ULF electromagnetic signature possibly generated under the ground

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- Introduction
- Interstation transfer function (ISTF)
  - Variation of ISTF
  - Noise reduction (global) with using ISTF
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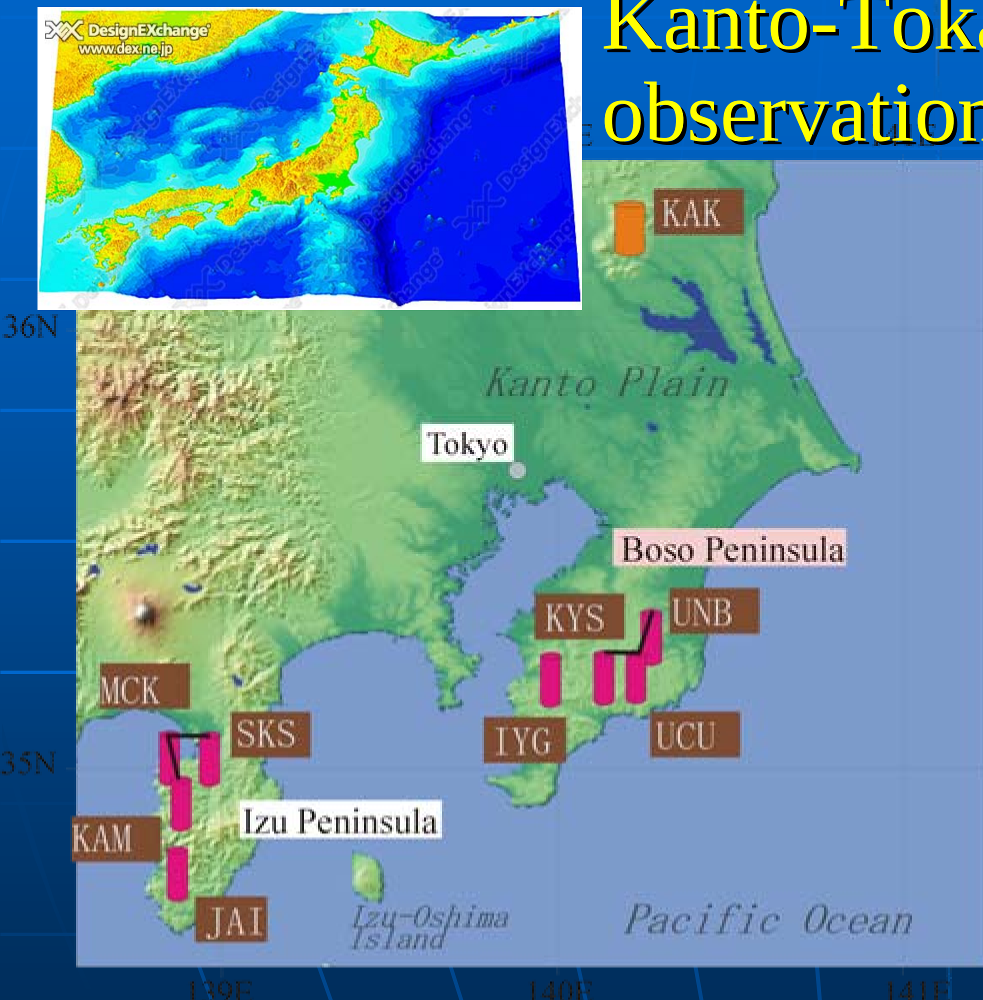
(1) Introduction

Kanto-Tokai ULF electro-magnetic observation network



Instrument： Torsion-type magnetometer
（Manufactured by SPbF IZMIRA

Data：
Magnetic Field : 3 components
(NS,EW, Vertical)
Electric Potential Difference: 2 channe

Sampling ： 50Hz (0.02 s)

Clock： Synchronized by GPS clock

Array with intersensor distance of 5km at Boso and IzuPeninsula.
3 Mag. and 2 Elec. fields are observed

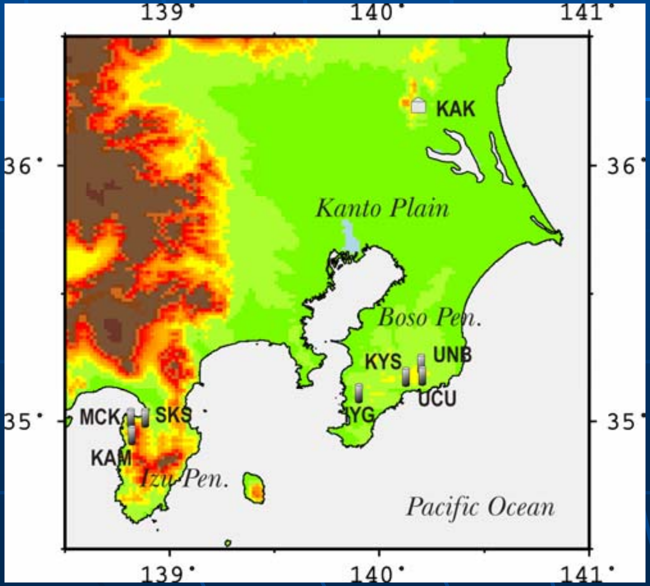
Reference station：
Kakioka Magnetic Observatory
(Japan Meteorological Agency)
- Fluxgate type
- Sampling = 1Hz

