High Voltage Direct Current (HVDC) Interference Determination for Duluth Superior Harbor

Final Report Ver. 8.0

Prepared for

NTH/WTA JOINT VENTURE
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Background

The U.S Army Corps of Engineers (Detroit, MI) has reported that steel sheet piling and steel sheathed support columns (e.g., docks and bridges) located in the Duluth-Superior Harbor appear to be corroding at an accelerating rate. Local experience and some preliminary data point to an increase in the rate of corrosion in the late 1970s. The accelerated attack has typically manifested itself as hemispherical-shaped pits on submerged areas of the bare steel piling primarily in a region several feet below the high water line and moderating with greater depths down to the mud line. Owners and managers of sheet and "H" pile structures are facing an enormously expensive problem. At a replacement cost estimated to be at least $1,500 per linear foot of sheet pile the approximately 13 miles of sheet pile alone would cost more than $100 million to replace prematurely. Currently, the exact cause or causes of this accelerated corrosion is not definitively known. Instantaneous corrosion rates measured at various locations within the Harbor (using the linear polarization resistance technique) have confirmed the relative corrosion rates at several different sites but not elucidated mechanism(s) for the accelerated degradation.

Further information on this earlier work is provided in US Army Corps of Engineers ERDC/CERL SR-05-3 Study "Freshwater Corrosion in the Duluth – Superior Harbor Summary of Initial Workshop Findings, 9 September 2004. The abstract for this report states: "*The authors met in Duluth (September 2004) to examine harbor corrosion and consult with interested parties. The corrosion appears as pock marks primarily in the 4 feet just below the water surface. The corrosion extends down to about 10 feet, but decreases from 4 feet below the surface to 10 feet. The corroding pock marks are covered by an orangish coating that tends to cover the corroded pit. Water chemistry, dissolved oxygen content, and dissolved chlorides from de-icing salts seem to be the most likely agents of accelerated corrosion of 12 causes discussed. A lack of data made it unclear whether microbiological factors or functional harbor changes are unduly influencing corrosion in the harbor. The authors recommend immediately quantifying the corrosion rate, conducting a water chemistry analysis, checking for microbiologically influenced corrosion,* ***testing for stray DC currents*** (bold and underline by this report author), *and assessing the condition* *of critical steel structures. They encourage long-term monitoring of corrosion in the Duluth-Superior Harbor and other Great Lakes ports, as well as developing a condition based strategy for steel replacement and repair."*

The objective of the field testing described in this report was to "definitively and quantitatively assess, characterize and document the effect or non-effect of an operating HVDC transmission line located in Duluth, MN on the corrosion of local buried and/or submerged steel structures". This requirement was stipulated by The U.S. Army Corps of Engineers through an existing contract with NTH/WTA Joint Venture. (Detroit, MI). Refer to Detroit District, USAED Contract No. W911XK-07-0002 with the NTH/WTA Joint Venture dated July 18, 2007; and to Delivery Order No. 5 Scope of Work, High Voltage Direct Current (HVDC) Interference Determination for Duluth Superior Harbor.

The purpose of the field testing was to determine if the HVDC system was causing stray-current corrosion of the sheet piling. The field test was designed and conducted by Bushman & Associates, Inc. (B&A) with assistance from the following organizations in Duluth, MN: AMI Engineers, Minnesota Power & Light (MP&L), Hallet Dock, Duluth Harbor Port Authority, Midwest Energy, and the U.S. Army Corps of Engineers. James B. Bushman, President of the B&A, served as the Project Manager and Principal Engineer. B&A's Senior Corrosion Scientist, Dr. Bopinder Phull, assisted Mr. Bushman in all phases of the project and prepared all instrument operating instructions and calibration of the instruments used on the project.

Field Test Locations

Based on discussions between the aforementioned organizations, the following four (4) locations were selected by consensus for the stray-current field testing:

- Hallet #5 Pier - sheet pile
- Midwest Energy Wharf - H. piles
- Duluth Port Authority Wharf - sheet pile
- South Side Superior Entry (Wisconsin Point Pier) - sheet pile

Since the nearest earth-current groundbed for the HVDC system is approximately 35 miles West and slightly North of the Duluth Harbor (near Floodwood, MN), the Hallet No. 5 Wharf was selected as representing one of the nearest structures to the potential stray current source, followed by the Duluth Port Authority Wharf and with slightly less effects anticipated for the Midwest Energy Site; while the Superior Entry site was considerably further from the potential stray current source. Aerial views of the test sites are shown in Appendix A.

Field Testing

The field testing consisted of simultaneously monitoring changes in electrical potential gradients in the water, adjacent to the piling, at each of the four locations mentioned above. Gradients were measured as potential difference between a silver/silver-chloride/saturated potassium-chloride (Ag/AgCl/sat-KCl) reference electrode located within 1 – 2 feet of the structure wall or pile and two copper/copper-sulfate ($Cu/CuSO_4$) reference electrodes – one deployed laterally 5 ft from and at the same distance from the structure wall as the Ag/AgCl/sat-KCl electrode and the other located normally from the structure wall or pile 5 ft further into the water from the Ag/AgCl/sat-KCl electrode, as depicted schematically in Figure 1. All electrodes were submerged approximately 3 feet below the waterline.

The potential difference between the reference electrodes was measured using a Pico ADC-20 data logger (with a resolution of 1 micro-volt when using the +/- 1250 mV range) and the data recorded automatically once every second using a laptop computer and the data-logger manufacturer's software. All equipment including computers, data loggers, data recording software, reference electrodes and terminal boards were fully tested and calibrated prior to shipping the equipment to Duluth.

Trial setup by each measurement team and data logging was successfully tested in the field at one location on 21st September, 2008. In addition, all four sites were inspected and means for suspending the reference electrodes at each site were determined on the 21st and 22nd of September. Finally, on the evening of September 22nd, all four computers were synchronized to the US atomic clock which facilitated test time coordination between all sites as well as ground current injection variations conducted by MP&L at precise US atomic clock synchronized test times.

Starting at 6:30 a.m. on Wednesday, September 23rd, the four test teams (two from B&A and two from AMI deployed to their respective test sites. Due to the previous field training, all crews were able to complete their test setups by 9:00 a.m. Actual testing was performed between 9:30 a.m. and 11:30 a.m. local time. At each test location, the data logger and laptop computer was placed inside a small tent to protect it from any inclement weather conditions and also to allow easy reading of the monitor screen. The laptop computer was plugged into a 400 or 800 watt DC to 120 Volt AC inverter powered by a 12V, heavy-duty, marine lead-acid battery. The setup at each location was identical in every respect. A typical test setup is shown in Figure 2.

The data loggers were set to the following parameters:

a. Recording method – Real-time continuous
b. Data sampling interval – 1 second
c. Sampling Time – Stop after preset time (e.g. 8 hours)
d. Readings per sample – As many as possible
e. Channel 1 – Ag/AgCl/sat-KCl vs. laterally deployed Cu/$CuSO_4$
f. Channel 2 – Ag/AgCl/sat-KCl vs. normally-deployed Cu/$CuSO_4$
g. Mains frequency selection: 60 Hz
h. Conversion time – 340 ms
i. Voltage range ± 1250 mV
j. Display, record, save automatically – data table and autoscale graph (mV vs s)

Baseline recording by the data loggers at all four test sites commenced concurrently at precisely 9:30:00 a.m. Based on previous discussions, MP&L varied the HVDC system so that a known current flowed through the ground/water for a known time interval, starting precisely at 10:00:00 a.m. local time. MP&L refers to the current flow as ground current injection. Based on a previously agreed protocol, the ground current was ramped up quickly from zero to +50 A, maintained for 1 minute, then ramped down quickly back to zero and maintained in this condition for 4 minutes. This cycle was repeated but with current flowing in the opposite direction. Then the +50 A and -50 A cycles were repeated again sequentially. The current was then ramped up from zero to +100 A, back to zero, then to -100 A and back to zero for the same time intervals described previously; and again the cycles were repeated. This procedure was followed for ± 200 A, +500 A, and ±700 A cycles. The following table provided by MP&L lists their HVDC cycle details:

Table 1 - MP&L HVDC Imbalance Test Current

10:00	Ramp to +50 Amps
10:01	Ramp to 0 Amps
10:05	Ramp to -50 Amps
10:06	Ramp to 0 Amps
10:10	Ramp to +50 Amps
10:11	Ramp to 0 Amps
10:15	Ramp to -50 Amps
10:16	Ramp to 0 Amps
10:20	Ramp to +100 Amps
10:21	Ramp to 0 Amps
10:25	Ramp to -100 Amps
10:26	Ramp to 0 Amps
10:30	Ramp to +100 Amps
10:31	Ramp to 0 Amps
10:35	Ramp to -100 Amps
10:36	Ramp to 0 Amps
10:40	Ramp to +200 Amps
10:41	Ramp to 0 Amps
10:45	Ramp to -200 Amps
10:46	Ramp to 0 Amps
10:50	Ramp to +200 Amps
10:51	Ramp to 0 Amps
10:55	Ramp to -200 Amps
10:56	Ramp to 0 Amps
11:00	Ramp to +500 Amps
11:01	Ramp to -200 Amps
11:05	Ramp to -700 Amps
11:06	Ramp to 0 Amps
11:10	Ramp to +700 Amps
11:11	Ramp to 0 Amps
11:15	Ramp to -700 Amps
11:16	Ramp to 0 Amps
11:16	Test Sequence Complete

The monitoring and recording of the field potential gradients, i.e. potential differences between the reference electrodes (as described earlier) was continued uninterrupted at the four test locations during the above HVDC cycle variations performed by MP&L.

