Seismo-electromagnetics: Modelling and Observation

Hong-Jia Chen 24 March 2020 @ NCU, Taiwan

Education:
2008-2010: Master Degree of Earth Science, Department of Earth Sciences, National Central University.
2013-2018: PhD Degree of Earth Science, Department of Earth Sciences, National Central University.

Experience:
2016-2017: Guest PhD Student, ETH Zurich, Switzerland (MOST project).
2019-2020: Postdoc Researcher, Department of Earth Sciences, Graduate School of Science, Chiba University (MOST project).
References


What is seismo-electromagnetics?

- A coupling between mechanics and electromagnetics in the crust
- Various electromagnetic phenomena generated by tectonic forces acting on the earth's crust, associated with seismic activity
- Final goal: to provide a basis for short-term earthquake forecasts

[Hayakawa, 2018]
Literature Survey

Lab Experiments → Seismo-electromagnetics → Field Observations

- Case study
  - Power spectral analysis
    - $P(f) = \alpha f^{-\beta}$

Model Simulations → Scarcity

Possible mechanism:
- Peroxy-defect theory
- Piezoelectricity
- Electrokinetics

[Freund et al., 2009]

[Eftaxias et al., 2003]
Chen-Ouillon-Sornette (COS) model

Seismo-electric model:

- Crustal mechanics: Burridge-Knopoff spring-block model
- Crustal electricity: ???
- Rock-fracturing experiment: positive relationship between stress & voltage

Mechanical component

Electrical component

How to couple with?

[Mavromatou et al., 2004]

[Burridge & Knopoff, 1967]

[Freund, 2007]
Single-block COS model

Basic principles:

1. Kirchhoff’s voltage law
   \[ V_{in} - \hat{r}i_r - \frac{q}{\hat{c}} = 0. \]

2. Current-charge relation
   \[ i_c = \frac{dq}{dt}. \]

3. Kirchhoff’s current law
   \[ i_r = I + i_c. \]

4. Equality for the grounded part
   \[ I + \hat{L}\frac{dl}{dt} = \frac{q}{\hat{c}}. \]
Ranges of the Mechanical-Electrical Coefficient:

\[ V_{in}(\tau) = \beta \cdot \tau \]

\( \beta \) is the ratio of voltage to stress, depending on materials and physical conditions, such as saturation, porosity, and temperature.

In this study, \( \beta = 1 \).

<table>
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<tr>
<th>參考文獻</th>
<th>岩樣</th>
<th>應力(MPa)</th>
<th>電壓(mV)</th>
<th>( \beta ) 值</th>
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</table>
Analytic Solution

Laplace transform

\[ 1 - \hat{r}\hat{c} - \frac{\hat{q}}{\hat{c}} = 0, \]
\[ \hat{\zeta}_c = s\hat{q}, \]
\[ \hat{\zeta}_r = \hat{I} + \hat{\zeta}_c, \]
\[ \hat{I} + \hat{L}\hat{s}\hat{I} = \frac{\hat{q}}{\hat{c}}. \]

\[ \hat{q}(s) = \frac{(s+\frac{1}{s})}{\hat{r}s^2 + (\frac{1}{\hat{r}\hat{c}} + \frac{1}{\hat{c}\hat{L}})s + (\frac{1}{\hat{r}\hat{c}} + \frac{1}{\hat{c}\hat{L}})}. \]

\[ \hat{\zeta} = \frac{1}{\hat{r}\hat{c}} + \frac{1}{\hat{L}}, \quad \eta = \frac{1}{\hat{r}\hat{L}} + \frac{1}{\hat{c}\hat{L}}, \quad \text{and} \quad \Delta = \xi^2 - 4\eta. \]

The determinant forms an electric phase space.

\[ \Delta(r_c, c_c, L_c) = 0 \]

Case 1 ($\Delta > 0$) - overdamping solution:

\[ q_{gf}^{(od)}(t) = \frac{e^{-\xi\sqrt{\eta}}}{\hat{r}\sqrt{\Delta}} \left( \frac{\xi}{\hat{r}} + \frac{1}{\sqrt{\Delta}} \right) + \frac{1}{\hat{r}}. \]

