Manitoba Hydro

Integrated Resource Planning Division
Grid Infrastructure Planning (GIP) Department

Bipole III Electric and Magnetic Field Effects Monitoring Project Report
FOR MANITOBA PROVINCIAL GOVERNMENT REVIEW
GIP 2021-07

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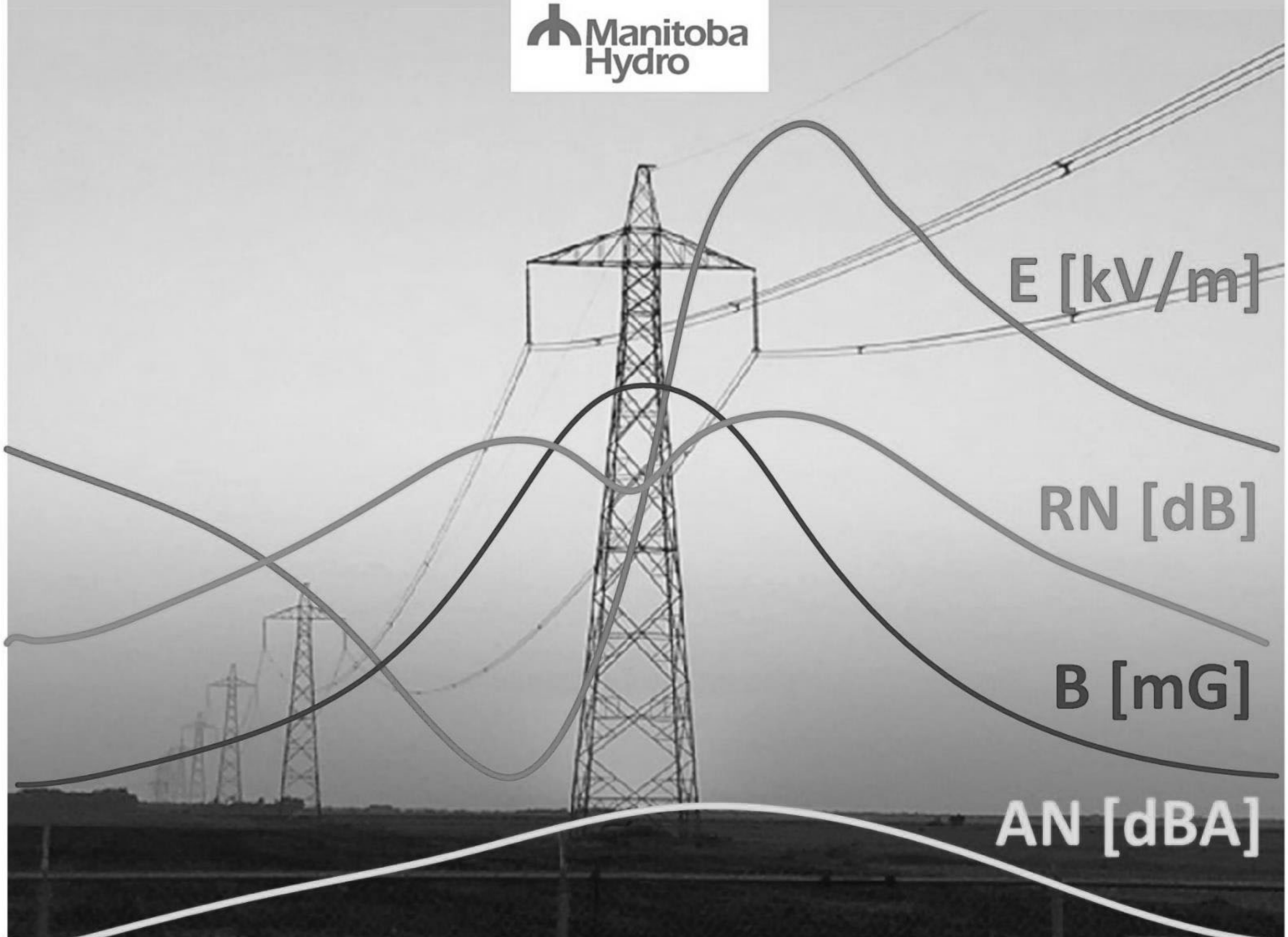
This document has been prepared in good faith on the basis of data collected from the Manitoba Hydro BP3 EMF Monitoring Site that was available at the date of publication without any independent verification. By sealing this report the Engineer and Manitoba Hydro confirm they have taken reasonable care in developing and applying in-house and commercial model(s) for the transmission line EMF study identified in this report.

Any reference in this report to commercial products, processes, or services by trade name, manufacturer or otherwise is for the purpose of detailing the methodology and equipment used to produce the data and analyses herein. The inclusion of any such references does not constitute or imply its endorsement, recommendation or favoring by Manitoba Hydro.

Manitoba Hydro
Bipole III Electric and Magnetic Field (EMF) Electrical Effects Monitoring Project

Report



Dean Reske, P.Eng.
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Integrated Resource Planning Division

For Manitoba Provincial Government Review

September 14, 2021

Summary

Manitoba Hydro's newest High Voltage Direct Current (HVDC) transmission line – the 2000 Megawatt (MW) Bipole III (BP3) running 1,388km south from Keewatinohk converter station near Gillam in northern Manitoba to Riel station just east of Winnipeg, entered into service in July 2018.

BP3 Electric and Magnetic Field (EMF) environmental field effects monitoring is required under the stipulations of the Bipole III Environment Act Licence #3055 issued on August 14, 2013 by the Province of Manitoba due to commitments made in the Environmental Impact Statement (EIS) and supporting documents. EMF effects monitored are comprised of four primary effects: electric fields, magnetic fields, radio noise, and audible noise; plus secondary air chemistry effects and weather parameters that influence EMF effects. The four primary measurements in this report allow for a comparison of EMF levels modelled for the EIS. The monitoring of the secondary effects is for the purpose of investigating air chemistry changes and for improving simulation models, which are largely based on empirical formula ascertained from measured data. The secondary effects of air chemistry reported in sections 5.1-5.5 are for completeness, and the measurements demonstrate that they are within typical levels.

A BP3 EMF monitoring site was installed under the BP3 transmission line southeast of Winnipeg during the completion and commissioning of BP3. The BP3 EMF monitoring site became fully operational in the fall of 2019. Outdoor scientific instruments continuously take measurements, and the data is collected by a computer in a trailer on site.

BP3 EMF field effects data has been collected since the fall of 2019 and is summarized in this report. The measured data demonstrates that BP3 primary field effects are within the simulation results released in a 2011 Exponent Inc. consultant report for the public hearings and in the EIS [1].

Unlike the simulations, the measured data demonstrates variability due to various factors. The dominant factors that affect the measurements are instrumentation and data acquisition variation due to pests, snow cover, ice formation, pooled water, dust, pollen and other random environmental and weather issues. Regular observation of data and their trends made it possible to identify malfunctioning instrumentation on an ongoing basis. This allowed for technicians to clean, calibrate and rectify the instrumentation to maximize the usable data during the available time intervals of desired BP3 operational loading levels.

The 2000MW rated BP3 had most of its operation under 1200MW to date, with short intervals of higher power loading enabling analysis for all power levels, as seen in

Figure 1. Although BP3 has mostly operated at lower power levels, this report focuses on the data analysis at the higher power levels due to overall EMF effects being greater at high power levels and thus presenting the statistical spread of the worst case measurements.

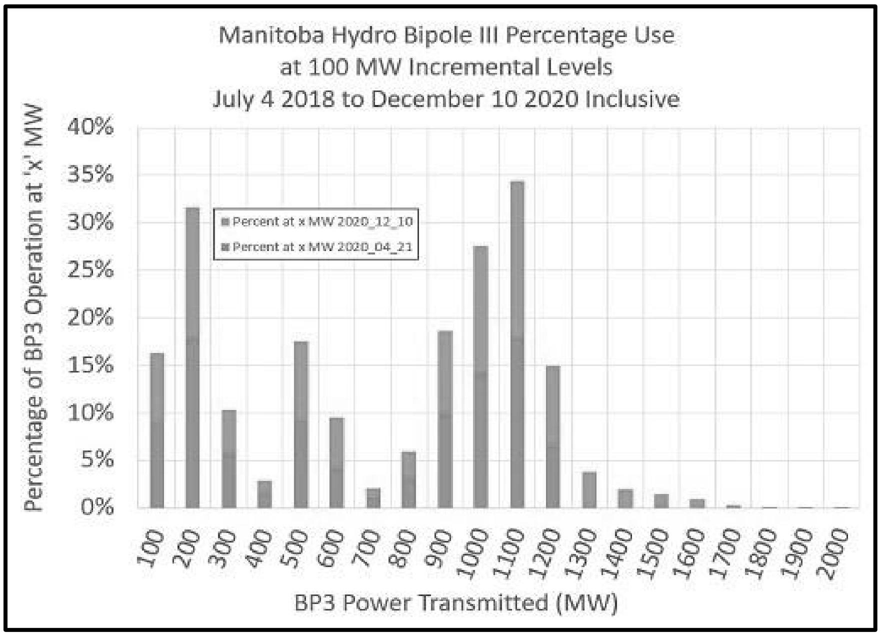

Figure 1: Percentage use of BP3 vs. MW transmission levels.

The 2000MW operation is comprised of 500 kilovolt (kV) Voltage and 2000 Amps (A) of current. Although much of the observed BP3 power loading levels were below 2000 MW, it is worth noting that the operating voltage is consistently at 500kV at all power levels for nearly all operating configurations, with the exception of low voltage operation. EMF parameters are dominantly a function of the voltage level of the transmission line. Therefore, with the exception of the current dependent effect, which is the magnetic field, all other voltage dependent effects such as electric fields, radio noise, and audible noise remain at highest levels for all BP3 loading levels.

To observe magnetic field levels at 2000MW, 2000A of current is necessary for it is the current level that determines magnetic field. Hence, a 2000MW test operation was coordinated, as well as some special 2000A and 2300A metallic return operations to produce 2000A and 2300A current flow at the expense of lower voltages and lower power transmission. This allowed magnetic data to be gathered at the worst case current level, equivalent to the current exhibited at the rated 2000MW operating level that was desired to be studied by this project.

Results exhibited within this report show that the measured results of all EMF quantities are at or below the levels predicted. Successful data collection to total data collected has improved from under 60% at the end of 2019 to 100% by the end of 2020. Manitoba Hydro is scheduled to continue the monitoring and data collection of the BP3 EMF quantities until the end of September 2021.

This report gives an overview of the results to date, demonstrating that the actual EMF effects experienced under the Bipole III HVDC line during its varied operating power levels and environmental conditions are well within the levels predicted by simulation. Therefore, this report satisfies and completes the requirements set about with the BP3 EMF monitoring effort.

Technical results summary

This report examines the results for the four primary EMF field effects obtained from the BP3 EMF site during the period from September 2019 to December 2020. These four primary EMF effects are Electric Field (E-Field or EFD), Magnetic Field (B-Field or BFD), Radio Frequency Interference or Radio Noise (RN), and Audible Noise (AN). The purpose of the measurements are to compare the field measurements to predicted simulated results in [1] and to determine if any mitigation or other action is required. Data analysis concentrated on the periods of highest BP3 loading levels displayed in Figure 1. Seven BP3 operating loading level scenarios are examined in the report: five in bipolar configuration at 1200MW, 1500MW, 1600MW, 1700MW, and 2000MW, and two brief 2-day metallic return configuration tests to obtain B-field measurements at full current rating operation of 2000A and 2300A. Data sampling rates at all power levels are consistent, but the length and amount of data collection time intervals at the different power levels do vary as per the system power delivery needs and other operating restrictions (see Table 2 on page 25). Figures 2-9 in this section summarize all results of EMF profiles.

Electric field results

During the first year of operating the BP3 EMF monitoring site, electric field (EFD) measurements had a moderate percentage of useful data. Electric field levels at 1500MW, 1600MW, and 2000A metallic return had maximum 95-percentile (L95)[1] data values exceeding the fair weather simulations, observed in Figure 2 and Figure 3 on the following pages. This is explainable because the data measurements are for all weather conditions. The EMF measurements shown in Figure 2 are for ‘bipolar’ operation where the conductors (poles) are energized to ±500kV voltage, with the two poles at opposite polarities. The bipolar configuration is the normal operating configuration. The ‘metallic return’ operating configuration is a special, but operable configuration that is used when converters of one pole are taken out of service. This configuration was used to test a high current operating condition. Measurements of this special operating configuration are reported separately on Figure 3.

The maximum 95-percentile EFD levels for 1200MW, 1700MW, and 2000MW BP3 operation are observed to be much lower than predicted in simulation (Figure 2). Much of the 1200MW data was collected in fall of 2019 and winter of 2020 when weather issues greatly affected the instrumentation and data collection. Causes of the discrepancy for the 1700MW data is suspected to be dust, pollen and weather related issues due to the timing of the data concentration for those power levels. The 2000MW data was collected in one day, and the discrepancy may be attributable to

[1] L95 refers to the level at which 95% of the data falls below that level.

the small sample size gathered having levels occurring at the lower end of the population distribution, lacking an adequate sample size to be able to tend to the true statistical EMF parameter level. The excessive magnitude for the 2000A metallic return scenario observed in Figure 3 may also be due to the small data sample distribution (from only two intervals of data collection, one being as short as 1 hour and 16 minutes – see Table 2 on page 25). However all measured levels stay within the predicted levels of electric field.

The maximum 95-percentile measurements at the edge of ROW in Figure 2 show that they are generally much less than the measurements observed within the ROW, as expected.

The 0MW measurements in Figure 2 are for when BP3 is not delivering any power or when BP3 is shut off. Therefore, the measurements at 0MW can be considered as the baseline background EFD level and serves as the reference level for comparing with the levels when BP3 is operating at various power levels.

As described in [1], experimental studies have established high sensory responses associated with high static electric fields. There is no evidence of health effects relevant to the very weak static electric fields associated with HVDC transmission lines. Therefore there is no standard to be met, and measured levels of electric fields are not compared to any standard or guideline. They are only compared to the predicted levels generated by simulation in [1].