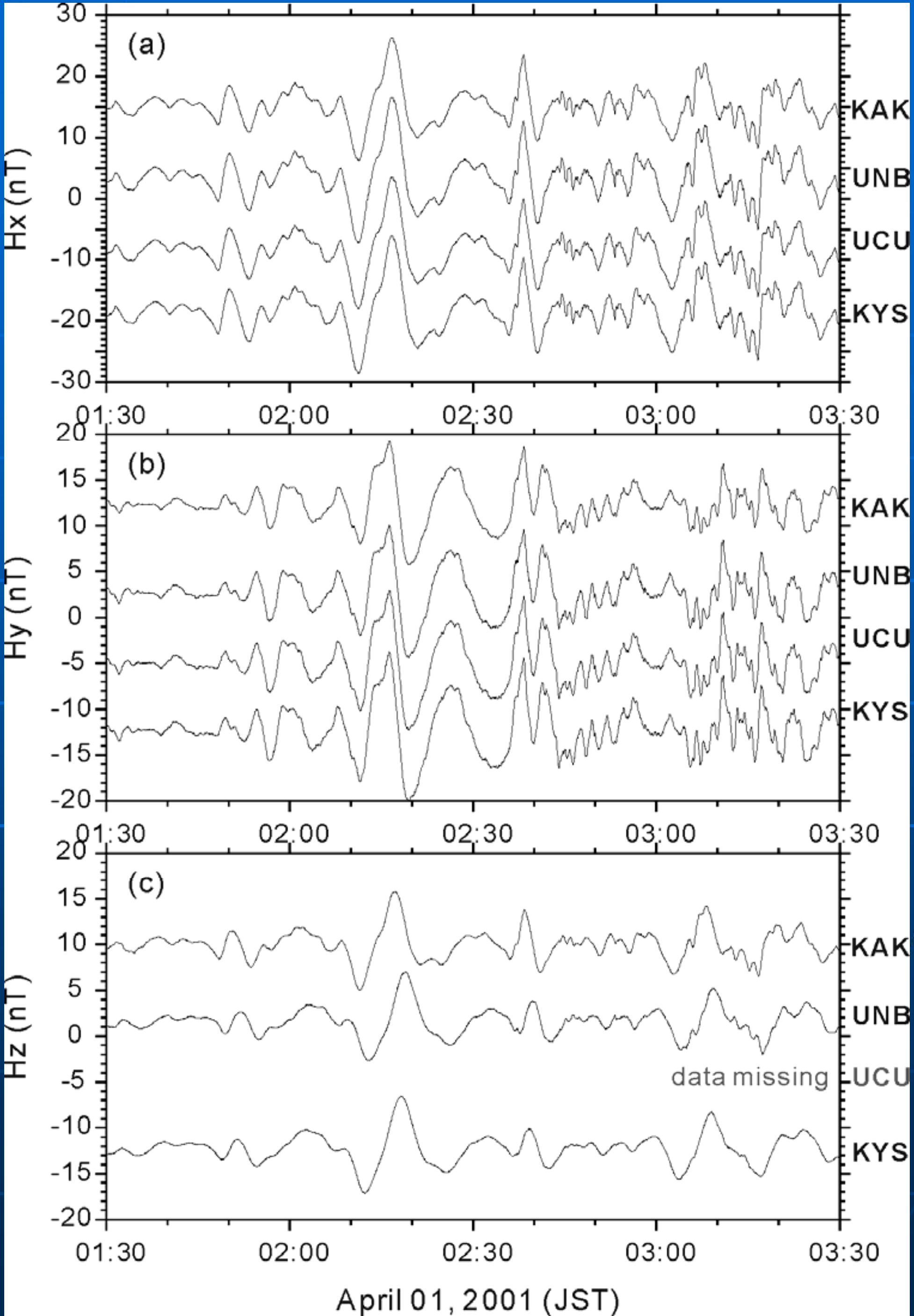
Boso Pen. UNB, UCU, KYS, IYG
Izu Pen. SKS, MCK, KAM, JAI

An example of observed magnetic data

April 1, 2001
  01:30 – 04:30 (JST)
  Sampling rate 1.0Hz
  T ≦940 s (high-pass filtered)

ULF station ： UNB, UCU, KYS
Reference site ： KAK （Kakioka）

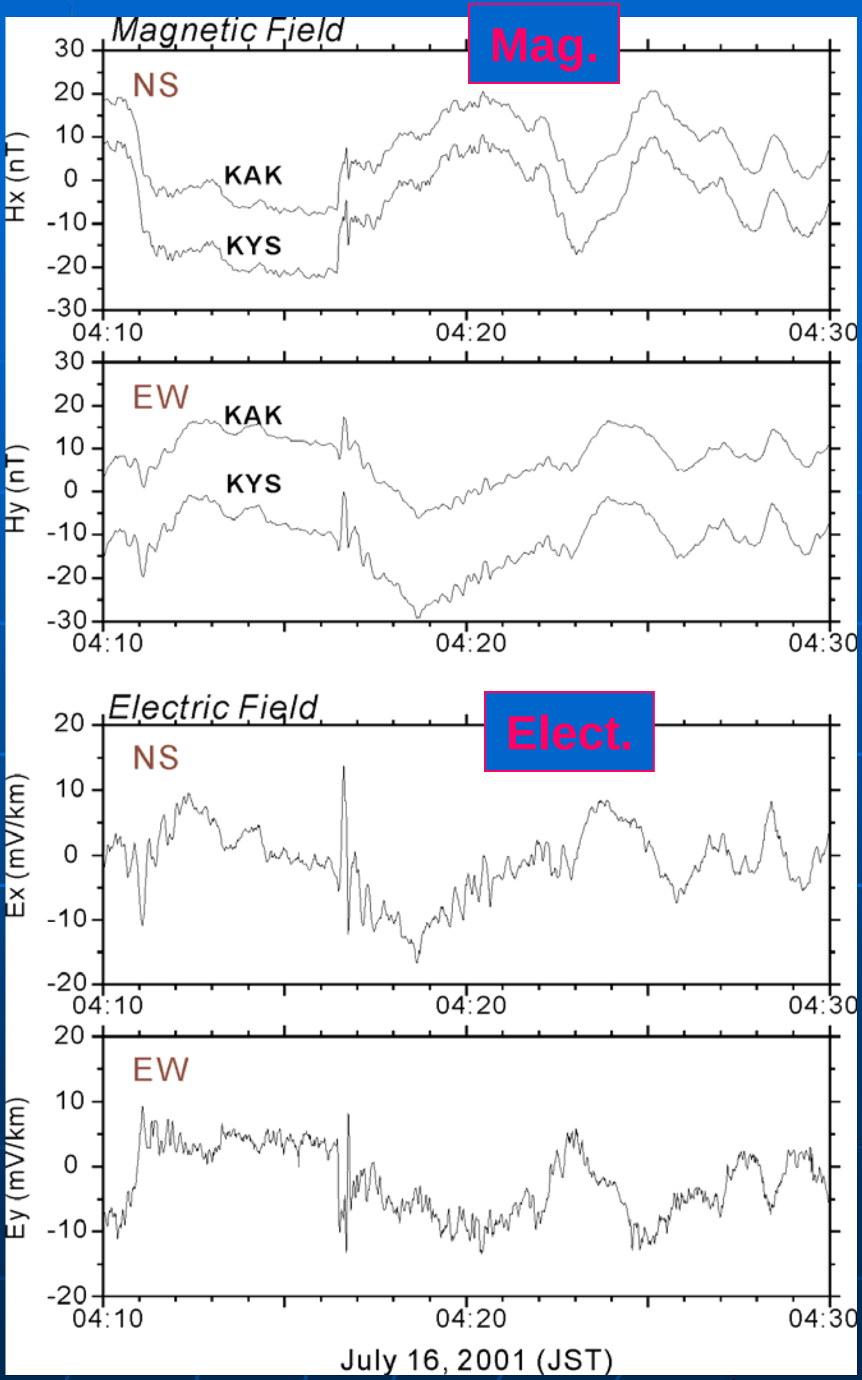




An example of observed magnetic and electric field data

Magnetic. ： **KAK,KYS**
Electric. ： **KYS**

July 16, 2000
04:10-04:30 (JST)
Kp=9 HPF (T≦940s)