Rationale for methodology used in this stray current study

Stray current is defined by NACE International in their Standard Practice SP0169-2007 as "current through paths other than the intended circuit" and Interference as "any electrical disturbance on the metallic structure as a result of stray current". Such disturbances are normally related to direct currents (DC) rather than alternating current (AC). To cause corrosion on a structure, stray DC must flow from an outside source onto the structure in one area (where corrosion is then reduced or eliminated) and then flow along that structure to some other area or areas where they leave the structure to re-enter the Earth (corrosion is accelerated at this location).

NACE International states in their Standard Test Method TM-04-97 "Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems" that "4.2.2 Measurement of pipe-to-electrolyte potentials on pipelines affected by dynamic stray currents may require the use of recording or analog instruments to improve measurement accuracy. Dynamic stray currents include those from electric railway systems, HVDC transmission systems, mining equipment, and telluric currents.

Chapter 11, "Stray Current Corrosion" of NACE International's book entitled "Peabody's Control Of Pipeline Corrosion-Second Edition", states that "Stray current sources include the following:

- Impressed current cathodic protection systems
- DC transit systems
- DC mining operations
- DC welding operations
- High-voltage DC transmission systems and
- Disturbances of the Earth's magnetic field (Telluric Currents)."

This same chapter contains numerous examples of means for testing for the presence of stray current corrosion. All of these methodologies incorporate the measuring of the strength of the electric field gradient produced by the stray current using DC volt meters and reference electrodes.

Measuring electric field gradients as a means for detecting stray DC currents is based on Ohms law. It states that **E = I x R** where “**E**” is the Electro-Motive Force or EMF (measured in Volts), “**I**” is the Direct Current Flow (measured in Amperes = Coulombs/Second) and ”**R**” is the Resistance to Current Flow (measured in Ohms). Thus, if there is any stray DC current flowing in an electrolyte (e.g. soil moisture or lake water) resulting in stray current corrosion, simultaneously there must be a corresponding EMF caused by this current flow through the resistive water or earth. If the stray current is dynamic (changes in magnitude with respect to time such as is the case with HVDC), then this stray current can be detected and quantified by measuring the corresponding change in EMF with respect to time.

According to Peabody's Chapter 11 on stray current corrosion, a change of 20 to 50 mV EMF measured over a span of several feet in the Earth or typical potable waters simultaneously with cycling of the stray current source would give rise to concern for stray DC current corrosion. Thus, for the Duluth Harbor study, given the very high resistivity nature of the freshwater in the harbor, measuring for the presence of changing EMFs in the range of 20 to 50 mV as a result of the intentional operating of the HVDC with substantial levels of Earth return current (commonly referred to as imbalance current) was considered conservative. Had the water been much more conductive such as is the case with seawater, a lower voltage range would have been required. In either case, given the one micro-volt resolution of the data acquisition systems used in the Duluth study, detection of any stray currents generated by the HVDC system was possible.

In addition, it was decided that the strength of the electric field gradient should be measured both normal to and parallel to the sheet steel pile. This would allow detection of any voltage vector regardless of the direction of the vector. It was decided that a silver-silver chloride reference electrode should be used to represent the sheet pile structure surface rather than using the steel pile itself. This decision was made since the reference electrode is extremely stable whereas the sheet pile's energy level (voltage) can vary by tens of millivolts over the duration of the anticipated test due solely to corrosion activity on the pile’s surface unrelated to stray current activity.

The use of Copper-Copper Sulfate outboard electrodes with similar stability were selected so that the natural voltage difference of 100 mV between the silver chloride and copper sulfate in electrodes would preclude measuring voltages on either side or very close to zero. While this would not been a problem for the instrumentation ultimately selected for use on this project, the reference electrodes had to be procured prior to the final selection of data logging instrumentation used. Other instruments that were being considered for use can be somewhat unstable when measuring values very close to zero.

With the full cooperation of Minnesota Power & Light, it was decided that the HVDC system would be cycled at a number of different direct earth return current levels in both directions at very specific time intervals (coordinated to the atomic clock) and that measurement sites would be located at dock facilities within the harbor which were closest to the stray current source, at intermediate Harbor locations and at one site that was at the most remote location.

It should be understood that the HVDC transmission line normally operates in nearly perfect balance with virtually all current flowing on the two aerial DC conductors used for transmitting this power between South Dakota and Minnesota. According to MPL, less than 1/2 ampere is typically carried through the Earth in parallel to these aerial conductors. Further, on rare occasions there may be as much as 5% to 10% of the total current carried through the earth. These imbalanced load conditions occur for only a few hours at a time and only several times each year. Finally, perhaps once a year or less, there is a brief period (usually for a few minutes) when the system operates in mono-polar mode when the entire load current is carried through the Earth return. It should be noted, however, that under this condition, the system is never operated at more than 500 amperes which is substantially below the maximum test current (700 amperes) at which the system was operated during this investigation.

<u>Partial list of additional source information on stray current corrosion and analysis:</u>

- "Stray Current Corrosion", M. Szeliga, Editor, NACE International, 1440 S. Creek Drive, Houston, Texas -1994
- "Peabody's Control Of Pipeline Corrosion", First and Second Additions, A. W. Peabody, NACE International, 1440 S. Creek Drive, Houston, Texas - 1967 & 2001

- "Corrosion and Corrosion Control", Third Edition, Herbert H. Uhlig (MIT) and R. Winston Revie (Canada Centre for Mineral and Energy Technology), John Wiley & Sons, New York, New York - 2001
- “Underground Corrosion”, Melvin Romanoff, National Bureau of Standards (now the National Institute of Standards and Technology) Circular 579, Originally issued April 1, 1957 and later published by NACE International, 1440 S. Creek Drive, Houston, Texas - 1989
- "Basic, Intermediate and Advanced Textbooks", Appalachian Underground Corrosion Short Course, West Virginia University, Morgantown, West Virginia - 2008

Results

Spreadsheets and graphical plots of the complete data are included on the CD contained in Appendix “C” of this report as an Excel file. The Excel file has multiple tabs under which the data are separated systematically with respect to test location sets and various HVDC ground current injection magnitudes/cycles. The tabbed worksheets are:

- Hallet No. 5 Dock Test Data
- Midwest Energy Wharf Test Data
- Duluth Port Authority Wharf Test Data
- South Side Superior Entry Test Data
- MP&L HVDC Current Output vs Real Time
- Detail Graphs of 50 Ampere Test Currents
- Detail Graphs of 100 Ampere Test Currents
- Detail Graphs of 200 Ampere Test Currents
- Detail Graphs of 500 & 700 Ampere Test Currents

Figure 3a – 3d (page 13 & 14) show plots of the field potential gradients (in mV) measured (using the reference electrodes) and the overall HVDC ground current injection ramps (in amps) versus time (in sec) for the entire test duration at the four test locations. The first 1800 seconds represents the baseline field potential gradient data for the time period 9:30 a.m. to 10:00 a.m.

when there was no ground current injection from the HVDC system; i.e. the system was operating under normal "balance". Three features are apparent for the baseline data. First, there was a small potential difference between the laterally and normally-deployed $Cu/CuSO_4$ reference electrodes relative to the Ag/AgCl/sat-KCl reference electrode. Second, there was a small, almost parallel drift in the potential difference versus the Ag/AgCl/sat-KCl reference electrode. Third, there were small oscillations in the measured potentials due to wave action.

Inspection of the entire plot for each location (Figures 3a – 3d) shows no significant changes in the field potential gradients as MP&L ramped the HVDC ground current injection from ±50 A through ±700 A in progressive cycles during the test from duration (10:00 a.m. to 11:16 a.m.). This is much more clearly corroborated by the detailed graphical data shown in Figures 4a – 4d for the ±700 A HVDC ground current injection cycle, which represents the highest DC current value tested. Data in the appended Excel file for the other HVDC ground current injection magnitudes and cycles also shows no effect on the field potential-gradient measurements. These detailed graphical analyses were made for each site and each "off", forward "on", "off", and reverse "on" current cycle (2 cycles each for 50, 100, 200 and 500 to 700 amperes) resulting in a total of 32 detailed graphs which are included in the Excel file provided as a separate appendix to this report. In addition, the actual potential-gradient values measured were synchronized with MP&L's ground-current injection data and graphs for each site for the entire test period are included in the first 4 tabbed worksheets within the Excel workbook.

The spikes in the potential-gradient data shown in Figure 3c at the Port Authority wharf test location between the ~ 3600 and ~ 4300 time span correspond with the arrival of a large cargo ship at the wharf. The ship stopped within a few feet of the test location at ~ 10:30 a.m. and then moored along the wharf a few hundred feet away by ~ 10:45 a.m. The spikes in the data are ascribed to water turbulence created by the ship and possibly electric field effects created by submerged dissimilar metals on the ship, e.g., steel hull, bronze propeller, cathodic protection system/materials; and perhaps interference with the steel piling. The spikes are not related to the HVDC system because no such effects were observed at other times when the ground current injection was even much higher. It should be noted that there was also somewhat larger oscillations in the wave action generated cyclic potentials since there were larger waves at this site. Nonetheless, review of the detailed graphical data for this and the other sites made it possible to clearly and conclusively rule out any impact from the HVDC system at the ground-current injection values tested.

It should be noted that according to the National Climatic Data Center (NCDC), the weather condition were very normal for the month of September, 2008 with average precipitation (highest single day of 1.14 inches rainfall) and temperatures in degrees Fahrenheit varying from the mid 60's during the day to the high 40's at night. The climatologically conditions during the test week were considered to be very representative of the conditions that would exist under "worst case" conditions. While lower winter temperatures would tend to minimize any stray currents (frozen earth is an electrical insulator), the somewhat warmer summer temperatures would not cause any significant increase in the propensity for stray current from the HVDC system from those encountered during the test week.