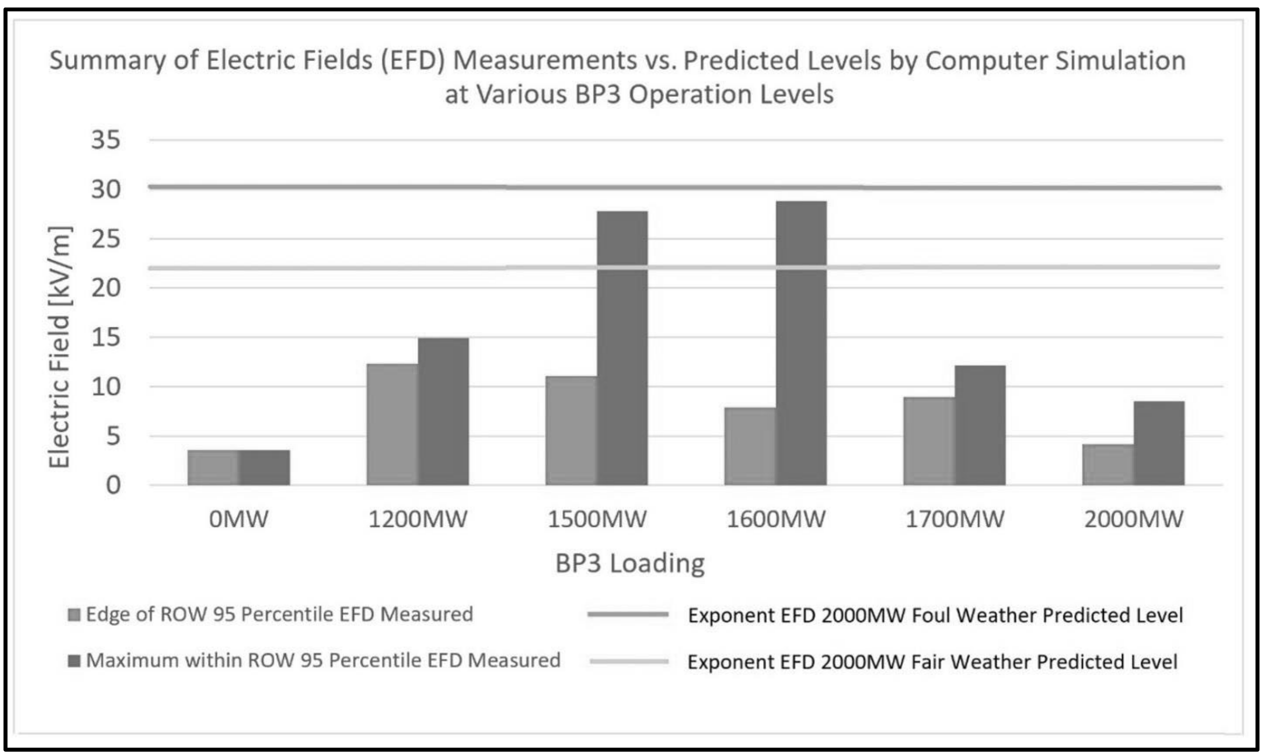

Figure 2: Plot of maximum 95th percentile electric field (EFD) magnitudes vs maximum values in simulation results from Exponent Inc. 2000MW report [1].

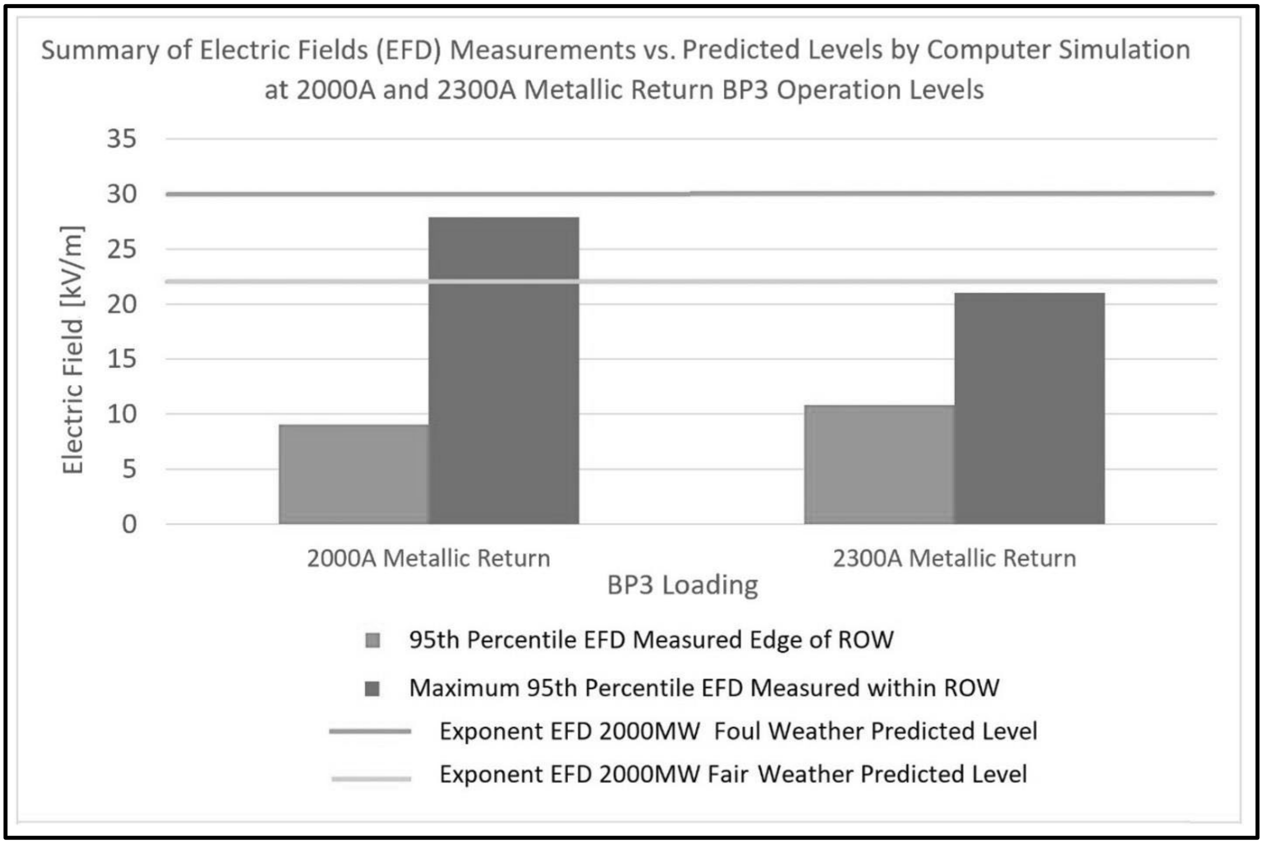

Figure 3: Plot of maximum 95th percentile electric field (EFD) magnitudes vs maximum values in simulation results from Exponent Inc. 2000MW report [1].

Magnetic field results

Magnetic field (BFD) measurements over all BP3 operating levels was much more successful. Field measurements conformed to expectations, as shown in Figure 4. The 2000A and 2300A monopolar metallic return operation, although different to bipolar operation, attempted to replicate the magnetic field simulation results from the Exponent report as the tests put equivalent amounts of current on the physical conductors of BP3 matching Exponent simulations (Figure 5). The average conductor height at the BP3 EMF site are higher at mid-span (18.5) than assumptions made at the time of the Exponent report (14m), which is predominantly responsible for the significantly low measurement of magnetic field magnitudes.

Here again, the maximum 95-percentile measurements at the edge of ROW shown in Figure 4 fall significantly below the measurements observed within the ROW, as expected. The edge of ROW measurements for the short 2000MW operating time were not available due to the ROW edge magnetometers being out of service during that period.

The 0MW measurements in Figure 4 are for when BP3 is not delivering any power or when BP3 is shut off; therefore, the measurements at 0MW can be considered as the baseline background BFD level and serves as the reference level for comparing with the levels when BP3 is operating at various power levels.

As described in [1] there is no evidence of health effects relevant to the very weak static magnetic fields associated with HVDC transmission lines. Therefore, the measured levels of magnetic fields are not compared to any standard or guideline. They are only compared to the predicted levels in [1].

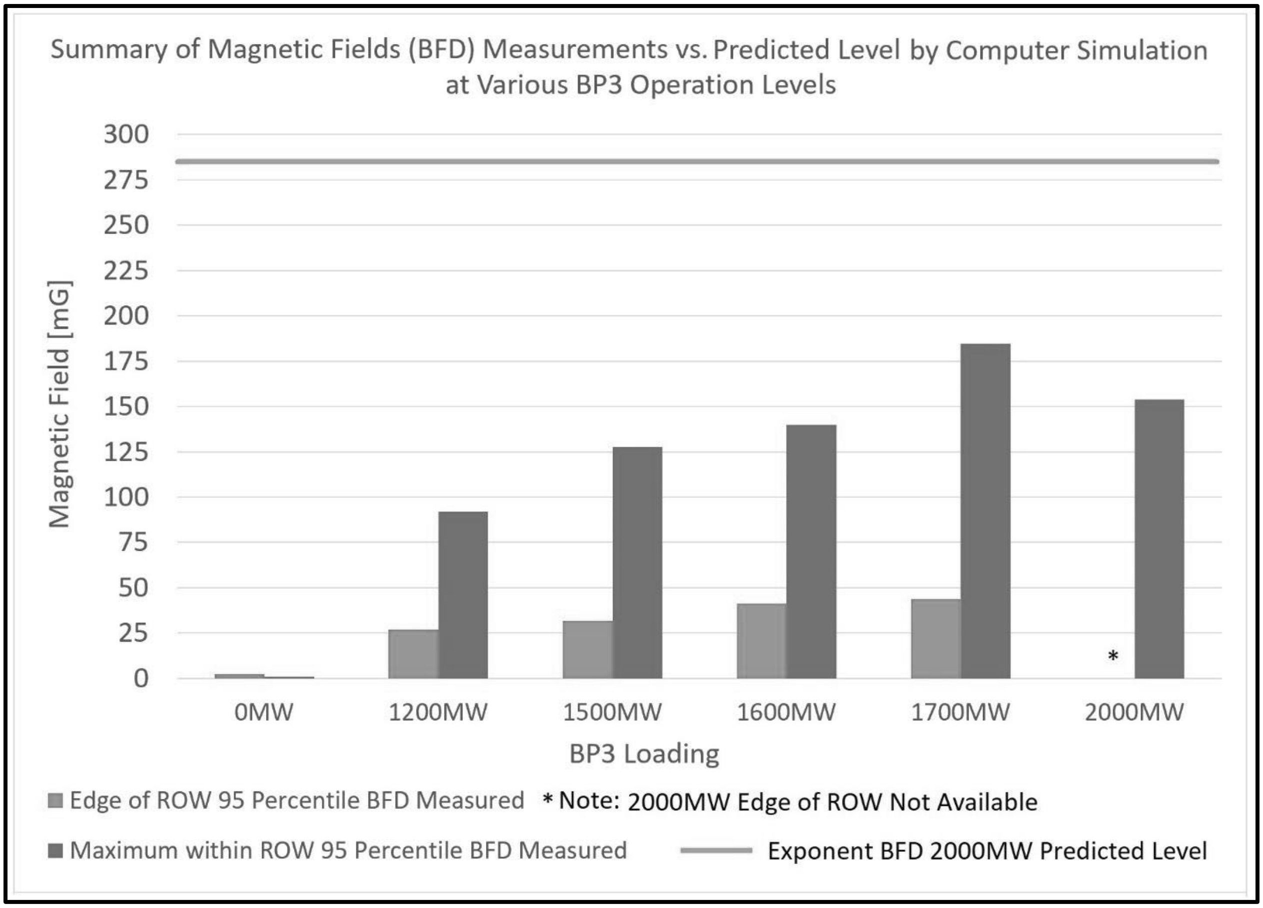

Figure 4: Plot of maximum 95th percentile magnetic field (BFD) magnitudes vs maximum values in simulation results from Exponent Inc. 2000MW report [1].

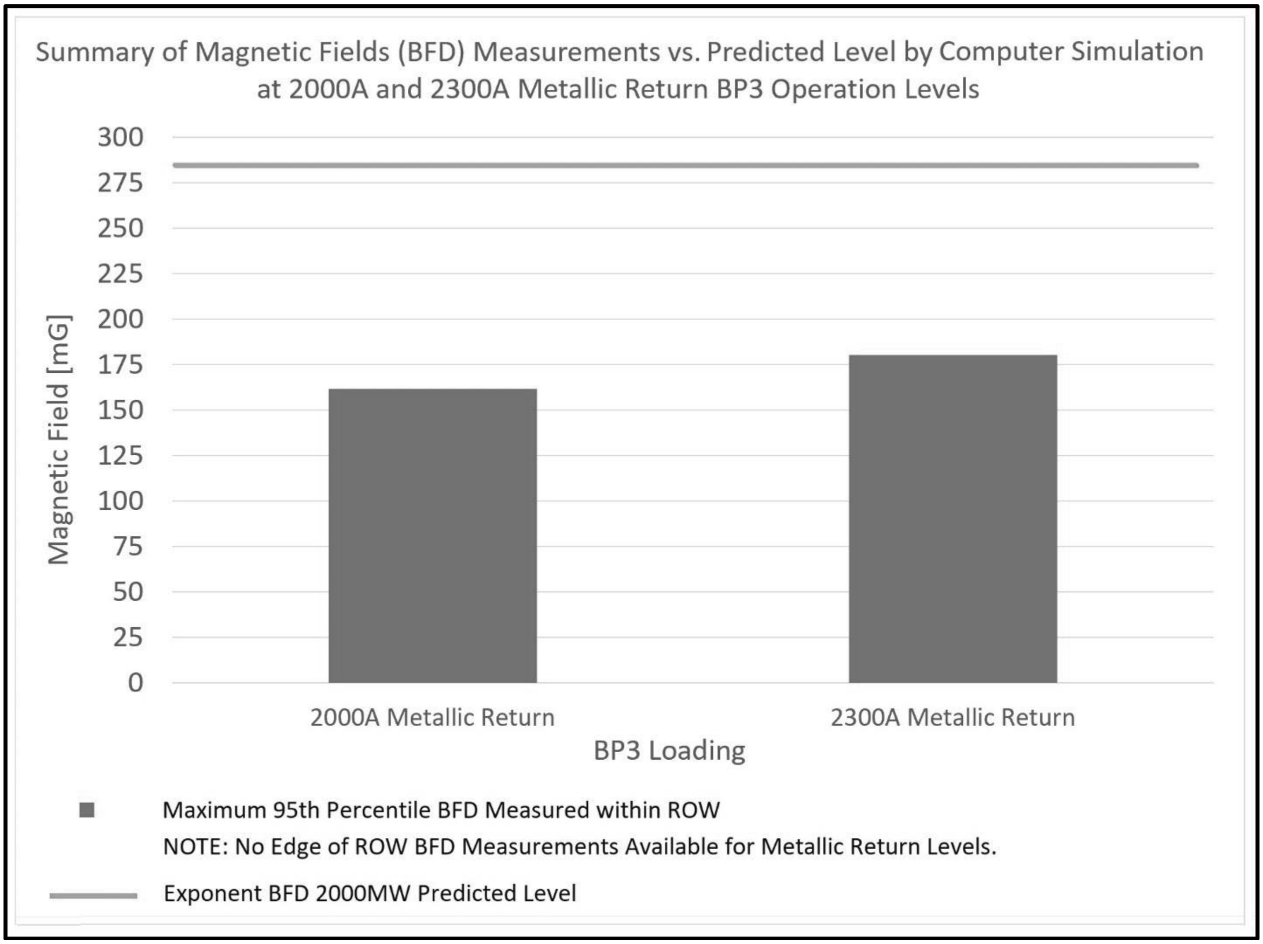

Figure 5: Plot of maximum 95th percentile magnetic field (BFD) magnitudes vs maximum values in simulation results from Exponent Inc. 2000MW report [1].

Radio frequency interference or radio noise results

The median average (L50)[2] value of the radio frequency interference or radio noise (RN) measured at the edge of the BP3 transmission line right of way (ROW) are clearly less than what was predicted in simulations, as shown in Figure 6 and Figure 7 on the following pages. Measurements at all power levels are well below predicted levels. The predicted levels are below the Industry Canada standard for RN for a 500-kV transmission line, which is a 60 dBµV/m at 15 m from the nearest conductor [1].

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[2] L50 refers to the level at which 50% of the data falls below that level.

The 0MW measurements shown in Figure 6, similar to EFD and BFD, are for when BP3 is not delivering any power or when BP3 is shut off. Therefore, measurements at 0MW can be considered as the baseline background RN level and serves as the reference for comparison with the various BP3 operating levels.

