Review of Peer-Reviewed Research Regarding the Effects of Geomagnetic Latitude on Geoelectric Fields

Updated Based on the Latest Peer-Reviewed Research

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EPRI Project Manager

B. Arritt

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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The National Aeronautics and Space Administration Goddard Space Flight Center
(NASA GSFC)
8800 Greenbelt Road
Greenbelt, MD 20771

Principal Investigators
A. Pulkkinen, NASA GSFC
P. Schuck, NASA GSFC
S. Blake, NASA GSFC and The Catholic University of America

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ABSTRACT

This report is an examination of peer-reviewed research (updated since the publication of the North American Electric Reliability Corporation (NERC) Benchmark Geomagnetic Disturbance (GMD) Event Description white paper) regarding the effects of geomagnetic latitude on geoelectric fields (based on a reference earth model). This report includes an in-depth review of the new published work (e.g., by United States Geological Survey (USGS) and Los Alamos National Laboratory (LANL)), on the geomagnetic latitude scaling. The report determines whether modifications are needed to the industry-standard scaling factors and provides recommendations for further actions.

Keywords
Geoelectric field
Geomagnetic disturbance
GMD
Geomagnetic latitude
Solar storm
TPL-007

ACRONYMS AND ABBREVIATIONS

EPRI	Electric Power Research Institute
GMD	geomagnetic disturbance
GSFC	Goddard Space Flight Center
LANL	Los Alamos National Laboratory
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Corporation
USGS	United States Geological Survey

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1 INTRODUCTION

1.1 Overview

Subsections 1.2 and 1.3 of the report review the requirements for geomagnetic disturbance (GMD) benchmarks used in transmission planning studies and the current benchmark structure, respectively. Section 2 discusses new findings (*Love et al.*, 2016 [1,2]). Section 3 reviews additional new findings (*Woodroffe et al.*, 2016 [3]). Section 4 discusses the way forward in improving understanding of geomagnetic latitude scaling. Section 5 provides concluding remarks and recommendations.

1.2 GMD Benchmark Requirements

This section discusses the requirements for GMD benchmarks that are used in transmission planning studies. Both engineering and science factors need to be considered.

The requirement for scientists is to provide information about physical parameters that is directly applicable to power engineering analyses. Geoelectric field is the physical parameter that provides the interface between the scientists and engineers (*Pulkkinen et al.,* 2017 [4]). Specifically, for the information to be actionable in engineering analyses, scientists need to address the following key characteristics of extreme geoelectric fields:

i Amplitude

ii Spatial structure

iii Temporal waveform

Scientific analyses also need to characterize the occurrence rates of these three characteristics.

From the geophysics standpoint, the geomagnetic induction process that generates the geoelectric field is dependent on external and internal factors that also need to be considered in the development of GMD benchmarks:

i Many different near-space electric currents systems contribute to driving of the geomagnetic induction process. Consequently, the effect of the geomagnetic latitude, and possibly other factors, need to be considered.

ii The local ground conductivity dictates the ground response. Consequently, local geological conditions need to be considered.

These five factors form the top-level requirements for the information that needs to be considered in developing GMD benchmarks. Meeting the requirements ensures that the benchmarks are both actionable and based on the key physical factors contributing to the geomagnetic induction process under extreme space weather conditions.

1.3 GMD Benchmark Structure

This section describes the approach, including the series of approximations, which were used to develop the GMD benchmark for TPL-007-001. The structure of the benchmark considers all key requirements described in the previous section.

The fundamental challenge is to describe the spatio-temporal evolution of the geoelectric field, $\bar{E}(x, y, t)$, under extreme space weather conditions. $\bar{E}(x, y, t)$ depends on external magnetic field excitation, $\bar{B}_{ext}(x, y, t)$. The ground conductivity structure, $\sigma(x, y, z)$, dictates the ground response.

