An ML Approach to Forecasting Space Weather Impacts on Critical Infrastructure from Ground-Based Arrays

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Evolution of the MTArray – Magnetotelluric measurements used to mitigate risk to the power grid from space weather

For the past sixteen years under the support of NSF, NASA and most recently the US Geological Survey, we have been systematically measuring electric and magnetic field time series from moving arrays of magnetotelluric (MT) instrumentation spanning the conterminous US and the interior of Alaska. While originally motivated by questions of the structure and evolution of the North American continent, the resulting 3-D electrical conductivity structure of the Earth's crust and upper mantle and the electromagnetic impedance data derived from this work have in recent years proved of considerable importance to mitigating risk to critical infrastructure (most notably, the power grid) from geomagnetically induced currents caused by space weather and electromagnetic pulse events.

Under current NSF support we are exploring how to combine real-time magnetic observatory data streams with this information and with power flow simulations of the power grid to provide real-time alerting information of GIC impacts on high-voltage transformers to electric utilities.

In the present work we go beyond real-time and present preliminary results of our efforts to train neural networks to assimilate data from dense arrays of ground-based MT stations in Alaska to provide forecasts of ground electric and magnetic field time series that could in future, with installation of permanent MT arrays, provide actionable intelligence to utilities ahead of GICs impacting their networks.

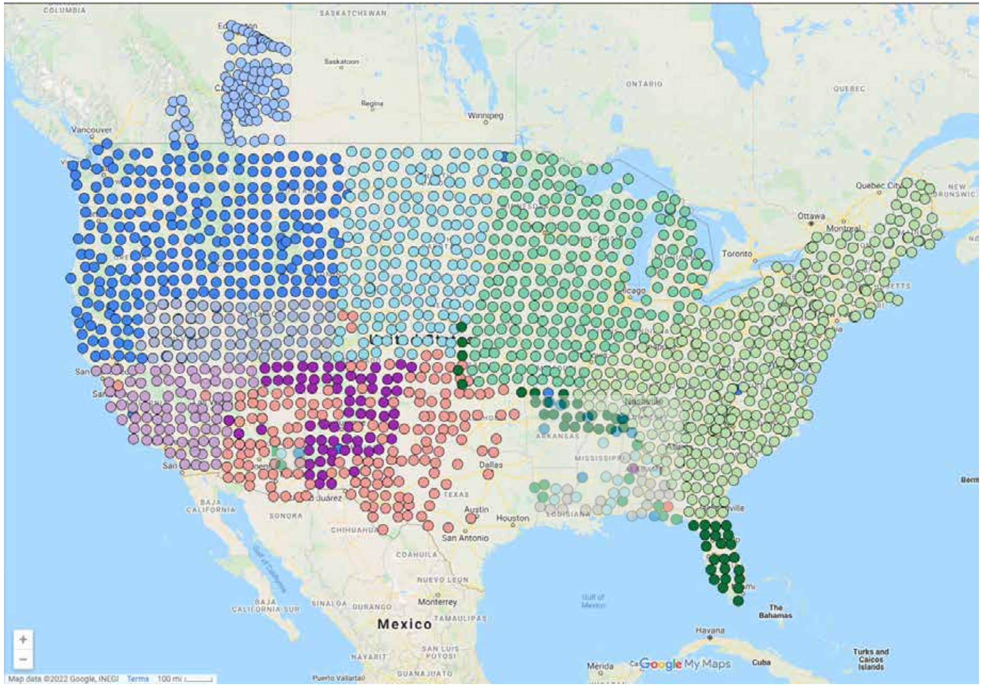
Evolution of the MTArray – Magnetotelluric measurements used to mitigate risk to the power grid from space weather

Oregon State University and its subawardees continue to install temporary (weeks-to-months) long-period MT stations that measure ground-level vector electric and magnetic fields on a 70-km grid of points spanning the conterminous US.