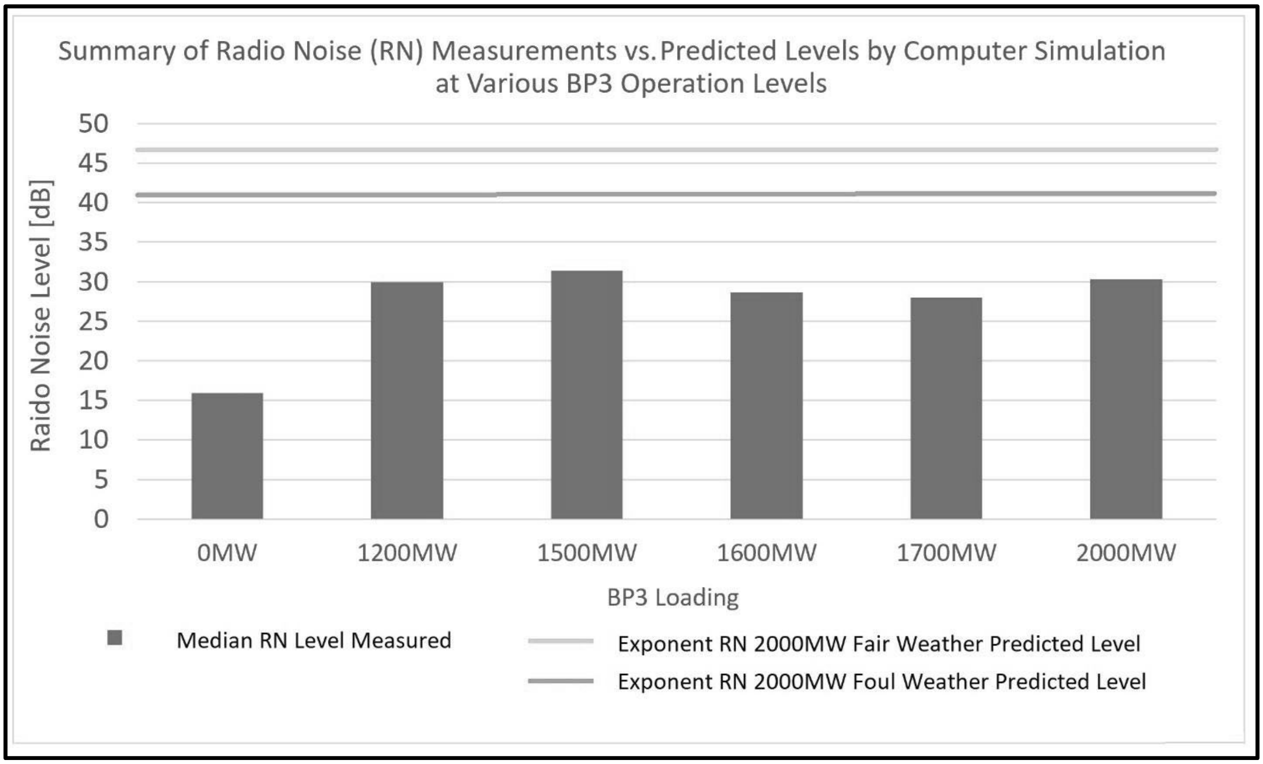

Figure 6: Plot of median radio noise level (RN) magnitudes vs L50 values in simulation results from Exponent Inc. 2000MW report [1].

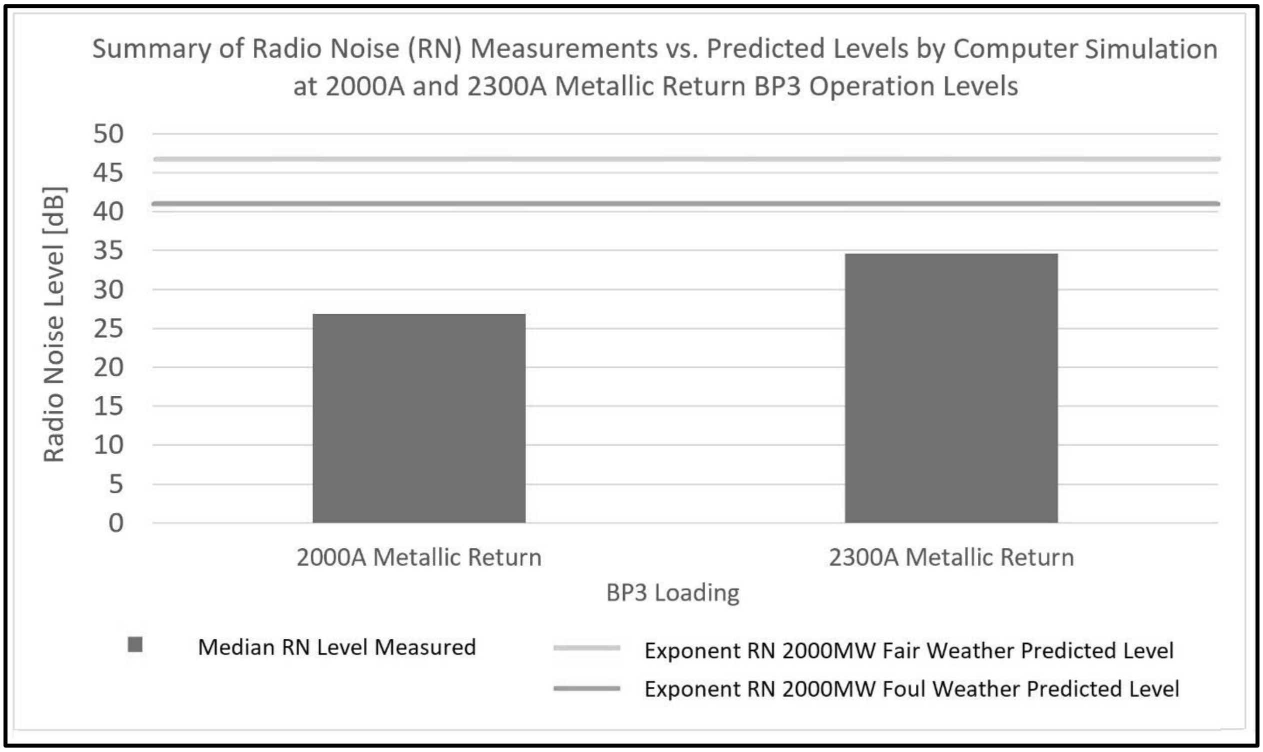

Figure 7: Plot of median radio noise level (RN) magnitudes vs L50 values in simulation results from Exponent Inc. 2000MW report [1].

Audible noise results

The median average (L50) audible noise (AN) levels for the first five BP3 loading scenarios was less than or close to the Exponent results under fair weather conditions, shown in Figure 8 and Figure 9 on the following page. However, the measured data exceeded the foul weather simulation data. This is explained by the data measured being a mix of these two weather conditions. With regards to the 2000A and 2300A metallic return test data for audible noise, the excessive measurement median values may solely be a symptom of a single (4 hour) measurement period. This data sample appears inadequate for the distribution average to tend to the expected audible noise L50 levels obtained by simulation.

Note that the measurements of RN are at the edge of the ROW. All measurements are below the predicted levels. It should be noted that the predicted levels are well below Manitoba's provincial guidelines for residential and commercial areas, where the recommended levels are 55 dBA and 45 dBA, for day-time and night-time periods, respectively [1]. In foul weather, the levels of AN are lower and typically masked by noise from wind and rain.

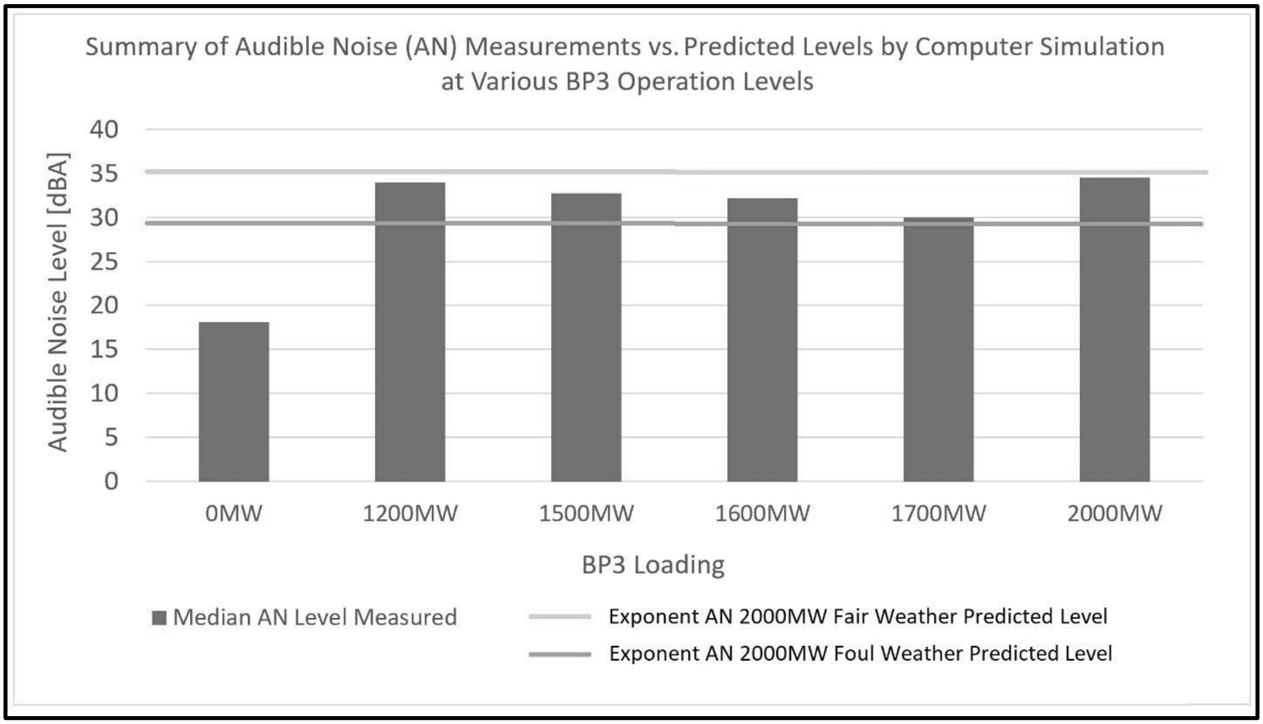

Figure 8: Plot of median audible noise level (RN) magnitudes vs L50 values in simulation results from Exponent Inc. 2000MW report [1].

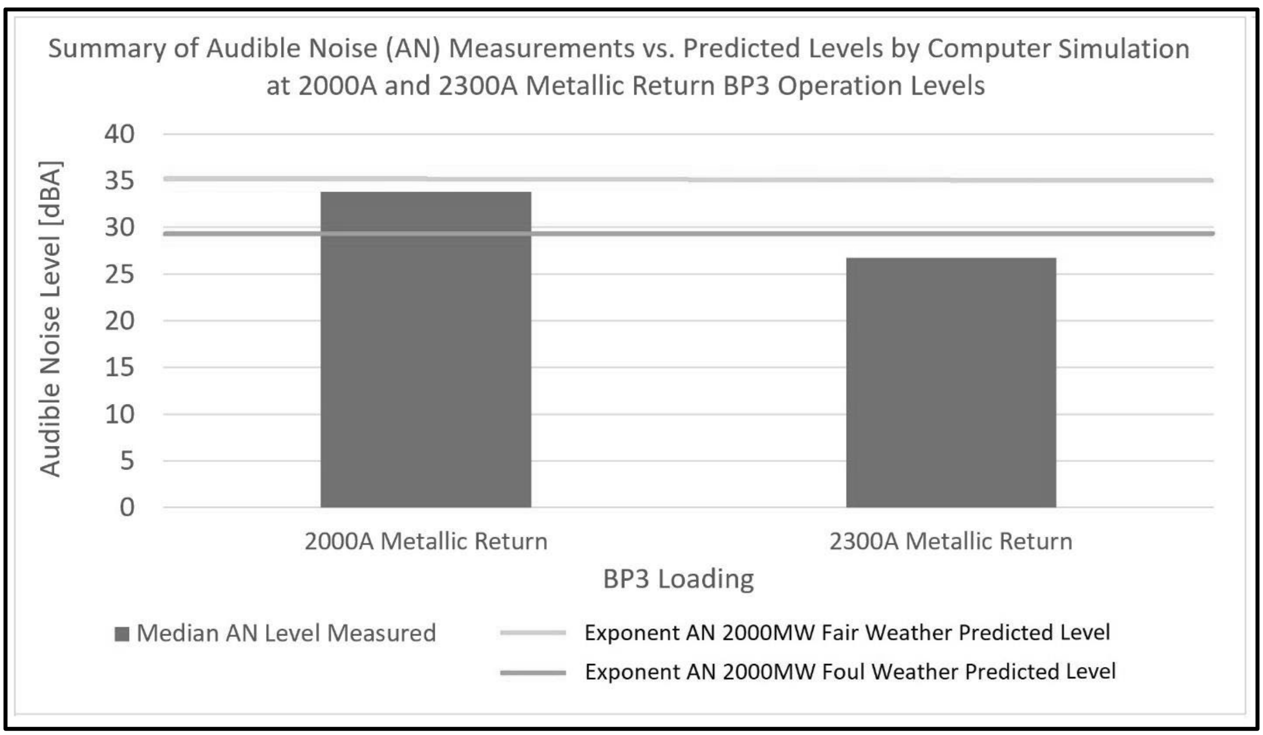

Figure 9: plot of median audible noise level (RN) magnitudes vs L50 values in simulation results from Exponent Inc. 2000MW report [1].

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Nomenclature

Table 1: Nomenclature, or discussion of terms used in this report

Alternating Current (AC)	Current, voltage potential, or fields that change between positive and negative polarity cyclically over time (time varying, or time-variant), typically 60 times per second (60 Hz) in North American AC power systems. Opposite to Direct Current – see Direct Current (DC) below.
Corona	A luminous burst of electricity discharge due to ionization of the air surrounding an electrode caused by a voltage gradient exceeding a certain critical value.
Direct Current (DC)	Current, voltage potential, or fields that are held at a continuous positive or negative polarity value over time (time-invariant). Opposite of Alternating Current – see Alternating Current (AC) above.
DC Electric Field (E-Field or EFD)	The time-invariant vector force on a unit charge, produced by power systems and space charge, described by its space components along three orthogonal axes (i.e.: x, y, z). The magnitudes of the electric field components are expressed in volts per meter (V/m) or kilovolts per meter (kV/m).
DC Magnetic Field (B-Field or BFD)	The time-invariant vector force on electric current and magnetic materials, described by its space components along three orthogonal axes (i.e.: x, y, z). The magnitudes of the magnetic field components are expressed in Gauss (G) or milliGauss (mG).
Electromagnetic Fields (EMF)	All changing electric fields have an associated changing magnetic field, and vice-versa. This coupling of a changing electric field and a changing magnetic field is called an electromagnetic field, or EMF. However, within the context of static electric and static magnetic fields generated by a DC transmission line, EMF is also used to designate the two separate static uncoupled Electric and Magnetic Fields (EMF).

Table 1: Nomenclature, or discussion of terms used in this report, cont.

Radio Frequency Interference or Radio Noise (RN)	Conductor corona discharges generate a broad spectrum of radio interference frequencies through current pulses into/out of the conductor at the discharge point. The sharp, transient current pulse generates a spectrum of EMF waves that propagate and radiate for many kilometers from the conductor, many of these within the radio frequency section of the electromagnetic frequency spectrum. EMF waves that radiate in the radio frequency spectrum can interfere with other signals, and thus are designated radio frequency interference or radio noise. Radio noise is expressed in decibels (dB): the measured voltage signal "X" is expressed as a logarithmic ratio relative to a base value of 1 microvolt per meter = log(X/1μV).
Audible Noise (AN)	Conductor corona discharges create air pressure waves that are audible (can be heard) at frequencies within the audible hearing spectrum (20 Hz – 20,000 Hz). These audible noise levels are measured in decibels, similar to RN as expressed above. However, measured audible pressure waves detected "Y" (in Pascals) are expressed as a logarithmic ratio relative to a base pressure value of 20 micro Pascals =log(Y/20μPa). The resultant values at various specific frequencies (Hz) are weighted according to the weight sensitivity of the human ear, with different weightings at different Hz levels. This weighting according to human hearing is called "A-Weighting" (as opposed to other types of weighting profiles – B, C, D, Z), and the corresponding converted measurements are expressed in logarithmic units of dBA.