Here,

$x, y, z,$ and t are the spatial dimensions, with z-axis pointing toward the center of the Earth

x is the longitude

y is the latitude

t is time

The horizontal components of the geoelectric field can be written as:

$$\bar{E}(x, y, t) = \begin{bmatrix} E_x(x, y, t) \\ E_y(x, y, t) \end{bmatrix} \quad \textbf{Eq. 1-1}$$

Equation 1-1 can be expressed in an approximate factorized form that uses a single static scaling factor for the peak amplitude:

$$\approx E_{peak}(x, y) \begin{bmatrix} f_x(t) g_x(x, y) \\ f_y(t) g_y(x, y) \end{bmatrix} \quad \textbf{Eq. 1-2}$$

Where

$f(t)$ captures the temporal evolution of the field

$g(x,y)$ is the spatial structure of the field

E_{peak} is the peak amplitude of the field that varies as a function of location

Assuming a spatially homogeneous geoelectric field over the footprint of the system, Equation 1-2 can be further simplified to read:

$$\approx E_{peak}(x, y) \begin{bmatrix} f_x(t) \\ f_y(t) \end{bmatrix} \cdot 1 \quad \textbf{Eq. 1-3}$$

Equation 1-3 can be further simplified by further factorization and writing the primary source and response dependencies for the E_{peak}:

$$\approx E_0 \cdot \alpha(y) \cdot \beta(x, y) \begin{bmatrix} f_x(t) \\ f_y(t) \end{bmatrix} \cdot 1 \quad \textbf{Eq. 1-4}$$

Where

E_0 is the peak 1-in-100 year geoelectric field amplitude at high latitude reference location

$\alpha(y)$ is the geomagnetic latitude scaling factor capturing the source structure variation

$\beta(x,y)$ is the ground response scaling factor that approximates the scaling of the response (peak amplitude for the reference waveform) as a function of location

Equation 1-4 is the present form of the GMD benchmark associated with TPL-007-001. $f(t)$ is given by the geoelectric field waveform calculated with the Ottawa 10-s geomagnetic field observations and Ottawa ground model for the March 1989 solar storm.

In Equation 1-4, with regard to the five requirements in subsection 1.2:

- E_0 captures requirement *i*
- The field is assumed to be spatially homogenous, addressing requirement *ii*
- The Ottawa waveform for *f(t)* addresses requirement *iii*
- The α-scaling captures requirement *iv*
- The β-scaling addresses requirement *v*

In TPL-007-002, requirement *ii* is modified by introducing localized source structures that give rise to an enhanced localized geoelectric field in addition to the larger-scale regional field prescribed in TPL-007-001. Modification also changes the peak 1-in-100 year amplitude and waveform of the field (i.e., also affecting requirements *i* and *iii*).

The α-scaling in the GMD benchmark white paper that supported TPL-007-001 was based on various work (*Thomson et al.,* 2011 [5]; *Pulkkinen et al.,* 2012 [6]; and *Ngwira et al.,* 2013 [7]). These works analyzed major geomagnetic storms observed since the 1980s. The works indicated an order of magnitude decrease in the geoelectric field amplitude across the band of 40 to 60 degrees of geomagnetic latitude. The α-scaling addresses the *source* variations due to the external magnetospheric-ionospheric electric current structure. Ground response (i.e., β-scaling) can give rise to comparable or even larger variations as a function of location.

Since the preparation of the GMD benchmark white paper that supported TPL-007-001, new peer-reviewed research has been conducted to further investigate the geomagnetic latitude scaling behavior. The new work, *Love et al.* (2016a) and *Woodroffe et al.* (2016), is discussed in Sections 2 and 3, respectively. *Thomson et al.* (2011), *Pulkkinen et al.* (2012), *Ngwira et al.* (2013), *Love et al.* (2016), and *Woodroffe et al.* (2016) use essentially the same global geomagnetic field observations. No significant new observational geomagnetic field information has become available between these studies.[1] However, *Love et al.* (2016a) and *Woodroffe et al.,* (2016) used new analysis techniques to characterize the extreme values and functional form of the geomagnetic latitude scaling.

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[1] By contrast, magnetotelluric surveys have become available since introduction of the GMD benchmark white paper (e.g., *Love et al.*, 2016b). Magnetotelluric surveys are significant for characterizing the ground response. However, due to the campaign mode of the surveys, observations are not as significant for characterizing the extreme storm α-scaling.

2
SUMMARY OF FINDINGS BY *LOVE ET AL*. (2016a)

Love et al. (2016a) analyzed 1-minute global geomagnetic observations from 1974-2014. The researchers conducted an extreme value analysis of the following measures of the magnetic field for individual geophysical observatories:

- ΔB_h is 1-minute differences (nT/min)
- S is 10-minute differences (nT/min)
- R is the root-mean-square of change over 10 minutes (nT/min)

Log-normal distributions that were fitted with least-squares and maximum likelihood methods were assumed for the studied quantities at individual stations. Further, to quantify the latitude scaling, a polynomial with a "kink" was fitted to the extreme value estimates.

