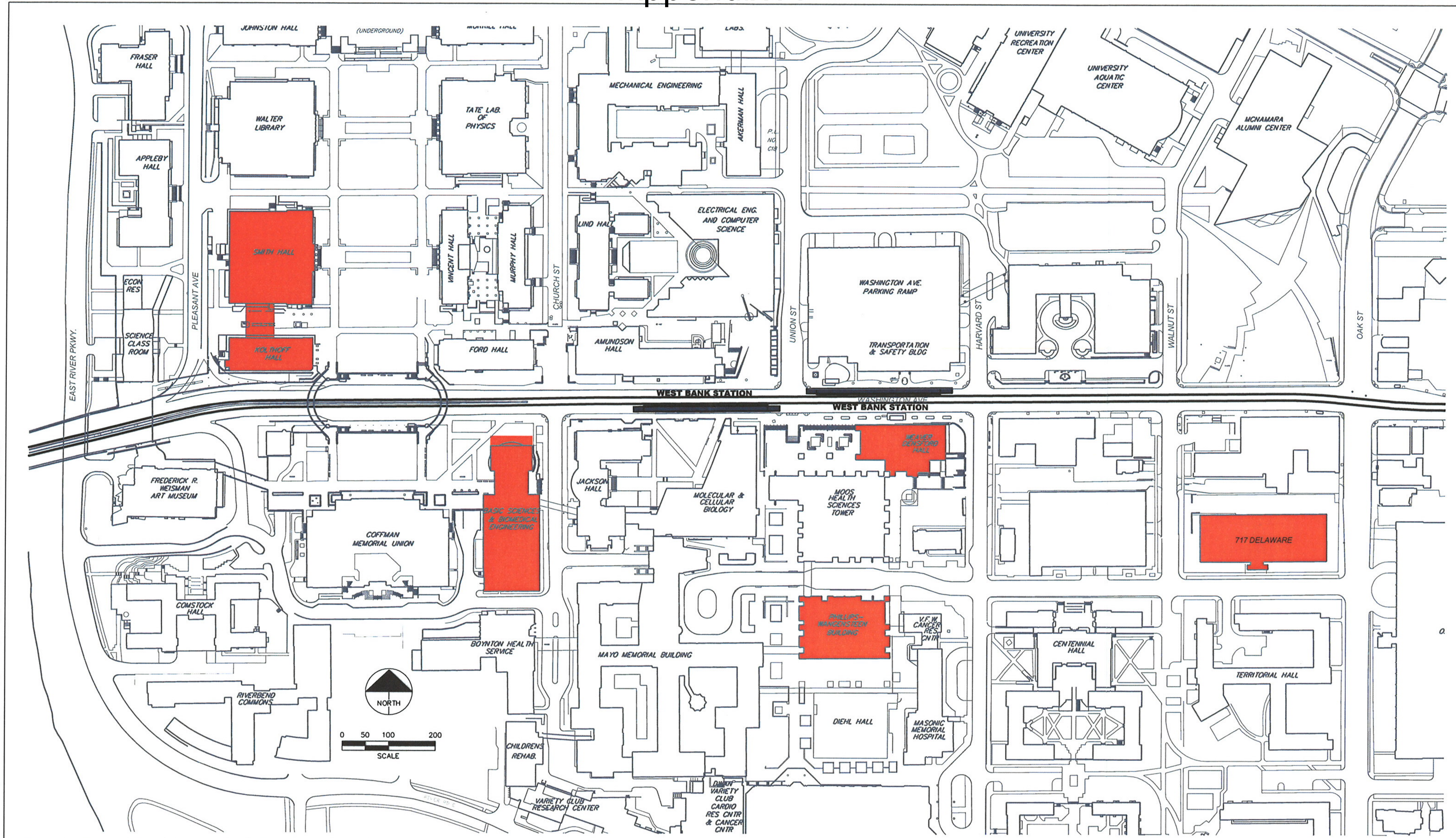
## Appendix A

## Map of University of Minnesota Facilities with known NMR equipment along Washington Avenue

## Appendix B

## Test Site Maps / Data

# Appendix A

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DMJM HARRIS | AECOM

LTK Engineering Services

EMF STUDY

Central Corridor
Light Rail Transit
Metropolitan Council

**FACILITIES WITH KNOWN NMR EQUIPMENT**
**CENTRAL CORRIDOR**
**UNVIERSITY OF MINNESOTA**

DISCIPLINE: SYSTEMS
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SHEET 1 OF 1

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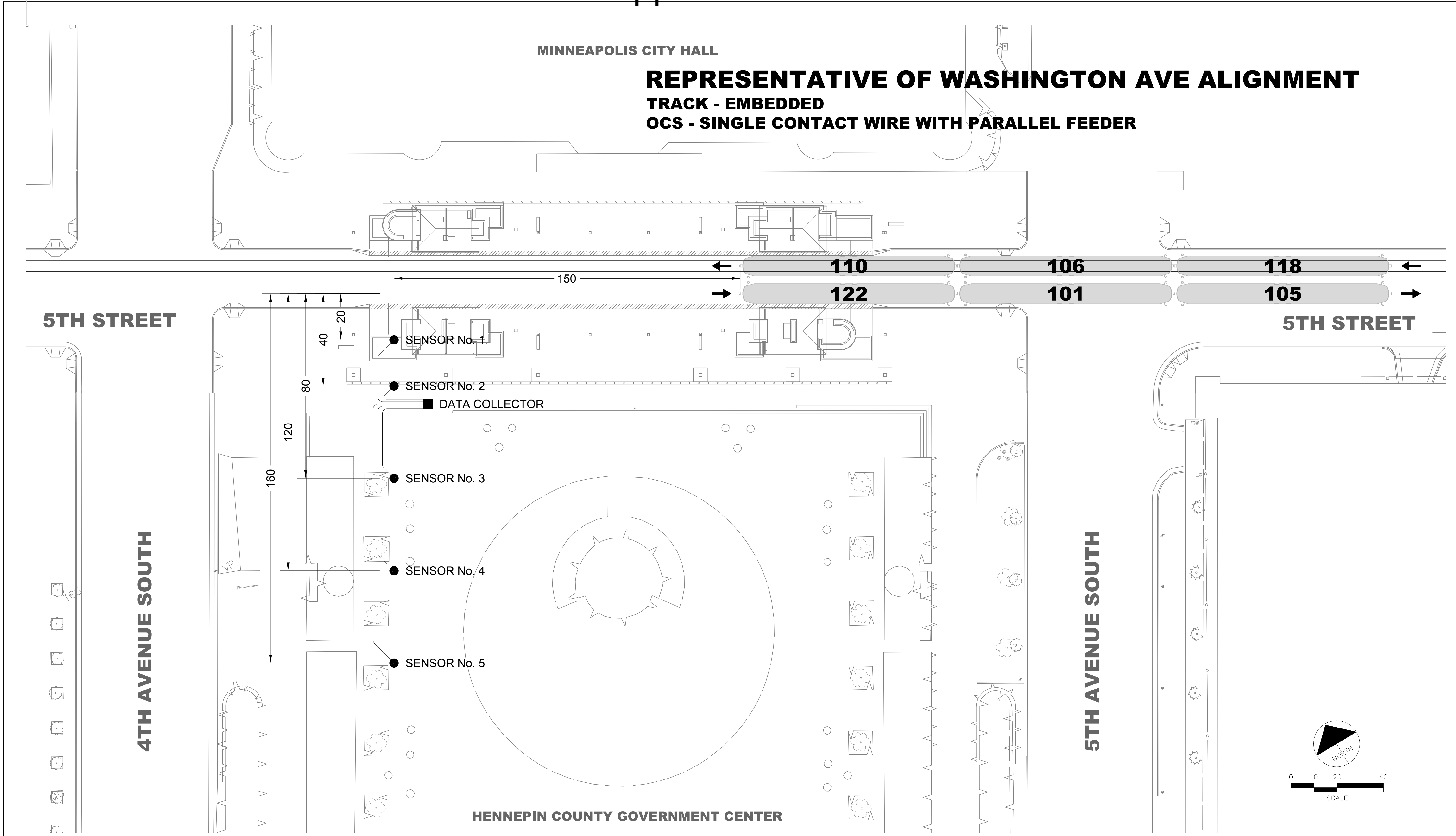
Final

# Appendix B-1

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DMJM HARRIS | AECOM
LTK
LTK Engineering Services
EMF STUDY

Central Corridor
Light Rail Transit
Metropolitan Council

EMF FIELD TESTING - HIAWATHA LRT
GOVERNMENT CENTER PLATFORM
TEST EQUIPMENT CONFIGURATION

DISCIPLINE: SYSTEMS
SHEET NAME: EMI Test - Gov Cntr

SHEET 1 OF 1

Final

# Government Plaza

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 60.8844 |
| 40 | 18.4637 |
| 80 | 6.9582 |
| 120 | 4.7304 |
| 160 | 2.6246 |

Y

| Distance | Peak-to-Peak |
|---|---|
| 20 | 128.7881 |
| 40 | 51.7289 |
| 80 | 17.8228 |
| 120 | 7.5381 |
| 160 | 4.6998 |