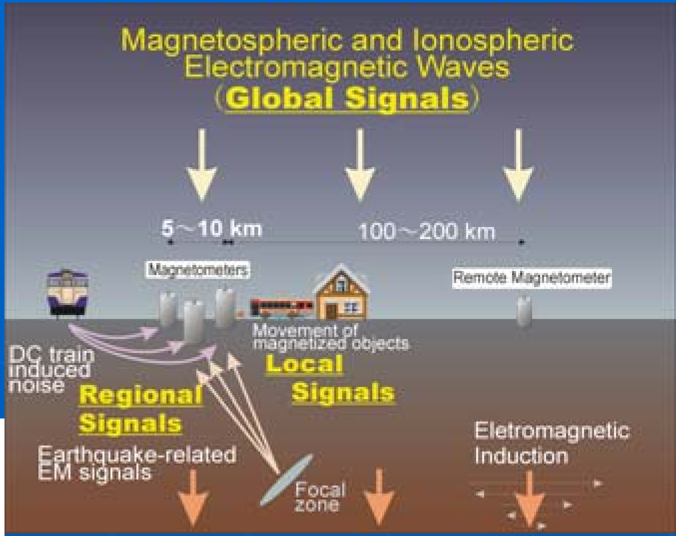


(2)Interstation Transfer Function(ISTF)

Response function of magnetic component between two stations

（Magnetic field at the site ）＝(external fields (normal)＋ (inductive fields(anomalous)) + (uncorrelated signals)

$$\begin{pmatrix}\Delta X_s(\omega)\\ \Delta Y_s(\omega)\\ \Delta Z_s(\omega)\end{pmatrix}=\begin{pmatrix}\Delta X_n(\omega)\\ \Delta Y_n(\omega)\\ \Delta Z_n(\omega)\end{pmatrix}+\begin{pmatrix}\Delta X_a(\omega)\\ \Delta Y_a(\omega)\\ \Delta Z_a(\omega)\end{pmatrix}=\begin{pmatrix}\Delta X_n(\omega)\\ \Delta Y_n(\omega)\\ \Delta Z_n(\omega)\end{pmatrix}+\begin{pmatrix}C(\omega) & D(\omega) & G(\omega)\\ E(\omega) & F(\omega) & H(\omega)\\ A(\omega) & B(\omega) & I(\omega)\end{pmatrix}\cdot\begin{pmatrix}\Delta X_n(\omega)\\ \Delta Y_n(\omega)\\ \Delta Z_n(\omega)\end{pmatrix}+\begin{pmatrix}\delta X(\omega)\\ \delta Y(\omega)\\ \delta Z(\omega)\end{pmatrix},$$



A~I: Inter Station Transfer Function (ISTF)

δ X, δ Y, δ Z:uncorrelated noise

Assume a plane wave as an external field with vertical incident angle and ignore uncorrelated signals(ΔZ=0).

$$\begin{pmatrix}\Delta X_s(\omega)\\ \Delta Y_s(\omega)\\ \Delta Z_s(\omega)\end{pmatrix}=\begin{pmatrix}C(\omega)+1 & D(\omega)\\ E(\omega) & F(\omega)+1\\ A(\omega) & B(\omega)\end{pmatrix}\cdot\begin{pmatrix}\Delta X_r(\omega)\\ \Delta Y_r(\omega)\end{pmatrix}$$

Magnetic field at the site

ISTF

Magnetic field at the reference site

C'=C+1
F'=F+1

Survey of changes in ISTF (conventional approach)

(1) Kakioka data (JMA) are used for as a reference data.
(2) Night time data
(3) Instead of FFT, we use wavelet transform.
(4) To estimate ISTFs, high multiple coherency is taking account.
(5) ±5days running median is plotted.

(3) Variation of Interstation Transfer Function for Izu Data

Station Map and Earthquake Activity

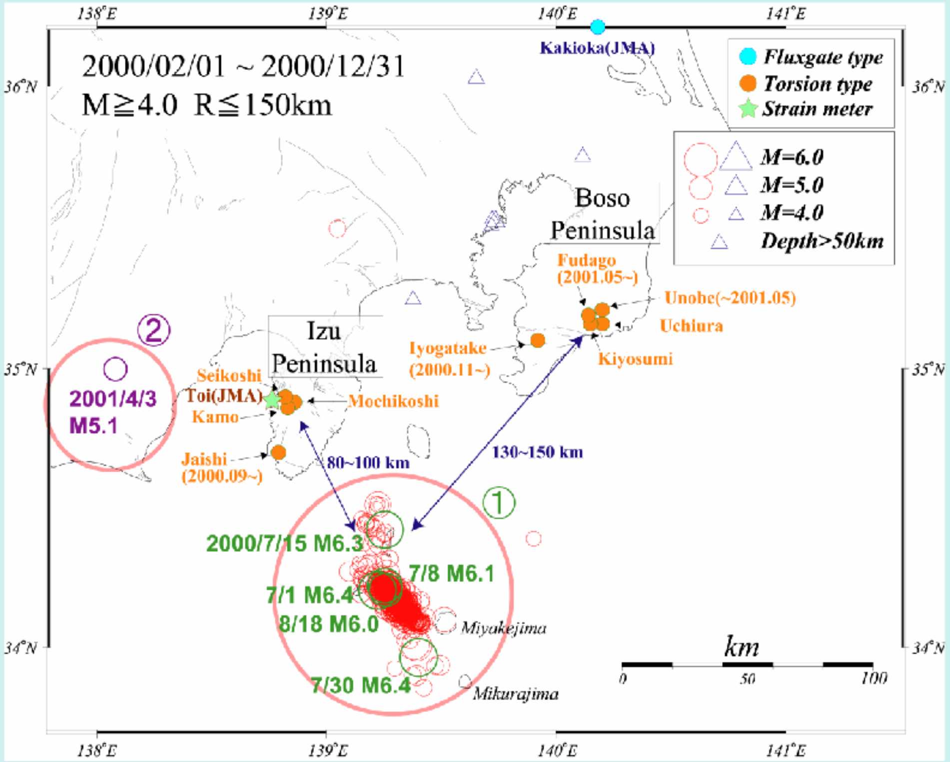
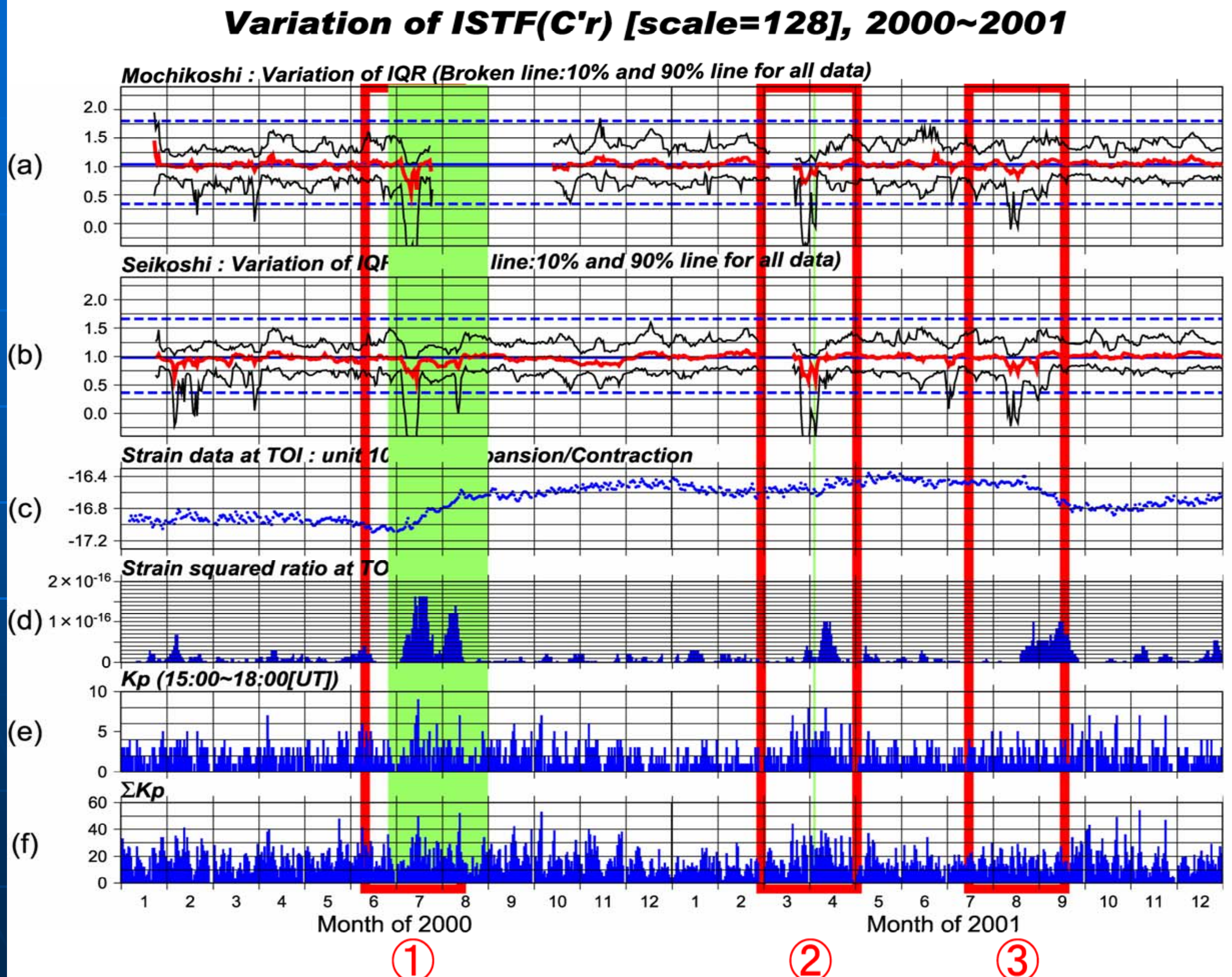