1. Introduction

With the announcement of a planned Bipole III (BP3) High Voltage Direct Current (HVDC) transmission line to be constructed from northern Manitoba to Winnipeg, Manitoba Hydro undertook engagement for the project with the public, First Nations, the Manitoba Metis Federation, Northern Affairs communities, and other stakeholders between 2008 and 2013 [2] (Figure 10). Manitoba Hydro filed an Environmental Impact Statement (EIS) summarizing the potential effects of the project and associated mitigation for these effects. Manitoba Hydro was awarded provincial government Environment Act Licence #3055 on August 14, 2013 allowing for the construction of BP3 [3],[4]. Within the terms and conditions of the licence, Manitoba Hydro committed to study and address public concerns regarding any potential impact on the environment, notably (but not limited to) local flora and fauna, and questions raised with regards to electric and magnetic field (EMF) environmental effects. During the public hearings, attempts to alleviate concerns over EMF effects were addressed by presentations and a report by experts at Exponent Inc. Consulting [1]. The report documented the predicted levels of EMF effects for the proposed transmission line, which was deemed acceptable. However, concerns remained if actual EMF levels would fall within predicted levels, and requests for Manitoba Hydro to monitor EMF effects were added to conditions of the licence and EIS, through the accompanying document: "*Bipole III Transmission Project: Socio-Economic Monitoring Plan For Construction*" [5]. This committed Manitoba Hydro to "*compare measurements to the predictions made in the EIS*". Hence, the terms of the licence committed Manitoba Hydro to measure and monitor these EMF effects.

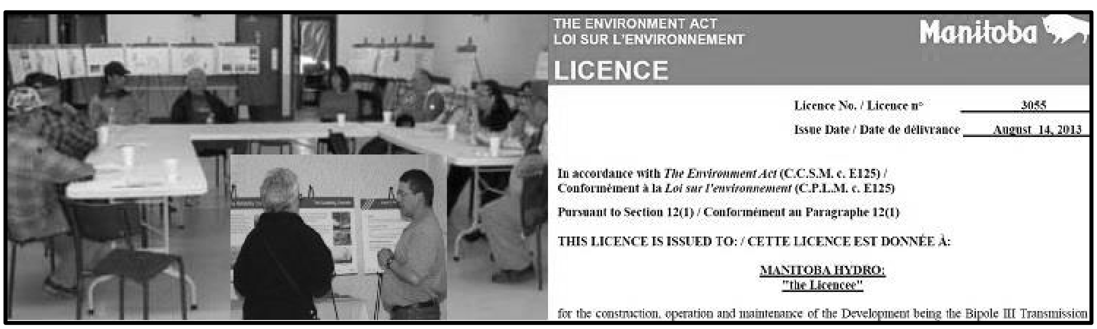


Figure 10: Pictures from community open houses (left), Manitoba Provincial Environment Act Licence 3055 (right).

Manitoba Hydro contracted Manitoba Hydro International to plan, develop, engineer and install the BP3 EMF monitoring site, situated southeast of Winnipeg under a span of the BP3 transmission line running east to west in this location. Three stations were set up at the site; one main station under the line and two remote stations situated 500m away perpendicularly from the line. Scientific instruments were installed at the stations and fiber optic data transmission cables were run from the instruments at the stations back to a trailer at the main station. A computer within the trailer collects the EMF levels measured by the instruments. This data is analyzed for reporting purposes (exhibited in this report), as well as for instrument status checks and maintenance, and for later data mining to study EMF effects in more detail. A full discussion of the site is in Section 3: Bipole 3 EMF monitoring site.

Actual physical monitoring of EMF effects on HVDC transmission lines have been rarely performed in the history of the power utility industry. Reference [6] reports the following four known sites where the monitoring of the actual transmission line was done. It also reports two test lines monitored for data collection.

1. **BPA ± 500 kV HVDC Transmission Line:** Monitoring and data collection of the transmission line operating at ± 500 kV during a period of one full year in 1986.
2. **FURNAS ± 600 kV HVDC Transmission Line:** The measurement program was carried out during four separate one-month periods in 1996 and 1997.
3. **Manitoba Hydro ± 450 kV HVDC Transmission Line:** BP1&2 HVDC system monitoring.
4. **Hydro-Québec – New England ±450 kV HVDC Transmission Line:** Monitoring of the electrical environment commenced at Bath, NH in December 1988 and Hudson, NH in April 1989 on an existing right-of-way and continued after energization of the DC transmission line in July 23, 1990 for another two years ending in November 1992.
5. **IREQ Test Line Study of ± 450 kV HVDC Line Configuration:** Preconstruction studies of the Hydro-Québec – New England ±450 kV HVDC transmission line done in 1986.
6. **HVTRC Test Line Study of ±400 kV HVDC Line Configuration:** Pre-commissioning tests of the bipolar DC line configuration, used on the CPA-UPA HVDC transmission line in Minnesota and North Dakota. Test line monitoring during May 20-Dec 4, 1981.

Manitoba Hydro and its subsidiary Manitoba HVDC Research Center conducted the largest of these efforts on the Nelson River BP1&2 HVDC system from 1982-1995. Manitoba Hydro International, formerly The Manitoba HVDC Research Center, was hired to provide the expert services required for the BP3 EMF monitoring project.

2. Scope

This report reviews the monitoring results for the primary and secondary EMF effects exhibited by the BP3 transmission line at the BP3 monitoring site southeast of Winnipeg. Primary EMF effects are comprised of electric fields, magnetic fields, radio frequency interference (radio noise), and audible noise. The simulation results of these primary effects were released in a 2011 Exponent Inc. consultant report [1] during public hearings and in the EIS.

The purpose of this report is to offer an overall review of BP3 EMF data, comparing measured values to the predicted levels in the Exponent report for all operating configurations and power levels of the HVDC transmission line. Therefore the data has been partitioned by operating power levels and the operating configuration of the transmission line. The data has not been partitioned by the season and the weather condition for the analysis.

3. Bipole 3 EMF monitoring site

A site was selected for the BP3 EMF monitoring project southeast of Winnipeg, shown in Figure 11 below.

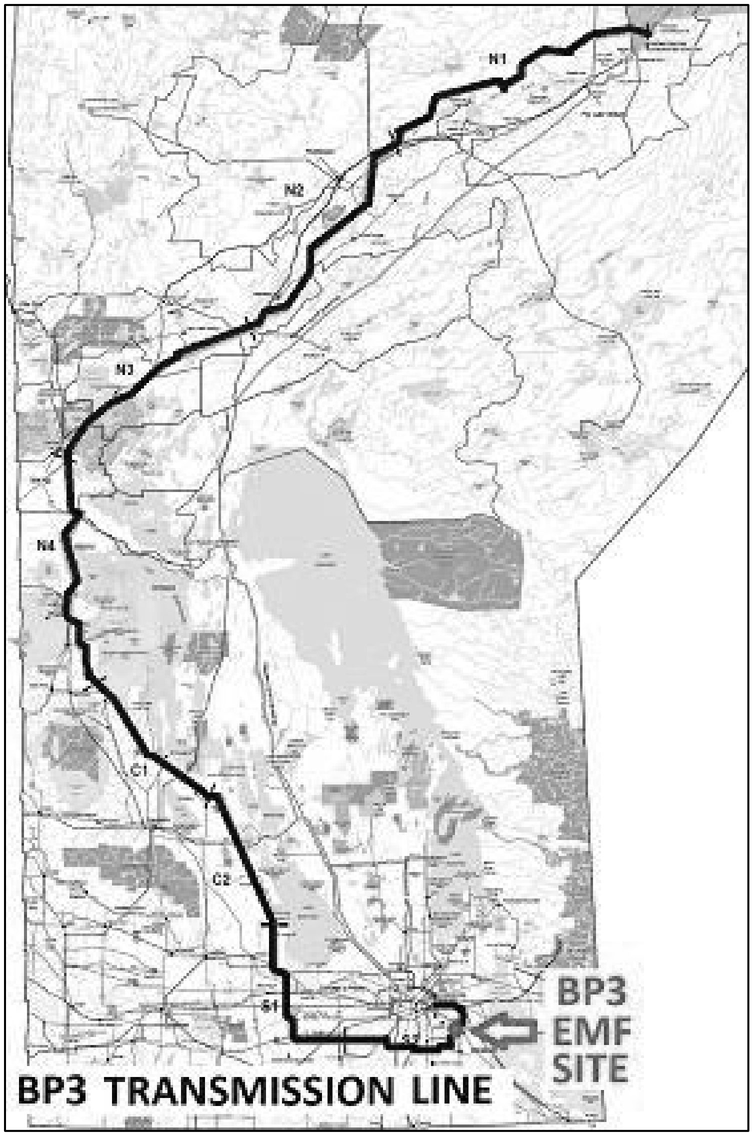


Figure 11: Location of the BP3 EMF monitoring site along BP3 transmission line – province view.

The monitoring site is comprised of a monitoring station under the east to west running transmission line within a span between two towers, centered at the mid-span. Two additional remote stations are setup 500m north and 500m south of the main station. The complex of these three stations is situated in an agricultural field within a section of land, illustrated in Figure 12 on the following page. The monitored section of the line is in the most populated parts of the transmission line route.

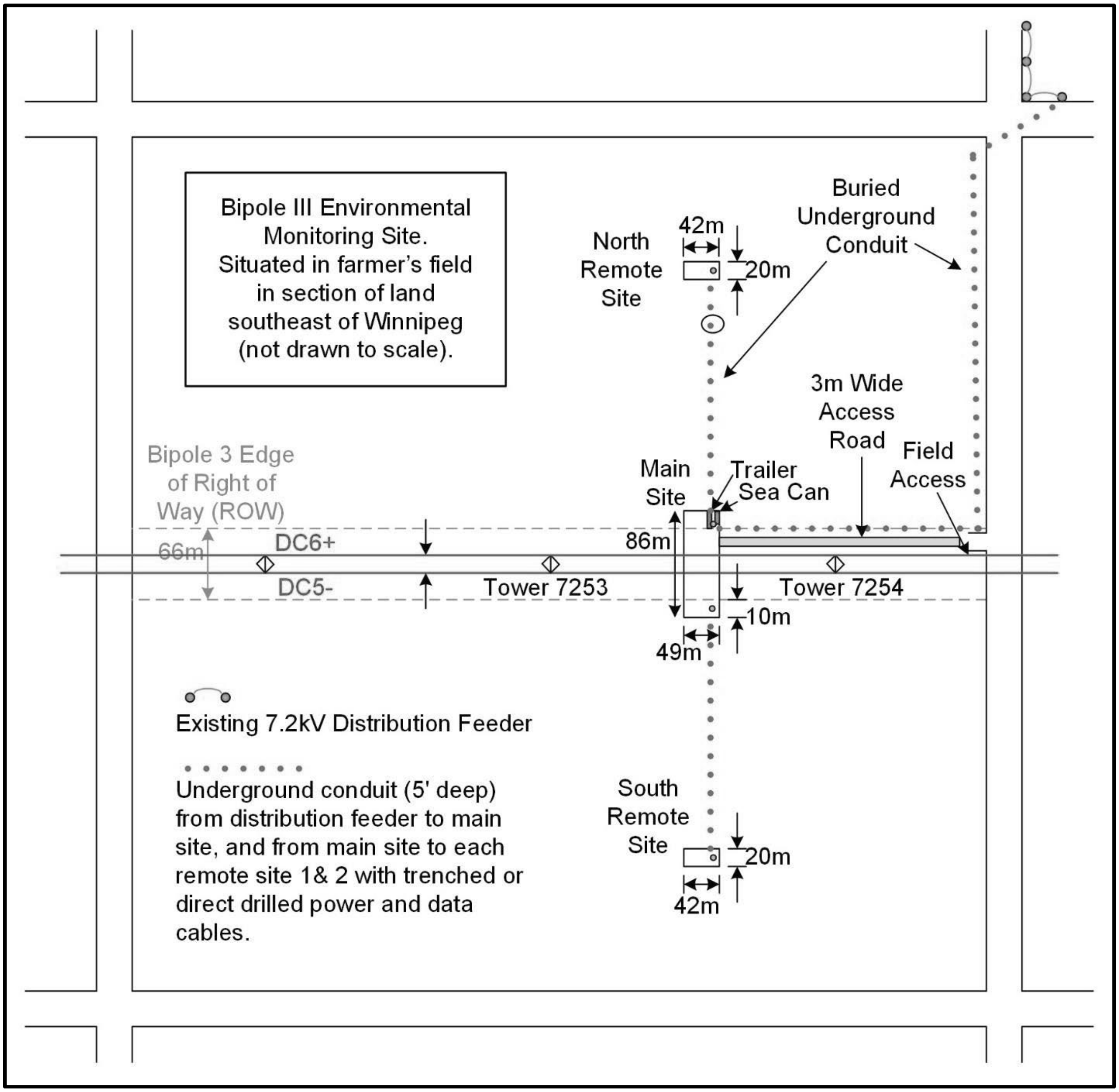


Figure 12: Layout of the BP3 EMF monitoring site.

The main station under the line is a 49m x 86m fenced in area, whereas the two remote stations are unfenced 20m x 42m areas. At the main station, instruments are mounted within gravel mounds and on wood posts or tables to measure the EMF field effects of the transmission line. A trailer is kept with electronics, instrument panels, and a computer to receive the data from the instruments at the three stations. The data is transmitted from the instruments to the trailer via buried fiber optic cables. The entire site is powered via buried power cable from a nearby distribution feeder to a transformer and power supply panels at the main station beside the trailer. Power is distributed to the instruments at the main station and the remote sites via additional buried cable from the main station to the remote stations. A layout of the main station is shown below in Figure 13.