Figure 2-1 shows the key results from *Love et al.* (2016a). All the panels in Figure 2-1, for all studied parameters, including the curves that correspond to 1-in-100 year estimates, show about a one order of magnitude decrease in magnitude approximately across the band of 60 to 40 degrees of geomagnetic latitude. However, the fitted curves display more structure above 60 degrees and below 40 degrees of geomagnetic latitude than the simple exponential used in TPL-007-001. This could be addressed in future revisions of the GMD benchmark.

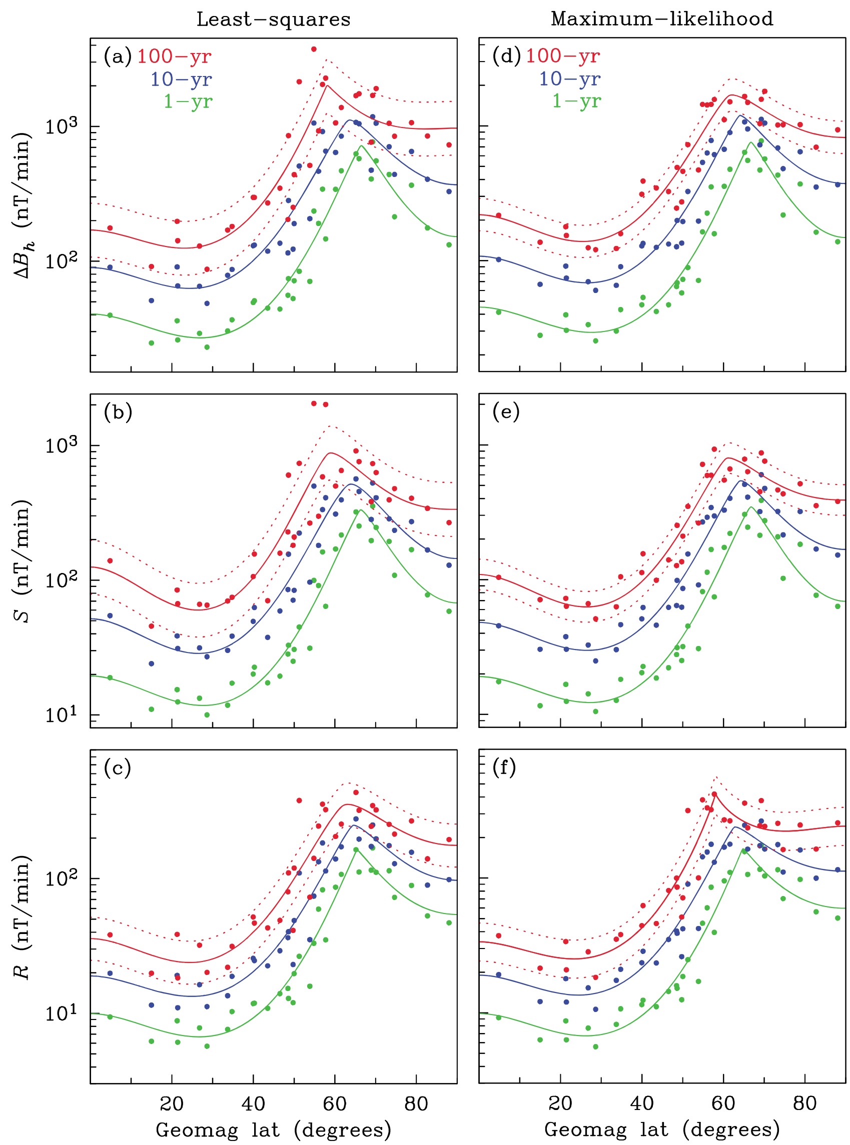

Figure 2-1
Summary of *Love et al.* (2016a) results [1]

Figure 2-1 shows magnetic latitude maps obtained, respectively, by least squares and maximum likelihood methods, of (Figure 2-1 (a, d)) ΔB_h, (Figure 2-1 (b, e)) S, and (Figure 2-1 (c, f)) R cumulative exceedances. The figure shows the threshold (nT/min) for which activity within a 24-hour period can be expected to occur once per year (green), one per decade (blue), and once per century (red). Dots correspond to values taken from log-normal fits to data from individual observatories; dotted lines show a one standard deviation (1 lower and upper) range.