Fig.2 Observatory and earthquake activity

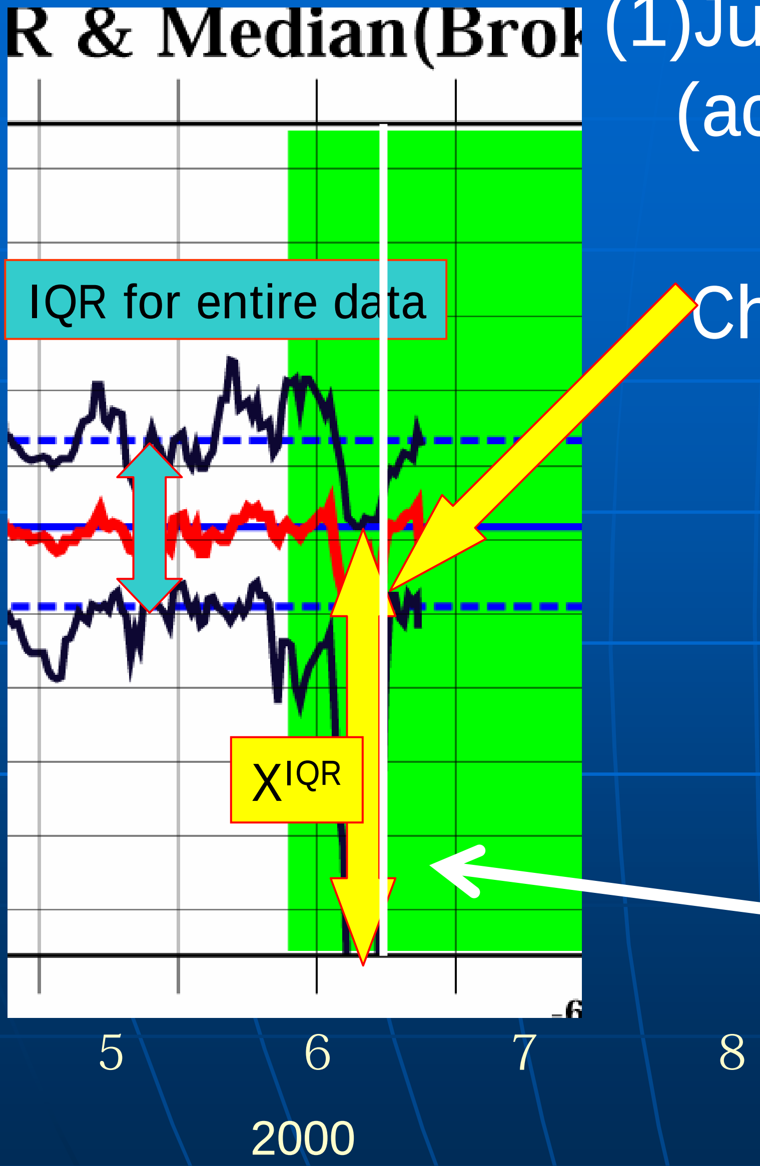
- Observation Site :
  Mochikoshi (mck), Seikoshi (sks) and Kamo (kam) in Izu Peninsula, Japan
- Reference Site : Kakioka (JMA)
- Analyzed Period : from 2000 to 2003
- Analsys Time : Using Data from 16:00 to 19:00(UT)
- For scale of 128s, 256s, 512s and 1024s, we estimate ISTFs.
- Remarkable Earthquake activity during the analyzed period
  - ① Izu Island Earthquake Swarm (from June 26 to September, 2000)
    - * During the Swarm, more than 10,000 earthquake (M>0), including 5 earthquakes with M>6, were recorded.
  - ② Shizuoka Midland Earthquake (April 3,2001 :M=5.1)

Result of ISTF analysis: Izu data (2000-2003)



(1)July 2000

(active period of 2000 Izu Islands EQ swarm)