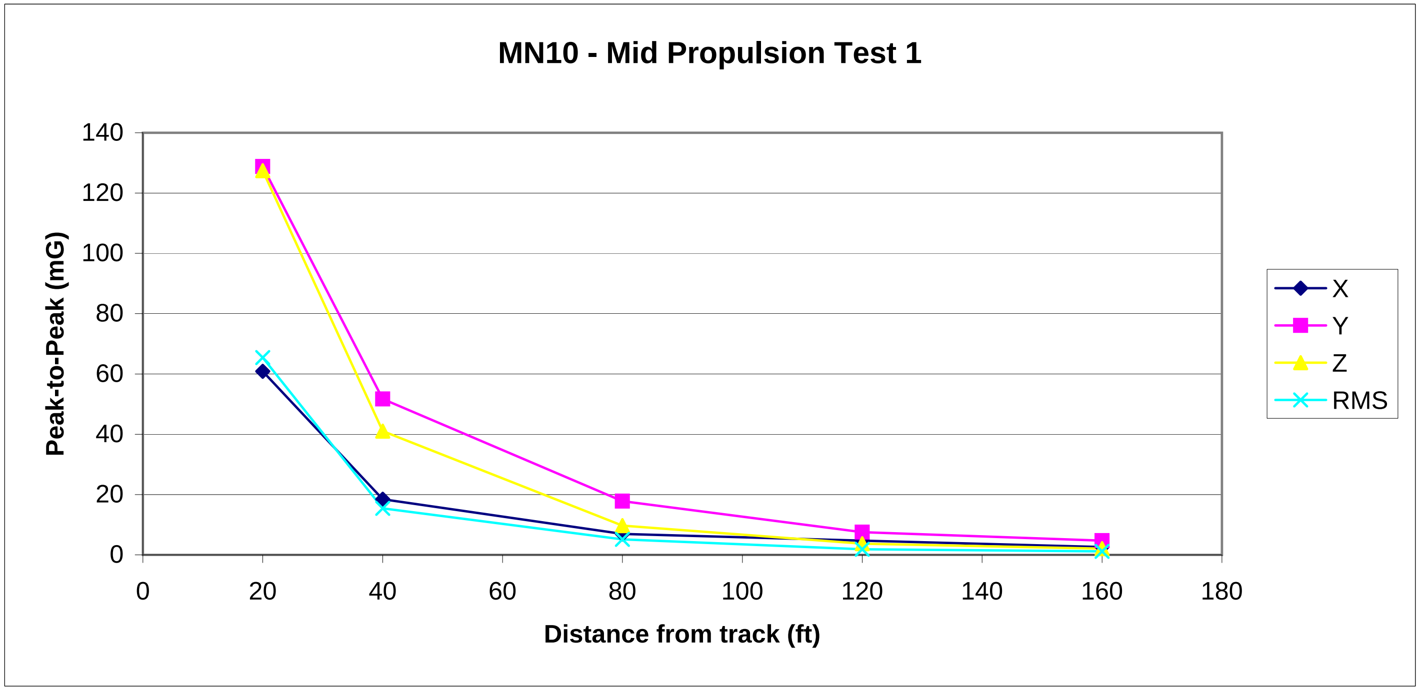
Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 127.4148 |
| 40 | 41.0474 |
| 80 | 9.7048 |
| 120 | 3.7233 |
| 160 | 2.0447 |

RMS

| Distance | Peak-to-Peak |
|---|---|
| 20 | 65.44076 |
| 40 | 15.41182 |
| 80 | 5.125024 |
| 120 | 1.872116 |
| 160 | 1.169525 |

samples:




Test Date 4/9/08

# Government Plaza

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 89.7244 |
| 40 | 29.1452 |
| 80 | 10.712 |
| 120 | 6.6836 |
| 160 | 3.5096 |

Y

| Distance | Peak-to-Peak |
|---|---|
| 20 | 189.2147 |
| 40 | 76.1436 |
| 80 | 26.6426 |
| 120 | 12.299 |
| 160 | 7.9959 |

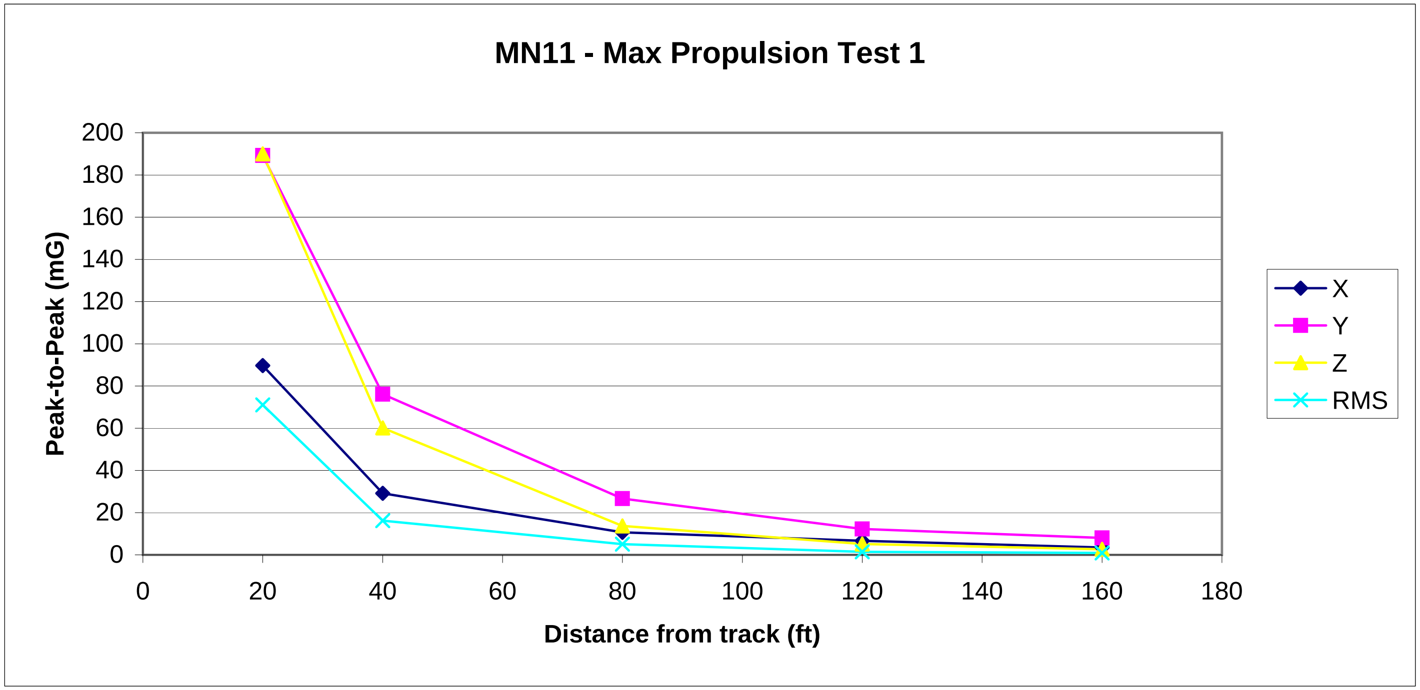
Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 189.9777 |
| 40 | 60.1215 |
| 80 | 13.7333 |
| 120 | 5.1576 |
| 160 | 2.6856 |

RMS

| Distance | Peak-to-Peak |
|---|---|
| 20 | 71.05517 |
| 40 | 16.21029 |
| 80 | 5.103033 |
| 120 | 1.462438 |
| 160 | 0.944336 |

samples:




Test Date 4/9/08

## Government Plaza

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 72.634 |
| 40 | 21.363 |
| 80 | 7.1414 |
| 120 | 5.0661 |
| 160 | 2.594 |

Y

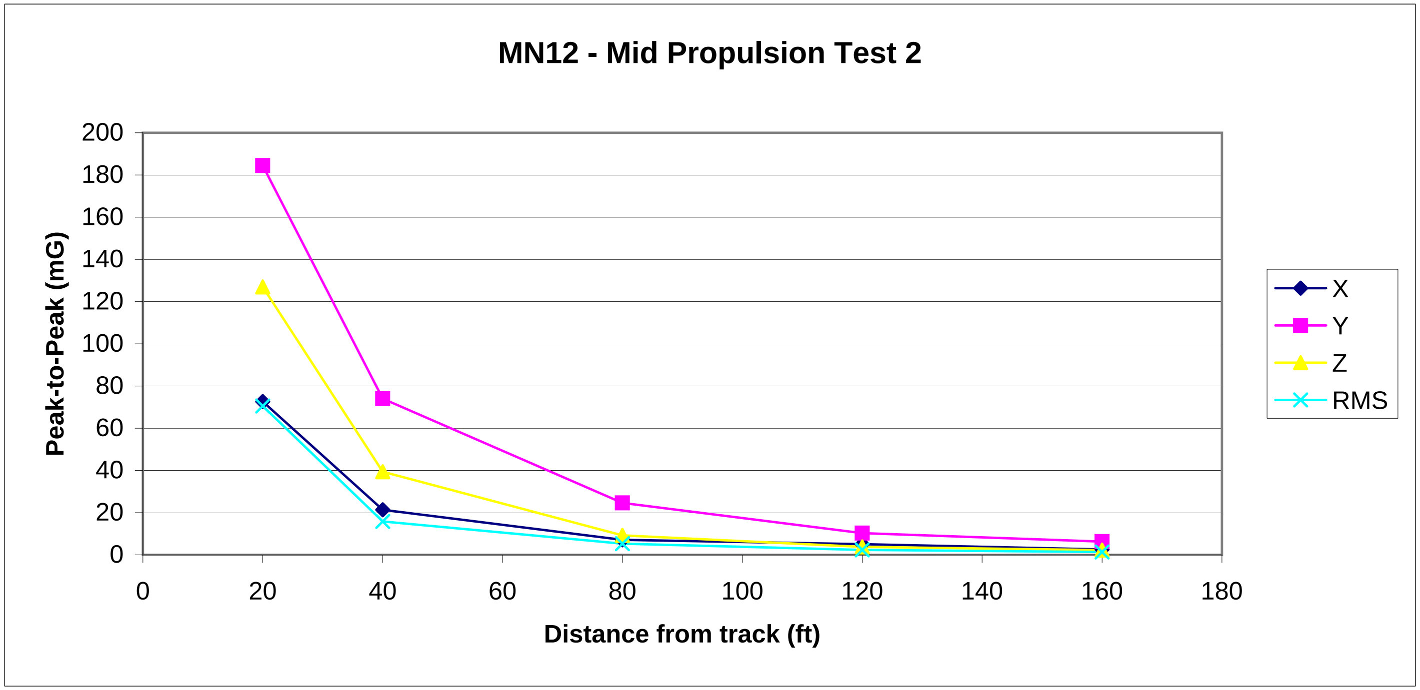
| Distance | Peak-to-Peak |
|---|---|
| 20 | 184.4844 |
| 40 | 74.0074 |
| 80 | 24.6284 |
| 120 | 10.3152 |
| 160 | 6.3173 |

Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 126.957 |
| 40 | 39.3689 |
| 80 | 9.2471 |
| 120 | 3.7538 |
| 160 | 2.2584 |

RMS

| Distance | Peak-to-Peak |
|---|---|
| 20 | 70.52713 |
| 40 | 15.83439 |
| 80 | 5.308388 |
| 120 | 2.36595 |
| 160 | 1.361785 |




Test Date 4/9/08

Final

## Government Plaza

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 92.7763 |
| 40 | 30.5185 |
| 80 | 11.2309 |
| 120 | 7.2024 |
| 160 | 3.7843 |

Y

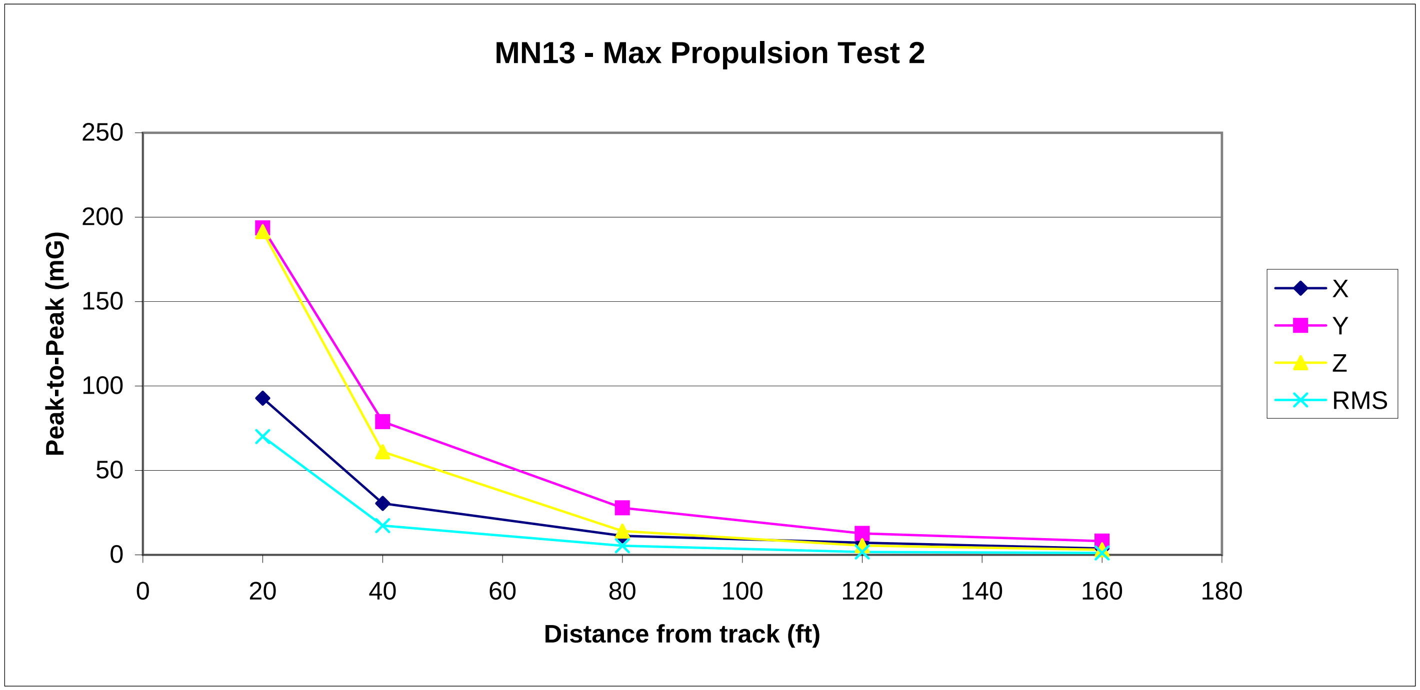
| Distance | Peak-to-Peak |
|---|---|
| 20 | 193.64 |
| 40 | 78.8904 |
| 80 | 27.8634 |
| 120 | 12.7262 |
| 160 | 8.179 |

Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 191.5037 |
| 40 | 61.0371 |
| 80 | 14.0996 |
| 120 | 5.4629 |
| 160 | 3.0518 |

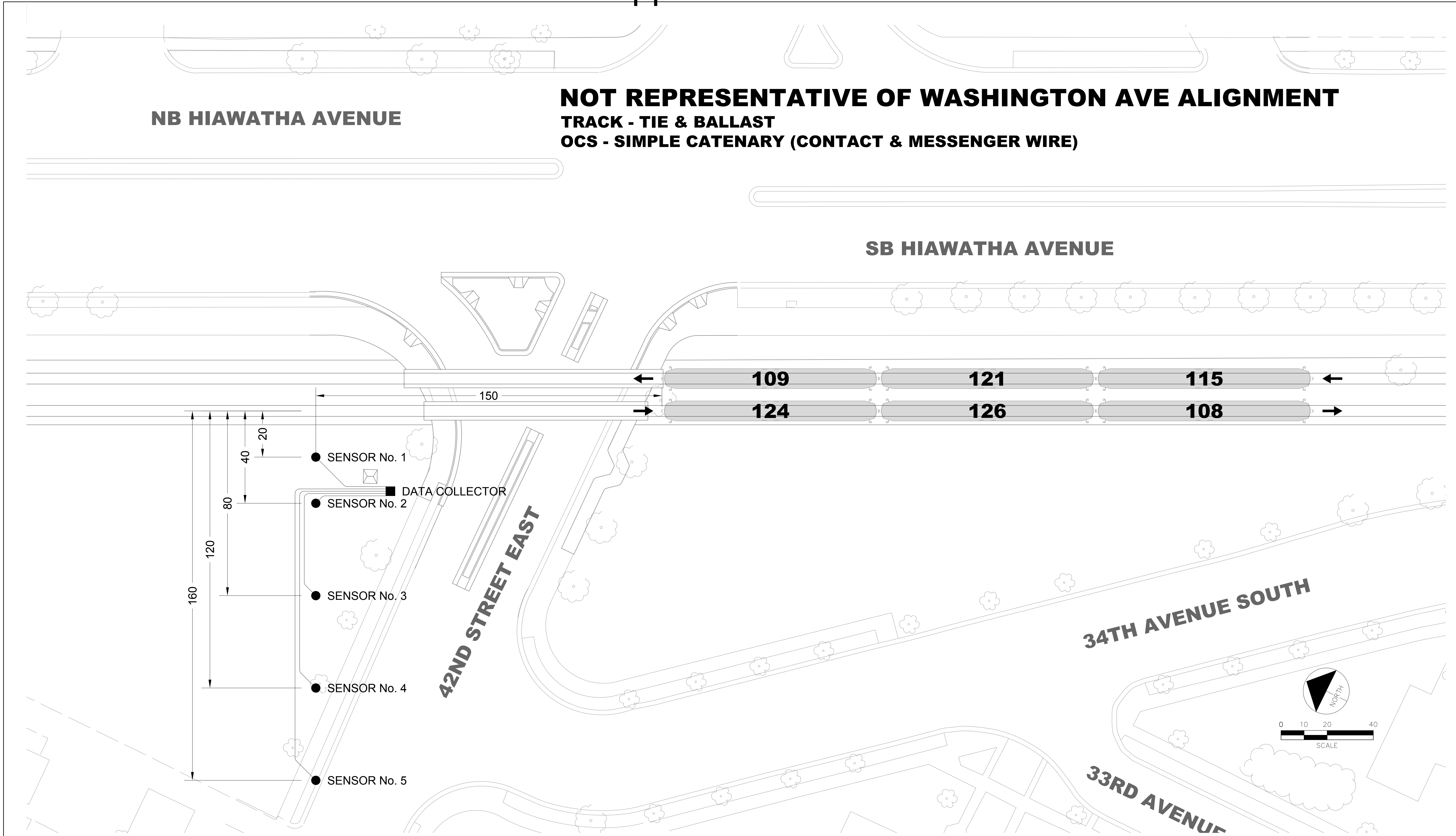
RMS

| Distance | Peak-to-Peak |
|---|---|
| 20 | 70.03672 |
| 40 | 17.33476 |
| 80 | 5.351767 |
| 120 | 1.720943 |
| 160 | 1.139319 |