In addition, there is a rock (granite) wall which rises approximately 500 feet above and ½ mile to the northwest of the harbor. This ridge may well help "shield" the harbor from any stray DC current effects from the MPL ground station which is located approximately 25 miles further inland from the ridge.

Finally, the voltage gradient developed by an HVDC current source propagates through the earth at approximately the speed of light and thus there would be no measureable time delay from the initiation of a test earth current generated 25 miles northwest of the harbor and the voltage gradient values measured at each of the four test sets around the Duluth Harbor.

Conclusion

The potential-gradient field testing described in this report demonstrates definitively and quantitatively that there is no stray-current effect of MP&L's HVDC system on the corrosion of the steel piling at the Duluth harbor test locations. There were no measureable potential changes or trends during any of the applied ground-current injection values regardless of polarity, including when the system was operated near the system maximum "imbalance" of 700 A DC amperes.

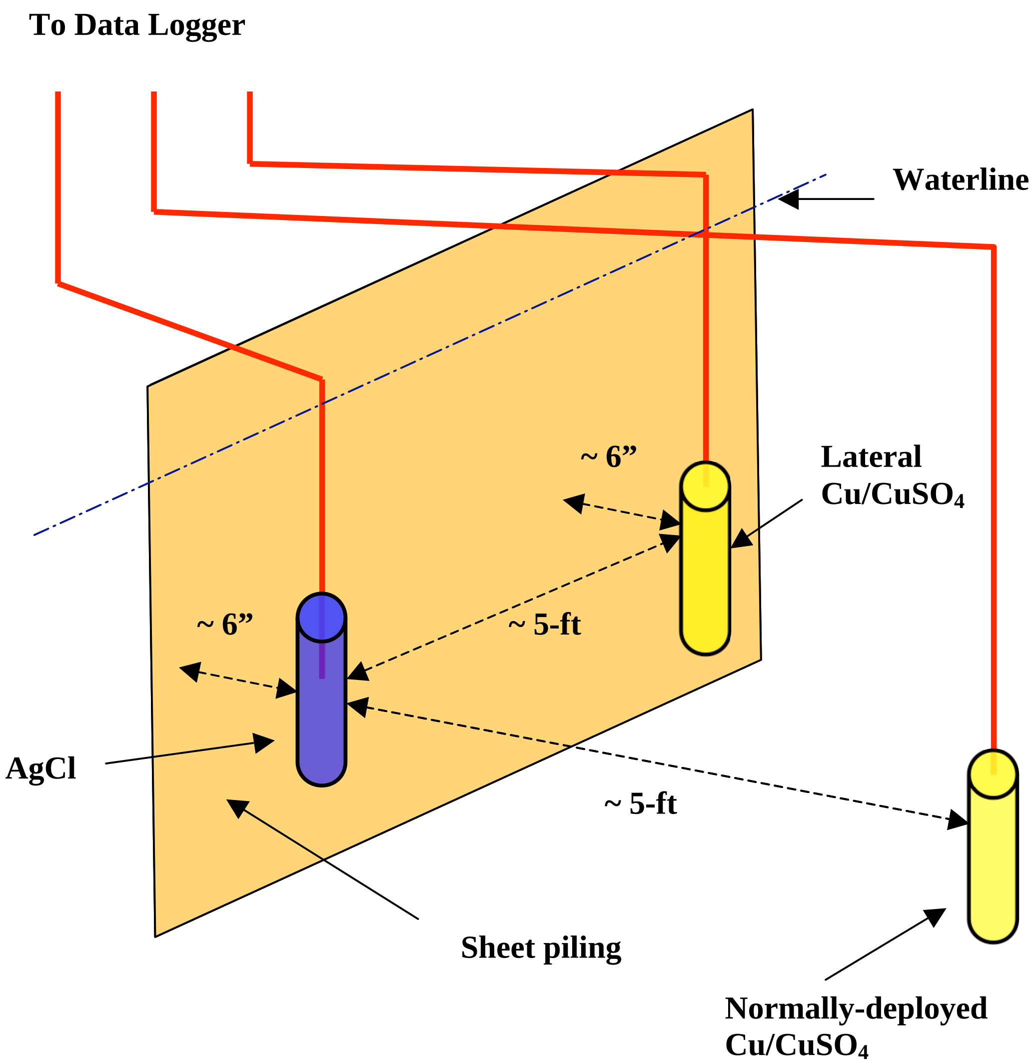


Figure 1. Schematic arrangement of 3 reference electrodes for field-gradient DC potential measurements