Case 2 ($\Delta = 0$) - critical damping solution:

\[ q_{gf}^{(cd)}(t) = \frac{e^{-\xi t}}{\hat{r}} \left( \frac{\xi}{\hat{r}} + 1 \right) + 1. \]

Case 3 ($\Delta < 0$) - underdamping solution:

\[ q_{gf}^{(ud)}(t) = \frac{e^{-\xi t}}{\omega t} \left( \frac{\xi}{\hat{r}} + \frac{1}{\sqrt{\Delta}} \right) + 1. \]

<table>
<thead>
<tr>
<th>Set</th>
<th>$\hat{r}$</th>
<th>$\hat{c}$</th>
<th>$\hat{L}$</th>
<th>Damping Region</th>
<th>$\xi$</th>
<th>$\eta$</th>
<th>$\Delta$</th>
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<td>0.414</td>
<td>3.43E-4</td>
<td>3.45E-4</td>
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</table>
Multi-blocks COS model

Stress-induced voltage:

\[ V_{\text{ink}}(\tau_k) = p_{dk}\beta_k\tau_k, \]

\[ p_{dk} = \begin{cases} 1, & \tau_{k-1} \geq \tau_{k+1} \\ -1, & \tau_{k-1} \leq \tau_{k+1} \end{cases} \]

(1) Kirchhoff’s voltage law

\[ \begin{align*}
V_{in1} - i_{r1}r_1 - \frac{q_1}{c_1} &= 0 \\
V_{in_k} - i_{r_k}r_k - \frac{q_k}{c_k} + \frac{q_{k-1}}{c_{k-1}} &= 0, & k = 2 \text{ to } N
\end{align*} \]

(2) Current-charge relation

\[ i_{ck} = \frac{dq_k}{dt}, \quad k = 1 \text{ to } N. \]

(3) Kirchhoff’s current law

\[ \begin{align*}
i_{r1} = I_k + i_{ck} + i_{r(k+1)}, & \quad k = 1 \text{ to } N - 1 \\
i_{rN} = I_N + i_{cN}
\end{align*} \]

(4) Equality for the grounded part

\[ \begin{align*}
l_1R_1 + \frac{dl_1}{dt}l_1 &= V_{in1} - i_{r1}r_1 \\
l_kR_k + \frac{dl_k}{dt}l_k - l_{k-1}R_{k-1} - \frac{dl_{k-1}}{dt}l_{k-1} &= V_{in_k} - i_{r_k}r_k, & k = 2 \text{ to } N
\end{align*} \]

(5) Total voltage of the system

\[ V_{SB} = \frac{1}{N} \sum_{k=1}^{N} \left( R_kI_k + L_k \frac{dl_k}{dt} \right) = \frac{1}{N} \sum_{k=1}^{N} \frac{q_k}{c_k}. \]
1) Q2 > Q1: small events generate most of small voltage fluctuations.
2) Q4 > Q3: large events do not usually generate large voltage variance.
3) Transition: between the upper and lower UD.
Electric signals:
1) be skewed by fracture-induced signals
2) be concentrated by fracture-induced signals
1) Transition: between the upper and lower UD
2) Local stress states change earth electrokinetic states in different earthquake preparation phases

\[ P(f) = af^{-b} \]

Simulations

Observations

[Refs: Eftaxias et al., 2003]
Summary of COS Model Analysis

- **Seismoelectric model**: spring-block system (mechanical component) + RLC circuit system (electrokinetic component), provides general theoretical framework for modeling and analyzing geoelectric precursors to earthquakes.

- Explanation:
  1) Skewness and kurtosis anomalies
  2) PSD’s power-law exponent transitions prior to large earthquakes.

- Precursory electromagnetic signals may be observed before large events if
  1) there are **small foreshocks**, i.e. small earthquakes that would be **too small to be detected seismically**;
  2) the **local electrokinetic damping conditions** allow them to leave a measurable electromagnetic fingerprint.
Observation (I): Long-term Behavior for Correlations between Mechanics and Electrics in the Crust

Purpose:
Analyzing self-potential signals related to natural and anthropogenic factors

Data:

- **Self-potential:**
  - 20 stations evenly distributed in Taiwan
  - sampling rate: 15 points per second
  - from 2012 to 2017

- **Earthquake:**
  - all events
  - from 2012 to 2017

- **GPS:**
  - from 2012 to 2017
  - downloaded from the GPSLAB
  - processed with GIPSY-OASIS software