3
FINDINGS BY *WOODROFFE ET AL*. (2016)

3.1 Overview

Woodroffe et al. (2016) analyzed 1-minute global geomagnetic observations from 1981-2011. The researchers conducted an extreme value analysis of the following measures of the magnetic field.

- ΔB is the change in the magnetic field (nT)
- dB/dt is the magnetic field change over time (nT/sec)
- E is the geoelectric field (V/km)

The geoelectric field was computed using the plane wave method and one-dimensional six-layer Quebec ground conductivity model. Importantly, the latitude dependence of the studied quantities was characterized also as a function of the *Dst*-index, which is a classical index for measuring the strength of geomagnetic storms.

3.2 Geomagnetic Latitude Scaling Results

Figure 3-1 shows the first set of key geomagnetic latitude scaling results from *Woodroffe et al.* (2016). The figure shows the data for studied parameters sorted as a function of three different levels of the *Dst*-index. As in the *Love et al.* (2016a) work, all the studied parameters display about a one order of magnitude decrease in magnitude approximately across the band between 60 and 40 degrees of geomagnetic latitude. A similar decrease is observed for all different levels of the *Dst*-index.

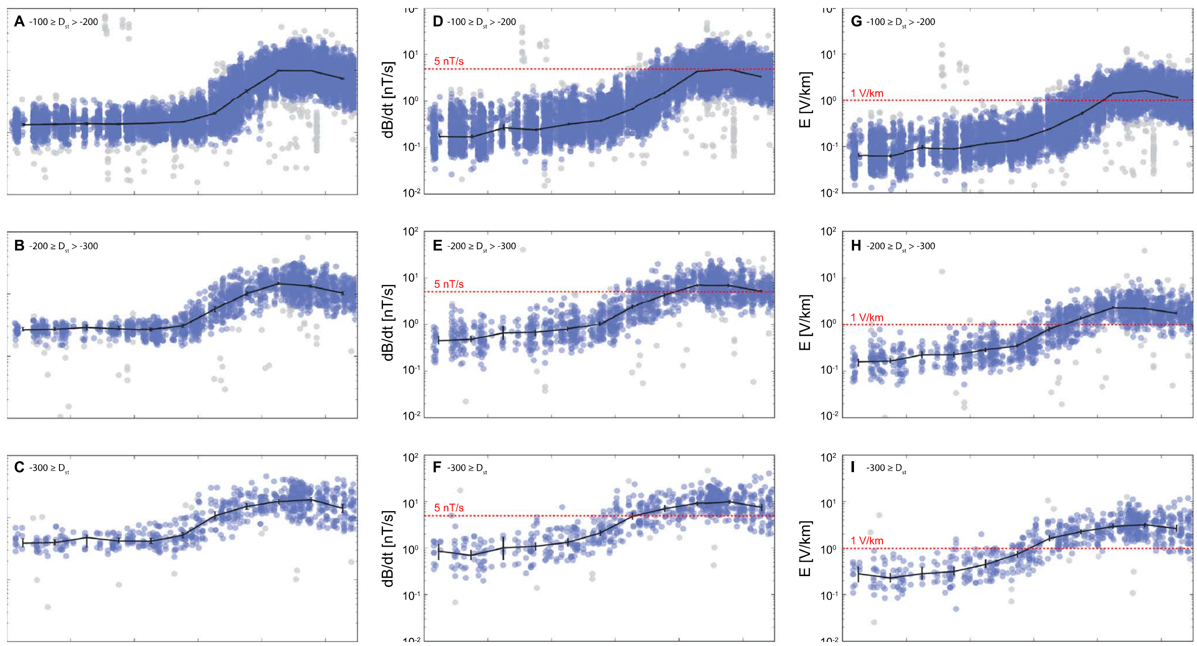

Figure 3-1
Summary of *Woodroffe et al.* (2016) results: Latitudinal dependence of GMD amplitudes for strong, severe, and extreme storms [3].

Figure 3-1 (a-c) shows ΔB; Figure 3-1 (d-f) shows dB/dt; and Figure 3-1 (g-i) shows E (calculated using the six-layer Quebec conductivity profile). In each panel, individual maxima from different stations are shown as a blue circle; and the concentration of points is indicated by the darkness of the circles. Also, in each panel, the median GMD amplitude (with 95% confidence interval) is plotted with a solid black line.