Test Date 4/9/08

# Appendix C-1

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DESIGNED BY: SMH
DRAWN BY: SCA
CHECKED BY: SMH

QC REVIEW
REVIEWER COMPANY DATE
ORIGINATOR COMPANY DATE
CAD COMPANY DATE
VERIFIED BY COMPANY DATE

DMJM HARRIS | AECOM
LTK Engineering Services
EMF STUDY

Central Corridor
Light Rail Transit
Metropolitan Council

EMF FIELD TESTING - HIAWATHA LRT
42ND STREET GRADE CROSSING
TEST EQUIPMENT CONFIGURATION

DISCIPLINE: SYSTEMS
SHEET NAME: EMI Test - 42nd St

SHEET 1 OF 1

Apr. 18 2008 11:47 am I:\400_Technical\Issue Resolution\EMI Study\U of M\Testing\Exhibits\EMI Test - 42nd Street.dwg By: hamilts

## 42nd Street

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 128.1777 |
| 40 | 18.4637 |
| 80 | 10.3763 |
| 120 | 6.2563 |
| 160 | 4.3947 |

Y

| Distance | Peak-to-Peak |
|---|---|
| 20 | 285.3481 |
| 40 | 108.7985 |
| 80 | 33.2957 |
| 120 | 15.5034 |
| 160 | 9.3387 |

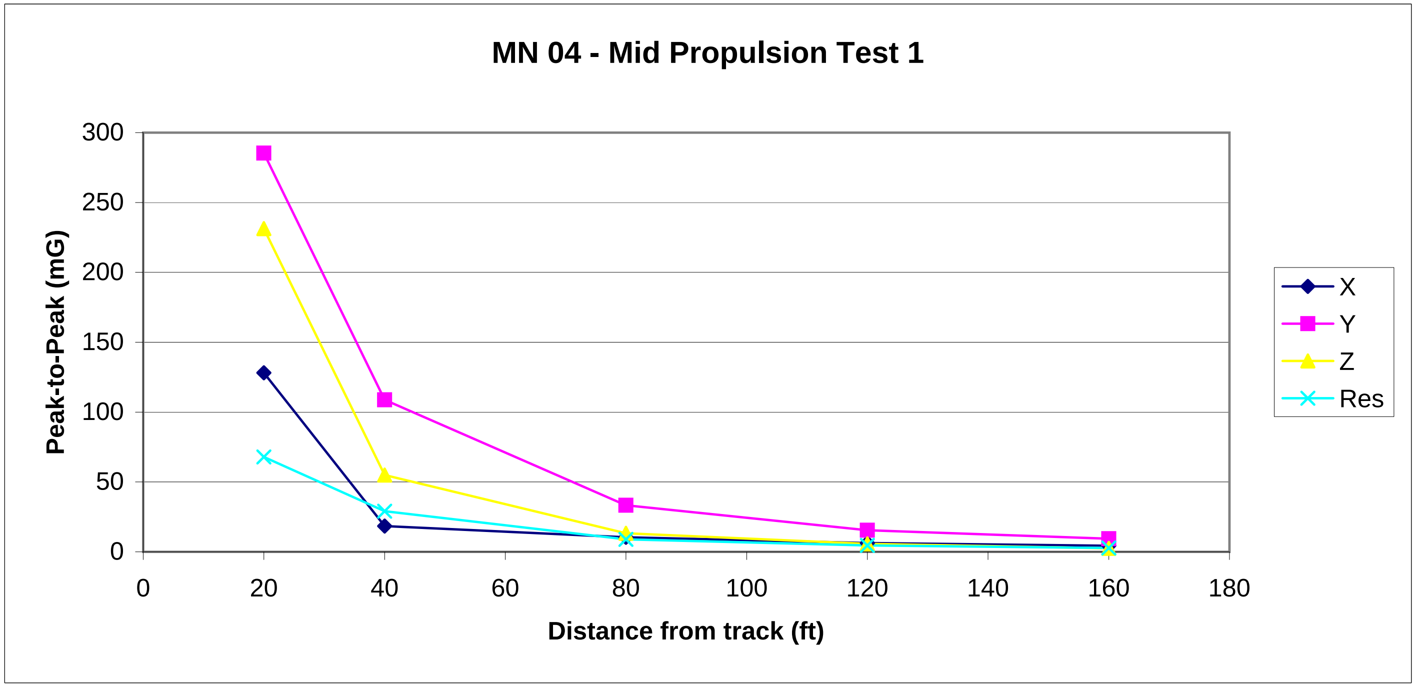
Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 231.3303 |
| 40 | 54.9334 |
| 80 | 13.306 |
| 120 | 5.768 |
| 160 | 2.5636 |

Res

| Distance | Peak-to-Peak |
|---|---|
| 20 | 67.89297 |
| 40 | 29.10589 |
| 80 | 8.953298 |
| 120 | 4.561459 |
| 160 | 2.705435 |

samples:



**42nd Street**

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 208.7466 |
| 40 | 29.7556 |
| 80 | 16.9073 |
| 120 | 9.5217 |
| 160 | 6.8056 |

Y

| Distance | Peak-to-Peak |
|---|---|
| 20 | 455.1836 |
| 40 | 176.7021 |
| 80 | 54.4145 |
| 120 | 25.4525 |
| 160 | 15.0456 |

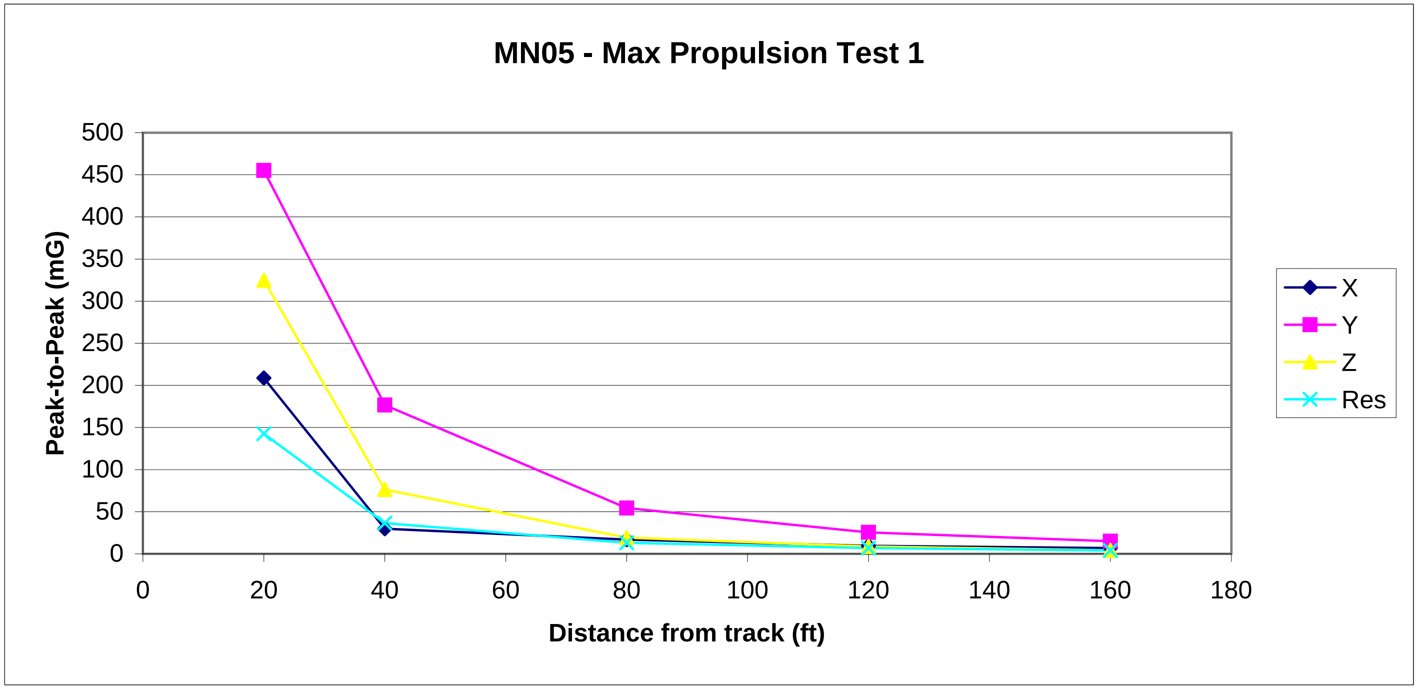
Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 324.8695 |
| 40 | 76.4489 |
| 80 | 19.1961 |
| 120 | 8.6672 |
| 160 | 4.2116 |

Res

| Distance | Peak-to-Peak |
|---|---|
| 20 | 142.7081 |
| 40 | 36.44675 |
| 80 | 13.17194 |
| 120 | 6.868287 |
| 160 | 4.079483 |

samples



**42nd Street**

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 124.0578 |
| 40 | 18.4637 |
| 80 | 10.1627 |
| 120 | 6.1952 |
| 160 | 4.3641 |

Y

| Distance | Peak-to-Peak |
|---|---|
| 20 | 296.3347 |
| 40 | 112.9184 |
| 80 | 34.608 |
| 120 | 16.1443 |
| 160 | 9.6438 |