- **Urbanization:**
  - values from 1 to 5
  - estimated by Huang et al., 2018
Take the average for $\beta$ with $R^2>0.8$:

$\beta_{WD,NS} = 1.48 \pm 0.26$

$\beta_{WD,EW} = 1.42 \pm 0.31$

The average $\beta$ with different frequency bands will be calculated.
Spatial Distributions of SP Exponent, b-value, and Dilation Rate

Self-potential power-law exponent $\beta_{NT, EW}$ with $f = 0.001$ - $0.1$ Hz

Gutenberg-Richter b-value
Epicentral distance to stations: $R_{thr} = 50$ km

Dilation strain rate
Self-potential power-law parameters with $f = 0.001 - 0.1$ Hz

Correlation Matrix EW

<table>
<thead>
<tr>
<th>$\alpha_{WD}$</th>
<th>$\beta_{WD}$</th>
<th>$\alpha_{DT}$</th>
<th>$\beta_{DT}$</th>
<th>$\alpha_{NT}$</th>
<th>$\beta_{NT}$</th>
<th>$U$</th>
<th>$b$</th>
<th>$D$</th>
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<tr>
<td>1.00</td>
<td>-0.35</td>
<td>0.92</td>
<td>-0.39</td>
<td>0.89</td>
<td>-0.19</td>
<td>-0.04</td>
<td>0.07</td>
<td>0.08</td>
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<td>-0.35</td>
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<td>-0.22</td>
<td>0.81</td>
<td>-0.12</td>
<td>0.88</td>
<td>0.09</td>
<td>-0.03</td>
<td>0.00</td>
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<tr>
<td>0.92</td>
<td>-0.22</td>
<td>1.00</td>
<td>-0.44</td>
<td>0.81</td>
<td>-0.08</td>
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<td>0.81</td>
<td>-0.44</td>
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<td>0.89</td>
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<td>0.81</td>
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<td>-0.30</td>
<td>0.00</td>
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<tr>
<td>-0.19</td>
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<td>0.74</td>
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<td>1.00</td>
<td>-0.48</td>
<td>0.30</td>
<td>0.03</td>
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<tr>
<td>U</td>
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<tr>
<td>b</td>
<td>0.07</td>
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<td>0.08</td>
<td>0.03</td>
<td>0.02</td>
<td>0.30</td>
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<td>D</td>
<td>-0.08</td>
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Correlation Matrix NS

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<th>$\alpha_{DT}$</th>
<th>$\beta_{DT}$</th>
<th>$\alpha_{NT}$</th>
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<th>$b$</th>
<th>$D$</th>
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<td>0.18</td>
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<td>-0.13</td>
<td>0.27</td>
<td>0.10</td>
<td>0.41</td>
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</table>
Summary of Long-term Seismo-Electromagnetic Behavior

• The moderate correlation exists between b-value and dilation rate, in agreement with a fact that crustal deformation affects the fractal behavior in the crust (Öncel & Wilson, 2004).

• The self-potential signals with $f = 0.006-1$ Hz are correlated with mechanics in the crust, but less correlated with human-made noises.

• The determination of the optimal frequency band allows us to filter and screen the self-potential signals and improve the quality of the analyses.
Observation (II): Pre-earthquake Anomalies of Geoelectric Monitoring System (GEMS)

Purpose:
(1) To test relationships between geoelectrics and earthquakes
(2) To build up short-term earthquake forecasts

Data:
- **GEMS:**
  - 20 stations evenly distributed in Taiwan
  - Continuous, real time data
  - from 2012 to 2016

- **Earthquake:**
  - 105 $M_L \geq 5$ EQKs
  - from 2012 to 2016
Data Analysis of Geoelectric Time Series

Histogram of the series

2013/03 PULI

2013/03/06

Selected Statistics

- Mean
- Variance (V): Broadness
- Skewness (S): Symmetry
- Kurtosis (K): Tailedness

Mean = -65.79
V = 16.87
S = 0.19
K = 9.20

\[
V = \frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n - 1}
\]

\[
S = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \mu)^3} \left( \frac{1}{\sqrt{n}} \sum_{i=1}^{n} (x_i - \mu)^2 \right)^{3/2}
\]

\[
K = \frac{1}{n} \sum_{i=1}^{n} (x_i - \mu)^4 \left( \frac{1}{n} \sum_{i=1}^{n} (x_i - \mu)^2 \right)^2
\]
Statistical time series for 2013 Puli M6 EQs

1. Skewness and kurtosis appear anomalous before the two M6 earthquakes.
2. The crustal system undergo critical states in the earthquake preparation process.