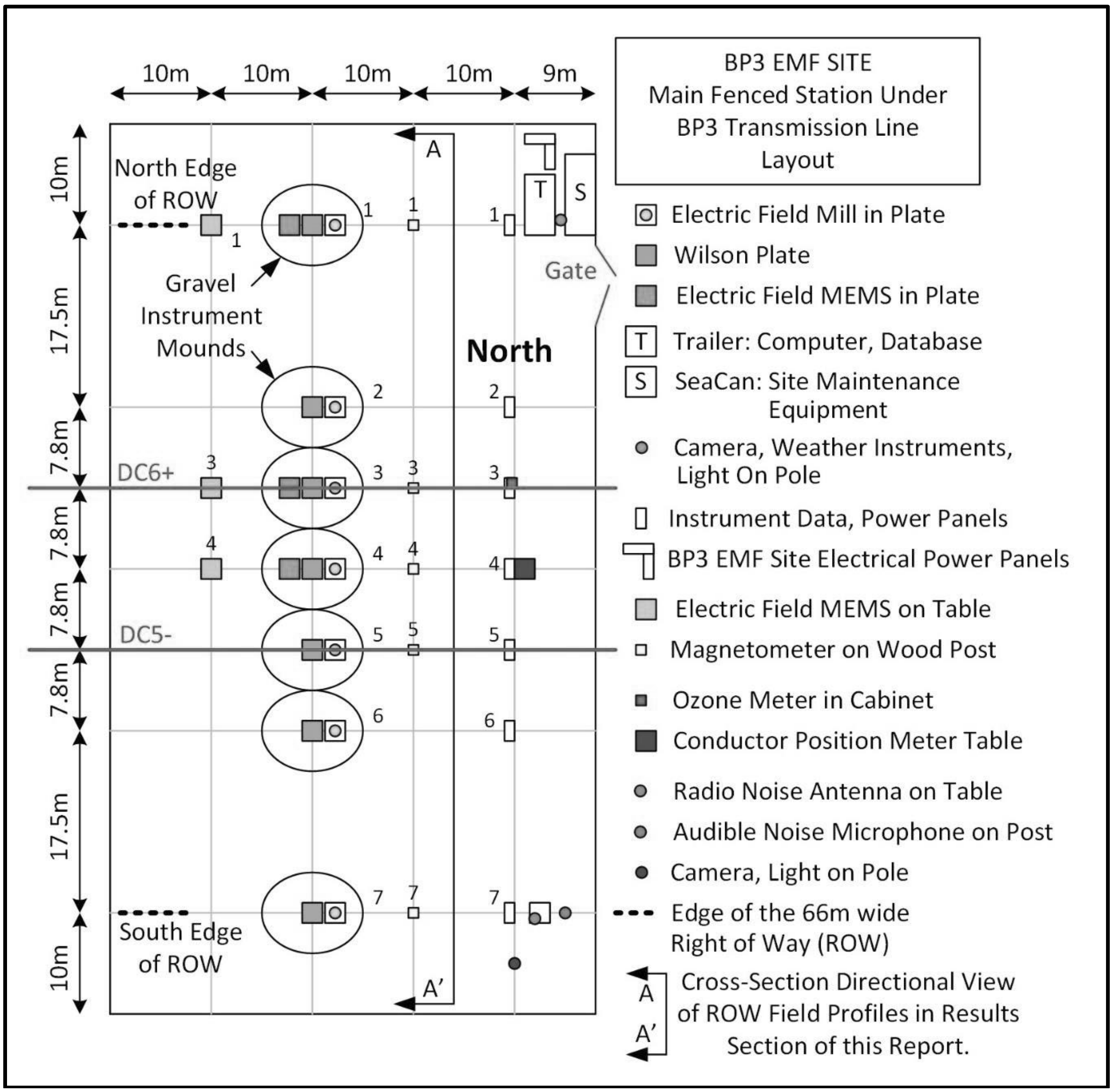


Figure 13: Layout of the main BP3 EMF monitoring station underneath the BP3 transmission line.

Most of the secondary field effects instrumentation relating to air chemistry are located at the two remote stations. Layout diagrams of the north and south remote stations are shown below in Figure 14 and Figure 15.

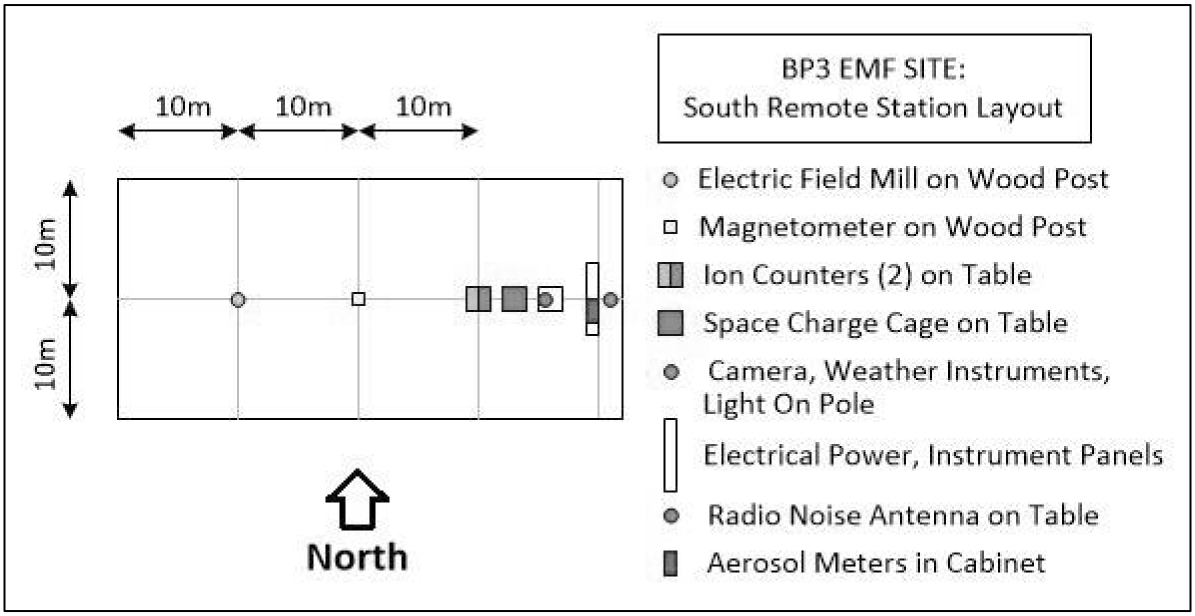


Figure 14: Layout of the south remote station.

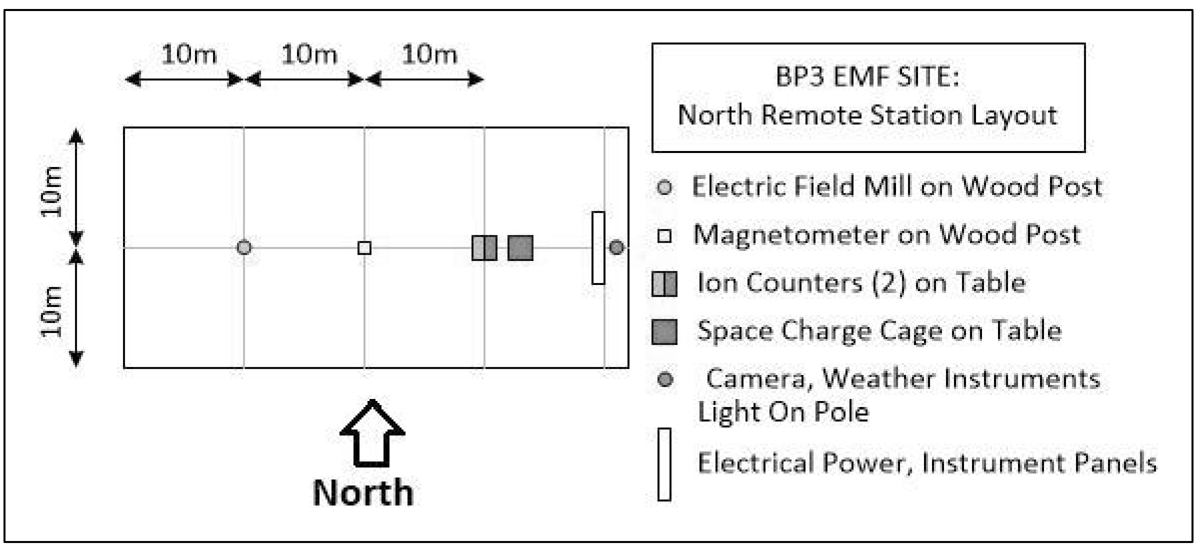


Figure 15: Layout of the north remote station.

4. Equipment and instrumentation[3]

The scientific instrumentation used at the BP3 EMF site had to meet wider, more demanding specifications than most other deployment situations due to the harsh environmental conditions experienced in the middle of an open agricultural field in Manitoba. All instruments had to meet a -40˚C operating temperature specification, apart from aerosol instrumentation that did not, and therefore was housed in a heated cubicle. Instruments were also selected for various other parameters including: cost, durability, imperviousness to outdoor elements, minimal maintenance requirements, various data acquisition requirements and interfacing to the central computer located in the trailer on site, and other constraints.

4.1 Electric field measurement

Stationary Direct Current (DC) electric fields (E-Field, EFD) are measured by a field mill, which uses a principle where a charge will collect on a detection plate due to exposure to a field overhead. The plate will discharge when a moving shutter moves over the plate and shields it from an overhead electric field. The rate of charging and discharging relative to the speed of shielding/unshielding from the overhead field is proportional to the intensity or magnitude of the overhead field.

Seven Boltek EFM-100 field mills are employed at the main station across the right of way (ROW) at mid-span to capture the E-field profile of the BP3 transmission line at mid-span. The Boltek EFM-100 is shown in Figure 16. To keep the electric field uniform and not induce fringing or distortion of the electric field that the instrument is trying to measure (due to the presence of the instrument), the field mill is placed under a metal, electrically grounded plate. The field mill and ground plate are installed into an enclosure mounted within a gravel mound to elevate it 0.5m – 0.75m above ground to protect it from weather, floral, and wildlife elements. The gravel mounds run across the main site ROW at mid-span, indicated on the layout diagram in Figure 13. Main site gravel mound instrument housings, and mounting within ground plate are shown in Figure 17 and Figure 18 on the next page.

Figure 16: Boltek EFM-100 Atmospheric Electric Field Monitor.

[3] Any reference in this report to commercial products, processes, or services by trade name, manufacturer or otherwise is for the purpose of detailing the methodology and equipment used to produce the data and analyses herein. The inclusion of any such references does not constitute or imply its endorsement, recommendation or favouring by Manitoba Hydro.

Figure 17: Main station instruments installed within enclosures in gravel mounds across the right-of-way (ROW) at mid-span.

Figure 18: EFM-100 installed in center opening in ground plane metal plate over enclosure in gravel mound (in foreground).

4.2 Magnetic field measurement

Various methods can be employed to measure DC magnetic fields (B-fields, BFD). Rotating coil magnetometers, solid state methods such as Hall-Effect sensors, and even quantum methods exist. However, a fluxgate magnetometer was selected for its availability, low power consumption, sensitivity, and familiarity as it was employed on previous monitoring work. The fluxgate principle works by two opposite windings carrying AC signals on a ring core (made up of two separate half cores) inducing and removing magnetic field saturation in the 1/2-cores at the same time. When an external field is present, the timing of each half coming out of saturation is proportional to the magnitude and direction of the external B-field. A voltage is induced into a sense winding around the core apparatus that indicates the strength of the magnetic field in the axis this core is placed in. Three of these fluxgate wound cores placed in an X-Y-Z Cartesian coordinate configuration can thus measure the 3-D field magnitude and direction in space.

Various fluxgate meters were surveyed for the project. Five Bartington Mag-03 fluxgate magnetometers were selected based on numerous criteria (most importantly the -40˚C temperature criteria) and were installed across the main site ROW similar to the electric field mills. The Mag-03 sensors are mounted on posts with no metal screws or any magnetic susceptible hardware. The sensor and its mounting are shown in Figure 19 and Figure 20 on the following page.

Figure 19: Bartington Mag-03 Fluxgate Magnetometer.

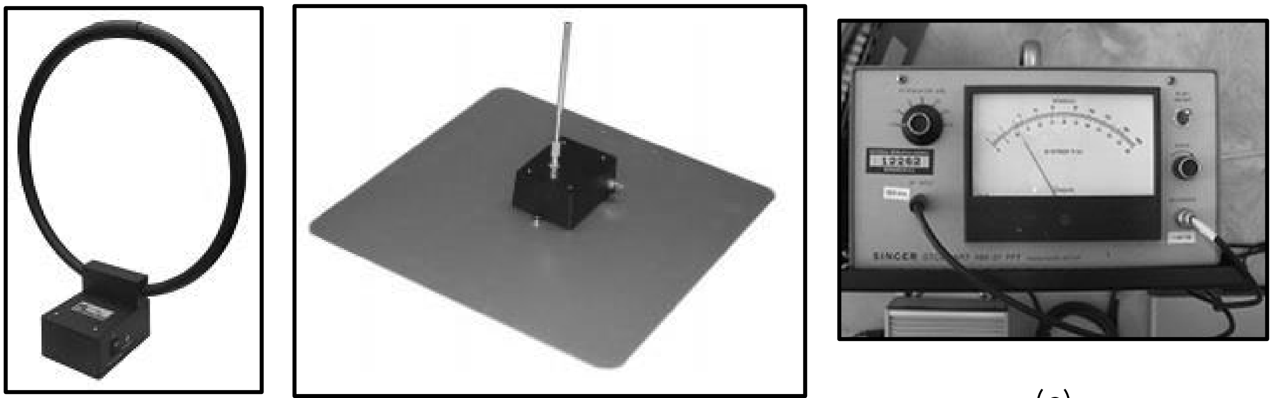
(a) (b) (c)

Figure 20: (a) Magnetometer mounted on wood post; (b) Magnetometers placed across ROW; (c) Close-Up of Bartington Mag-03.

4.3 Radio frequency interference / radio noise measurement

There are two Radio Noise (RN) antennas installed at the BP3 EMF site: one on the south edge of the ROW at the main station, and one at the south remote site as a reference. A rod antenna is installed at the remote station; and a loop antenna is used at the main station under the transmission lines to avoid induction of corona, as would be the case with a pointy rod antenna. This also allows for a variety of measurement methods of EMF radio noise, as the loop antenna couples to the magnetic field component of the electromagnetic noise signal, and the rod antenna couples to the electric field component. An A.H. Systems SAS-563B was selected for the loop antenna, and an SAS-551 for the rod antenna (Figure 21).

Although devices exist on the market for noise metering, older analogue Singer-Stoddart NM-25 and NM-21FFT noise meters were used due to availability within Manitoba Hydro, and hard-wired tuning to 834kHz with a 4kHz bandwidth preventing frequency drift. 834 kHz is a standard test frequency for RN measurement within the radio bandwidth absent from broadcast.



(a) (b) (c)

Figure 21: A.H. Systems radio noise antennas used at the BP3 EMF site. (a) SAS-563B Loop Antenna; (b) SAS-551 Rod Antenna. (c) Singer-Stoddart NM-21FFT Noise Meter.

4.4 Audible noise measurement

Measurement of audible noise (AN) in the workplace, airports, highways, etc. is standardized to meet criteria as set out in ISO 5130, IEC 61672, and various other standards for measurement in environmental noise assessment, occupational health and safety assessment, product noise, and various other applications.

The Brüel and Kjær 4952 microphone and 2250-L meter were selected for AN measurement installation at the south edge of the main site ROW (Figure 22 below). The microphone meets the -40˚C outdoor temperature specification, the meter complies with standardized noise filtering, and both were also selected for their reliability demonstrated by earlier iterations of these instruments within past Manitoba Hydro / MHI projects.

(a) (b)

Figure 22: (a) Brüel and Kjær 2250-L Noise Meter; (b) Brüel and Kjær 4952 Microphone.

Figure 23: Noise meter microphone (foreground) and radio noise loop antenna (background on far corner of table) on south edge of row at southeast corner of main station.

4.5 Secondary EMF environmental effects measurements

The remaining secondary EMF effects measurements involve the measurement of electrical air chemistry, encompassing total space charge, ion density, ion current density flowing to ground from the air, aerosol counts and aerosol charge, and ozone.