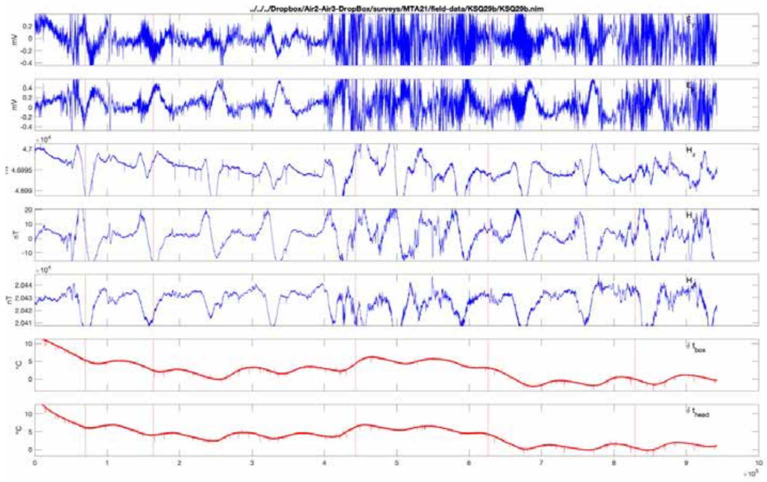
We plan to complete the MT Array in CONUS in mid-2024 with >1900 stations (a current snapshot of stations completed, currently installed or permitted is seen below).

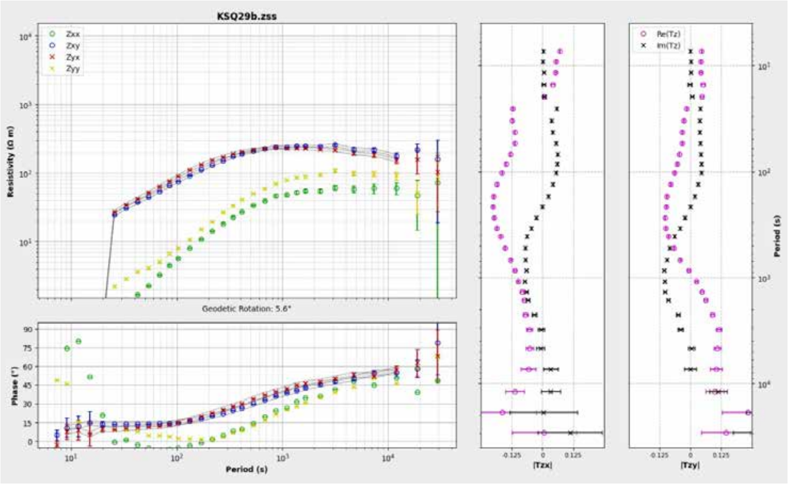
Our data are used to generate MT Impedance functions and related quantities suitable for determining the 3-D electrical structure of the crust and upper mantle.

The impedances and/or derived 3-D electrical models can be used to estimate ground-level electric fields from measurements or models of ground-level magnetic fields. These can be integrated along the paths of power grid transmission lines and flowed through power grid equivalent electrical circuits to determine GIC intensity, transformer heat and vibration, and reactive power loss.