For 2013/3/27 M6 EQ,
[1] Distance: ~21km
[2] Lead Time: 21days
[3] Anomaly Ratio: 7days/30days

For 2013/6/2 M6 EQ,
[1] Distance: ~16km
[2] Lead Time: 12days
[3] Anomaly Ratio: 19days/30days
Geoelectric Monitoring System’s Time of Increased Probability (GEMSTIP): **Two-phase optimization**

**Drawback in previous studies:**
- **Case Study:** No significance
- **Superposed Epoch Analysis:** Ignoring false alarms
- **One-Phase Optimization:** No testing study; Retrospective studies only in “training phases”

**In this study**

1. After the training phase, **true forecasts** can be proposed, which consist in selecting the optimal model parameters and applying them to an independent dataset.
2. Any prediction/forecasting method should be qualified by its reliability and skill within at least two independent phases: a training phase and a testing phase.
Step 1: Data & Targets

Data: Skewness and Kurtosis of geoelectric signals
Targets: Earthquakes with $M_L \geq 5$

Full Dataset

Training phase

Forecasting phase

Onset Time: 2016/12/31

End Time: 2016/12/31
Step 2: Predictive Model

Model free parameters:

\[ g = (M_c, R_c, A_{thr}, N_{thr}, T_{thr}, T_{obs}, T_{lead}, T_{pred}) \]

Definition of Time of Increased Probability (TIP):
1) Median±\(A_{thr} \times IQR\): Define an index as anomaly
2) Anomalous index number (AIN) ≥ \(N_{thr}\): Label one day as an anomalous day
3) Anomalous days ≥ \(T_{thr}\) within \(T_{obs}\): Alarm \(T_{pred}\) as TIP

Definition of Target Earthquake (EQK):
1) Select magnitude-\(M_c\)-above EQK
2) Select source-to-station distances within \(R_c\) km.
Model free parameters:

\[ g = [M_c, R_c, A_{thr}, N_{thr}, T_{thr}, T_{obs}, T_{lead}, T_{pred}] \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</tr>
<tr>
<td>(N_{thr})</td>
<td>1-4</td>
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<tr>
<td>(A_{thr})</td>
<td>1-10</td>
</tr>
<tr>
<td>(P_{thr})</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>(T_{thr})</td>
<td>([P_{thr} \times T_{obs}]) (day)</td>
</tr>
<tr>
<td>(T_{obs})</td>
<td>5-100 (day)</td>
</tr>
<tr>
<td>(T_{pred})</td>
<td>1 (day)</td>
</tr>
<tr>
<td>(T_{lead})</td>
<td>0-100 (day)</td>
</tr>
</tbody>
</table>

At a certain \(g\),

\[
Q(t | g) = \begin{cases} 
Q(t = t_i) = 1, & \text{if } M_{Li} \geq M_c \land \| (x_i, y_i, z_i) - (x_{sta}, y_{sta}, 0) \| \leq R_c, i = 1 \text{ to } N_{EQ} \\
Q = 0, & \text{otherwise}
\end{cases}
\]

\[
T_{TIP}(t | g) = \begin{cases} 
T_{TIP}(t = t_i + T_{lead} \text{ to } t_i + T_{lead} + T_{pred}) = 1, & \text{if } F_{SAT}(t_i) \geq T_{thr} \\
T_{TIP}(t = t_i + T_{lead} \text{ to } t_i + T_{lead} + T_{pred}) = 0, & \text{if } F_{SAT}(t_i) < T_{thr}
\end{cases}
\]

1: Alarm
0: No alarm

1: Earthquake
0: No earthquake

1) Generate millions of parameter combinations \(g\).
2) Estimate performance of each \(g\) by comparing the predicted time-space grids and the observed grids.