3.3 Functional Fits Analysis

In a similar manner to *Love et al.* (2016), *Woodroffe et al.* (2016) made a functional fit to quantify the geomagnetic latitude scaling behavior and conducted an extreme values analysis of the studied parameters. These results are shown in Figure 3-2. Both functional fits and 1-in-100 year estimates display the approximately one order of magnitude decrease across 60 and 40 degrees of geomagnetic latitude for all studies parameters. However, the functional form of the latitude scaling is more complex than a simple exponential drop across 60 and 40 degrees of geomagnetic latitude. Further, the data does show dependence on the *Dst*-index, indicating that the data can be meaningfully conditioned with a global geomagnetic storm parameter. This result introduces an interesting opportunity for studying extreme geoelectric field through conditioning with global storm indices (*Morley*, 2019 [8]).

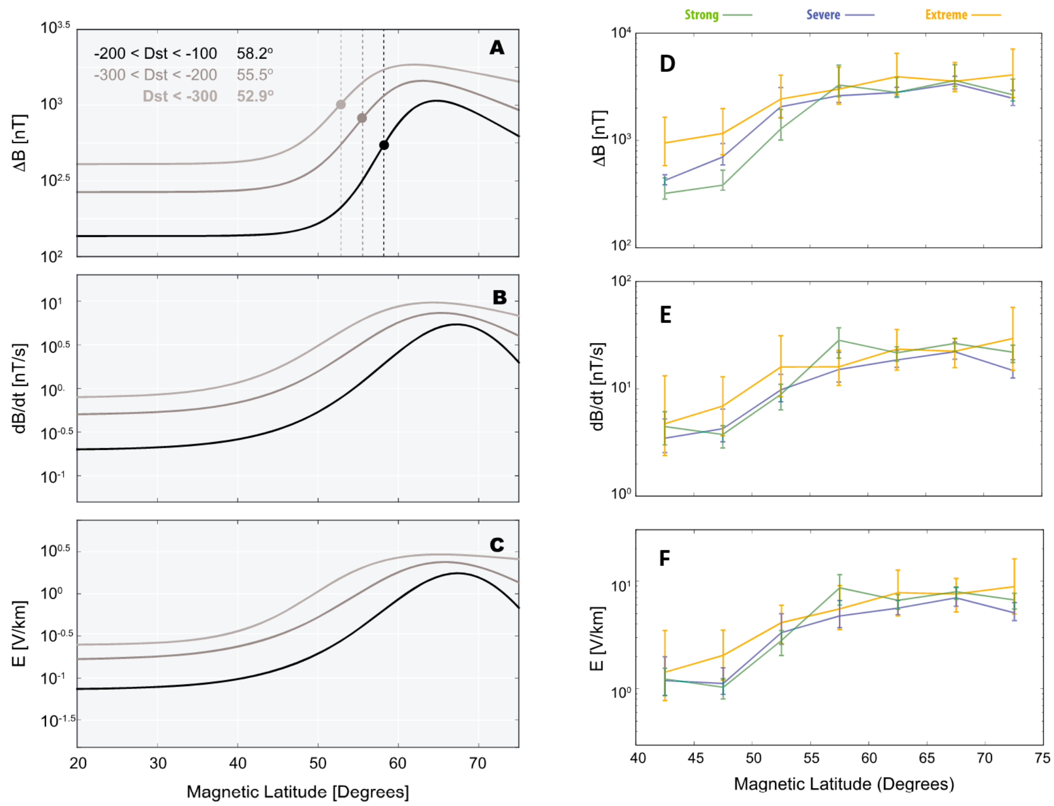

Figure 3-2
Functional Fits Analysis of *Woodroffe et al.* (2016) results [3]

Figure 3-2 (a-c) shows analytical fits to median GMD values as a function of latitude. Figure 3-2 (a) shows ΔB; Figure 3-2 (b) shows dB/dt; and Figure 3-2 (c) shows E (calculated using Quebec conductivity profile). Each panel shows:

- Fits for -100 nT $\geq Dst > -200$ nT (in black)
- Fits for -200 nT $\geq Dst > -300$ nT (in dark gray)
- Fits for $Dst \leq -300$ nT (in lighter gray)

In Figure 3-2 (a), the center of the transition region is indicated on each curve by a shaded circle, and the latitude of this transition is indicated by a vertical dashed line. In Figure 3-2 (d-f), shows the magnitude of 1-in-100 year events for different types of GMD. Figure 3-2 d shows B; Figure 3-2 (b) shows dB/dt; and Figure 3-2 (c) shows E, calculated using the Quebec conductivity profile. In each case, the values for strong storms are shown in green, values for severe storms are shown in blue, and values for extreme storms are shown in orange. Vertical error bars indicate the 95% confidence interval.