Principal MTArray Data Products



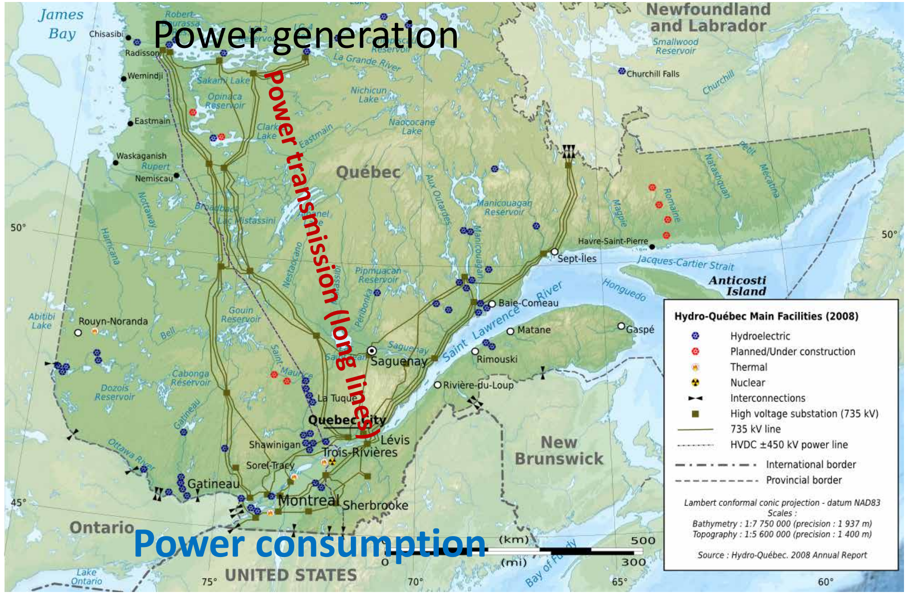


(LEFT) Time-series containing 11-d of ground-level electric field (from top-to-bottom: N-S component of E field, E-W component of E field, N-S component of B field, E-W component of B field, vertical component of B field; red curves are sensor and DAQ system temperatures).

(RIGHT) MT response functions shown as (top left) apparent resistivity vs. period, (bottom left) phase relationship between E and B fields, and tipper or induction arrows showing (center panel) relationship of vertical component of magnetic field to N-S component, and (right panel) vertical to E-W component.

By streaming in magnetic observatory and/or data from temporary MT or variometer stations, the MTArray impedance data and/or conductivity models along with power grid power flow models can be used to produce real-time estimates of GICs in the high-voltage transformers underpinning the power transmission network.

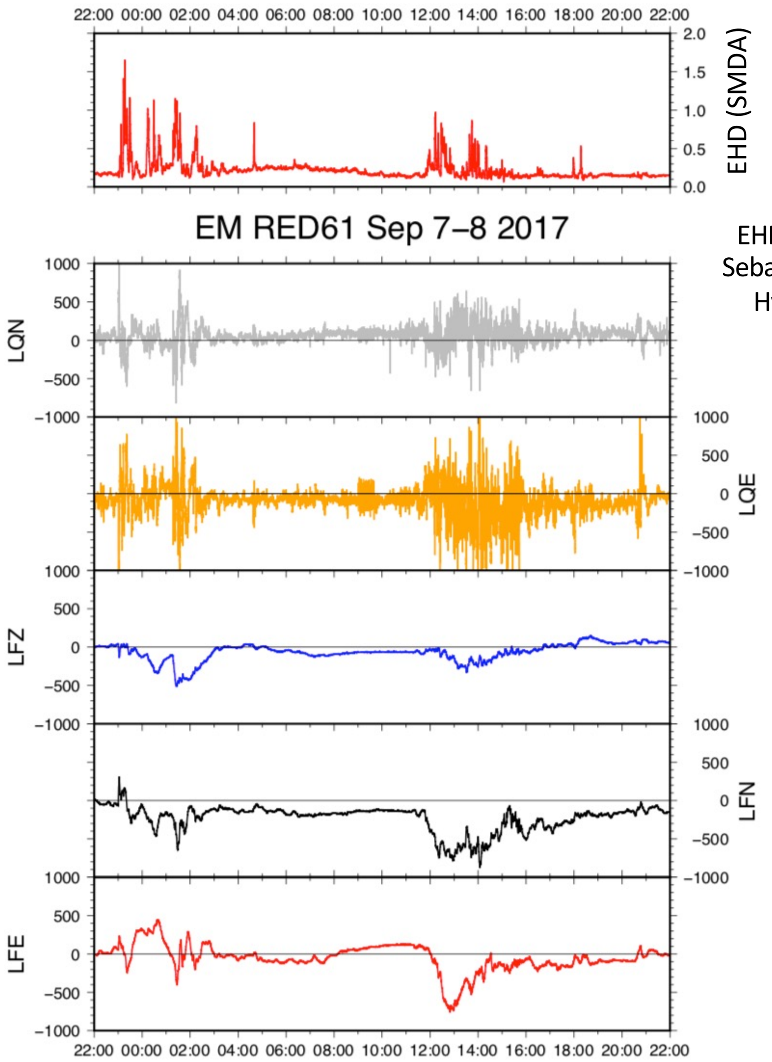
An example of simultaneous MT and transmission system sensor data during a GMD