**EQK(Q)**

| 1 0 0 1 0 1 0 0 1 …. |

**TIP**

| 1 0 0 1 0 1 0 0 1 …. |
Molchan Diagram

Single station method

1) Fraction of missing EQKs

\[ n(g) = \frac{\sum_t \mathbb{1}(TIP(t|g)=0 \& EQK(t|g)=1)}{\sum_t \mathbb{1}(TIP(t|g)=0 \& EQK(t|g)=1)} \]

2) Fraction of alarmed cells

\[ \tau(g) = \frac{\sum_t \mathbb{1}(TIP(t|g)=1)}{\sum_t \mathbb{1}(TIP(t|g)=1)} \]

3) Loss function of a parameter set

\[ d(g) = 1 - \tau(g) - n(g) \]

The quantity \( d \) is the distance from a point to the random guess line.
1) \( d > 0 \) means the performance is better than random.
2) \( d = 0 \) means the performance is random.
3) \( d < 0 \) means the performance is worse than random.

The model is significant when \( d > d_{CB}^{\text{max}} \).

1) Under the confidence bound: Parameters mean informative
2) Molchan diagram: Evaluate whether a prediction strategy is good
Results (I): Choice of phase lengths

Optimal length:
1) Training phase ~1000-1200 days
2) Forecasting phase ~90-180 days
Results (II): Choice of frequency band

High-pass filter:
\[ |H(f)| = \begin{cases} 1, & |f| < f_c \\ 0, & |f| > f_c \end{cases} \]

Low-pass filter:
\[ |H(f)| = \begin{cases} 0, & |f| < f_c \\ 1, & |f| > f_c \end{cases} \]

\( f_c = 10^{-4.0:0.25:-0.5} \) Hz

Earthquake-related signal:
1) High S/N ratio
2) Constrain the prediction model stably

Band-pass filter:
\[ |H(f)| = \begin{cases} 1, & f_1 < |f| < f_2 \\ 0, & \text{otherwise} \end{cases} \]

(1) \( 10^{-4.0} \leq f \leq 10^{-1.75} \) Hz
(T=~1min~3hr, optimal band)

(2) \( 10^{-3.5} \leq f \leq 10^{-1.75} \) Hz
(T=~1min~1hr, for control group)

Periods:
1) Training: Onset-2015/3/31
2) Forecast: 2015/4/1-2015/6/30
Results (III): Precursor-based Earthquake Probability Forecasts

Construct earthquake-forecasting probability $P(x,y,t)$ using True Positive Rate (TPR, $v=1-n$) multiplied by TIP.

$$P(x,y,t) = \frac{1}{N_{\text{top}}} \sum_{i=1}^{N_{\text{top}}} v(G_i) \cdot TIP(x,y,t|G_i),$$
Summary of GEMSTIP Analysis

• Quantitative examination: Testing relationships between geoelectric field statistics and earthquakes.

• Significance tests: Seismo-electric relationship objectively exists.

• Optimal frequency band \((10^{-4.0} \leq f \leq 10^{-1.75} \text{ Hz, } T=\sim1\text{ min}-\sim3\text{ hr})\): Earthquake-related signals with high S/N ratio
Observation (III): Pre-earthquake anomalies at Kakioka, Japan

**Purpose:**
1. To confirm the GEMSTIP algorithm can be valid for other regions
2. To improve the way of selecting optimal model parameters

**Data:**
- **Kakioka station (KAK):**
  - location: 36.23°N, 140.1°E
  - self-potential data
  - sampling rate: 1 point per minute
  - from 1993 to 2018

- **Earthquake:**
  - 488 $M_L \geq 5$ EQKs
  - from 1993 to 2018

Time: 19930101-20181231
☆ EQK of $M=\{5,6\}$
★ EQK of $M=\{6,7\}$
★☆ EQK of $M\geq 7$
Geoelectric time series

The nighttime data has less noises than the daytime data.
In this study we calculate variance, skewness, and kurtosis by using nighttime data.
Variance-Skewness-Kurtosis Time Series

Time series of V, S, K with their thresholds:
MD $\pm A_{thr} \times IQR$

Threshold:
Window length = 1000 days
$A_{thr} = 2$

EQ selection:
$M_{thr} = 5$
$R_{thr} = 100$ km
Anomaly Index Number (AIN) & Superposed Epoch Analysis (SEA)