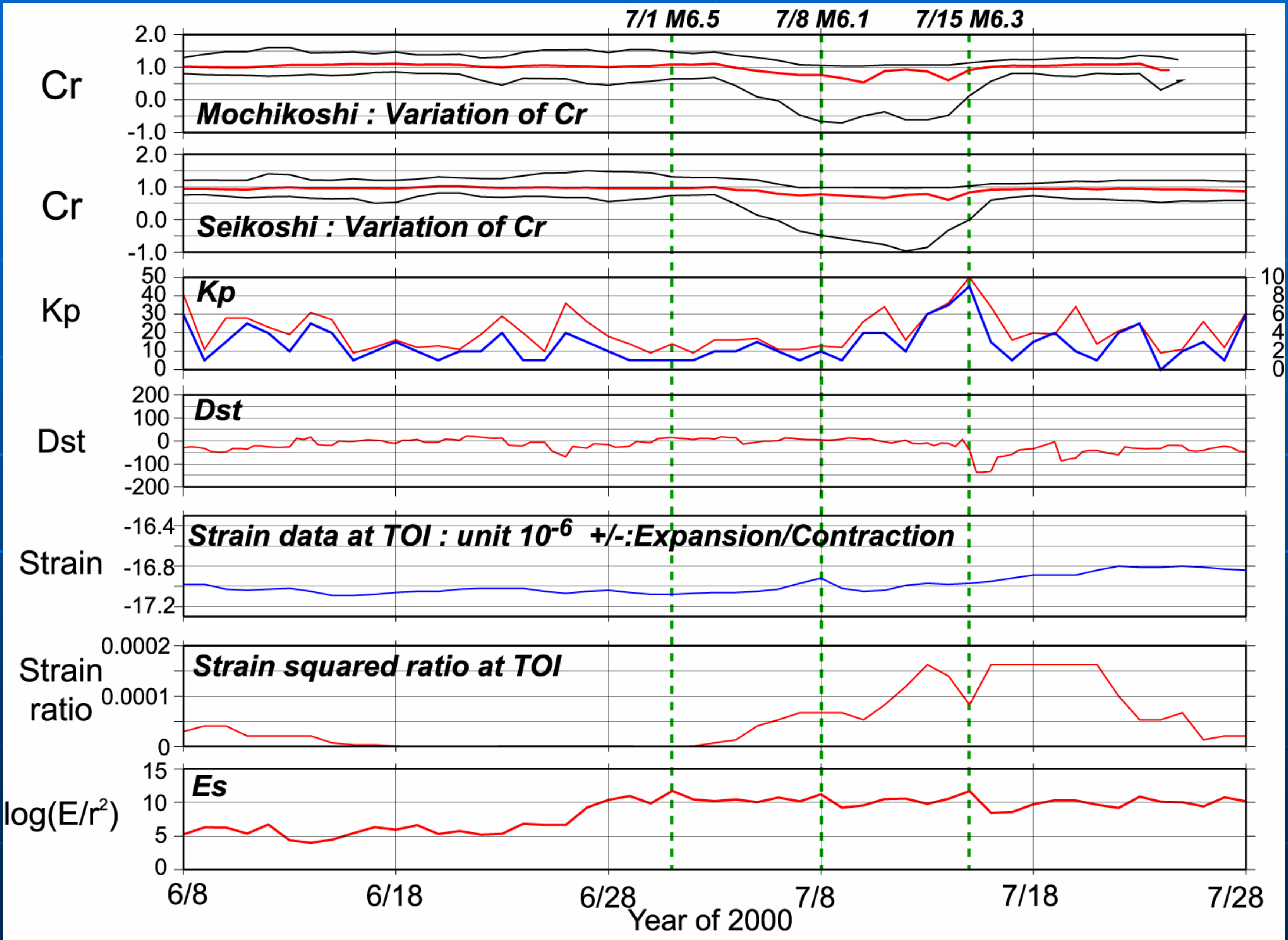
Change of distribution C '

shift of median value (decrease)