Coherency/clear association between ground electric fields recorded at OSU/NSF EarthScope MT stations (this example: SW Maine) and Even Harmonic Distortion in voltage measured on Hydro-Québec transmission system

Electric field (N-S at top, then E-W) components, magnetic field (vertical, N-S then E-W) components from an OSU EarthScope MT station in SW Maine during a GMD in September, 2017.

Top panel – Even Harmonic Distortion (harmonics 2,4,6,8 as percentage) in voltage, measured on Hydro-Québec power grid during the GMD.



EHD (top) credit: Sebastién Guillon, Hydro-Québec.

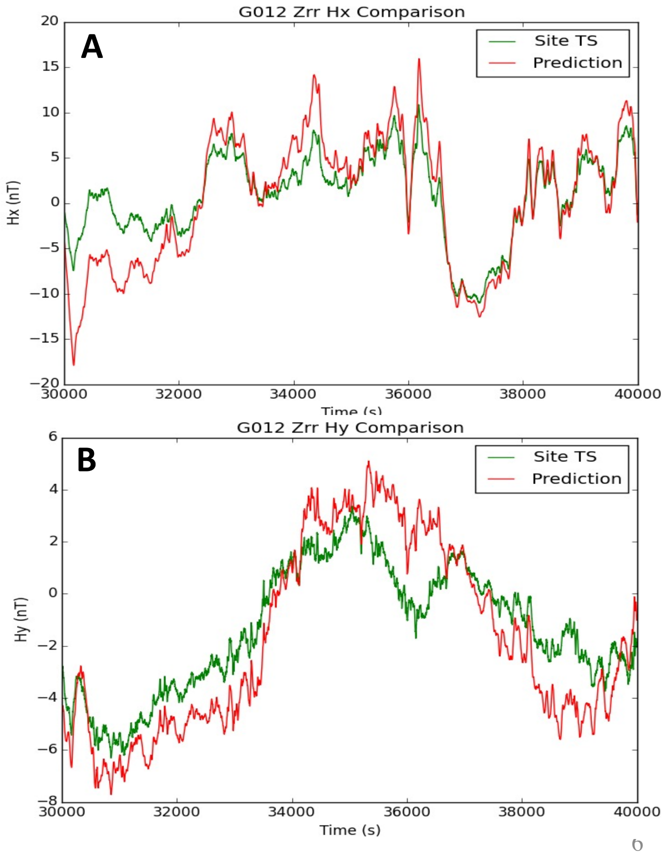
Predicting ground-level magnetic fields

Real-time prediction of the magnetic field near Portland, Oregon by projecting the magnetic fields at magnetic observatories:

- Newport, WA
- Fresno, CA
- Boulder, CO
- Honolulu, HI

through a multi-station transfer function for that location that was determined when the MT station was operating at that site (ref: Bonner & Schultz, 2017)

Given the predicted ground-level B field, the E field is then predicted…



Predicting ground-level electric fields

1. Our approach is to pipe the predicted magnetic fields at the locations of former MT stations through the impedance tensors we obtained for those locations, to obtain the predicted electric fields there