Time series of AIN for V, S, and K
Thresholds: MD $\pm$ Athr*IQR
$A_{thr} = 1, 2, \text{ and } 3$

EQ selection:
$M_{thr} = 6$
$R_{thr} = 100 \text{ km}$

SEA finds that anomalies are highly likely to occur **6 and 58 days** before strong earthquakes
Predictive Model

Model parameter:

\[ \mathbf{g} = [M_{thr}, R_{thr}, A_{thr}, P_{thr}, T_{obs}, T_{lead}, T_{pred}] \]

Target events:

\[ F_{\text{obs}}(t | \mathbf{g}) = B[(r_i \leq R_{thr}) \cdot (m_i \geq M_{thr}) \cdot (t = t_i)], t \in [t_s, t_e] \]

Time of increased probability (TIP):

\[ \theta_u(t; y) = \text{Median}(y_i) + A_{thr} \cdot IQR(y_i), i \in [t - \Delta t, t] \]

\[ \theta_l(t; y) = \text{Median}(y_i) - A_{thr} \cdot IQR(y_i), i \in [t - \Delta t, t] \]

\[ N_{\text{AIN}}(t | \mathbf{g}) = \sum_y B[(y(t) > \theta_u(t; y)) + (y(t) < \theta_l(t; y))] \]

\[ \bar{N}_{\text{AIN},T_{\text{obs}}}(t | \mathbf{g}) = \frac{\sum_{t=\Delta t-T_{\text{obs}}+1}^{T_{\text{obs}}-T_{\text{obs}}} N_{\text{AIN}}(i | \mathbf{g})}{T_{\text{obs}}} \]

\[ R_{\text{AIN},T_{\text{obs}}}(t | \mathbf{g}) = \frac{\bar{N}_{\text{AIN},T_{\text{obs}}}(t | \mathbf{g})}{\max_{t \in [t_s, t_e]} \bar{N}_{\text{AIN},T_{\text{obs}}}(t | \mathbf{g})} \]

\[ F_{\text{at}}(t | \mathbf{g}) = B[R_{\text{AIN},T_{\text{obs}}}(t | \mathbf{g}) \geq P_{thr}] \]

\[ F_{\text{tip}}(t | \mathbf{g}) = B[(t = t_i|_{F_{\text{at}} = 1} + T_{\text{lead}} + 1) + (t = t_i|_{F_{\text{at}} = 1} + T_{\text{lead}} + 2) + \ldots + (t = t_i|_{F_{\text{at}} = 1} + T_{\text{lead}} + T_{\text{pred}})], t \in [t_s, t_e] \]
**Performance Score**

Ratio of alarmed cells

\[
\tau(g) = \frac{\sum_t F_{tip}(t | g)}{\sum_t B[F_{tip}(t | g) \geq 0]}
\]

Ratio of missed events

\[
n(g) = \frac{\sum_t B[(F_{tip}(t | g) = 0) \cdot (F_{obs}(t | g) = 1)]}{\sum_t B[(F_{tip}(t | g) \geq 0) \cdot (F_{obs}(t | g) = 1)]}
\]

Loss function:

\[
d(g) = 1 - \tau(g) - n(g)
\]

Maximum loss function

\[
D = \max_{i=1 \to N_{OM}} \{d(\tilde{g}_i; frc)\}
\]

Maximum probability gain

\[
PG = \max_{i=1 \to N_{OM}} \left\{ \frac{1 - n(\tilde{g}_i; frc)}{\tau(\tilde{g}_i; frc)} \right\}
\]

Ratio of numbers of positive to negative models

\[
\rho = \frac{\sum_{i=1}^{N_{OM}} B[d(\tilde{g}_i; frc) > 1]}{\sum_{i=1}^{N_{OM}} B[d(\tilde{g}_i; frc) < 1]}
\]
## Forecasting Performance