The large voltages on the BP3 HVDC conductors (in the hundreds of kilovolts [kV]: mainly ±500kV, sometimes reduced to ±250kV) produce large voltage gradients, or a large voltage per unit surface area on the conductors. This stresses the electrical insulation of the air around the conductor and breaks down the insulating properties of the nearby air, producing corona, or continuous electrical discharge of the conductor into the surrounding air. This corona discharge causes air chemistry reactions in the air around the conductor, producing charged particles and charged molecules (ions), ozone, and other elements. This project also measured the main elements of charged particles in the environment around the operating BP3 HVDC transmission line to assess the magnitude of air chemistry change due to the BP3 line. This involved five (5) measurements listed in the introduction of this section:

- Total space charge, comprised of its main components (separated out):
    - Ions
    - Charged aerosols
- Ion current density to ground
- Ozone (O_3)

4.5.1 Total space charge

Corona discharge of positive and negative charges off the conductor produce numerous charged elements in the air. Charges combine with various air molecules to produce charged molecules called ions. In addition to this activity, ions and the elemental positive and negative charges combine with air particles (moisture droplets, dust particles, pollens) to produce charged aerosols. In the outdoor environment around the HVDC transmission line, wind blowing across vegetation can also result in natural triboelectric generation of charged particles. Ions and charged aerosols together make up the total space charge produced in the air, both by natural effects and from corona on the BP3 HVDC transmission line.

Total space charge at the BP3 EMF site is measured by a space charge cage (Figure 24). The device essentially works by an electrical probe positioned at the center of the 1m^3 cage measuring voltage potential differences due to changes in charged air flowing through the cage. This device is custom built and not typically commercially available. Two space charge cages were built for the BP3 EMF project according to a standard developed for measuring electrical effects of HVDC transmission lines – IEEE Standard 1227-1990 (R2010): IEEE Standard for the Measurement of the DC Electric Field Strength and Ion Related Quantities [7].

Figure 24: Space charge cage mounted on table at north remote station.

4.5.2 Ion density/concentration

The ions component of the total space charge is measured using a Gerdian tube. This device uses a radially directed, inward electric field within the tube to force ions in airflow through the tube to bend towards a detector at the center of the tube. The total electrical current measured off the detector is proportional to the density or concentration of ions flowing in the air through the Gerdian tube per time monitored.

Four ion density instruments were constructed/modified for the BP3 EMF project according to IEEE Standard 1227-1990 (R2010). Two of them were installed at each of the remote sites (Figure 25). The two devices situated at the remote site upwind of the site complex are used to measure the natural ion levels carried by wind, which serves as the reference measurement. The two devices downwind measures the total natural and BP3 HVDC line generated ion levels. The total levels are subtracted from the reference levels to give a measure of the ion density due to the HVDC line.

Figure 25: Ion counters mounted on table at north remote station.

4.5.3 Aerosols – counts, charge

Charged aerosols, the second component of space charge, are measured at the south remote station. Charged aerosols are measured according to two parameters – particle counts and net charge. Particle counts are achieved with a condensation particle counter that condenses water or alcohol vapor onto aerosol particles, growing them larger for an optical detector to distinguish and count them. An aerosol electrometer measures charge by running a flow of air with aerosols through an electrically isolated filter and measuring current flow from the filter to ground.

Commercial laboratory TSI instruments are employed for measuring aerosol counts and net charge: The Aerosol Condensation Particle Counter (CPC) 3776 and Aerosol Electrometer 3068B respectively (Figure 26).

(a) (b)

Figure 26: (a) Aerosol Electrometer 3068B; (b) Aerosol CPC 3776.

4.5.4 Ion current density to ground

Another secondary air chemistry effect measured is the magnitude of the electrical flow to ground of the ions generated in the air, or ion current density to ground. After being generated by corona on the transmission line, ions will travel on the electric field to neutralize at ground. 1m^2 metal plates (called Wilson plates) electrically isolated from ground are mounted at ground level across the right of way (ROW) to sample this electrical effect (Figure 27). These Wilson plates are assembled with electronics allowing for the charge collected on the 1m^2 plate to be measured as it drains off the plate to ground, allowing for an assessment of the ion current density to ground under the transmission line.

Figure 27: Wilson plate secured in gravel mound.

4.5.5 Ozone

Electrical discharges cause oxygen (O_2) molecules to combine in a reaction producing ozone (O_3) molecules. Outdoors, ozone can be produced by natural effects such as lightning and static electricity, as well as from corona on a HVDC transmission line. Production of ozone is measured under the positive DC pole of BP3 within the right-of-way (ROW) seen in the main site layout (Figure 13). A 2B

Technologies Model 205 Ozone Monitor is used to measure ozone levels (Figure 28). This device has the ability to detect ozone down to parts per billion (ppb) levels.

Figure 28: 2B Technologies Model 205 Ozone Monitor.

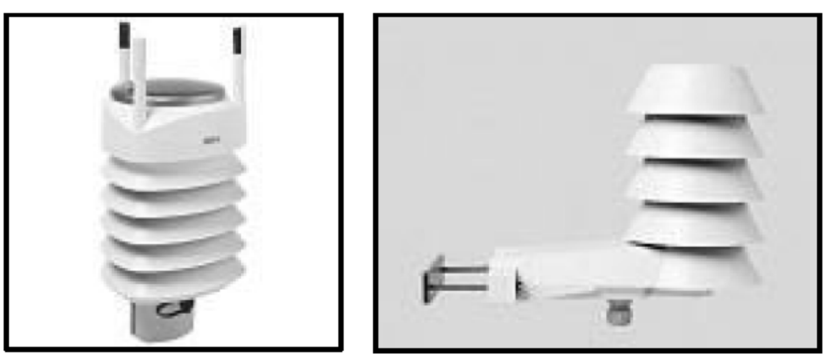
4.6 Weather parameter measurements

All instrumentation has acceptable weather ranges for data validity. In addition to this, weather parameters explain variation in data, and specifically for grouped measurements such as fair and foul weather, and seasonal variation.

Weather parameters collected are:

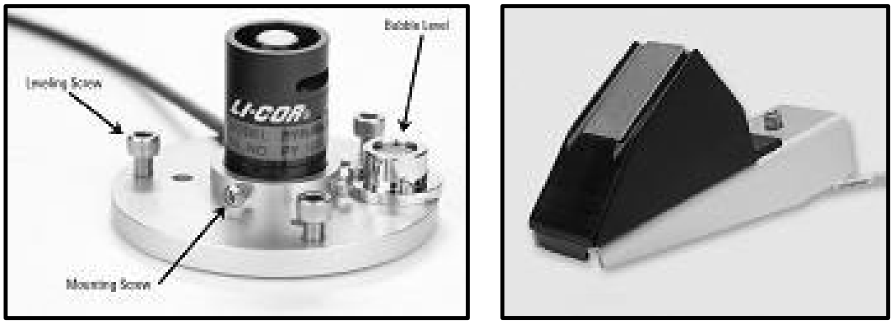
- Atmospheric temperature
- Atmospheric pressure
- Wind speed
- Wind direction
- Precipitation
- Relative humidity
- Solar irradiance
- Dew point
- Wet/dry conditions

The first six of these weather parameters (in blue) are collected by a Vaisala WXT-536 solid state weather station, along with an earlier model, WXT-520. Dew point is measured by a Vaisala HMDW110 meter. Solar irradiance is collected by a Campbell Scientific LI200S-L meter. Finally, wet or dry conditions are assessed by a Vaisala DRD11A wet-dry sensor. These instruments are shown in Figure 29 and Figure 30.



(a) (b)

Figure 29: (a) Vaisala WXT-536 Weather Station; (b) Vaisala HMDW110 Dew Point.



(a) (b)

Figure 30: (a) Campbell Sci LI200S-L Solar Meter; (b) Vaisala DRD11A Wet-Dry Sensor.

The weather instruments are mounted atop a 24' high pole. All instruments are on the pole at the north edge of the right of way of the main station (Figure 31 below). The poles at the north and south remote sites only contain the Vaisala WXT-536 or WXT-520 weather stations measuring the first six parameters.

(a) (b)

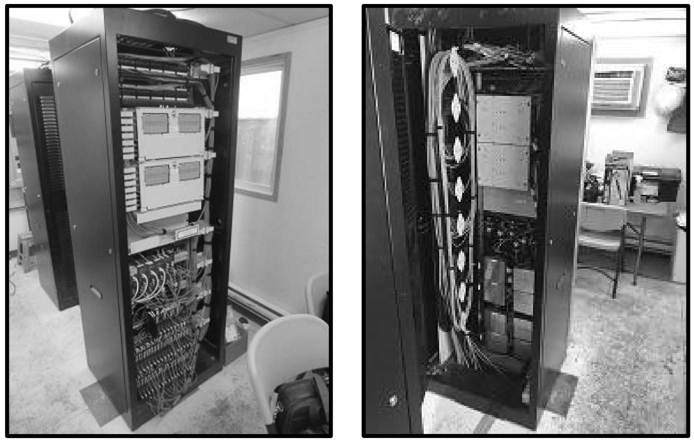
Figure 31: (a) Main pole between trailer and sea-can storage unit north-east corner of main station; (b) Detail of weather instruments, light, camera, and Wi-Max Data Communications Antenna at top of pole.

4.7 Data transmission electronics, computer data acquisition system

To prevent any EMF of the transmission line inadvertently corrupting or shifting analogue signals encoding the instrumentation data levels, analogue signals are converted at the source to optical signals for transmission through fiber optic cable. These fiber optic cables are run from the instruments back to the trailer at the main station via buried conduit, into a rack-mount cubicle cabinet (#1) shown in Figure 32.

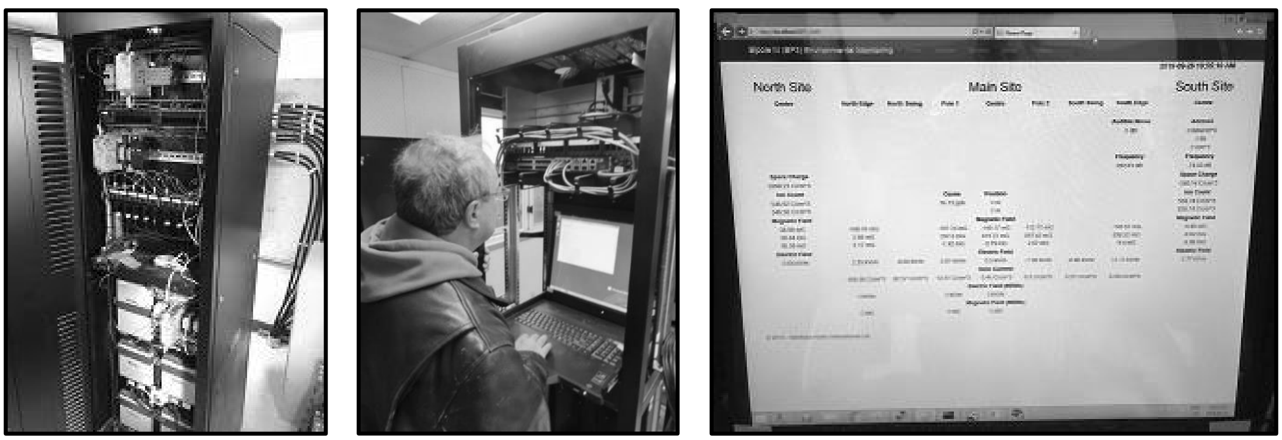
Fiber cables run to a patch panel, and then into transducers which convert data back to analogue signals for transmission to rack-mount cubicle (#2) housing five National Instrument digital analogue converters (NI-DAQ) for data acquisition into the computer, seen in Figure 33.

Data collection is fully automated and is collected continuously. The data collection computer for the project is an Advantech ECU-4784 running Windows Server 2012. A specially written BP3 EMF data acquisition program written by Manitoba Hydro International collects the data from the NI DAQs and writes it to a Microsoft 2012 SQL Server Database also running on the computer. The BP3 EMF data acquisition program displays the current timestep data on the screen for staff at site requiring real-time inspection of data values (Figure 33).



(a) (b)

Figure 32: (a) Front of cubicle #1 in trailer showing fiber optic patch panel, and connections to fiber / analog transducers; (b) Back of cubicle #1 showing fiber cable coming up into trailer from ground conduits to instruments in field.



(a) (b) (c)

Figure 33: (a) Back of cubicle #2 showing NI DAQs acquiring data from analog cables from cubicle #1; (b) Front of cubicle #2 where computer and networking equipment located; (c) MHI BP3 EMF data acquisition program.

4.8 Site pictures

(a) (b)

Figure 34: (a) Instrument gravel mound across ROW; (b) Main station trailer.

(a) (b)

Figure 35: (a) Space charge cage and (b) Ion counters at north remote station.

Figure 36: Installation of electronics for E-Field Mill.

5. Results

A sample distribution for each instrument's data in the ROW at the main station was created from all the data measurements made over the 11 x 1.5 hour intervals (in the case of the 1700MW BP3 loading) to the 35 x 1.5 hour intervals (in the case of the 1500MW BP3 loading). Sampling rates are consistent over all loading levels. See Table 2 on page 25 for all loading level measurement statistics. From these distributions, the maximum, 95th percentile (L95), median (L50), 5th percentile (L5), and minimum values are found for each instrument, described below in the form of a box plot (illustrated in Figure 37) for the respective EMF parameter.

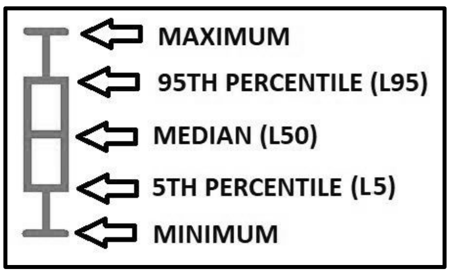


Figure 37: Description of instrument data measurement distribution for each EMF parameter in the form of a boxplot.

A data profile across the midspan ROW was generated for each BP3 loading level and EMF parameter from the perspective of looking west in viewing the EMF field profile at mid-span under the transmission lines of the main station, as illustrated in Figure 38 on page 24. Then the largest 95th percentile (in the case of EFD and BFD) or the largest median L50 value (in the case of RN and AN) was plotted against the Exponent simulation results, shown in Figures 2-9 on pages v-xi in the technical summary section at the beginning of this report.

A summary of all the data collected for the seven BP3 loading levels is displayed in Table 2 on page 25. Manitoba Hydro system operation data was searched to find operating periods for each BP3 loading level within ±5%, and then continuous time sequences of data at these loading levels were next found, optimizing the length of the intervals with at least 1 hour of data or greater. This was done to maximize the amount of data while minimizing inefficiencies of analyzing too small data collection intervals.

Although most of the data was for BP3 operation below the 2000MW (500kV, 2000A) operating capacity simulated in the 2011 Exponent report, the voltage on the line at the levels monitored was also 500kV at the lower BP3 loading levels. This allowed for examination of E-field, RN, and AN levels under the same conditions as predicted in the Exponent report. However, current levels at the 1200MW, and 1500MW-1700MW operating levels were not at the 2000A magnitude studied in the Exponent report. Thus, special operating conditions were arranged to operate the Bipole III transmission line at 2000MW. Four days of staged test operations were also performed in metallic return mode to achieve 2000A and 2300A of current in the conductors to acquire magnetic field (B-field) levels at the rated current levels.

All the data analysis results for the primary effects measured:

1. electric fields;
2. magnetic fields;
3. radio noise; and
4. audible noise

are exhibited in Figures 2-9 in Section 2: Technical Results.

The secondary air chemistry effects which are reported in this section, were monitored for the purposes of reporting on air chemistry changes and for improving our internal understanding of the simulation models.