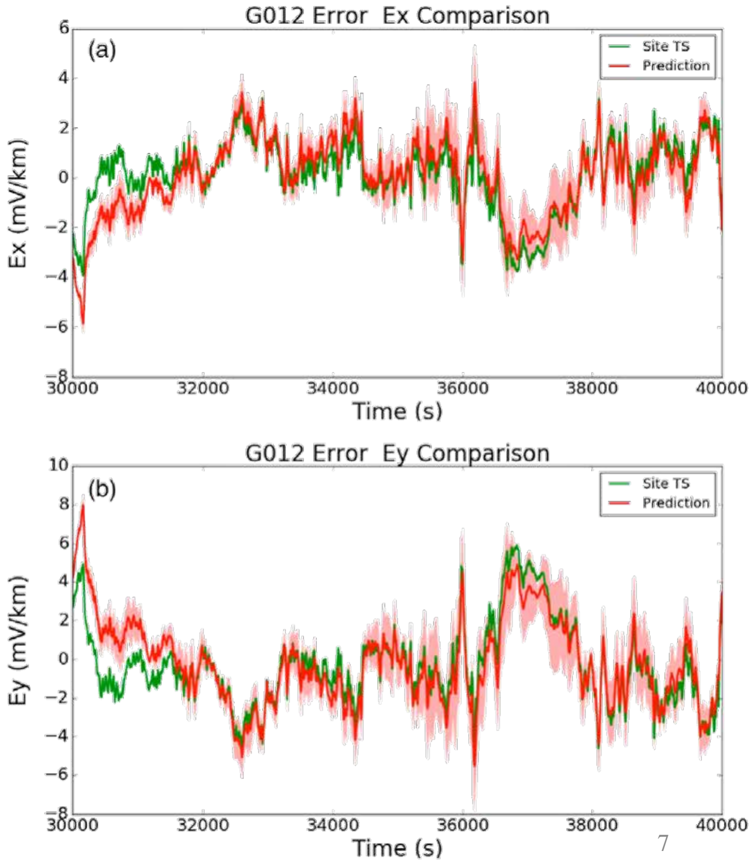
$$\begin{bmatrix} \widetilde{E}_x \\ \widetilde{E}_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} \widetilde{H}_x \\ \widetilde{H}_y \end{bmatrix} + \begin{bmatrix} \widetilde{U}_x \\ \widetilde{U}_y \end{bmatrix}$$

   where the tilde indicates the *predicted* field.

2. We use a distance weighted algorithm to project the predicted electric fields from all the neighboring MT station locations onto each point along the transmission line path.

3. Alternatively one can use 3-D models of ground conductivity derived from inversion of the impedance tensors; solve the forward problem, and derive electric fields on a grid of points. This is the USGS/NOAA approach.

4. For our approach, electric field prediction misfits at most sites are typically around 1–2 mV/km RMS at the great majority of MT sites that we have examined (for modest k_p levels, within the BPA operating area) where the distance to the nearest magnetic observatory is < 600 km.



Given measurements, predictions or forecasts of ground-level electric fields, the vector E fields can be integrated along the power transmission grid line paths and the space weather induced bus voltages used as inputs to an AC/DC powerflow solution – PowerModelsGMD.jl to determine GICs

Julia → PowerModels.jl → PowerModelsGMD.jl

Julia

- Open-source, general purpose dynamic programming language
- High-performance
- Just-in-time
- Well adapted for numerical analysis