<table>
<thead>
<tr>
<th>Case</th>
<th>Training phase</th>
<th>Validation phase</th>
<th>Forecasting phase</th>
<th>PG</th>
<th>D</th>
<th>p</th>
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<td>1994/1/1-1996/12/31</td>
<td>1997/1/1-1997/12/31</td>
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<td>0.39</td>
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<td>1999/1/1-1999/12/31</td>
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<td>0.42</td>
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<tr>
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<td>1997/1/1-1999/12/31</td>
<td>2000/1/1-2000/12/31</td>
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<td>0.41</td>
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<td>0.34</td>
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<td>2007/1/1-2009/12/31</td>
<td>2010/1/1-2010/12/31</td>
<td>15.21</td>
<td>0.93</td>
<td>0.83</td>
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<tr>
<td>15</td>
<td>2007/1/1-2009/12/31</td>
<td>2008/1/1-2010/12/31</td>
<td>2011/1/1-2011/12/31</td>
<td>1.71</td>
<td>0.41</td>
<td>1.49</td>
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<tr>
<td>16</td>
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<td>2013/1/1-2013/12/31</td>
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<td>0.14</td>
<td>0.88</td>
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<tr>
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<td>2011/1/1-2013/12/31</td>
<td>2014/1/1-2014/12/31</td>
<td>6.76</td>
<td>0.85</td>
<td>1.42</td>
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<tr>
<td>19</td>
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<td>2015/1/1-2015/12/31</td>
<td>3.38</td>
<td>0.55</td>
<td>4.08</td>
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<tr>
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<td>2013/1/1-2015/12/31</td>
<td>2016/1/1-2016/12/31</td>
<td>1.51</td>
<td>0.22</td>
<td>0.12</td>
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<tr>
<td>21</td>
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<td>2014/1/1-2016/12/31</td>
<td>2017/1/1-2017/12/31</td>
<td>1.4</td>
<td>0.14</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Average D = 0.49
Average PG = 3.68
p>1 case: 14 out of 22
Forecasting Probability & Optimal model parameters

Positive case

\[ P(t|G; frc) = \frac{\sum_{i=1}^{N_G} f_{typ}(t|\hat{G}_i; frc) \cdot \bar{v}(\hat{G}_i) \cdot w(\hat{G}_i)}{\sum_{i=1}^{N_G} w(\hat{G}_i)} \]

\[ \bar{v}(\hat{G}) = 1 - \pi(\hat{G}) \]

\[ w(\hat{G}) = 1 - \bar{r}(\hat{G}) \]

Negative case

Case 19
Summary of Pre-seismic Anomalies

• Pre-seismic anomalies for self-potential variance, skewness, and kurtosis are investigated and verified at Kakioka, Japan.

• The predictive model parameter can be optimized and selected through model scores of the training phase and validation phase.

• The optimal model parameters can be well-performed. There are 14 positive cases out of 22 cases through 26-year long-term analysis.
Conclusions

• Seismo-electric model (Chen-Ouillon-Sornette model)
  1) explains transient EM anomalies before large EQKs, such as skewness and kurtosis anomalies, PSD power-law exponent transitions.
  2) explains cases of no prominent EM anomalies before large EQKs

• For long-term average behavior, the self-potential signals with $f = 0.006-1$ Hz are correlated with mechanics in the crust, but less correlated with human-made noises.
Conclusions

• GEMSTIP algorithm
  1) provides a quantitative examination of relationships between geoelectric field statistics and earthquakes.
  2) provides significance tests for seismo-electric relationship objectively existing.
  3) determines $10^{-4.0} \leq f \leq 10^{-1.75}$ Hz ($T=\sim1\text{min}$$\sim3\text{hr}$) as the frequency bands with high S/N ratio.

• GEMSTIP algorithm is valid for the Taiwan and Japan regions. This means the geoelectric data distributions universally deviate from normal distributions before earthquakes.
Future Studies

➢ For physical perspectives, we need to further study the coupling between mechanics and electromagnetics in the crust
  • Geomagnetic and geoelectric data versus strain rates
  • Geomagnetic and geoelectric data versus seismic velocity ratio
  • Geomagnetic and geoelectric data versus attenuation ratio (Q)

➢ For model simulations, we have to consider the foreshock and aftershock effects into the stick-slip models.
Future Studies

- For statistical perspectives, we should test other precursory indices proposed by earlier studies, such as natural time analysis, principle component analysis, and network topology analysis.

- The logic of our future work:
  - The multi-phenomena nature of earthquake precursors
  - A unifying theory in terms of stress activation of mobile electric charges
  - Continuous multi-observational, multi-dimensional monitoring
  - Multi-dimensional analyses and synthesis of precursors
  - A decision-making process towards operational and practical forecasts

Thank you for listening!