4

THE WAY FORWARD: PARAMETRIZATION, HISTORICAL RECORDS, AND PHYSICS-BASED SIMULATIONS

4.1 Overview

This section discusses the way forward for extracting new information about geomagnetic latitude scaling. The issue is challenging in particular due to use of most if not all of the available modern (starting in about 1980s) geomagnetic field data records. Given that the current period of time is the solar minimum, several years and perhaps the next full 11-year solar cycle will be needed to gather significant new observations and accumulate them for studies of geomagnetic extremes. Meanwhile, new ways of analyzing the (same) data, and deploying entirely new physics-based tools for studies of extremes, are needed.

4.2 Parametrization

Parametrization of the geomagnetic latitude scaling as a function of the *Dst*-index carried out by *Woodroffe et al.* (2016) is an example of a new way to analyze the extreme data records. Conditioning the statistics with geomagnetic indices such as *Dst, K,* or *A* that are available for significantly longer time periods than the modern high-cadence records enable, in principle, statistical modeling of geoelectric field to new extremes (see also *Pulkkinen et al.*, 2008 [9]).

Anchoring the conditioned statistical models with historical records of geomagnetic indices for extreme storms from the 1800s and early 1900s could shed new light on geomagnetic latitude scaling. The geomagnetic latitude scaling is clearly associated with auroral oval and its motion during storms (e.g., *Morley*, 2019 [8]). Consequently, if analyses are supplemented with additional records about auroral boundaries (e.g., *Silverman and Cliver*, 2001 [10]; *Green and Boardsen* 2006 [11], and Figure 4-1), historical storms can provide additional value also for the geoelectric field studies.