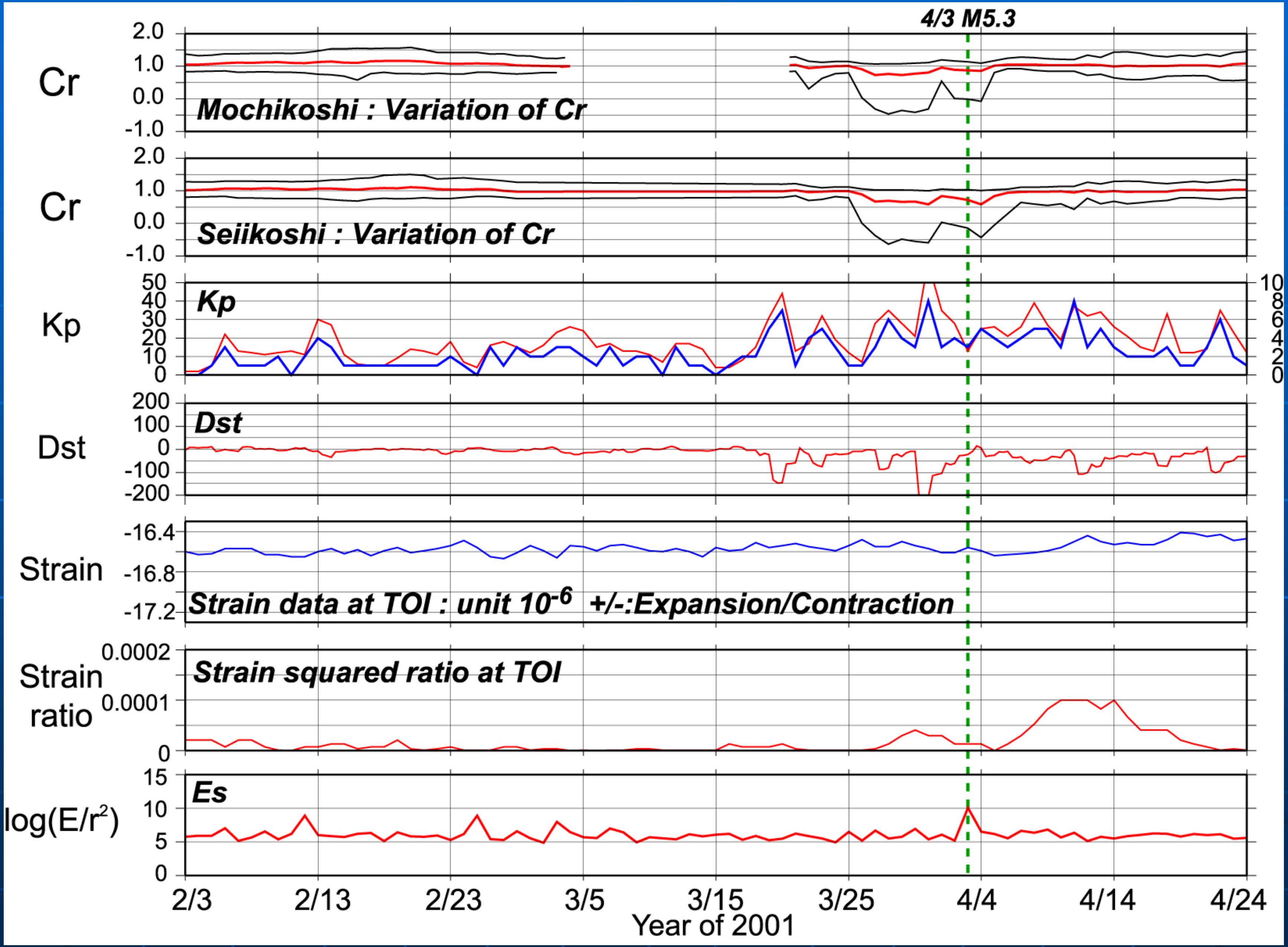
increase of half width

Nearest EQ 2000715M6.3 80km

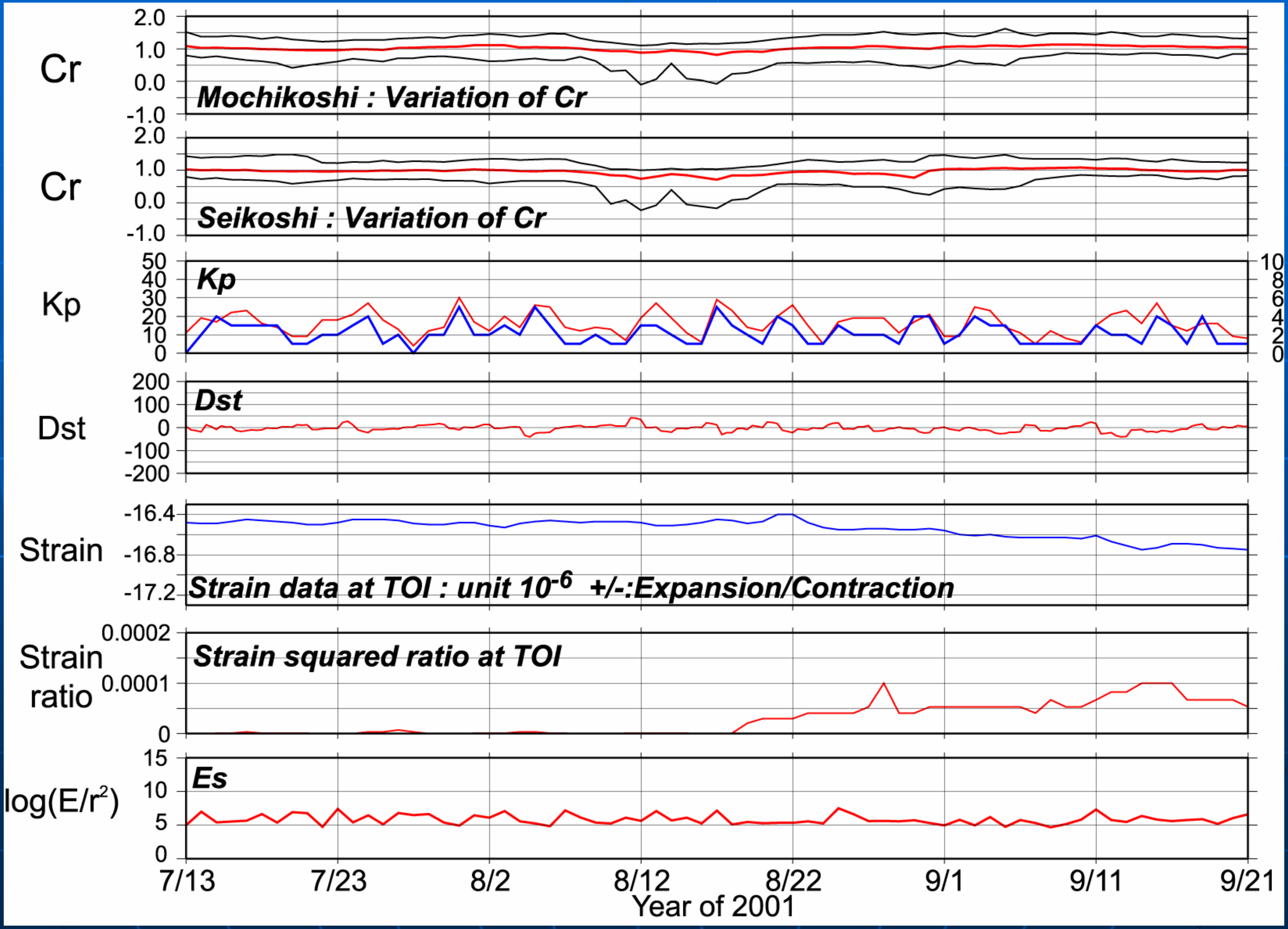
Case (1) 2000 Izu EQ Swarm



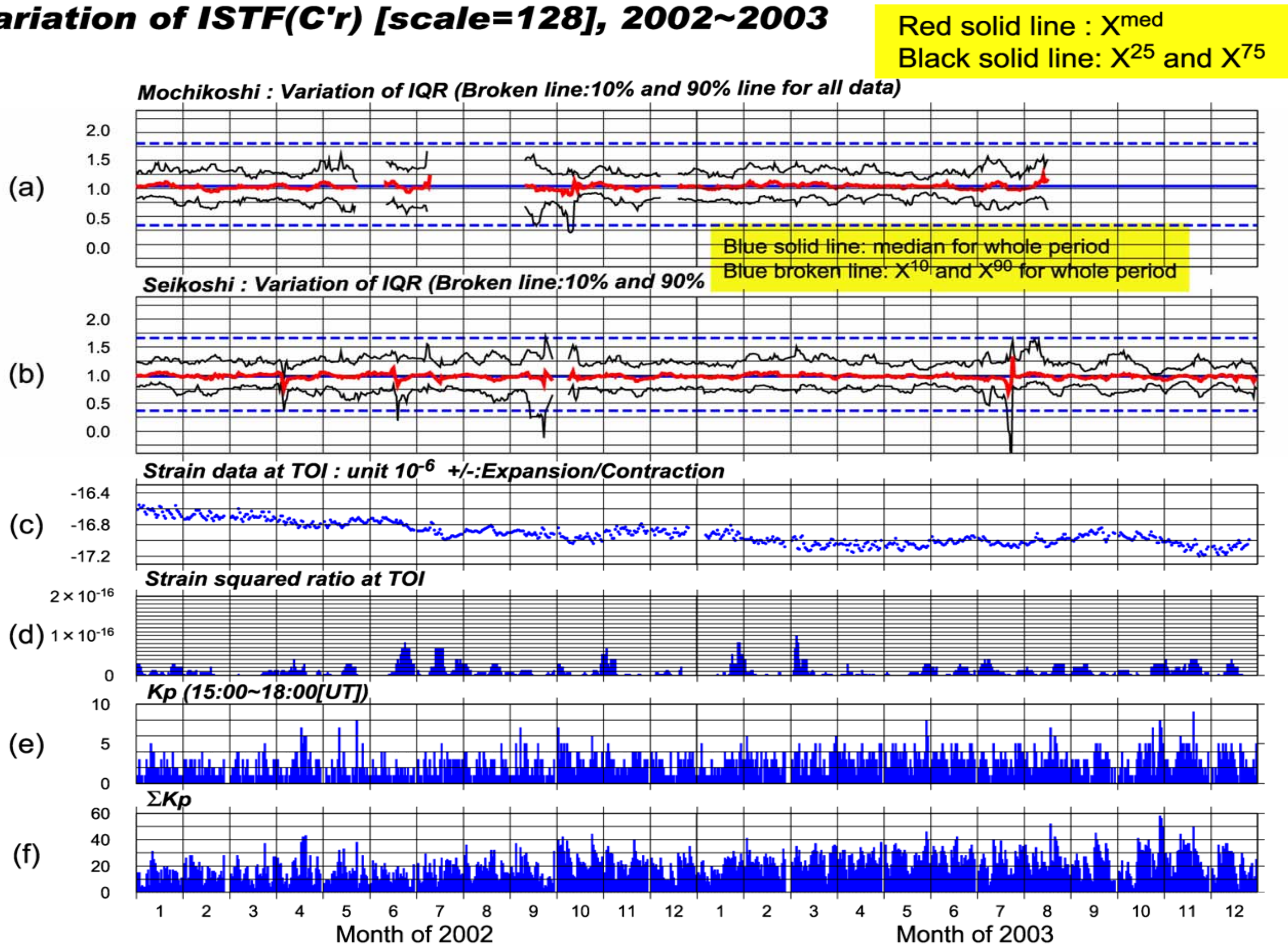
Case (2) 2001 Shizuoka EQ M5.1



Case (3) August-September, No EQ case



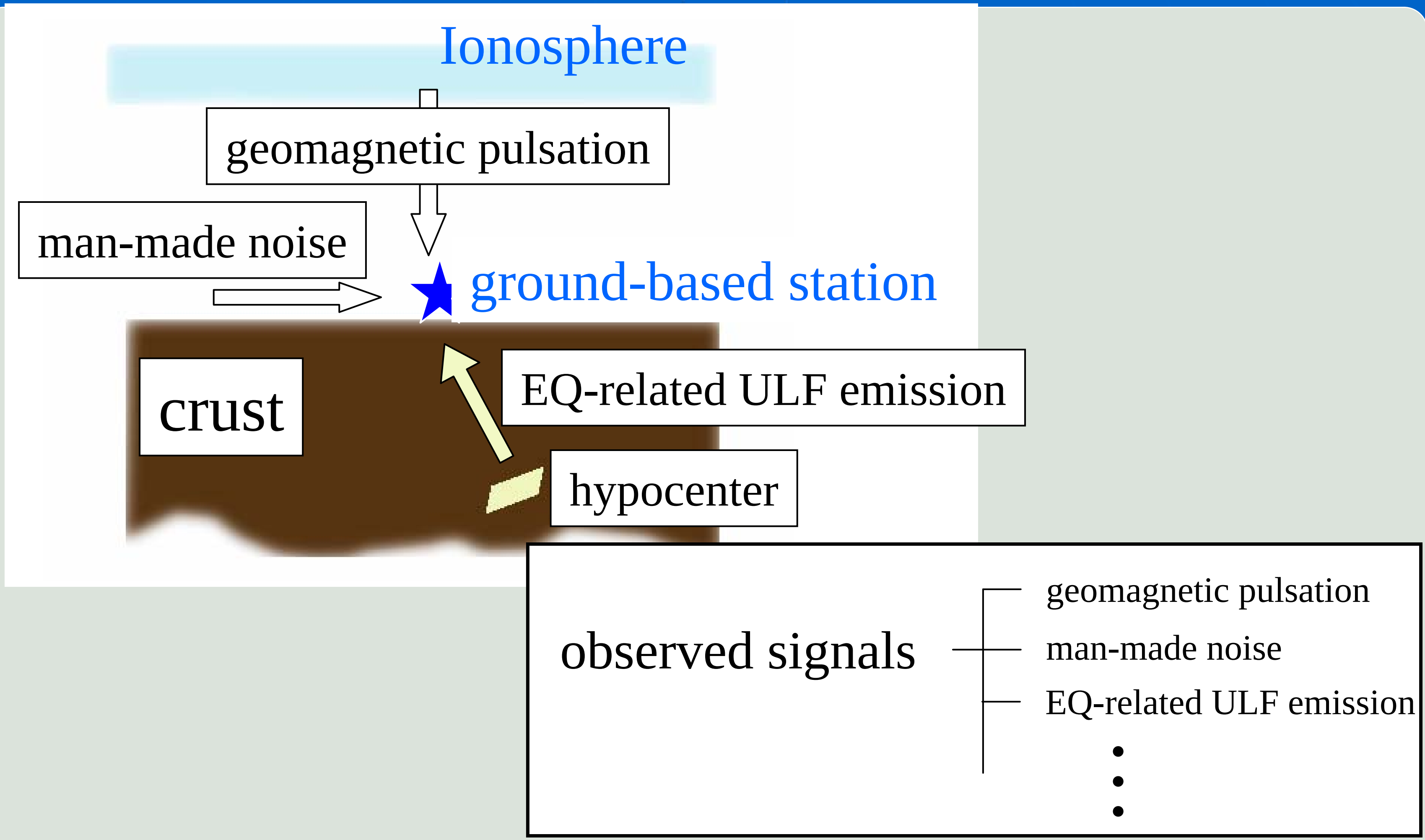
Variation of ISTF(C'r) [scale=128], 2002~2003



Summary of ISTF variation

- It is found that three obvious decreases of ISTF (C', F' values) have been detected simultaneously at SKS and MCK station (5km distance).
- Above changes are preceding the strain changes at Toi (5km distance from SKS and MCK).
- Variation of ISTFs suggests the change of underground (strain) near the sites.

(3) Remove the global components from the observed data using ISTF



How to distinguish the EQ-related ULF signals from other noises ?