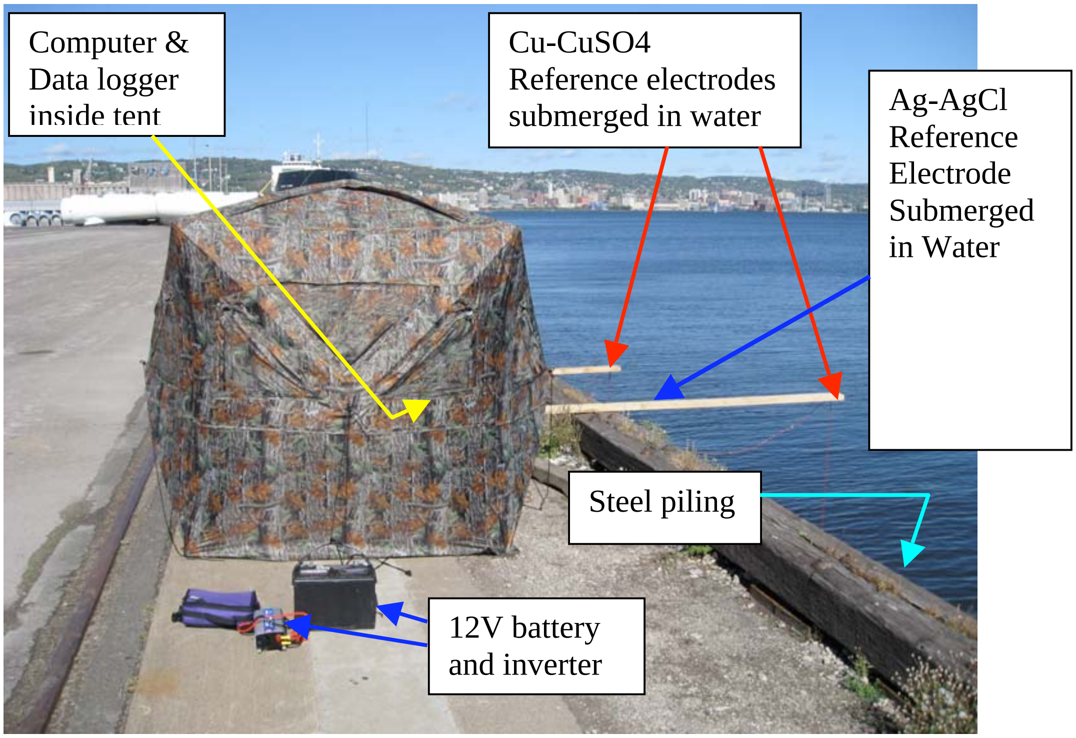


Figure 2a. Typical stray-current field test setup at each location

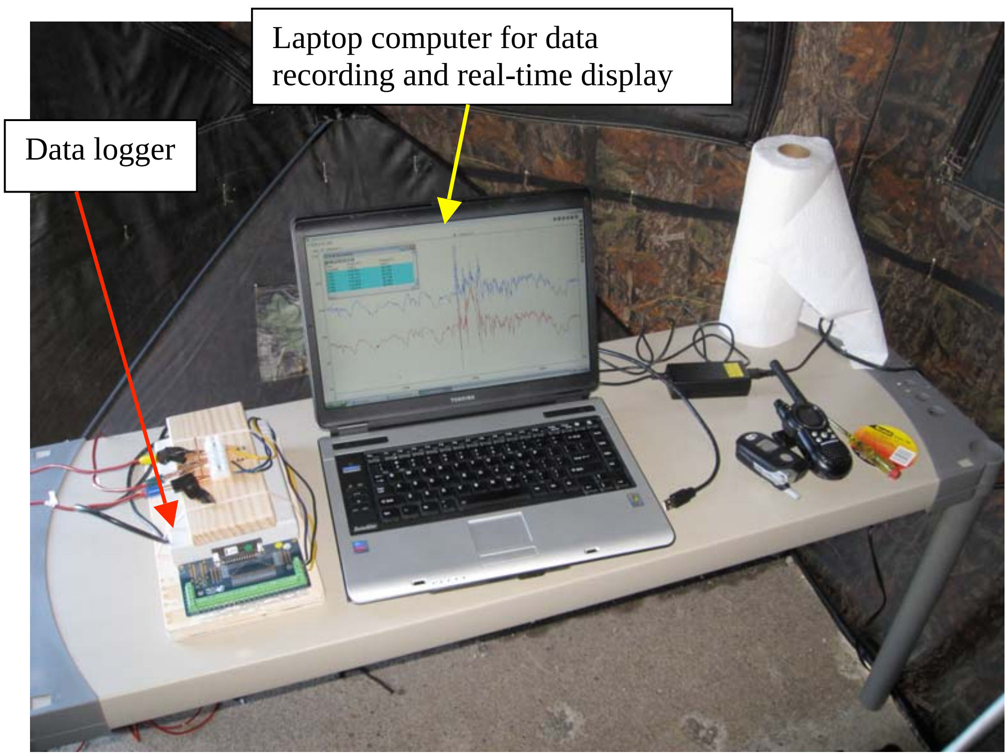


Figure 2b. Typical data logging system setup

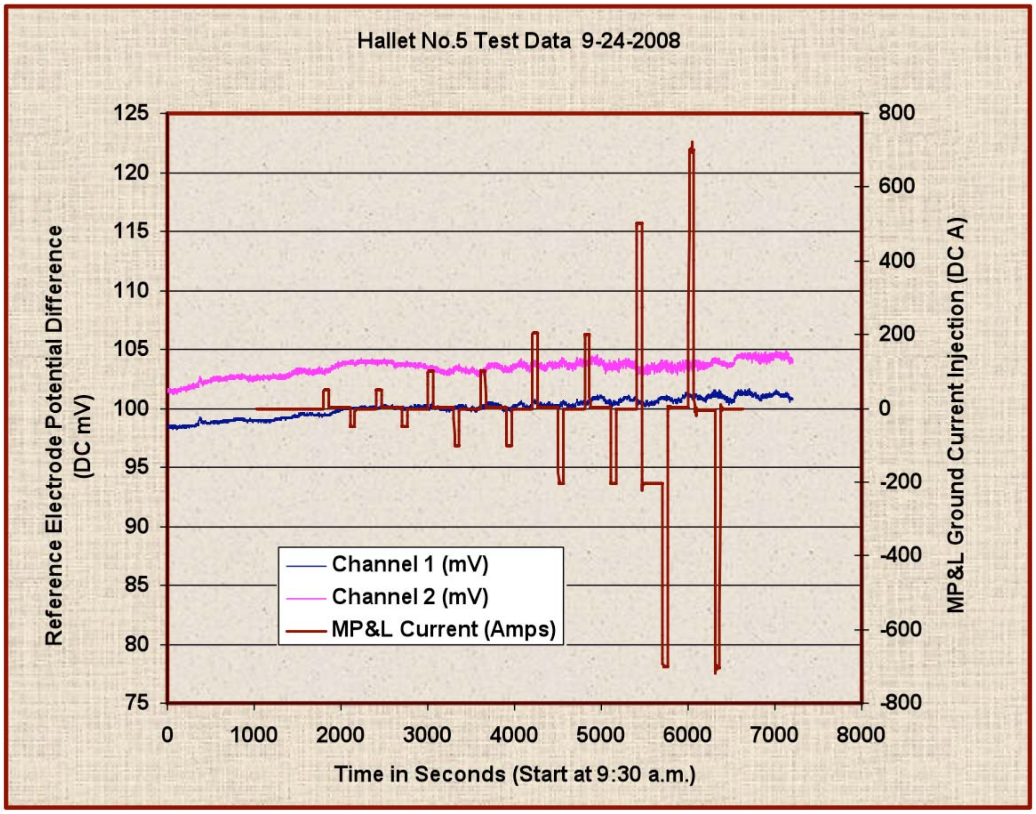


Figure 3a. Field gradient (mV, left) and HVDC ramps (A, right) vs. time at Hallet No. 5

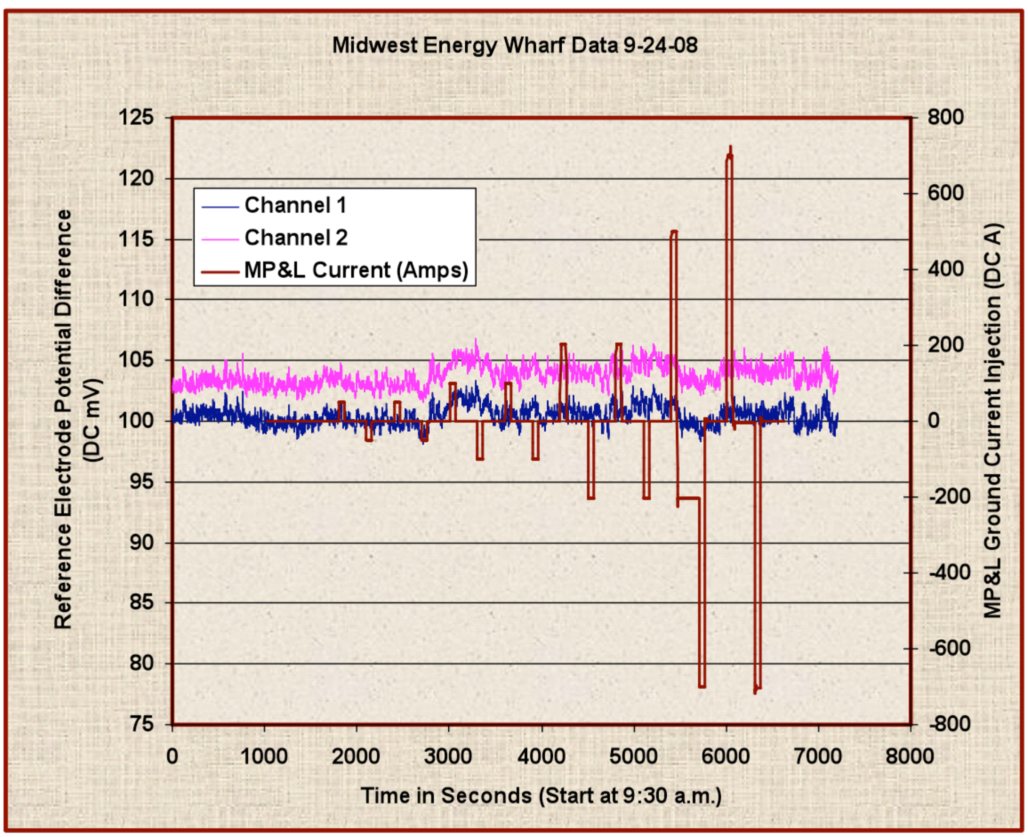


Figure 3b. Field gradient (mV, left) and HVDC ramps (A, right) vs. time at Midwest Energy Wharf

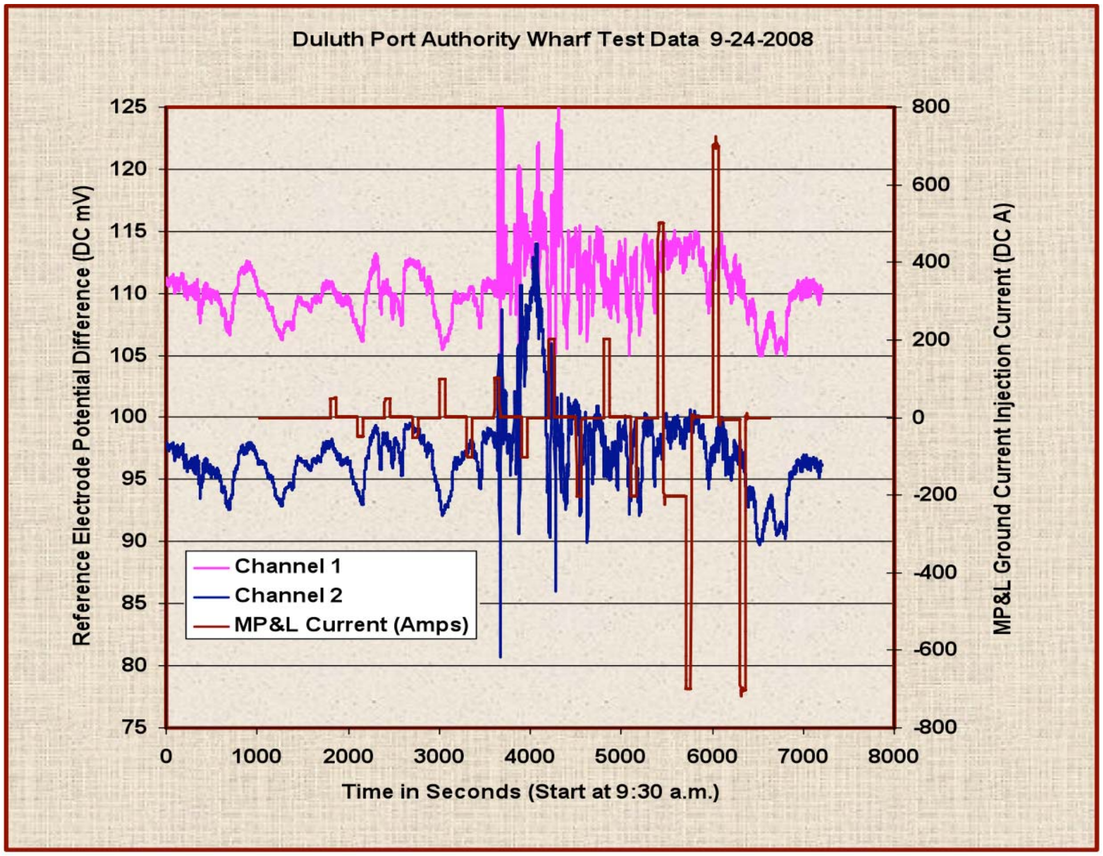


Figure 3c. Field gradient (mV, left) and HVDC ramps (A, right) vs. time at Port Authority