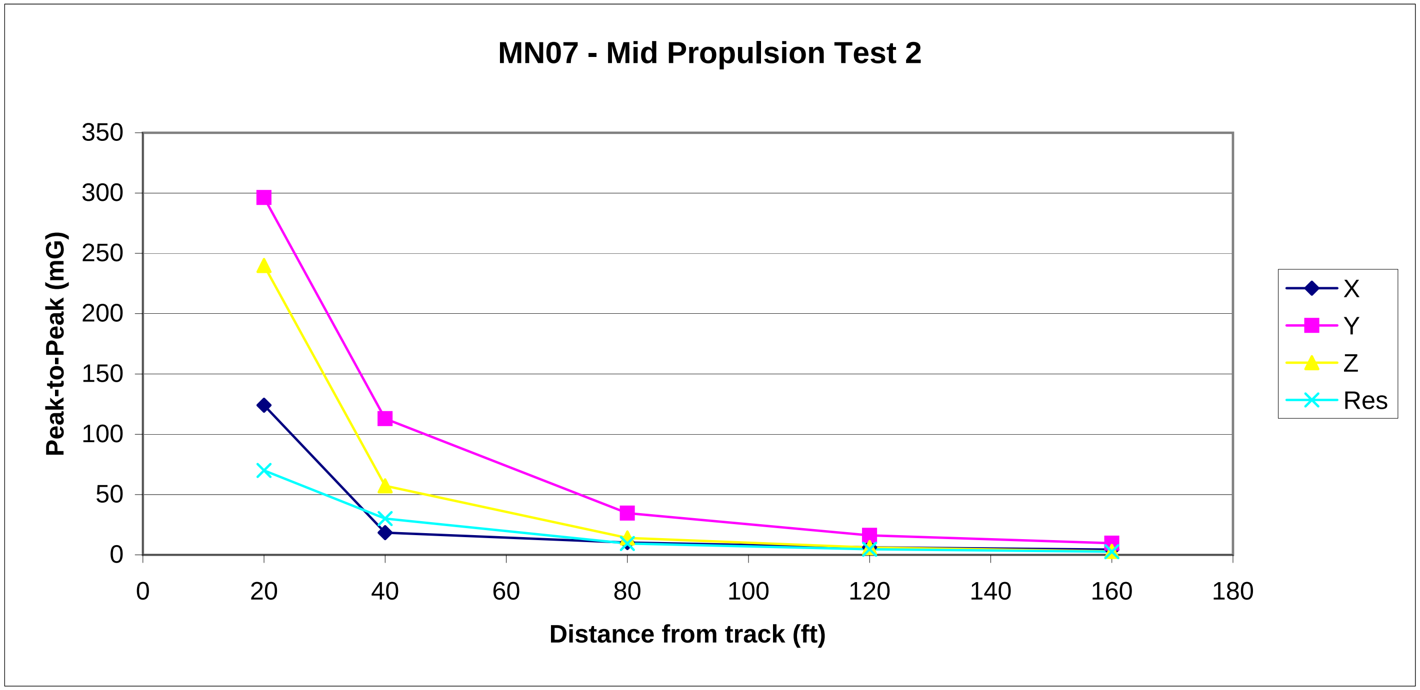
Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 240.0281 |
| 40 | 57.2222 |
| 80 | 14.0996 |
| 120 | 6.1342 |
| 160 | 2.8687 |

Res

| Distance | Peak-to-Peak |
|---|---|
| 20 | 69.95367 |
| 40 | 30.03879 |
| 80 | 9.385327 |
| 120 | 4.585084 |
| 160 | 2.702582 |

samples:



**42nd Street**

X

| Distance | Peak-to-Peak |
|---|---|
| 20 | 204.3214 |
| 40 | 30.0607 |
| 80 | 16.8157 |
| 120 | 10.1932 |
| 160 | 7.1108 |

Y

| Distance | Peak-to-Peak |
|---|---|
| 20 | 435.1939 |
| 40 | 168.4622 |
| 80 | 51.6983 |
| 120 | 24.3843 |
| 160 | 14.2522 |

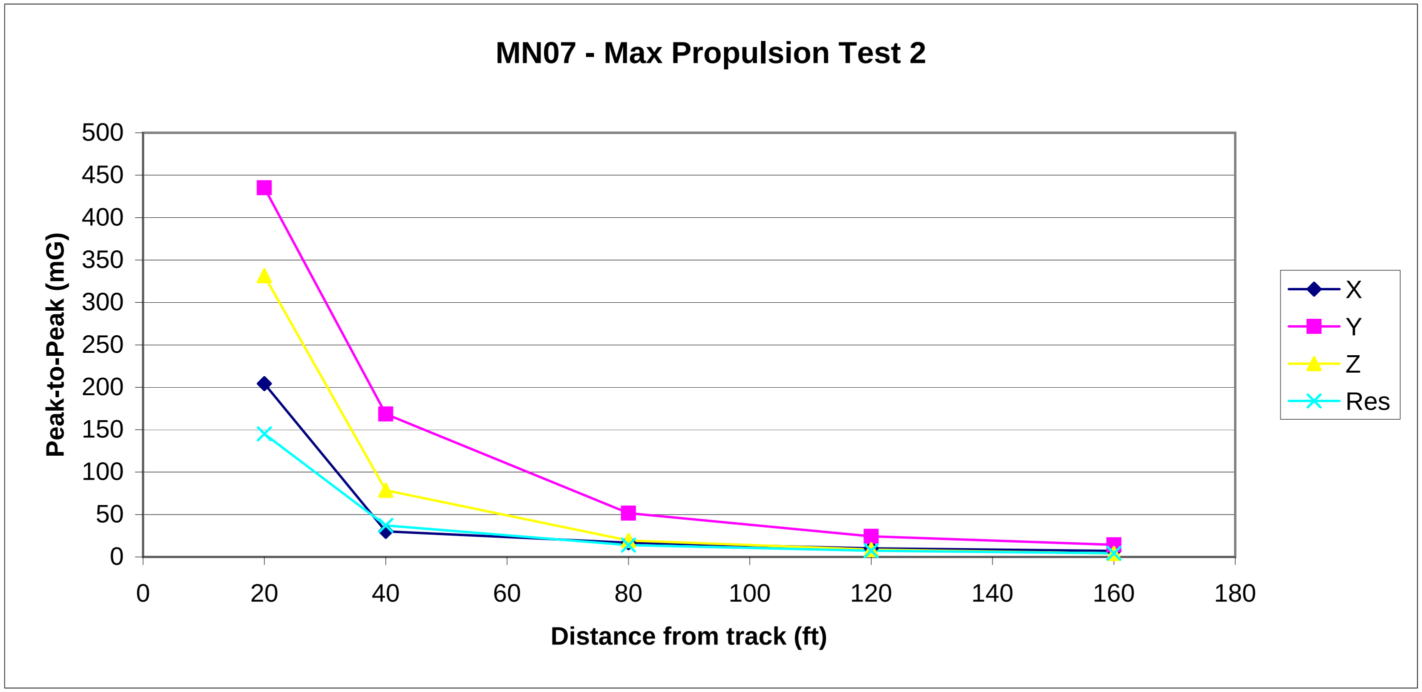
Z

| Distance | Peak-to-Peak |
|---|---|
| 20 | 331.431 |
| 40 | 78.5852 |
| 80 | 19.5014 |
| 120 | 8.6672 |
| 160 | 4.0895 |