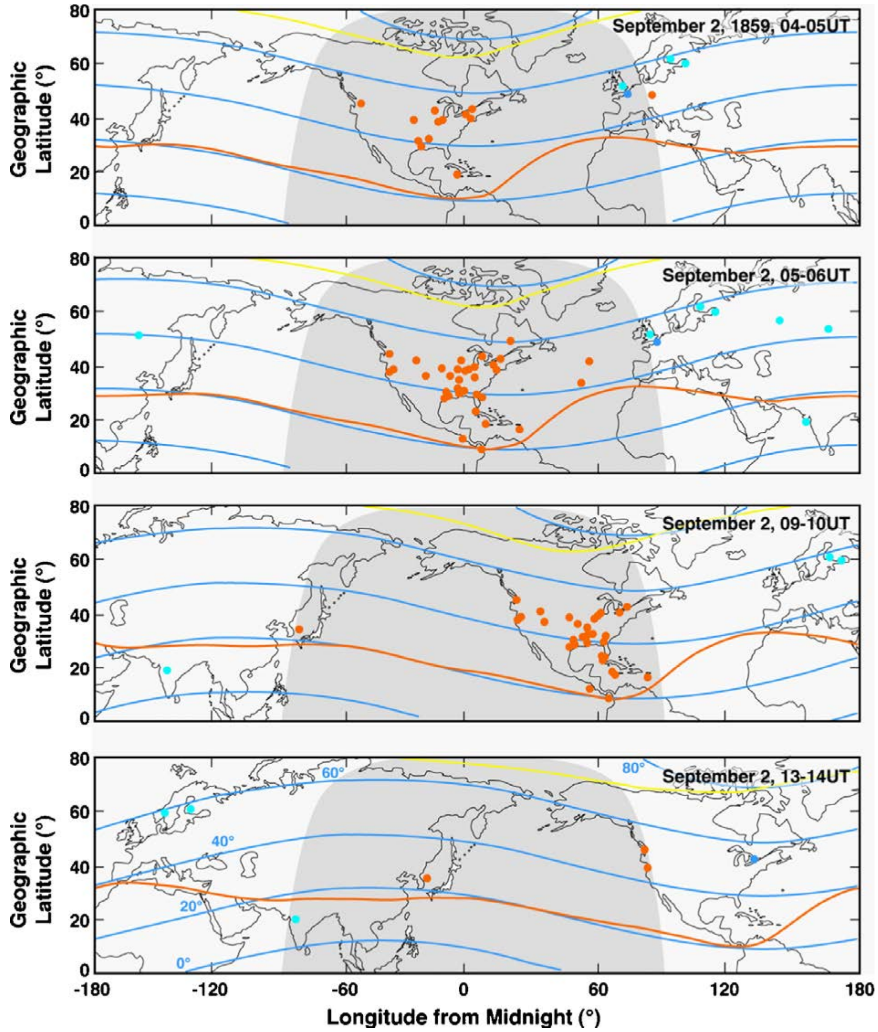

Figure 4-1
Historical eyewitness accounts and data from great aurora of September 2, 1859 [11]

Figure 4-1 shows the location of eyewitness accounts (orange dots) and magnetometer stations (blue dots) of the great aurora on September 2, 1859 for selected times as a geographic Mercator projection in the Northern hemisphere centered at local midnight. Geomagnetic dipole latitude is shown as blue wavy lines, with the yellow and orange lines the minimum and maximum extent of the auroral oval from Holzworth–Meng model, respectively. Many of the auroral observations were structures in the *horizon,* and thus do not necessarily indicate the location of auroral boundary, which would require observations of *overhead* auroras.

4.3 Geospace Models

State-of-the-art, physics-based geospace models have become viable over the past few years for GMD studies.[2] The modern geospace models now include key physics that is believed to drive the geoelectric field (e.g., during sudden storm commencements, auroral electrojet enhancement,

[2] To review a selection of modern geospace models, see https://ccmc.gsfc.nasa.gov.

substorm-like magnetotail dynamics, and geomagnetic pulsations). While further validation is necessary and care is needed when interpreting the simulated results, these models are ready for usage in exploring GMD extremes, including the geomagnetic latitude scaling behavior.

To illustrate how these modern tools can be used, Figure 4-2 shows simulation results from *Ngwira et al.* (2014). Figure 4-2 (a) shows a scenario in which Carrington-scale storm[3] auroral boundaries may propagate further south than 60 to 40 degrees of geomagnetic latitude. Figure 4-2 (b) in turn shows that modeling reproduced quite well the observed geomagnetic latitude scaling for the October 2003 "Halloween storm."

Figure 4-2 shows simulations in blue and observations in red. Each "*" represents a specific ground magnetometer site, and the time of the peak electric field varies from site-to-site. The vertical red dashed lines show the locations of the transition regions between middle and high latitudes (i.e., geomagnetic latitude scaling)