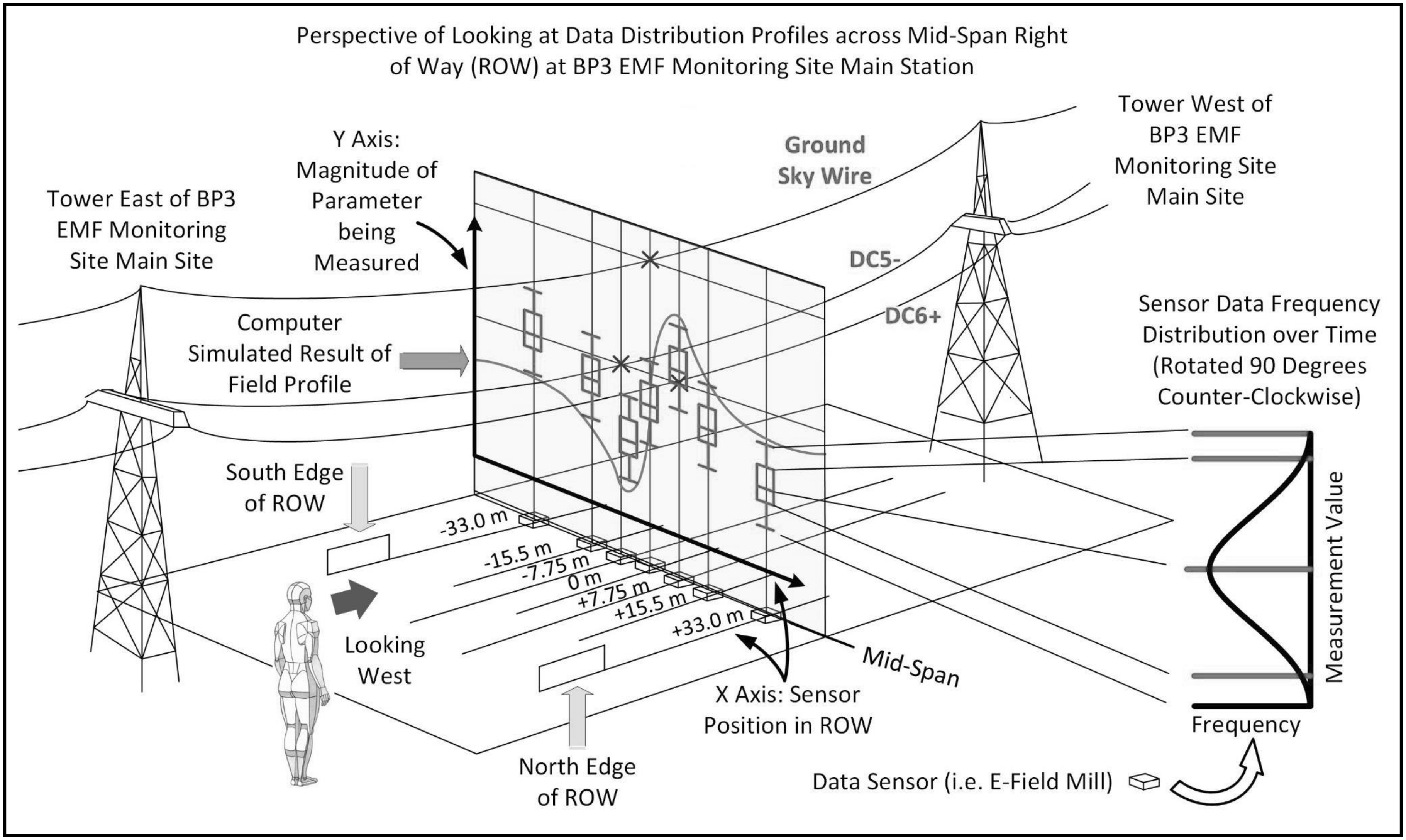


Figure 38: Perspective of looking at data distribution profiles across the mid-span right of way (ROW) at the main station

Table 2: Summary of data analyzed for report to date, broken down by BP3 loading levels.

BP3 Operating Level	Number of Time Intervals	Minimum Time Length of Intervals	Average Number of Data Points per Instrument. (Sample Rate – 1 sample / 10sec)
1200MW	21/44 (47.7%) to 26/44 (59.1%)	2 h	E: 49,574 B: 50,623 RN: 19,539 AN: 18,058
1500MW	35	1.5 h	E: 69,831 B: 70,044 RN: 34,072 AN: 70,009
1600MW	18	1.5 h	E: 57,123 B: 58,192 RN: 28,645 AN: 57,794
1700MW	11	1.5 h	E: 16,741 B: 17,834 RN: 8,536 AN: 17,826
2000MW	1	4 h	E: 1,442 B: 1,442 RN: 1,442 AN: 1,440
2000A Metallic Return	2	1 h 16 m	E: 1,982 B: 1,982 RN: 991 AN: 1981
2300A Metallic Return	2	4 h, 7 m	E: 3,722 B: 3,722 RN: 1,861 AN: 3,721

5.1 Space charge

As indicated in section 4.5.1 and in reference [1], electrical charges in the air are formed by many common natural sources. Collectively, the air ions and charged aerosols are referred to as space charge. However, it does not work out to be the sum total of the two measurements due to the collective negative and positive charge effects. Table 3 in the reference [1] provides a list of typical concentrations of air ions found naturally and around various common sources. In fair weather, open spaces can exhibit space charge levels of 500-2000 C/cm^3. Fair weather urban environment in Manitoba can present levels up to 5300 C/cm^3. On a highway with about 30 vehicles/minute the measurement can be as high as 15000 C/cm^3.

The following Figure 39 shows the average and the maximum levels of space charge measured at the remote sites 500m away from the main site as shown in Figure 12. The average measurements for all power levels are in the order of about 4000 C/cm^3 and the maximum levels reach close to 8000 C/cm^3. It can be concluded that the space charge measurements are in the normal expected range and no abnormalities are observed.

The measurements at 0MW can be considered the baseline background space charge level and serves as the reference level for comparing with the levels when BP3 is operating at various power levels.

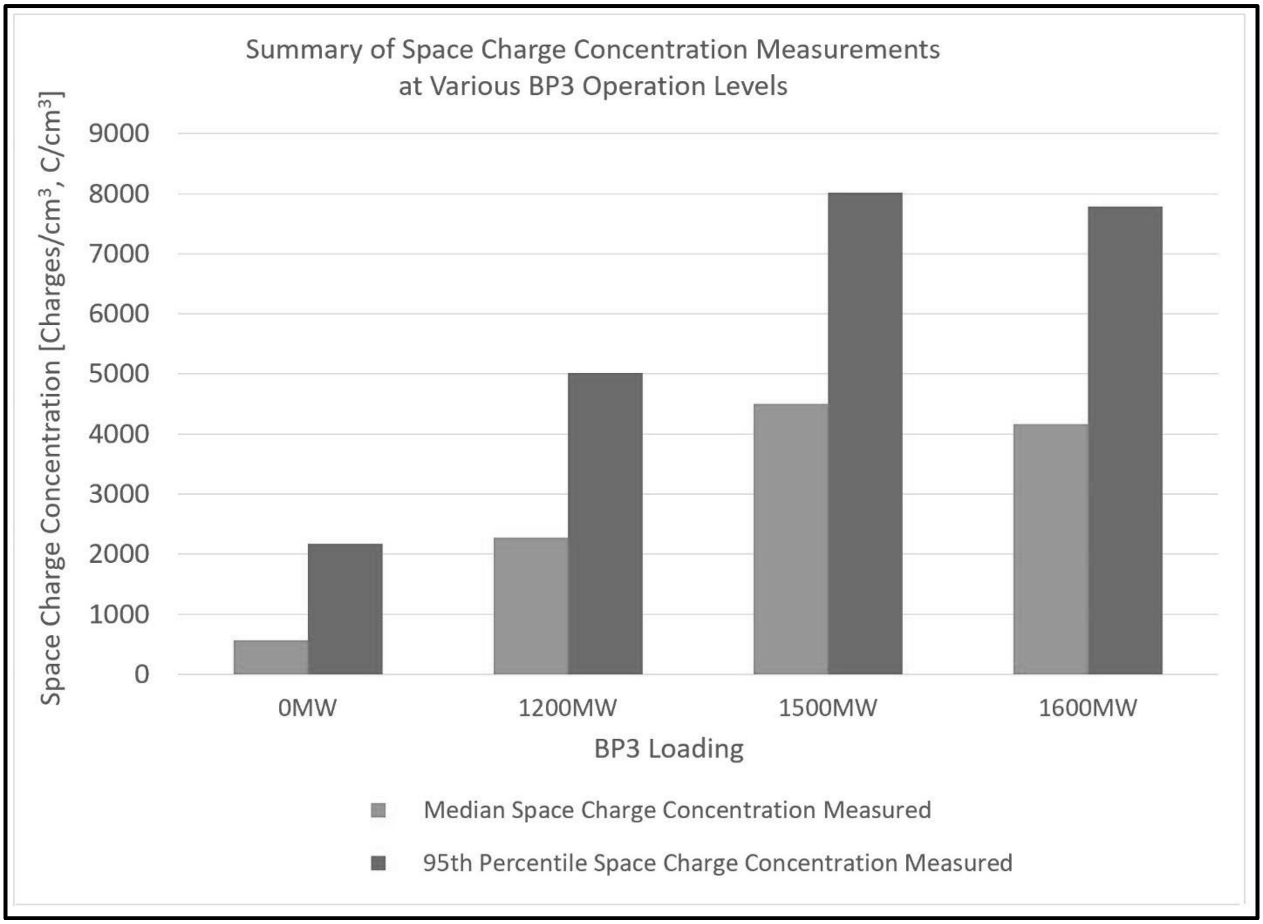


Figure 39: Space charge concentration measurements at the remote sites (500m away from main site) for various operating power levels of BP3.

5.2 Ion density

As mentioned in section 5.1, the ion density contributes to the space charge, which are at normal levels. The measurements of the ion density are shown in Figure 40.

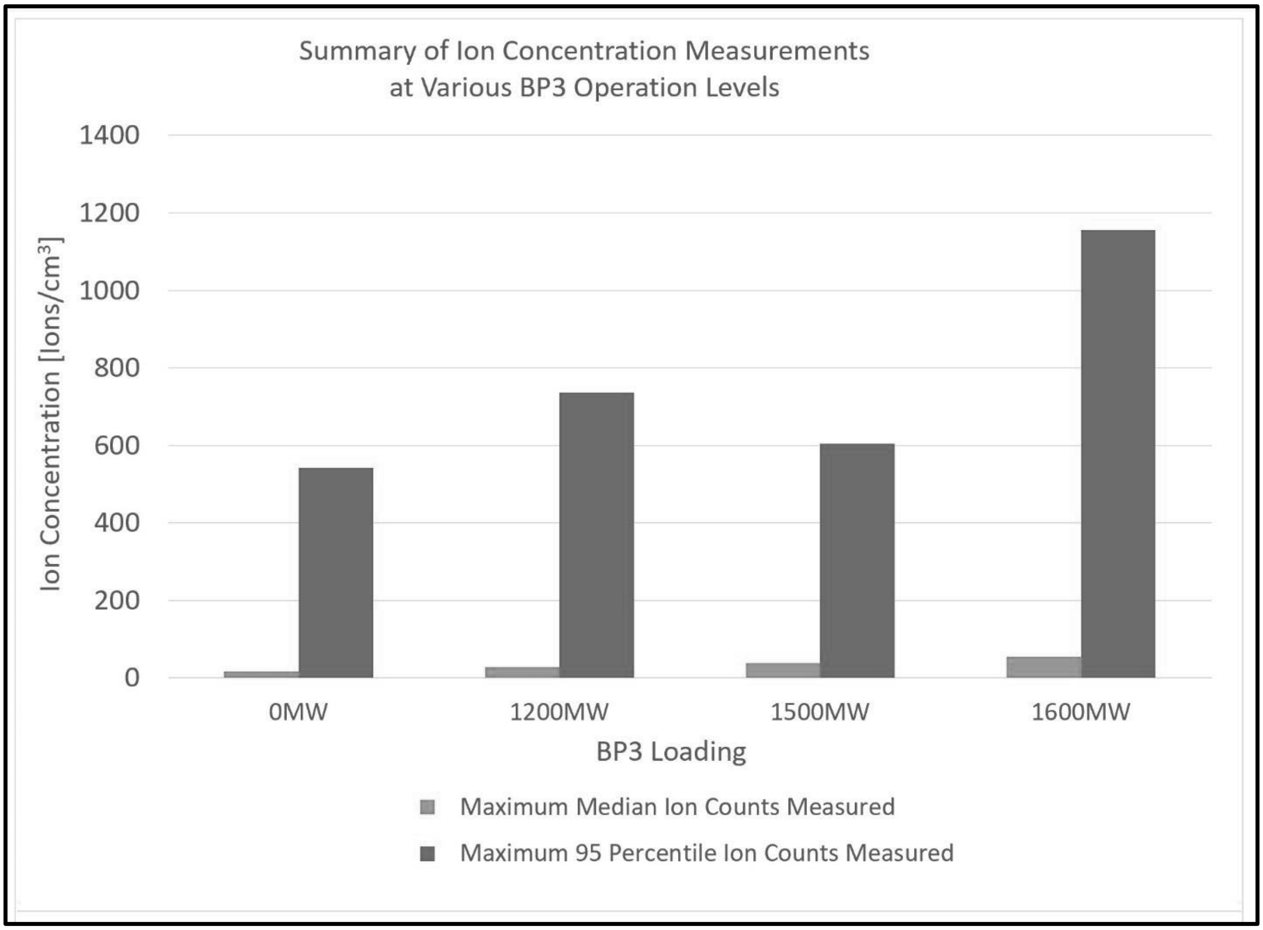


Figure 40: Ion density measurements at the remote sites (500m away from main site) for various operating power levels of BP3.

5.3 Aerosols

As mentioned in section 5.1, the aerosol levels contribute to the space charge, which are at normal levels. The measurements of the aerosols are shown in Figure 41 and Figure 42.

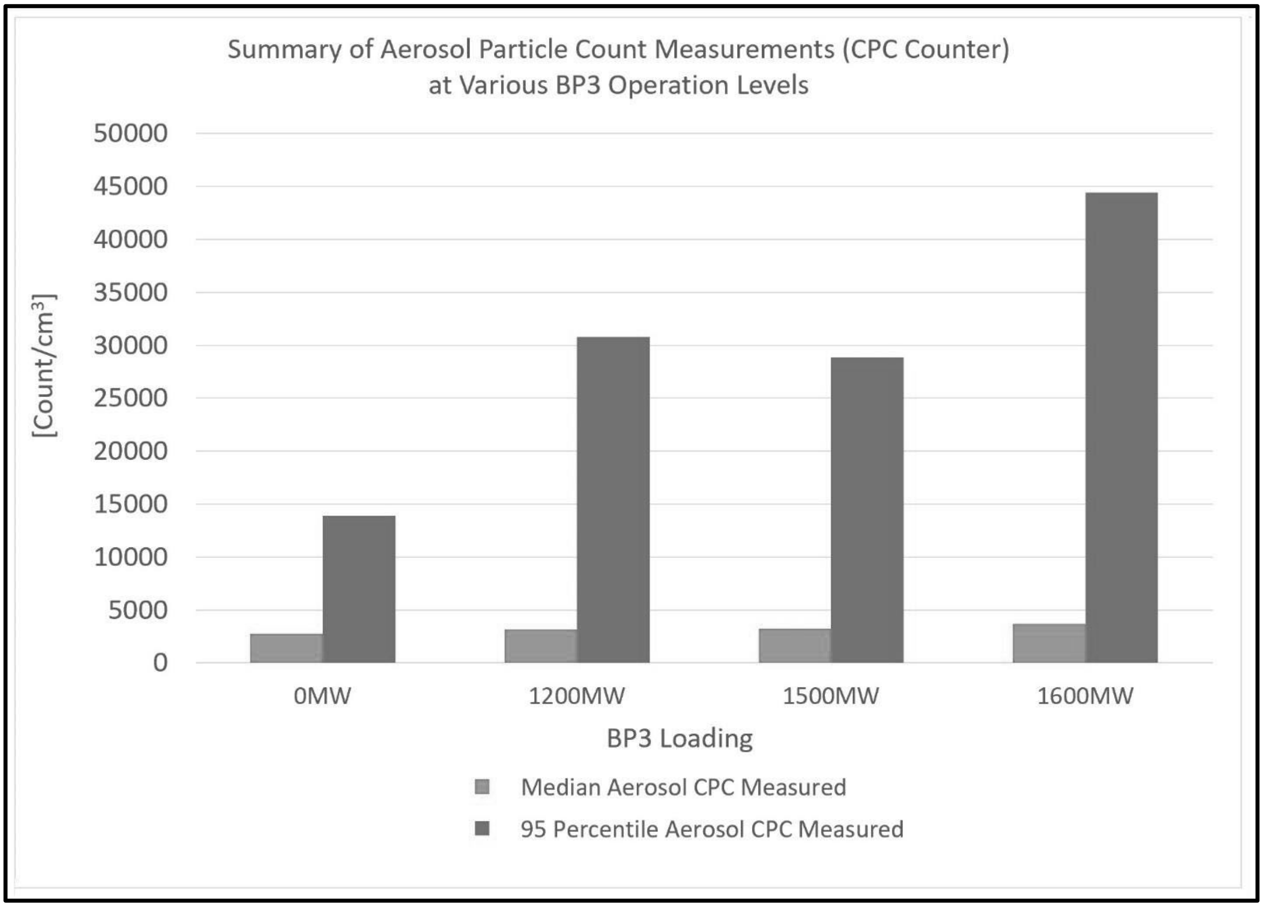


Figure 41: Aerosols counts at the remote sites (500m away from main site) for various operating power levels of BP3.