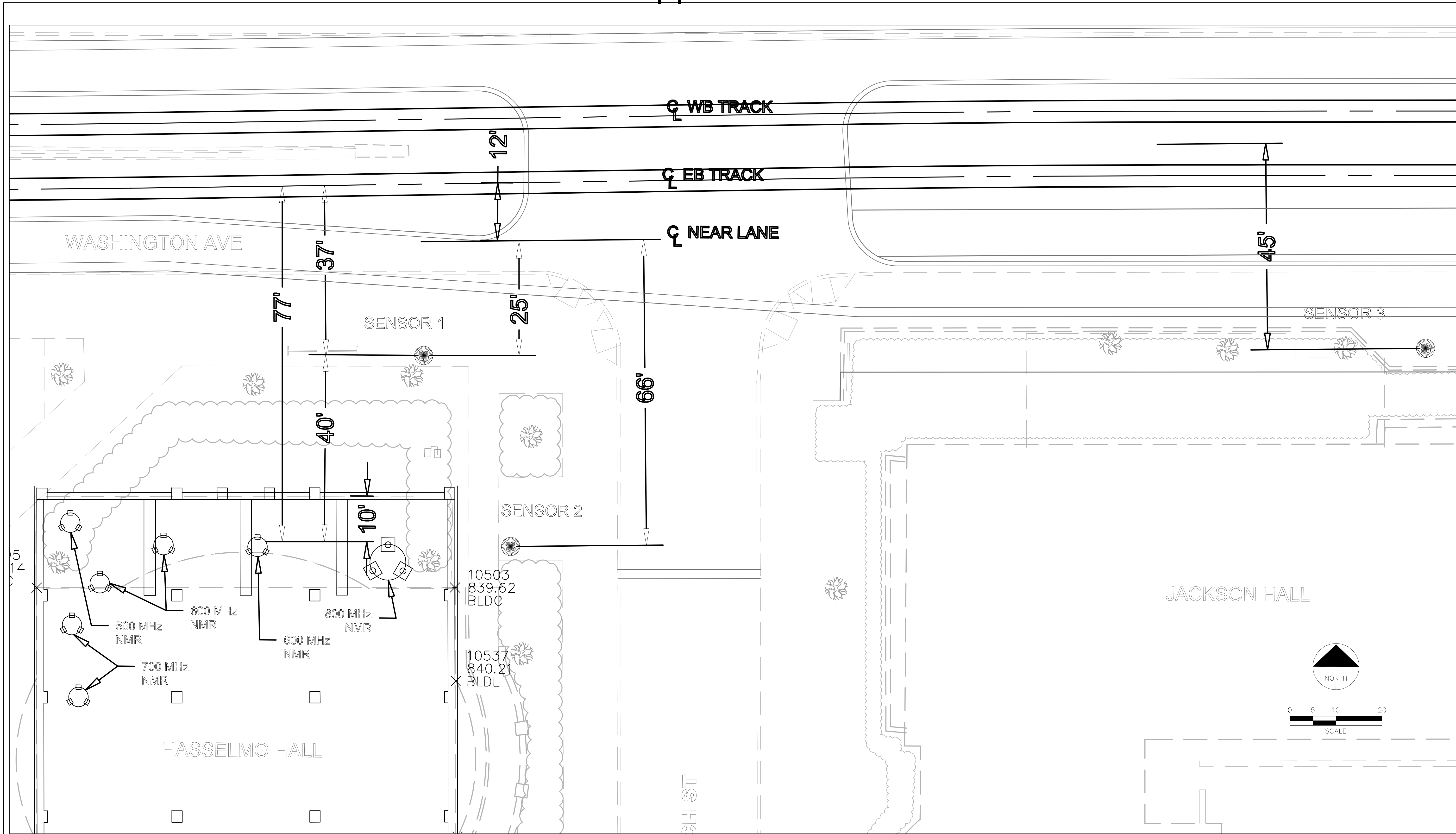
Res

| Distance | Peak-to-Peak |
|---|---|
| 20 | 145.0859 |
| 40 | 37.08186 |
| 80 | 13.87898 |
| 120 | 7.366406 |
| 160 | 4.404335 |

samples:



# Appendix D-1




Apr, 18 2008 11:48 am I:\400_Technical\Issue Resolution\EMI Study\U of M\Testing\Exhibits\EMI Test – Hasselmo Hall.dwg By: hamilts

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DESIGNED BY: SMH
DRAWN BY: KLM
CHECKED BY: SMH

| QC REVIEW | | |
|---|---|---|
| REVIEWER | COMPANY | DATE |
| ORIGINATOR | COMPANY | DATE |
| CAD | COMPANY | DATE |
| VERIFIED BY | COMPANY | DATE |

DMJM HARRIS | AECOM

LTK Engineering Services

EMF STUDY

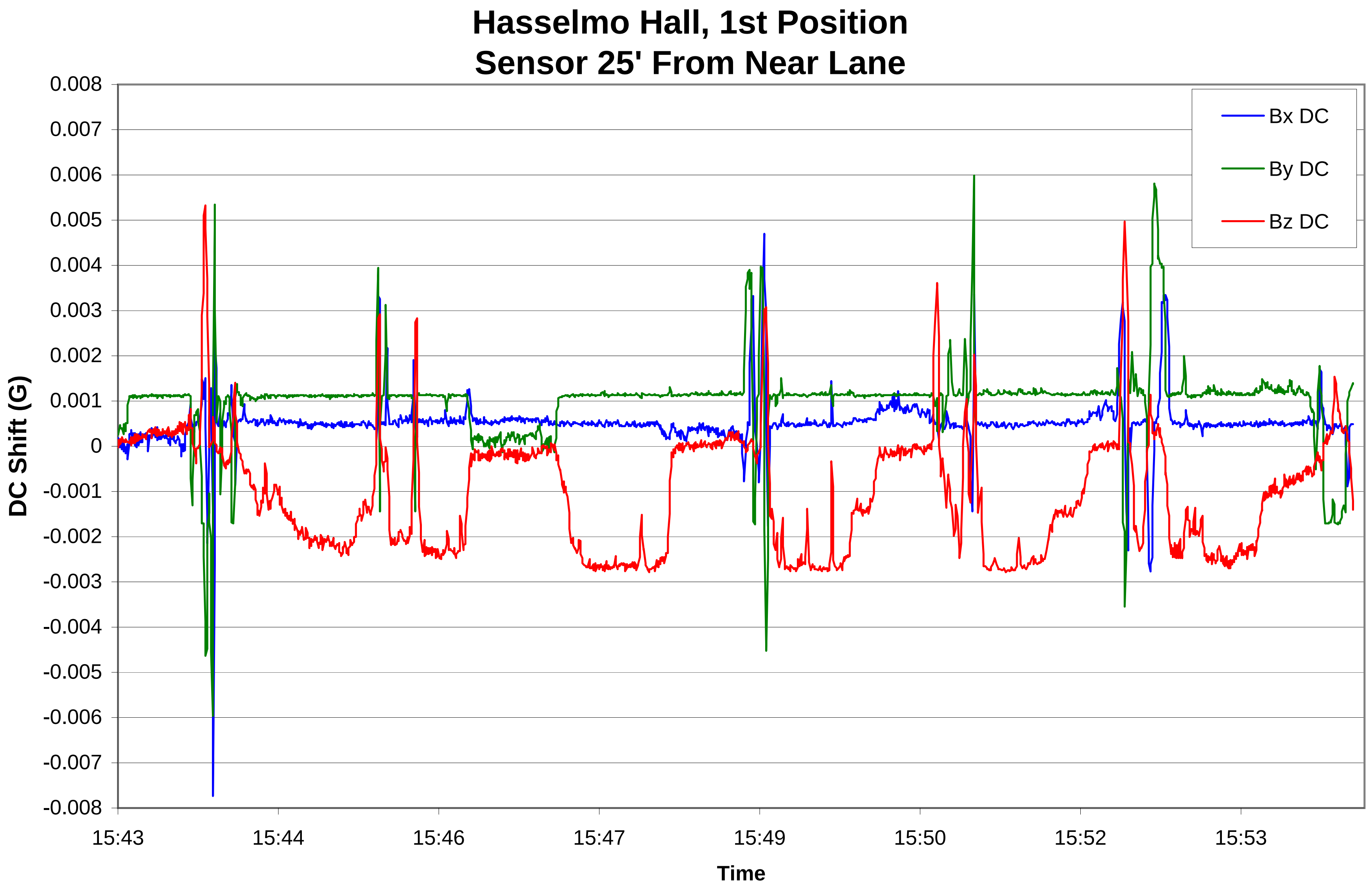
Central Corridor
Light Rail Transit
Metropolitan Council

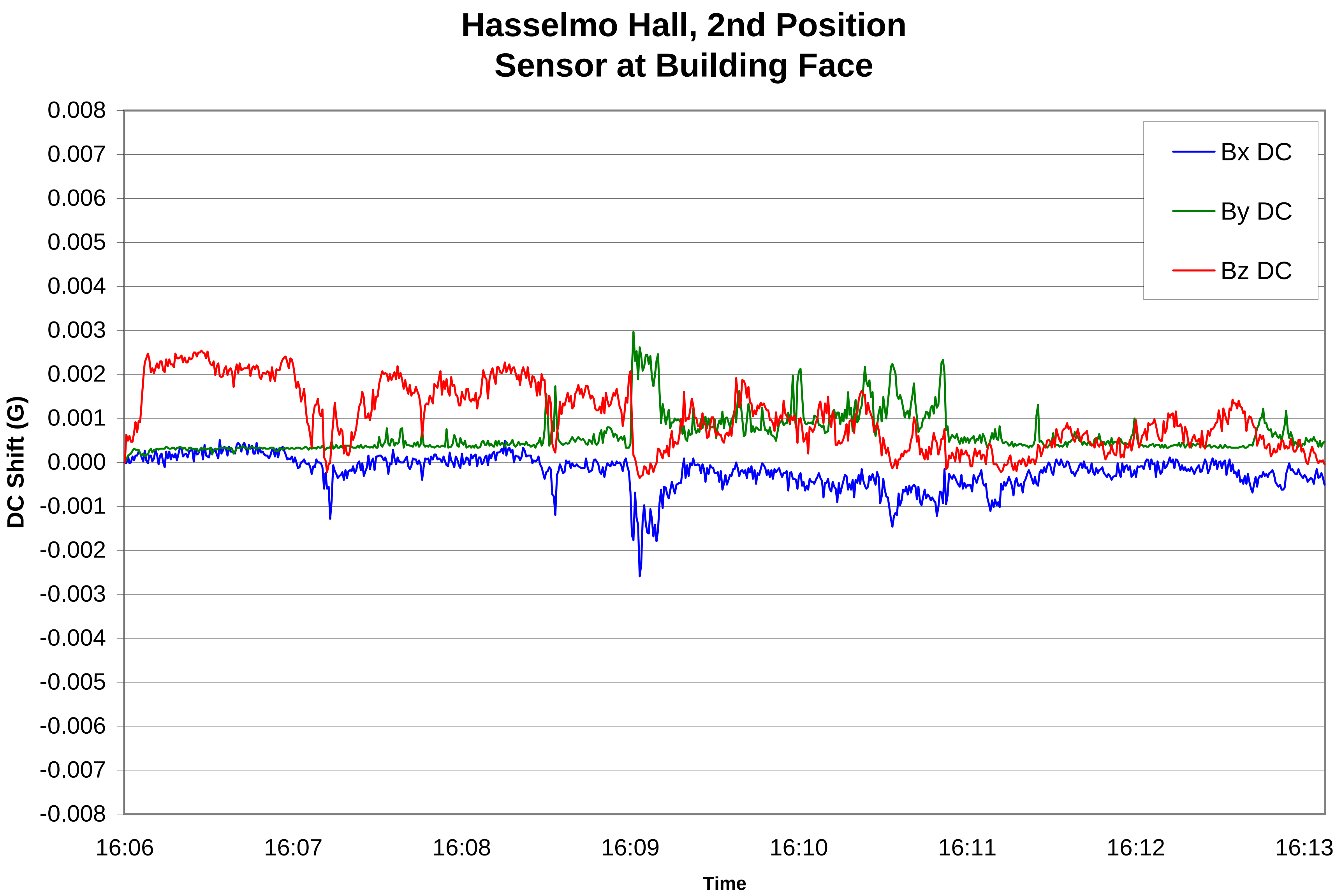
**EMF FIELD TESTING - CENTRAL LRT**
**HASSELMO HALL**
**TEST EQUIPMENT CONFIGURATION**