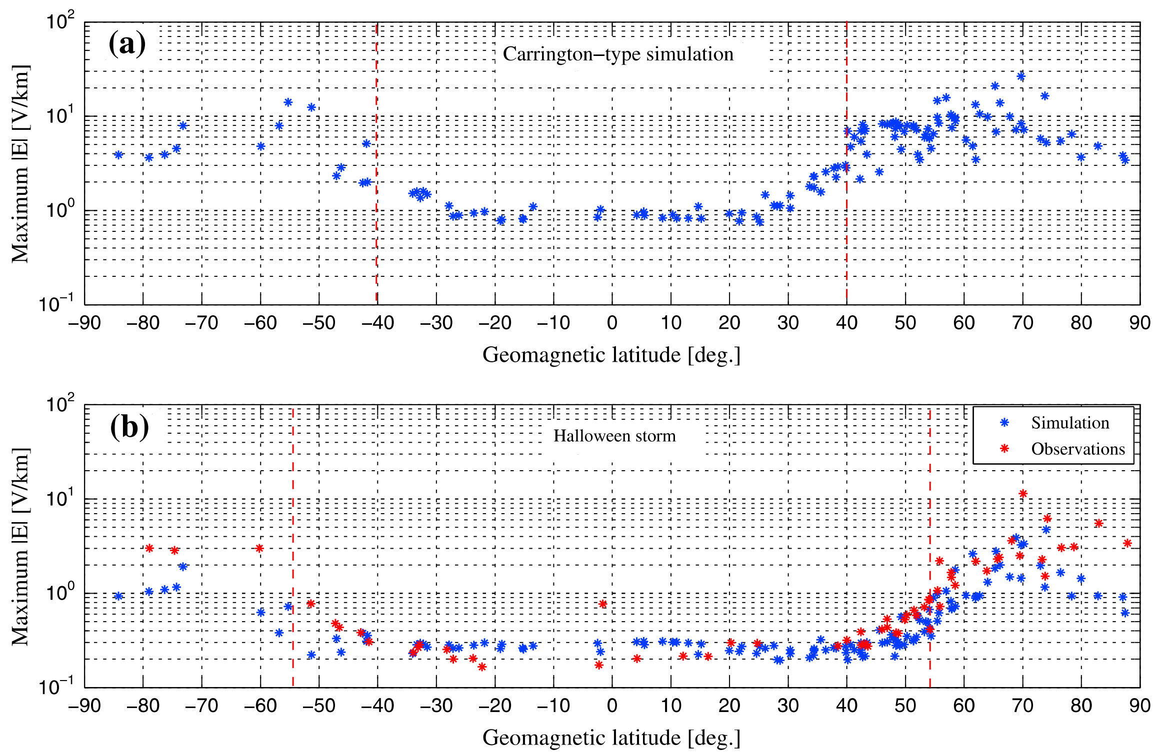

Figure 4-2
Global distribution of the peak geoelectric fields determined for (a) the Carrington-type event simulation, and (b) for the Halloween storm event [7].

Physics-based geospace modeling will be valuable also for investigating the spatial scales associated with geomagnetic latitude scaling. More specifically, the geomagnetic latitude scaling work discussed above relied on single station *local* readings for studying the change in the geoelectric field amplitude, or corresponding proxy quantity, as a function of latitude (α in eq.

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[3] The Carrington Event of September 1859, named after British astronomer Richard Carrington, is the most significant geomagnetic storm recorded in the last 160 years.

4). However, to account for a regional impact on the bulk power system, in TPL-007-001 the peak geoelectric field amplitude (E_0 in eq. 4) was built based on spatial averaging. These two approaches (single station versus spatial averages) introduce a potential disconnect in terms of analyzed spatial scales. Optimally, also geomagnetic latitude scaling should be studied for spatial averages. However, the spatial density of global geomagnetic observatories is generally not high enough to support robust analysis of the spatially-averaged field latitude scaling. Geospace models that resolve external electric current systems in the magnetosphere and ionosphere can in turn provide geomagnetic field evolution at any location on the surface of the Earth. This allows studies of geomagnetic latitude scaling also as a function of spatial scales.

All the approaches discussed in this section (i.e., parametrizations, investigation of historical records, and usage of modern geospace simulations including in studies of α-scaling as a function of spatial scale), are being used in the ongoing NERC/EPRI GMD research work [12].

5
CONCLUSIONS AND RECOMMENDATIONS

This study concludes that the new research from *Love et al.* (2016a) and *Woodroffe et al.* (2016) are in general agreement with the α-scaling associated with the GMD benchmark in TPL-007-001, which indicates about a one order of magnitude drop in geoelectric field amplitudes across the band of 60 to 40 degrees of geomagnetic latitude. However, the new work also indicates directions for possible refinements of the scaling, including:

- The more detailed shape of α-scaling (e.g., decrease of the geoelectric field amplitudes above 60 degrees of geomagnetic latitude) could be considered in future benchmark revisions.
- Further parametrization of the α-scaling should be studied. For example, *Dst*-index dependence is a promising way to parametrize the scaling. Further, *Morley* (2019) indicates that magnetic local time dependence could be considered in the future benchmark revisions.

Availability of modern geomagnetic data records that have mostly been exhausted in past studies challenges studies of geoelectric field extremes. New ways to analyze the same data (e.g., via conditioning with global geomagnetic indices and other relevant parameters, utilizing historical records of extreme storms, and modern geospace models) are the clear paths forward for improved understanding of the geomagnetic latitude scaling under extreme space weather conditions. All these areas are being addressed in the ongoing NERC/EPRI GMD research work.

Interest in extreme geoelectric fields has experienced growth over the past few years. A number of new groups around the globe are contributing to the body of research on the topic. These research investments are likely to lead to new findings that allow refinement and improvement of the TPL-007-001 GMD benchmark event, including the associated geomagnetic latitude scaling.

In summary, this study does not indicate the need for immediate changes to geomagnetic latitude scaling. However, the new peer-reviewed work indicates directions for further refinements that can be considered as overall understanding of the geospace dynamics during extreme storm conditions evolves.

6
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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com