PowerModels.jl

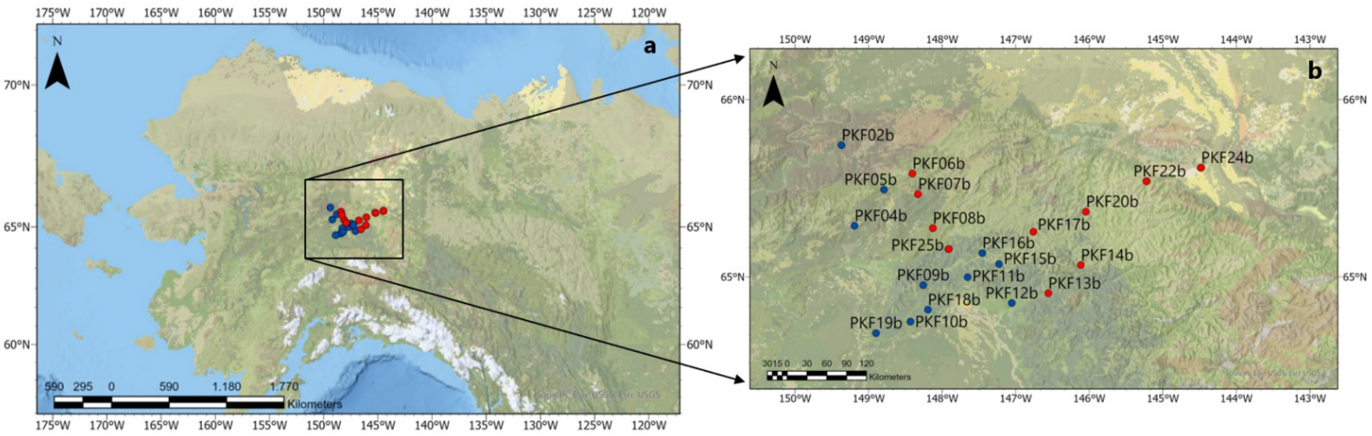
- Julia / JuMP package
- steady-state power network optimization

PowerModelsGMD.jl

- Extensions to PowerModels.jl for quasi-dc line flows and ac power flow problems for GMD/E3 HEMP (Primary author: Arthur Barnes, LANL)
- GIC DC Solve: Solve for steady-state dc currents on lines resulting from induced dc voltages on lines.
- Coupled GIC + AC Optimal Power Flow (OPF): Solve AC-OPF problems for network subjected to GIC.
- The dc network couples to the ac network through reactive power loss in transformers
- Fast and reliable results

Reference: Carleton Coffrin, Russell Bent, Kaarthik Sundar, Yeesian Ng and Miles Lubin, PowerModels.jl: An Open-Source Framework for Exploring Power Flow Formulations, 2018 Power Systems Computation Conference (PSCC), doi: 10.23919/PSCC.2018.8442948} https://github.com/lanl-ansi/PowerModelsGMD.jl

Forecasting ground-level E,B fields and then GICs 15, 30 or more minutes in advance from ground-based observations



(top) We operated a dense, synchronous array of MT stations in the interior of Alaska for several months centered at Poker Flat and extending 300 km E-W and 200 km N-S to test the applicability of the MT "plane wave" assumption used in MT to image the electrical conductivity structure of the crust and mantle, and to do so under the complex ionospheric current systems in the auroral zone, as well as to probe the otherwise unexplored electrical structure of the AK crust and upper mantle. This also afforded us a unique opportunity to see if the temporal-spatial patterns of a complex geomagnetic field in the auroral zone could be used to train a neural network to predict future ground-level magnetic and electric fields.

If this proves feasible, that is by showing the even complex auroral zone fields at ground-level can be forecasted in the near-term from ground-level field measurements, rather like the evolution of conventional weather fronts and pressure patterns as they move across the continent, then by combining the predicted fields with MT impedance data and with power flow models, one might be able provide actionable intelligence to power grid operators alerting them to possible GIC impacts in advance.

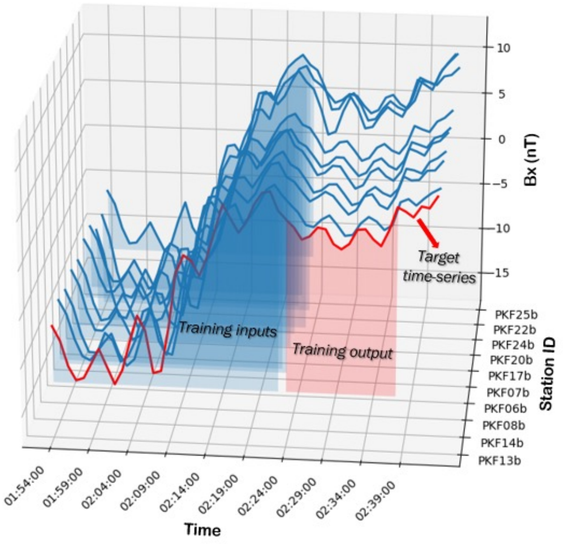
Neural network training sets for forecasting ground-level E,B fields