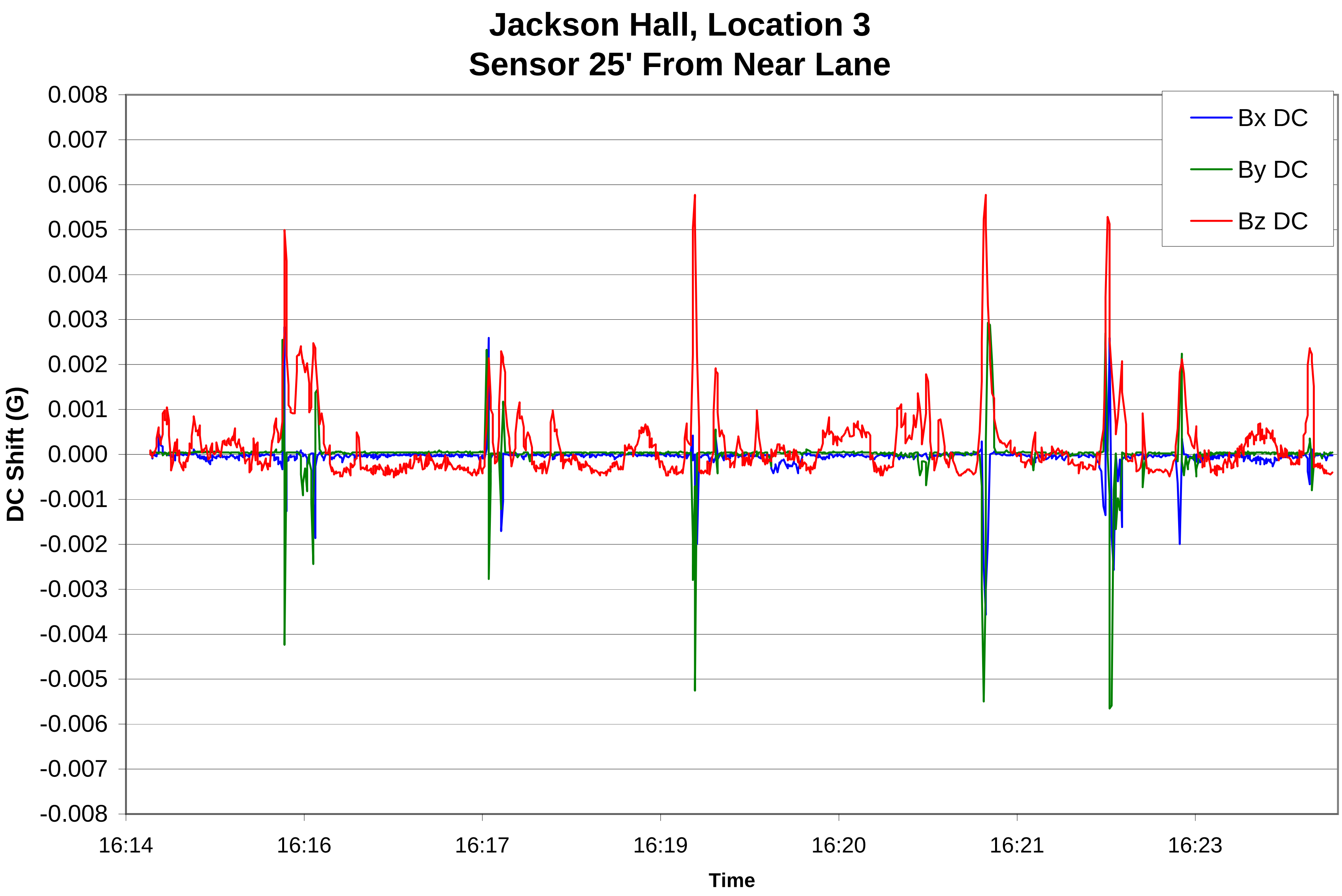
DISCIPLINE: SYSTEMS
SHEET NAME: 04/15/08

SHEET 1 OF 1

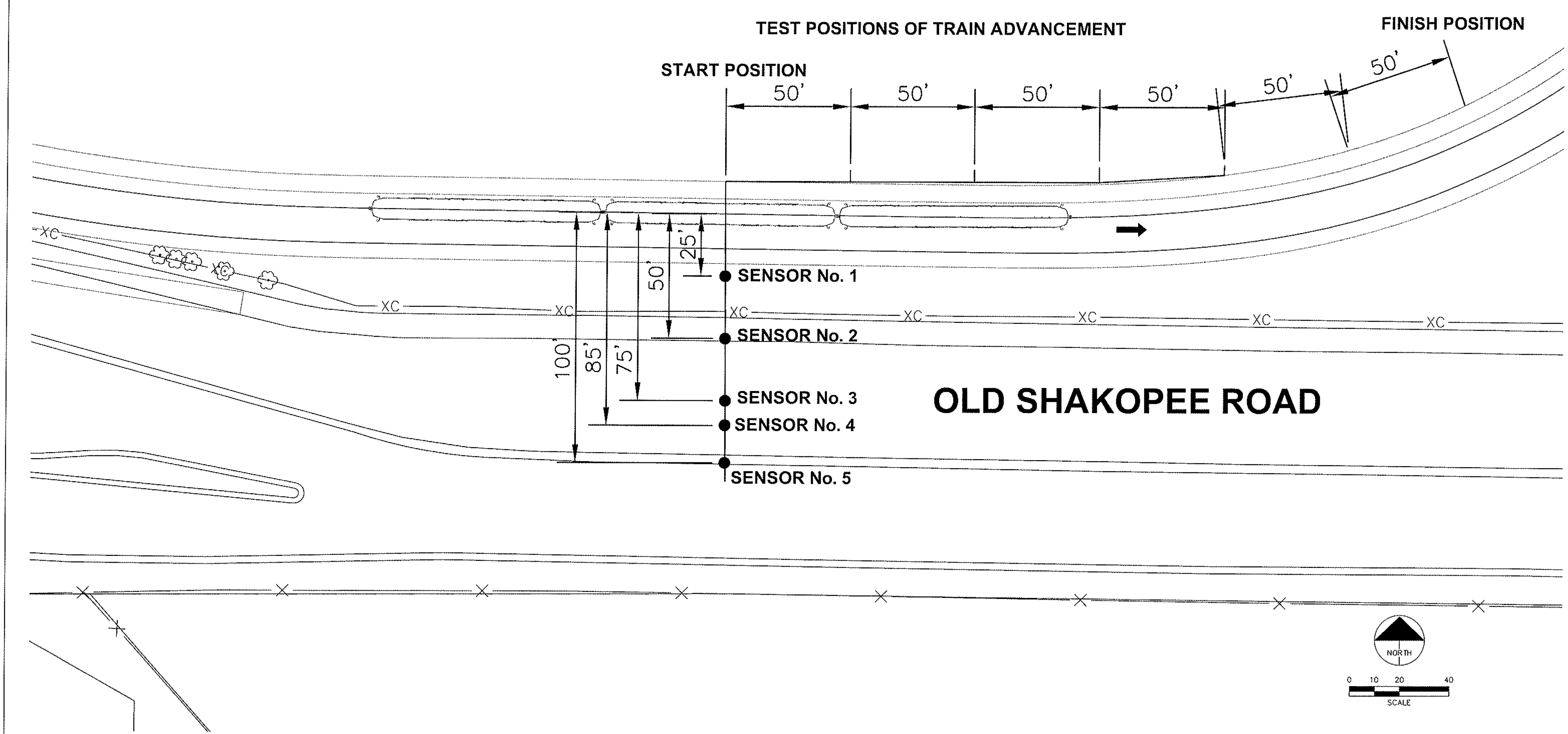
Final


Hasselmo Hall, 1st Position
Sensor 25' From Near Lane
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
-0.008
DC Shift (G)
15:43
15:44
15:46
15:47
15:49
15:50
15:52
15:53
Time
Bx DC
By DC
Bz DC


Hasselmo Hall, 2nd Position
Sensor at Building Face
DC Shift (G)
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
-0.008
16:06
16:07
16:08
16:09
16:10
16:11
16:12
16:13
Time
Bx DC
By DC
Bz DC