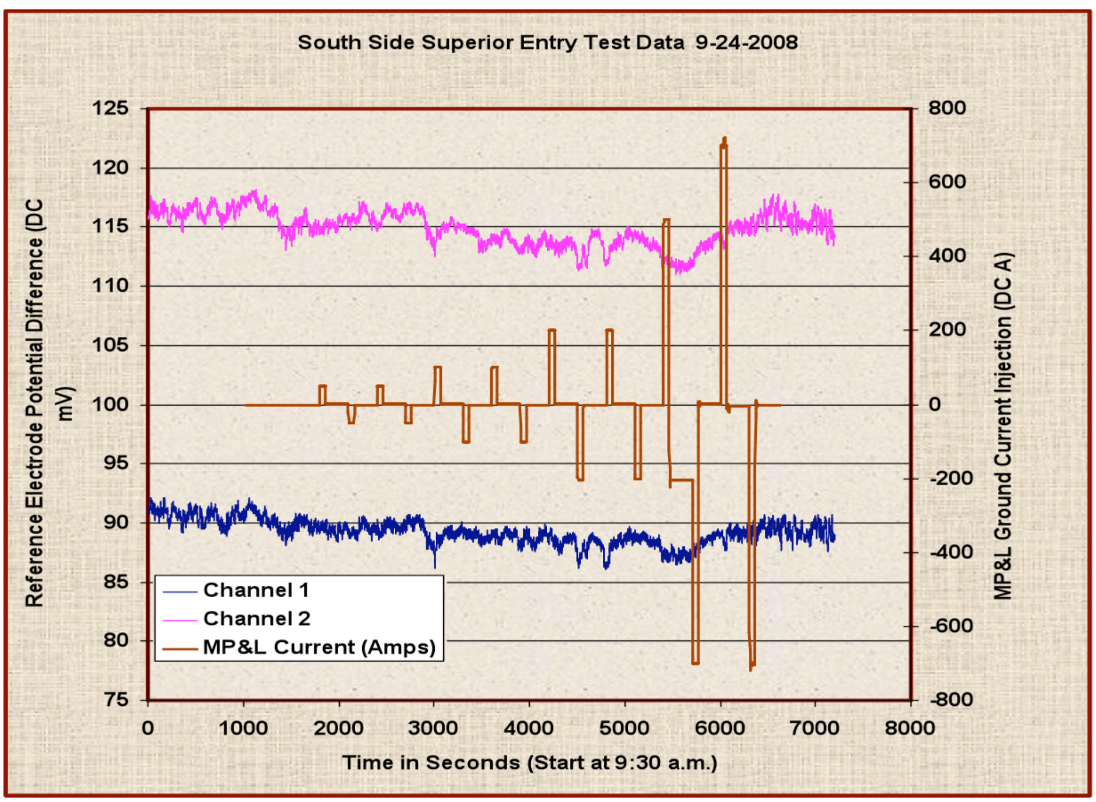


Figure 3d. Field gradient (mV, left) and HVDC ramps (A, right) vs. time at South Side Superior entry

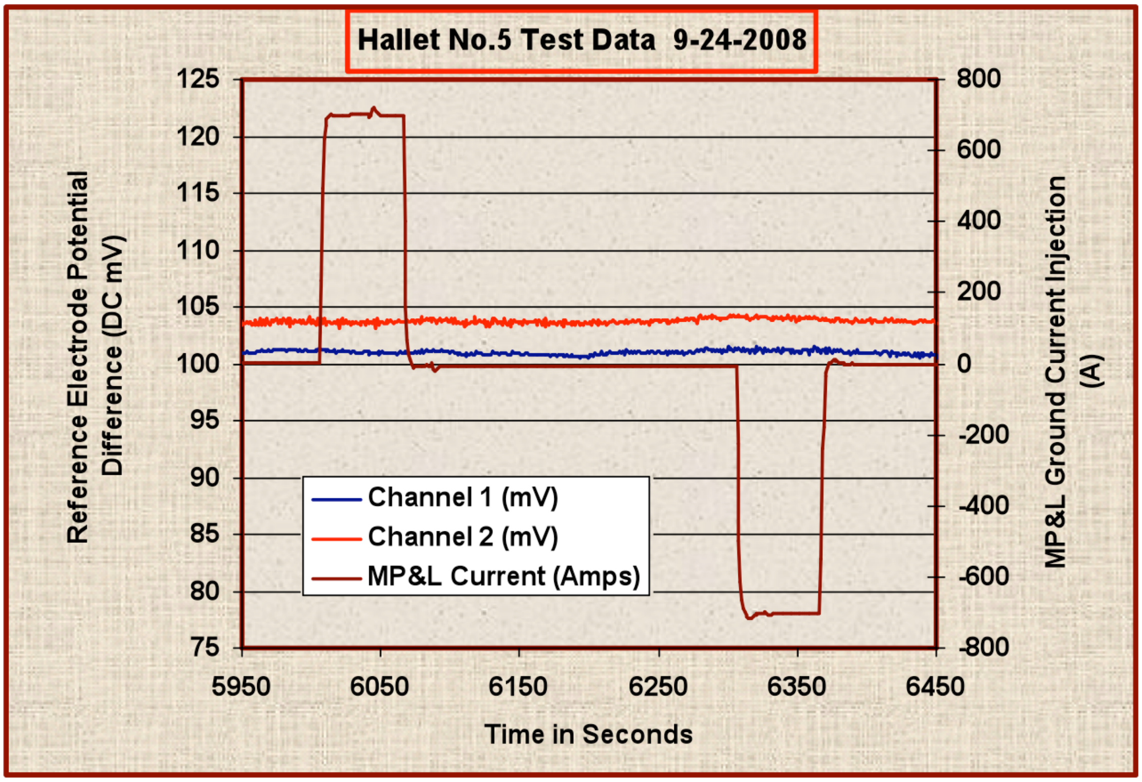


Figure 4a. Field gradient (mV, left) and ±700A HVDC ramps vs. time at Hallet No. 5 location

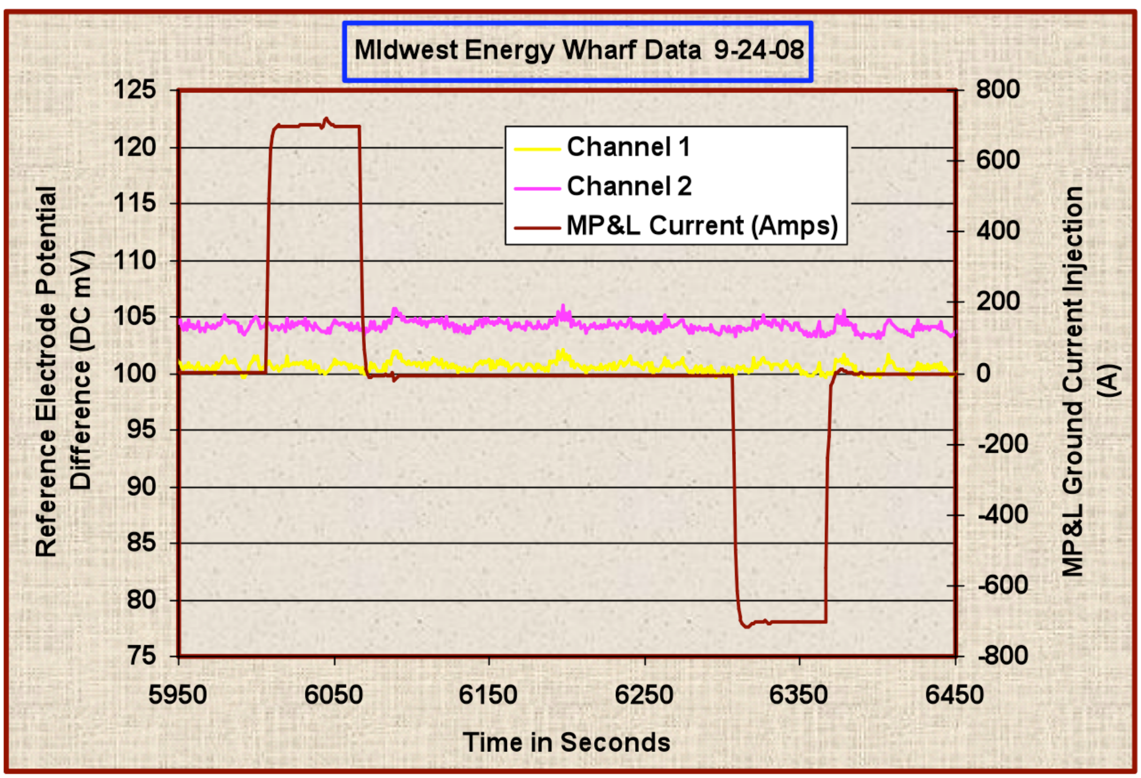


Figure 4b. Field gradient (mV, left) and ±700A HVDC ramps vs. time at Midwest Energy Wharf location