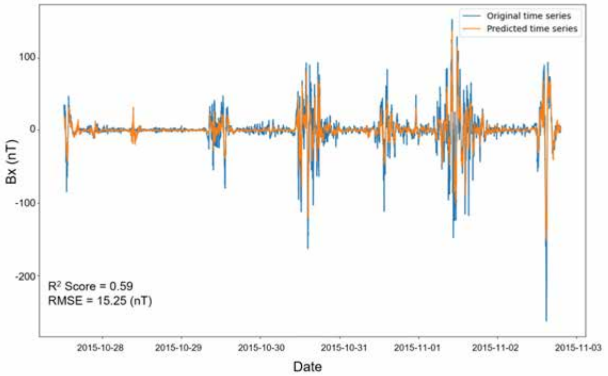
(Right-top) Example of input and output for the electromagnetic time-series. For the sake of brevity, only Bx components are shown here. The blue shadow outlines the input time windows while the red shadow indicates the training output used to predict the next 15 minutes of data.

In the present work, the output or the target is a 15-minutes window of the target time-series while the inputs are windows with the preceding 30 minutes of data for the time-series of all the stations surrounding the target location.

We apply a convolutional neural network (CNN), a multi-layered feed-forward neural network where each layer in the CNN applies different convolutional filters to the same data. The CNN we use is trained to learn a non-linear transfer function between *n* inputs and a target time series including past and future values of the time-series. Details of the algorithm will shortly be submitted in a paper to *Space Weather,* but some results appear here.

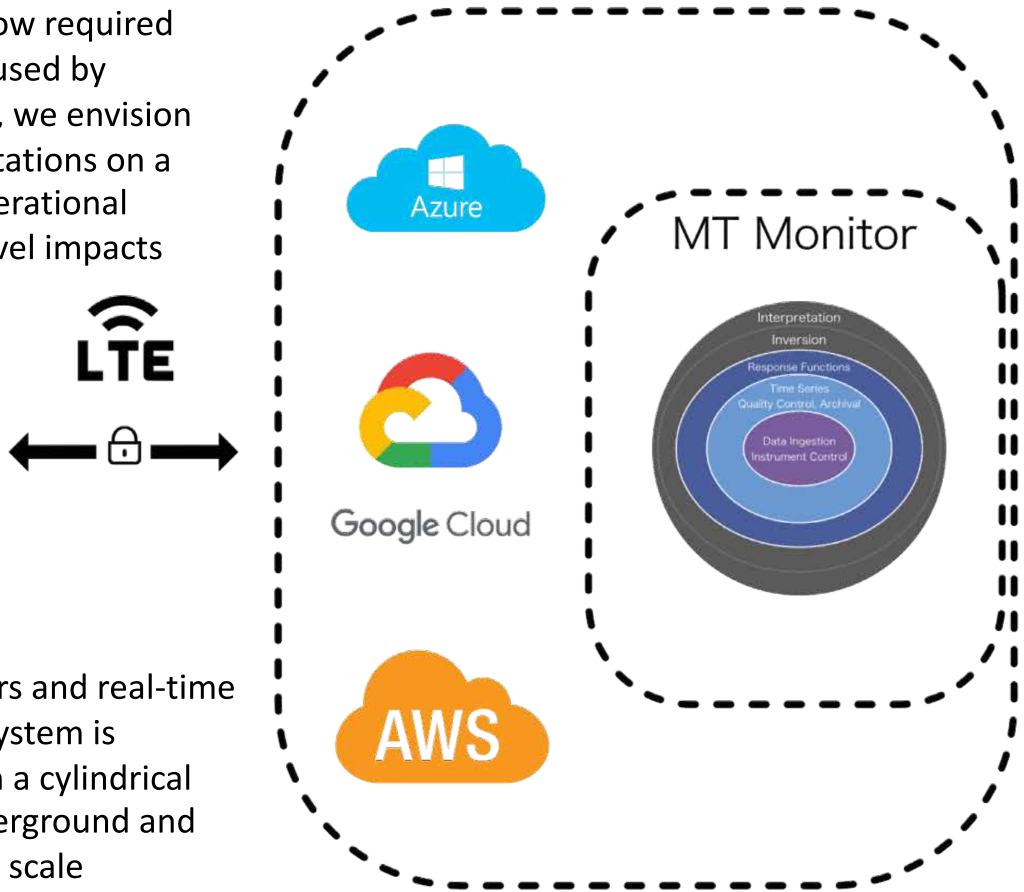
(Right-bottom) CNN prediction of Bx component of magnetic field vs. time (orange) at one of the Alaska interior MT stations plotted against actual time series (blue). The CNN was improved by using successive levels of low-pass filtration to the training set time series, each of which was decimated so lookback horizons of different length were applied to high-frequency and low-frequency content in the data, respectively.