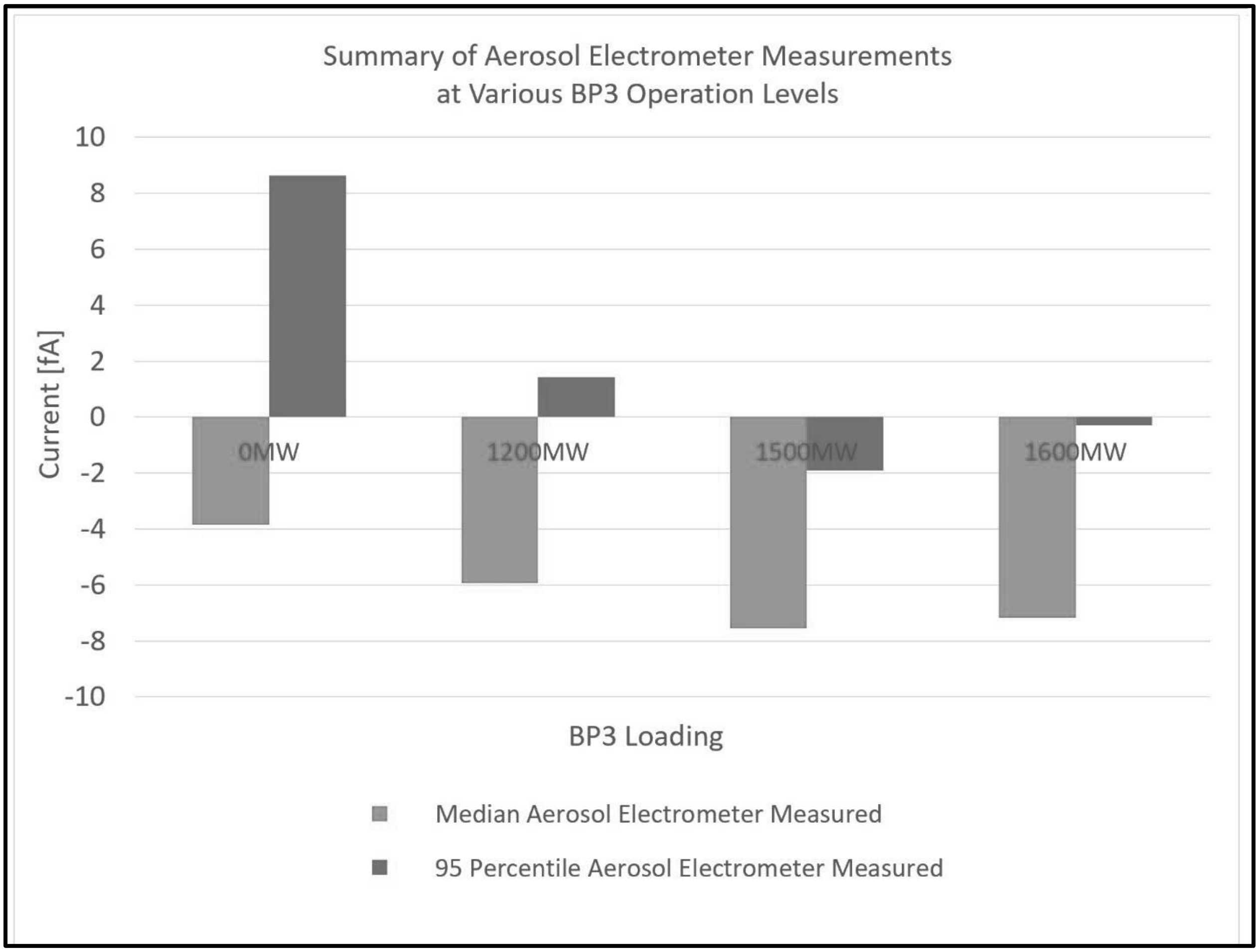


Figure 42: Aerosol charge at the remote sites (500m away from main site) for various operating power levels of BP3.

5.4 Ion current density to ground

Ion current density to ground can be described as flow of charge through air to the ground [1]. Ion current density is a function of electric field and ion concentration reported in the technical results summary (electric field results), and in section 5.2 respectively. Therefore these measurements of ion current density to ground made using the Wilson Plates shown in Figure 43 are of interest for understanding the interrelated phenomenon.

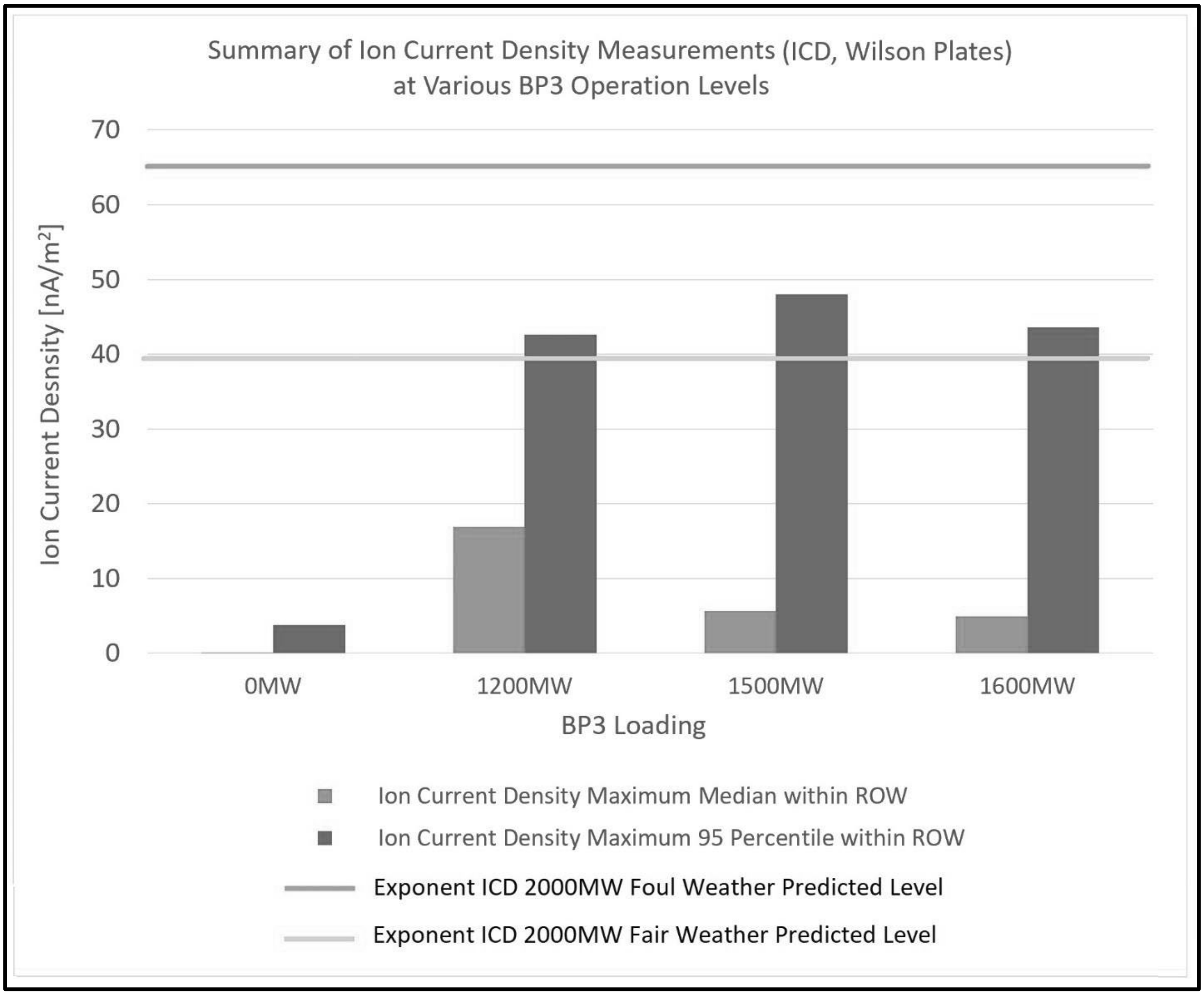


Figure 43: Ion current density to ground measurements within the right of way (row) for various operating power levels of BP3.

5.5 Ozone

Per the description in [1], corona discharges on HVDC transmission lines can give rise to traces of ozone (O_3). There is no theoretical or empirical basis to suggest that HVDC lines would significantly increase the background levels of O_3. The measured data in Figure 44 confirms this hypothesis, as the BP3 line has not significantly affected the ozone level in the right-of-way, because there is little difference between the baseline background measurement at 0MW power level to the other power levels of BP3 operation.

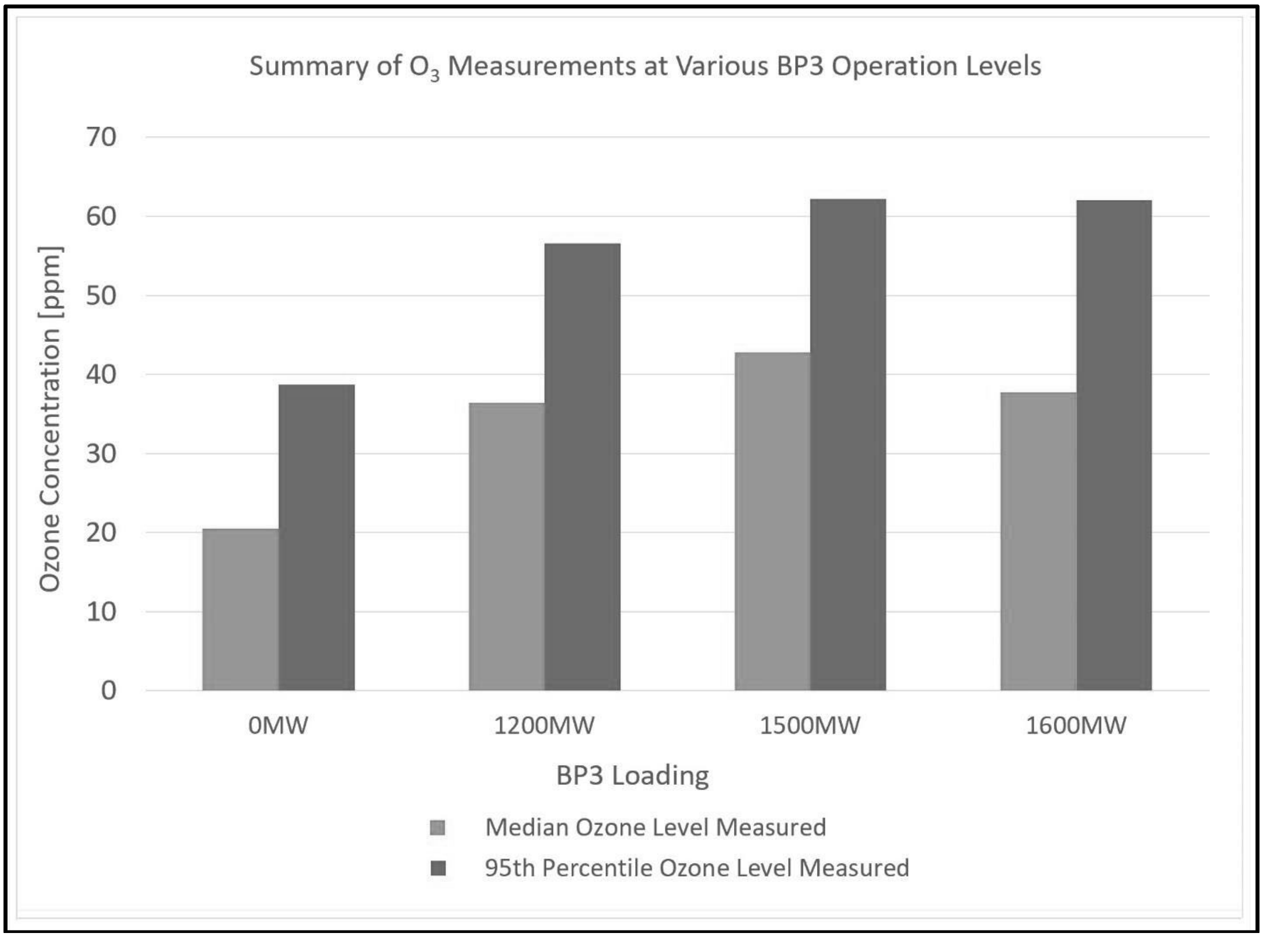


Figure 44: Ozone measurement within the right of way (ROW) for various operating power levels of BP3.

6. Conclusion

Up until the end of December 2020, BP3 has mostly transmitted power below its specified operating level of 2000MW (500kV, 2000A). The bulk of power loading has been at 1200MW and lower, which is typical for the low loss operation for the currently demanded level of transmission needs. There have been intervals of 1500MW-1700MW, and planned test operations allowing for analysis of data from all levels of power. The analysis presented in this report demonstrates that the EMF levels observed for all operating configurations and loading levels of the Bipole III transmission line are within the predicted levels by simulation (as described in the Exponent report) for all weather conditions experienced over the monitoring period. The secondary EMF effects monitored for the purposes of reporting on air chemistry changes and for our internal understanding and improvement of simulation models have also not shown any abnormalities. The data monitoring period has been from early 2019 to date.

7. References

[1] Bipole III Transmission Project: Electromagnetic Fields (EMF) Technical Report. Exponent Inc. November 2011. Last accessed on Saturday, January 16, 2021, 4:04PM at: https://www.hydro.mb.ca/docs/regulatory_affairs/projects/bipole3/eis/BPIII_Electromagnetic_Fields_EMF_Technical_Report_November_2011.pdf

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[7] IEEE Std. 1227 – 1990 (R2010). IEEE Standard for the Measurement of DC Electric-Field Strength and Ion Related Quantities. IEEE-SA Standards Board. June 17, 2010.