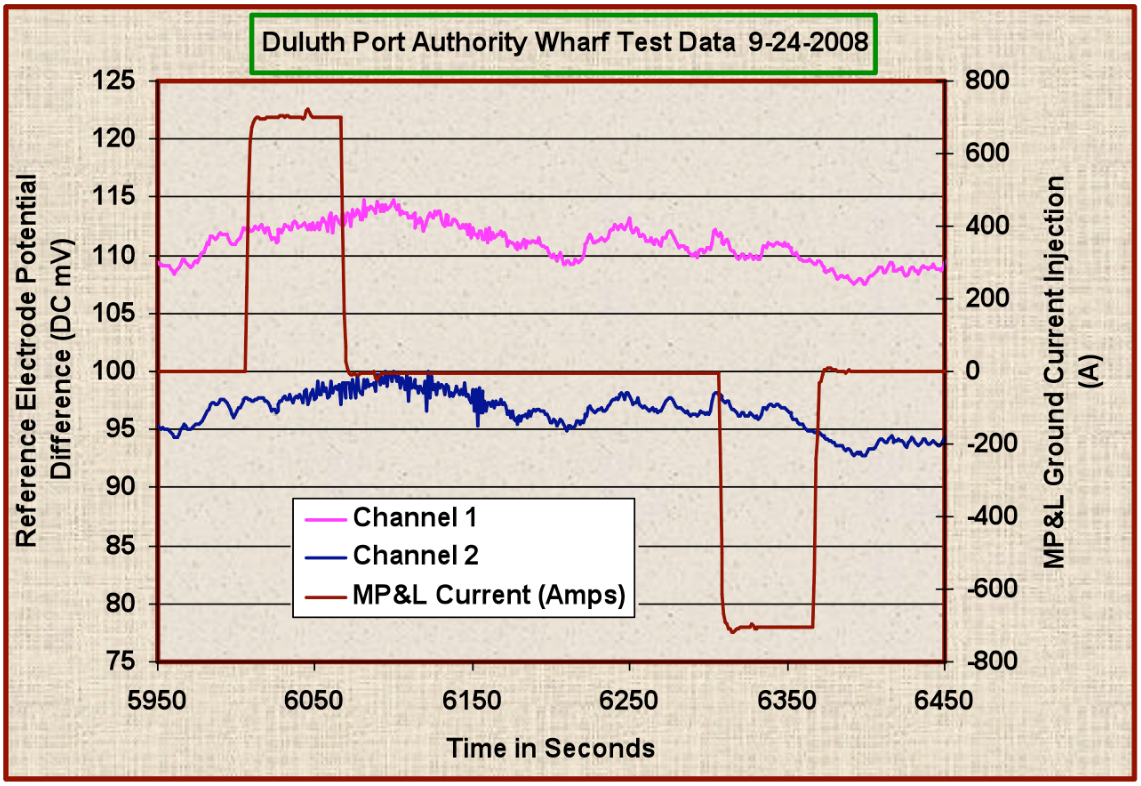


Figure 4c. Field gradient (mV, left) and ±700A HVDC ramps vs. time at Port Authority Wharf location

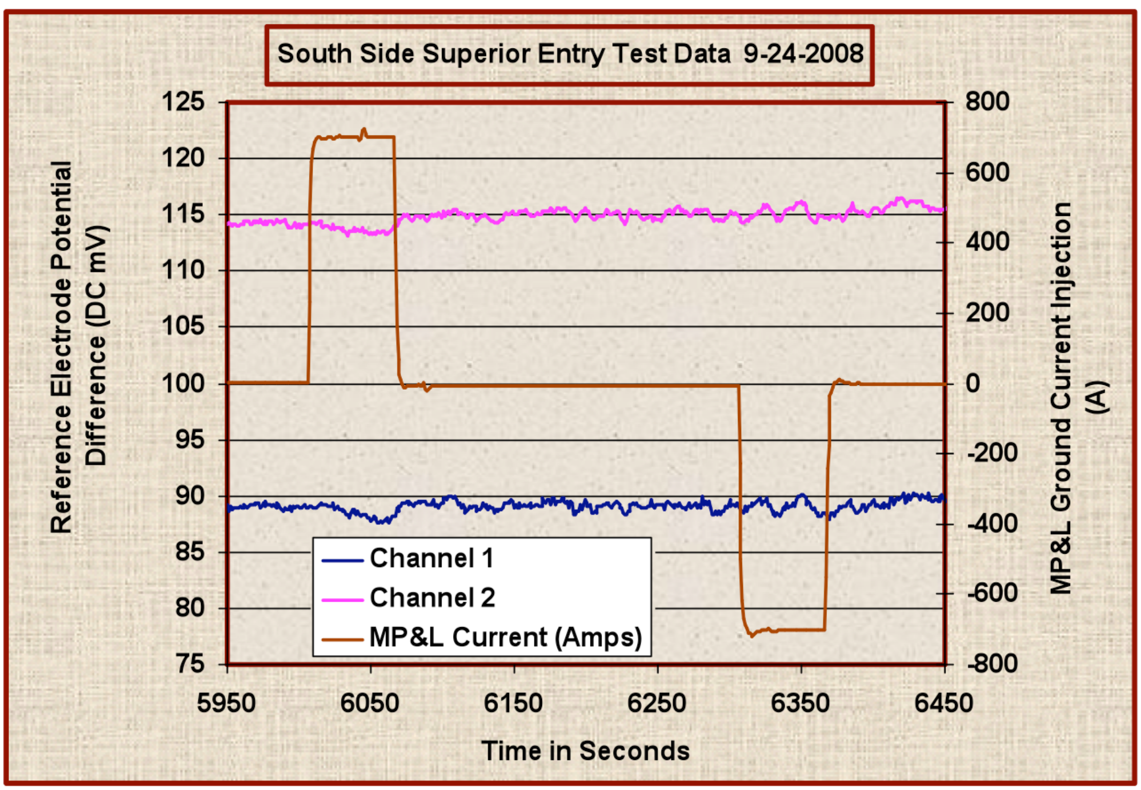


Figure 4d. Field gradient (mV, left) and ±700A HVDC ramps vs. time at South side Superior entry location

Appendix A – Aerial Views of the 4 Test Site Locations

Hallet No. 5 pier test site

Midwest Energy wharf test site

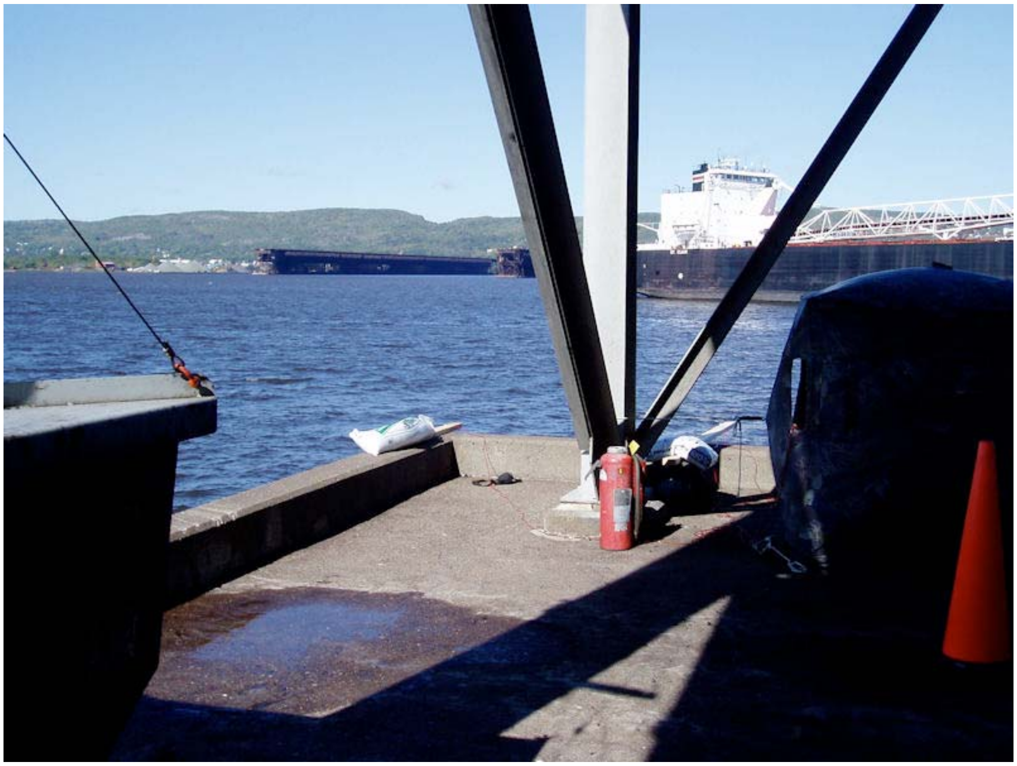
Duluth Port Authority wharf test site

Southside Superior entry (Wisconsin Point pier)