IoMT© [the internet of MT]

To provide the continuous real-time data flow required for forecasting of ground-level E,B fields caused by space weather across the conterminous US, we envision a national network of 400 permanent MT stations on a 140-km grid covering CONUS to provide operational forecasting of GICs in advance of ground-level impacts



We've developed a low-cost cloud synced, MT system (the DART™) with 32-bit digitizers and real-time LTE telemetry, where the data acquisition system is integrated with a fluxgate magnetometer in a cylindrical environmental housing easily installed underground and suitable for such permanent installations at scale

Conclusions

The long-running MTArray program, where ground-level electric and magnetic fields are measured for a period of weeks-to-months at (ultimately) ~1900 locations spanning the conterminous US (CONUS) on a station grid spaced nominally 70-km apart has provided an invaluable collection of MT impedance tensors, frequency-domain quantities that relate measured ground-level vector electric to magnetic fields vs. frequency. The MT impedances can then be used as input to 3-D geophysical inversion algorithms to produce 3-D models of the electrical conductivity of the crust and upper mantle beneath CONUS. The 3-D variations in electrical conductivity (a 3-4 order-of-magnitude variation at any depth within the crust and upper mantle) is the dominant factor governing the intensity of space weather induced electric fields and geomagnetically induced currents in the power grid.

Such 3-D models, or the impedance tensors from which they are derived, allow one to estimate or “predict” the vector electric field at any location within CONUS at any instant of time if one has knowledge of the magnetic field at the former locations of the original MT measurements. We have devised algorithms that can take magnetic field data streams from remote stations and that can predict the magnetic field at any location within CONUS with reasonable fidelity. The B fields are then projected through the MT impedance at that location to obtain predicted E fields that can then be integrated along power line paths and then coupled to power flow solutions for the power grid to determine GIC intensity at each of the high-voltage transformers in the power transmission system. Other derived quantities include transformer heating and vibration, reactive power loss, phase and frequency instability, etc.

By training a convolutional neural network on MT data acquired over a 2-month period from 25 simultaneously operating MT stations in the interior of Alaska under the auroral zone, and by aggregating predictions of ground magnetic fields at any given location within the footprint of the MT array by using progressively longer retrospective time windows for progressively lower frequency bands, we have shown that the ground-level magnetic fields may be forecast ahead of time (15 minutes, 30 minutes or longer) with reasonable fidelity, suggesting that the permanent installation of an array of perhaps 400 MT stations spanning CONUS may provide electric utilities with the capability of forecasting which transformers are likely to be stressed by space weather events sufficiently ahead of time for human intervention in the power grid configuration to take place.

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Disclaimer: The views expressed in this presentation are those of the authors alone and are not to be taken as representing the views of the US government or of the funding agencies.

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