Jackson Hall, Location 3
Sensor 25' From Near Lane
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
-0.008
DC Shift (G)
16:14
16:16
16:17
16:19
16:20
16:21
16:23
Time
Bx DC
By DC
Bz DC

# Appendix E-1




| NO. | DATE | BY | REVISION / SUBMITTAL |
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DESIGNED BY SMH
DRAWN BY SMH
CHECKED BY SMH

QC REVIEW
REVIEWER COMPANY DATE
ORIGINATOR COMPANY DATE
CAD COMPANY DATE
VERIFIED BY COMPANY DATE

DMJM HARRIS | AECOM
LTK
LTK Engineering Services
----

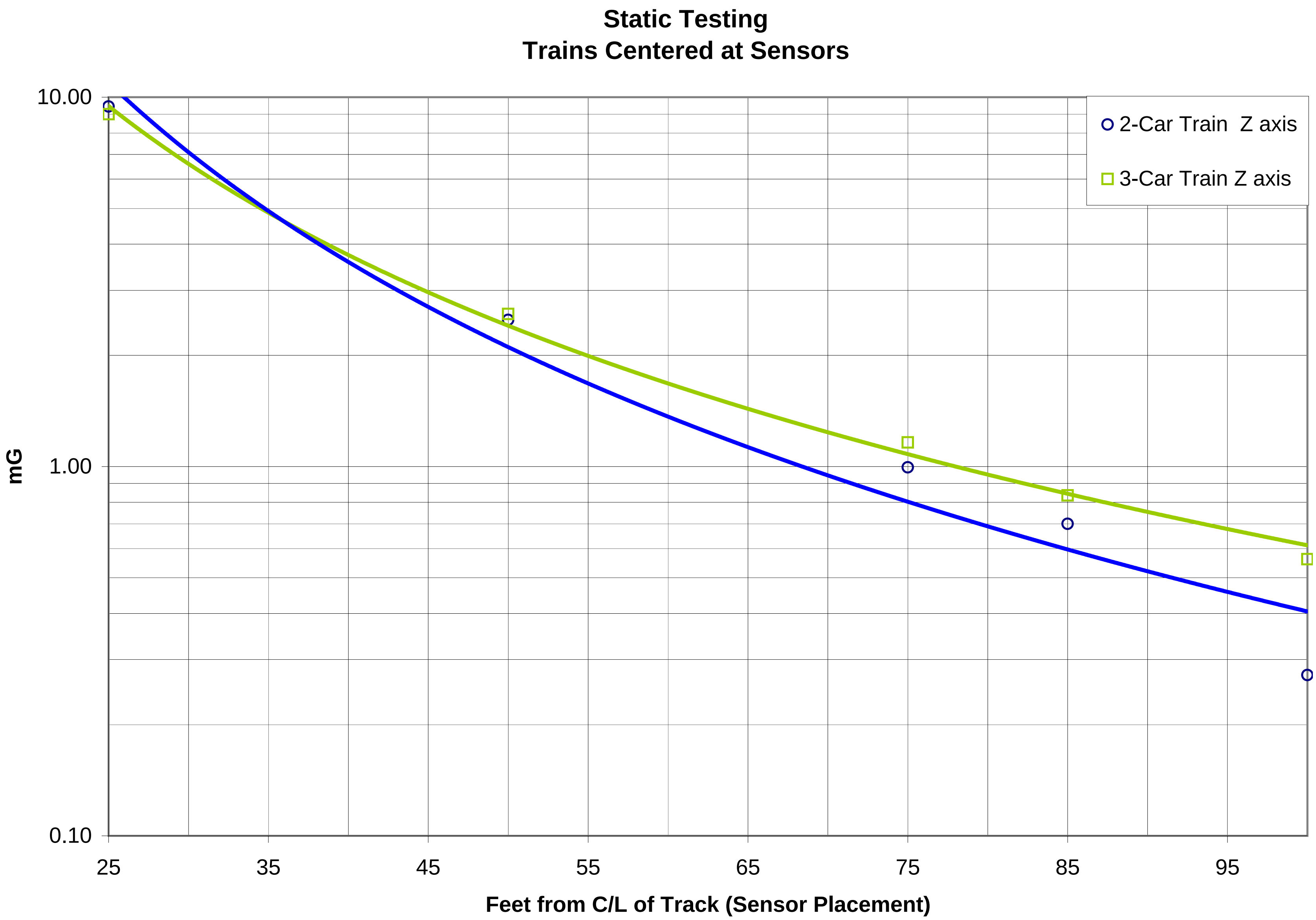
Central Corridor
Light Rail Transit
Metropolitan Council

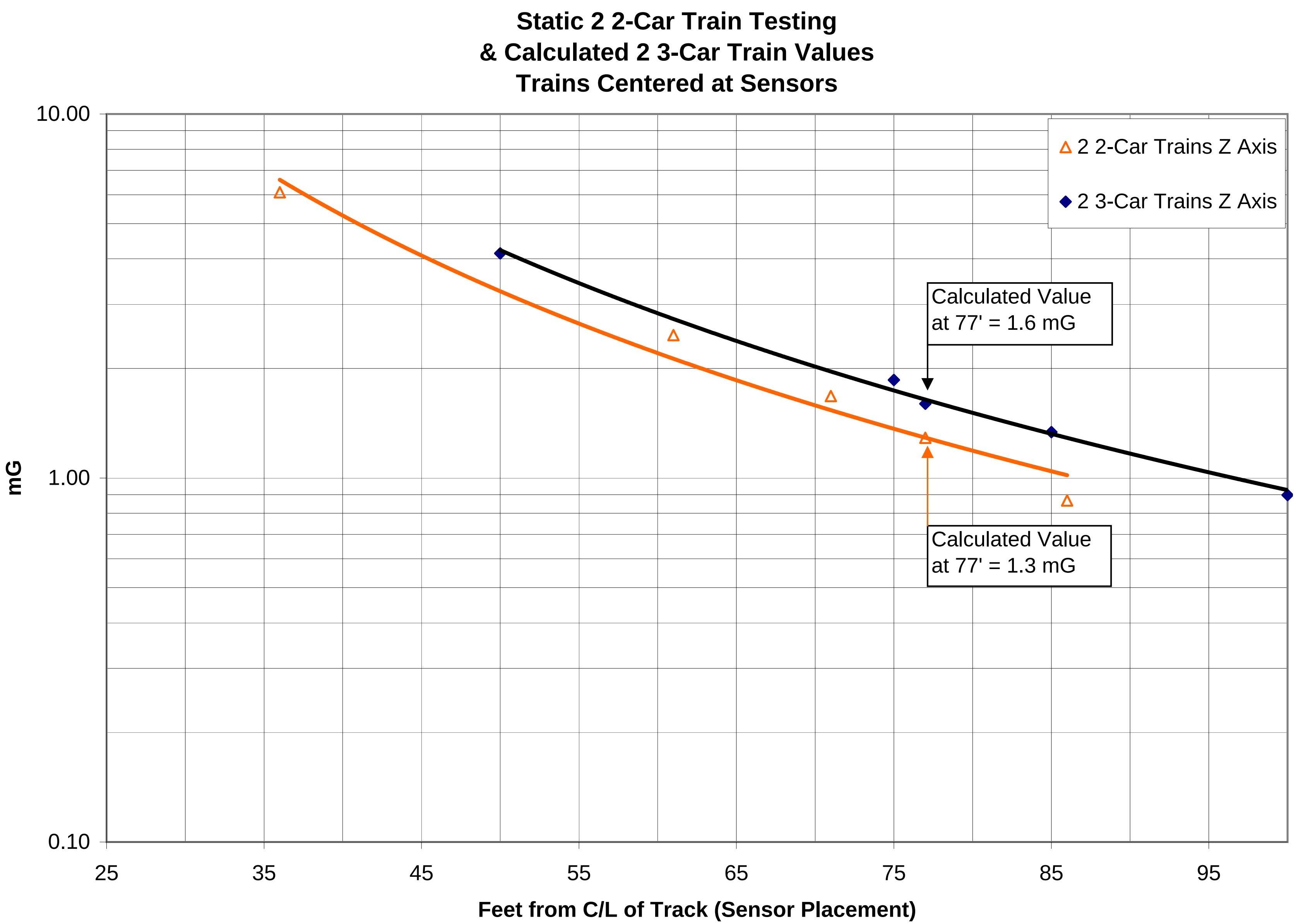
GEOMAGNETIC PERTURBATION TESTING
MALL of AMERICA SITE
TEST EQUIPMENT CONFIGURATION

DISCIPLINE: SYSTEMS
SHEET NAME: 5/13/08

SHEET 1 OF 1

May. 13 2008 11:19 am I:\900_CAD\DESIGN\LTK\Exhibit-Misc\MOA-Site-40.dwg By: hamilts


Static Testing
Trains Centered at Sensors
10.00
1.00
0.10
mG
25
35
45
55
65
75
85
95
Feet from C/L of Track (Sensor Placement)
2-Car Train Z axis
3-Car Train Z axis


Static 2 2-Car Train Testing
& Calculated 2 3-Car Train Values
Trains Centered at Sensors
10.00
1.00
0.10
mG
25
35
45
55
65
75
85
95
Feet from C/L of Track (Sensor Placement)
2 2-Car Trains Z Axis
2 3-Car Trains Z Axis
Calculated Value
at 77' = 1.6 mG
Calculated Value
at 77' = 1.3 mG