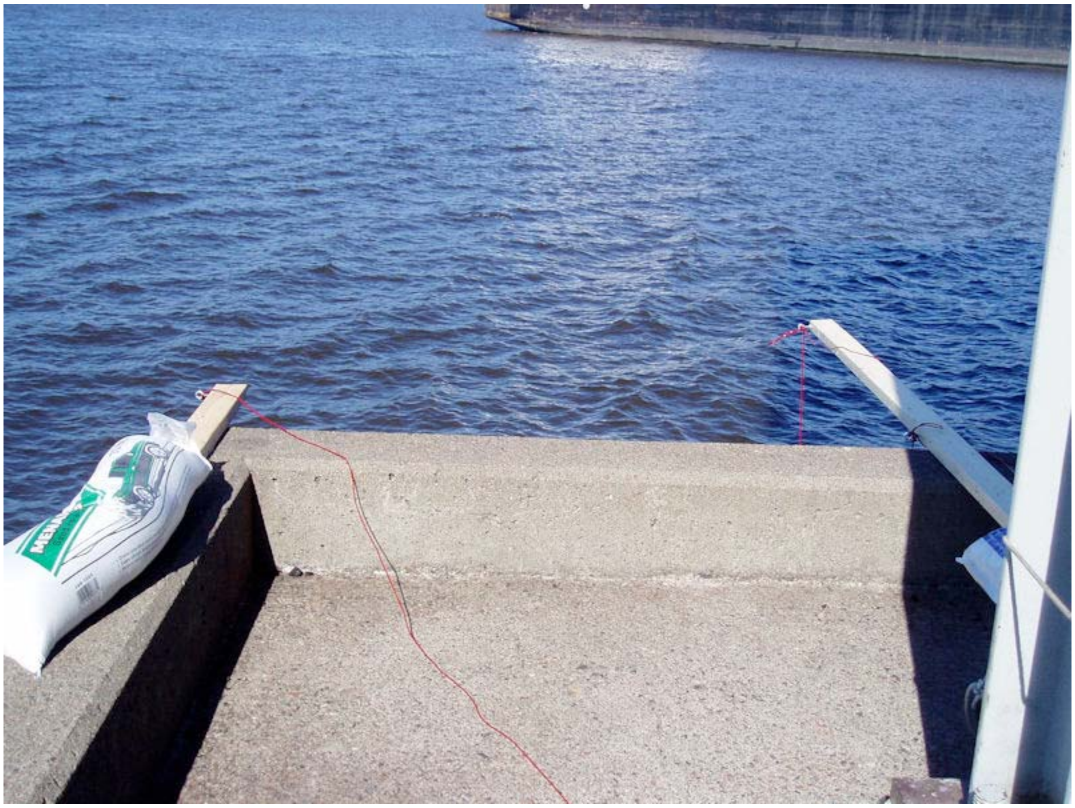
Appendix B –General Testing Photos

Test Setup with Tent at Port Authority Test Site Terminal

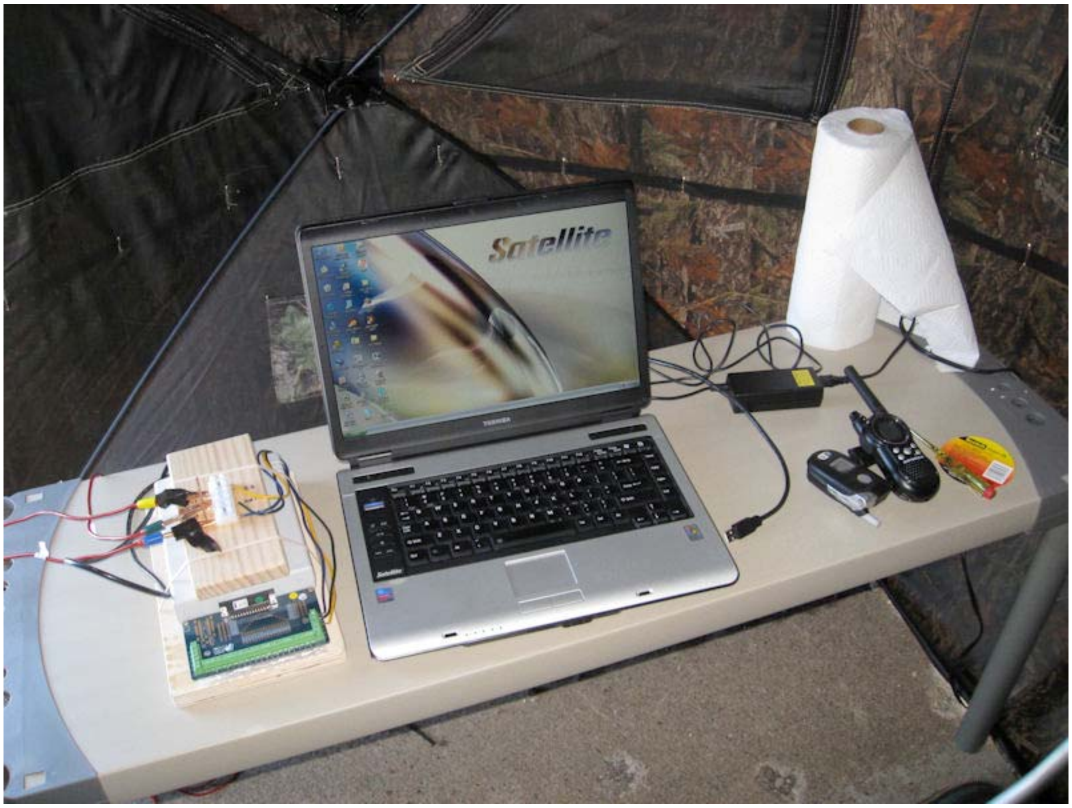
Superior Entry Reference Cell Array



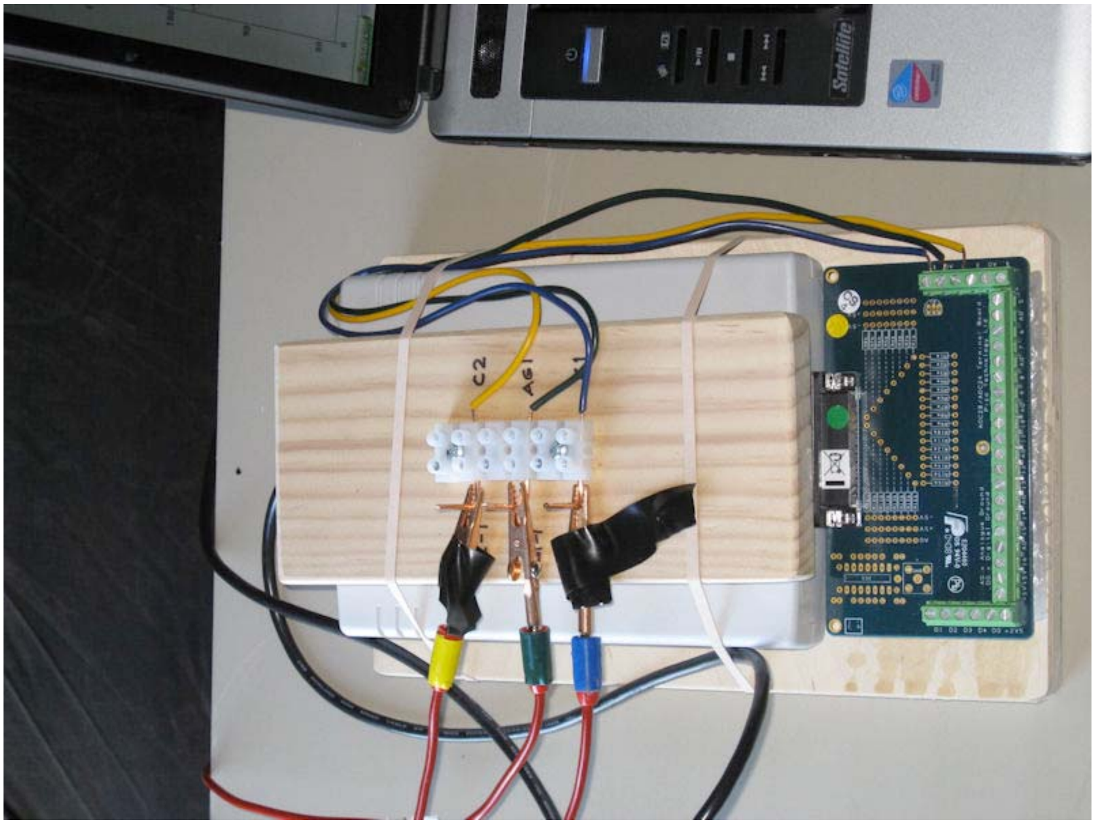
Midwest Energy Test Site showing Tent and Electrode Supports



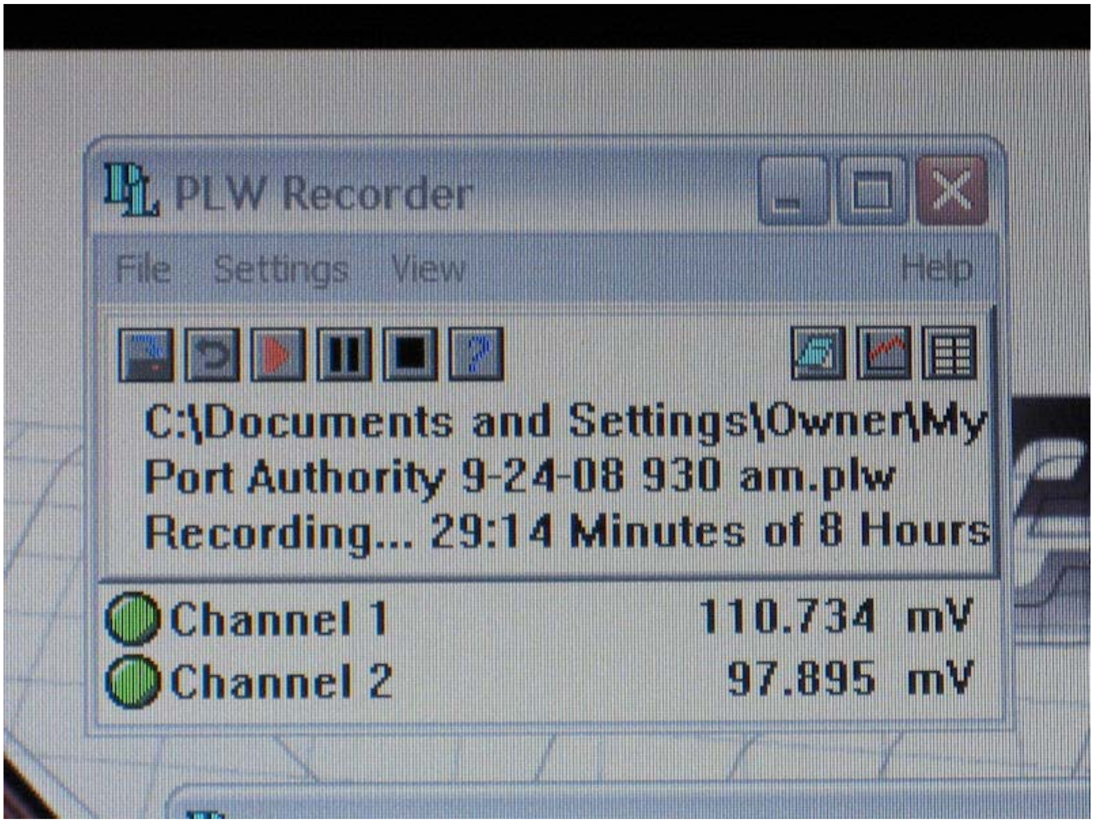
Midwest Energy Site Reference Electrode Support Boards



Test Set Up Inside Tent

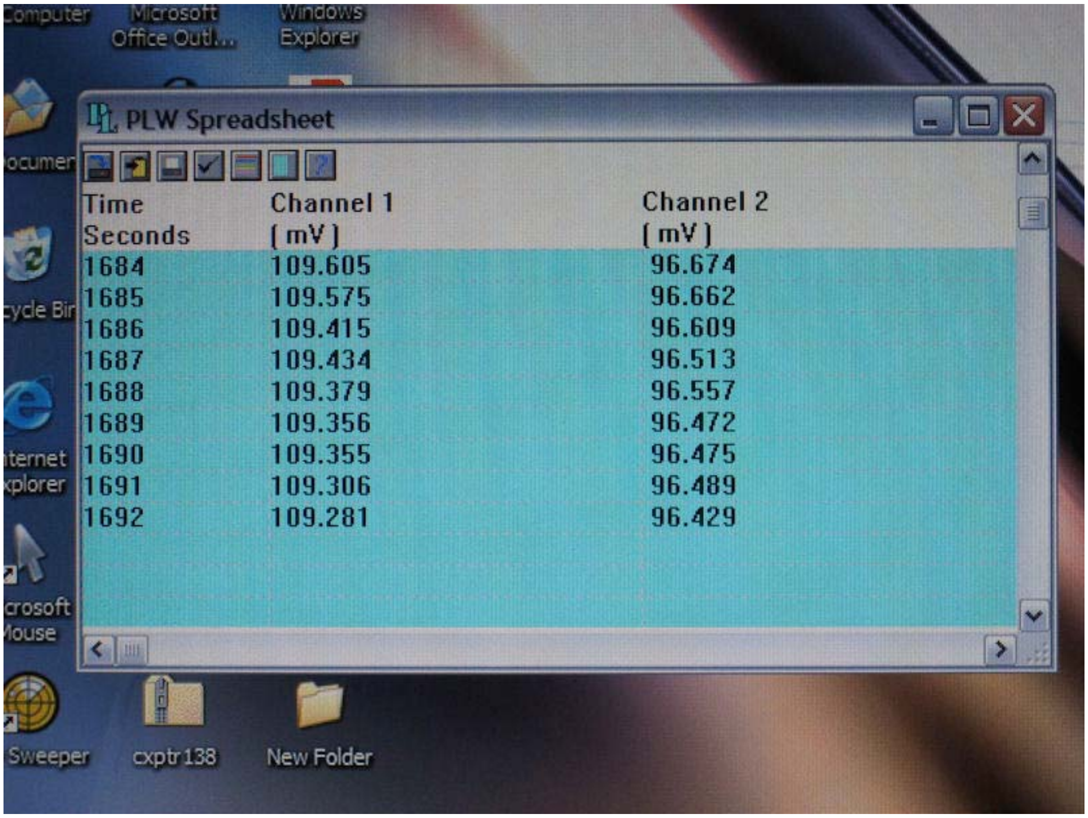


Custom Terminal Board Showing Connections to Data Logger and Reference Electrodes



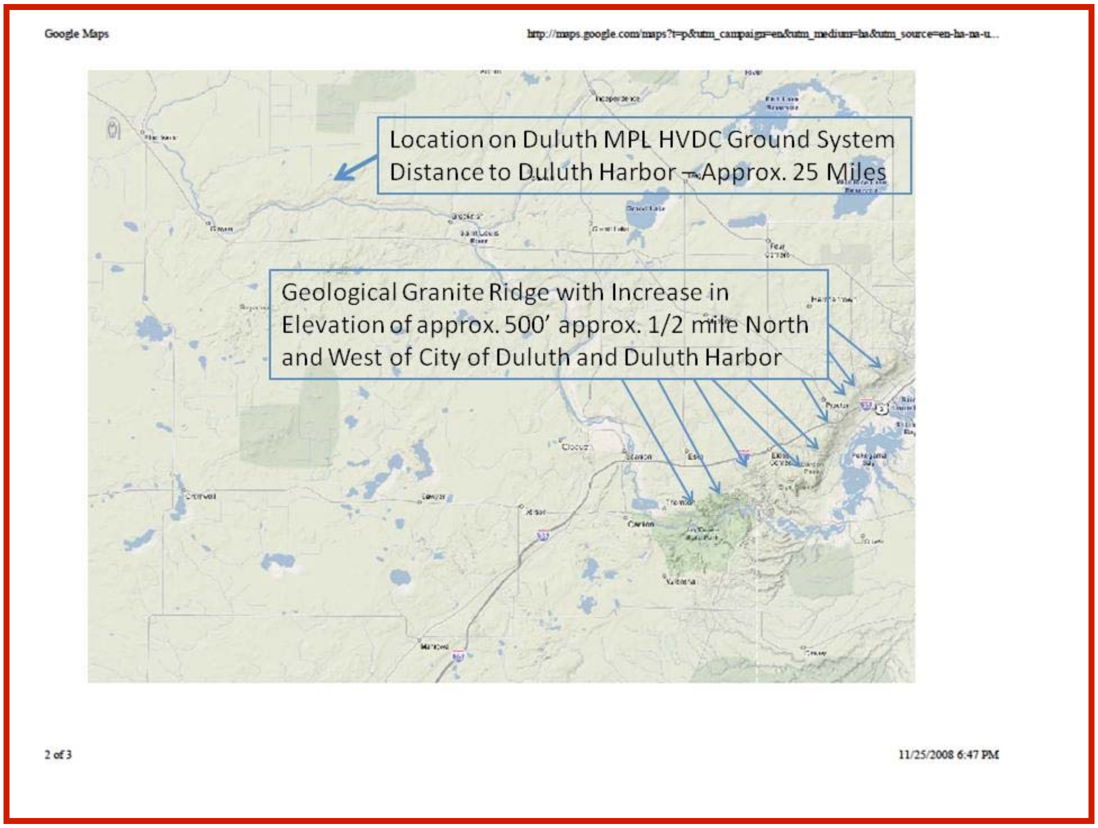
Program Main Control Panel on Computer Screen

Computer Screen with all Three Real Time Charts Displayed

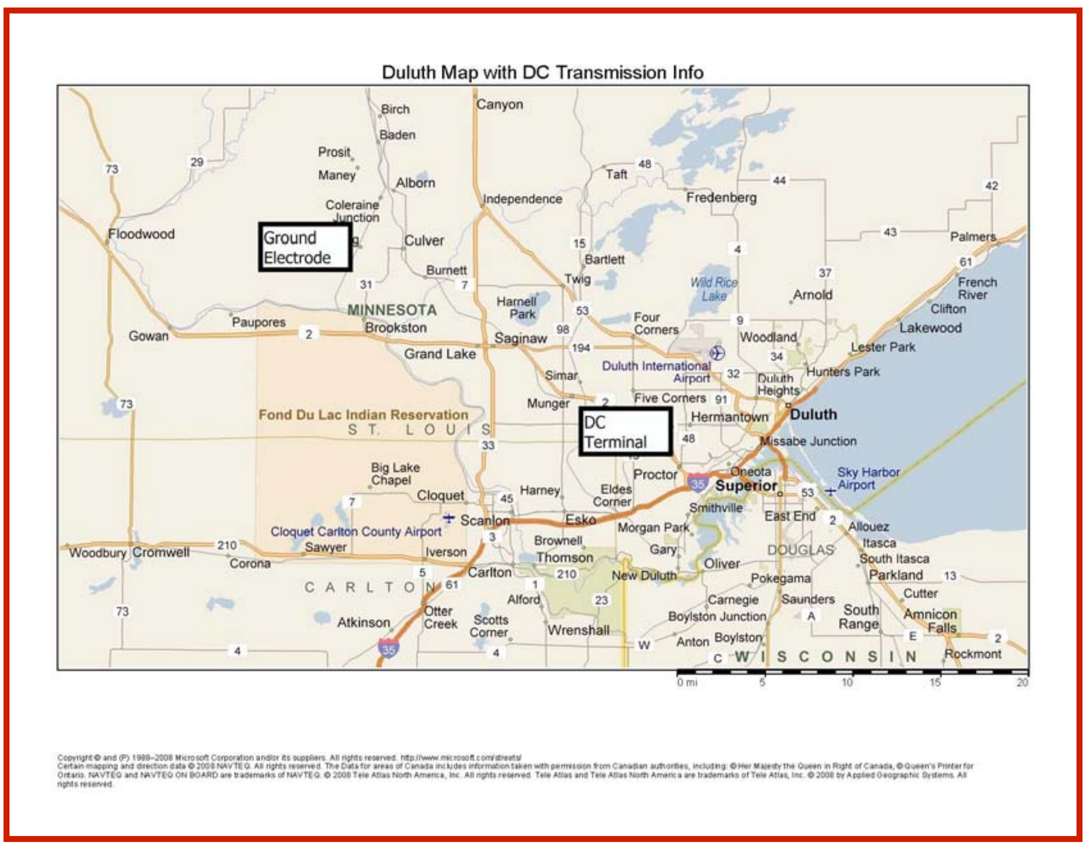


Real Time Tabulated Data

Real Time Graphical Display of Test Data



Geography of Area between Duluth Harbor and the HVDC Ground System



Location of HVDC Ground Electrode and MPL Control Terminal

Appendix “C”

CD with MS Excel Spreadsheet with all Data & Graphical Analysis & All Project Photos