Interstation Transfer Function；ISTF for magnetic fields

$$\mathbf{H}_s(\omega) = \mathbf{T}(\omega) \cdot \mathbf{H}_r(\omega)$$

or

$$\begin{pmatrix} X_s(\omega) \\ Y_s(\omega) \\ Z_s(\omega) \end{pmatrix} = \begin{pmatrix} T_{xx}(\omega) & T_{xy}(\omega) \\ T_{yx}(\omega) & T_{yy}(\omega) \\ T_{zx}(\omega) & T_{zy}(\omega) \end{pmatrix} \cdot \begin{pmatrix} X_r(\omega) \\ Y_r(\omega) \end{pmatrix}$$

Magnetic fields at the observation site

ISTF

Magnetic fields at reference site

$$\mathbf{H}_{sg}(\omega) = \overline{\mathbf{T}}(\omega) \cdot \mathbf{H}_r(\omega)$$

$$\Delta\mathbf{H}(\omega) = \mathbf{H}_s(\omega) - \mathbf{H}_{sg}(\omega)$$

Residuals contain following signals near the site

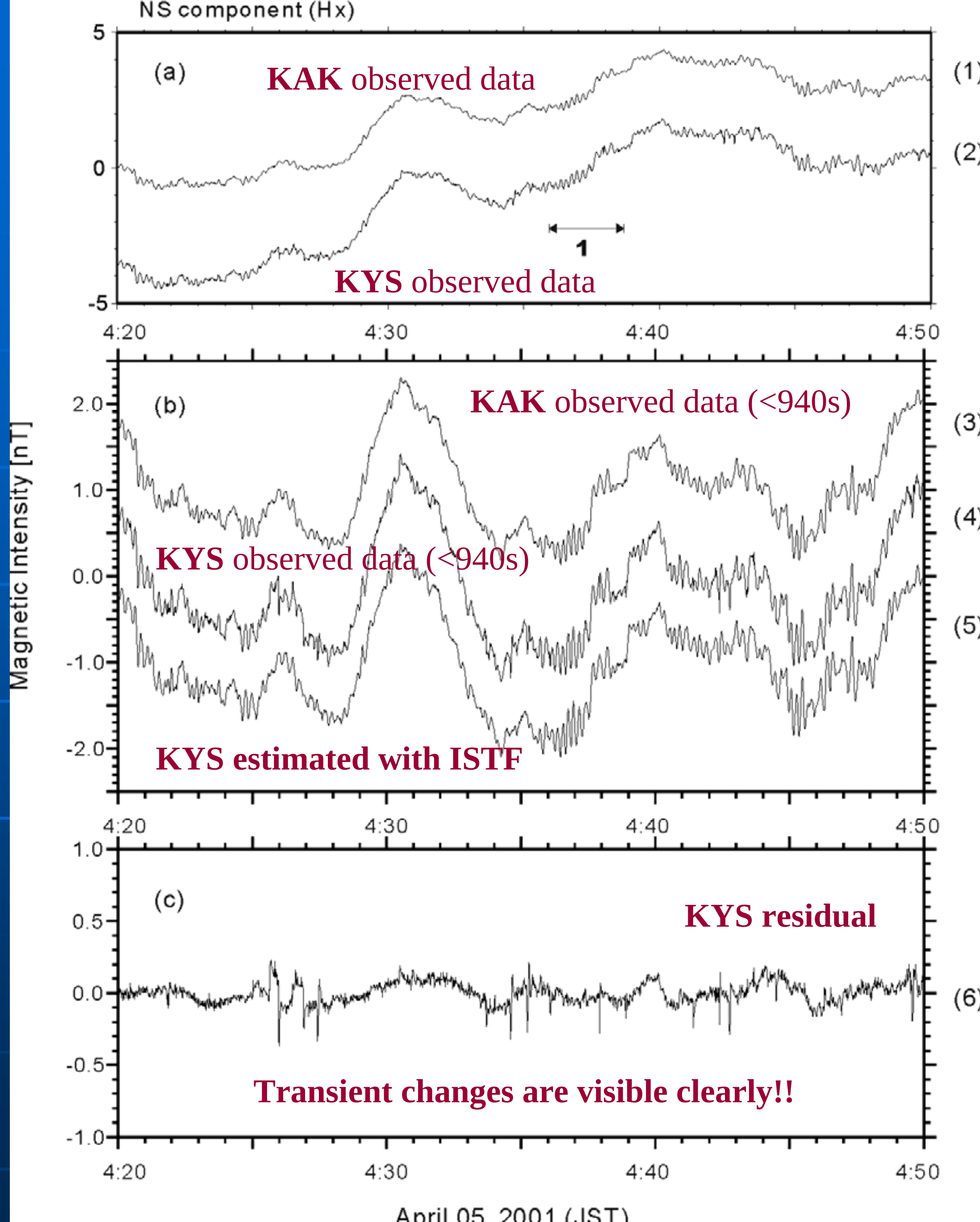
artificial noises

EQ-related EM signals

Result of Magnetic Component

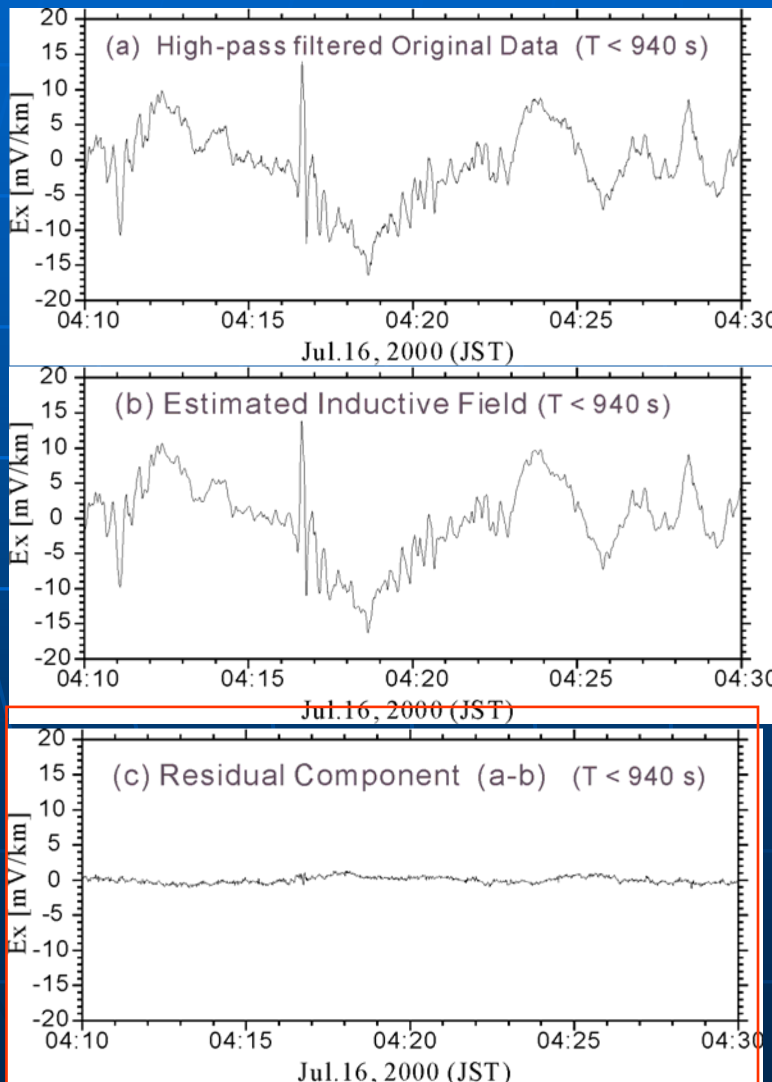
KAK, KYS

April 5, 2001
04:20～04:50 (JST)

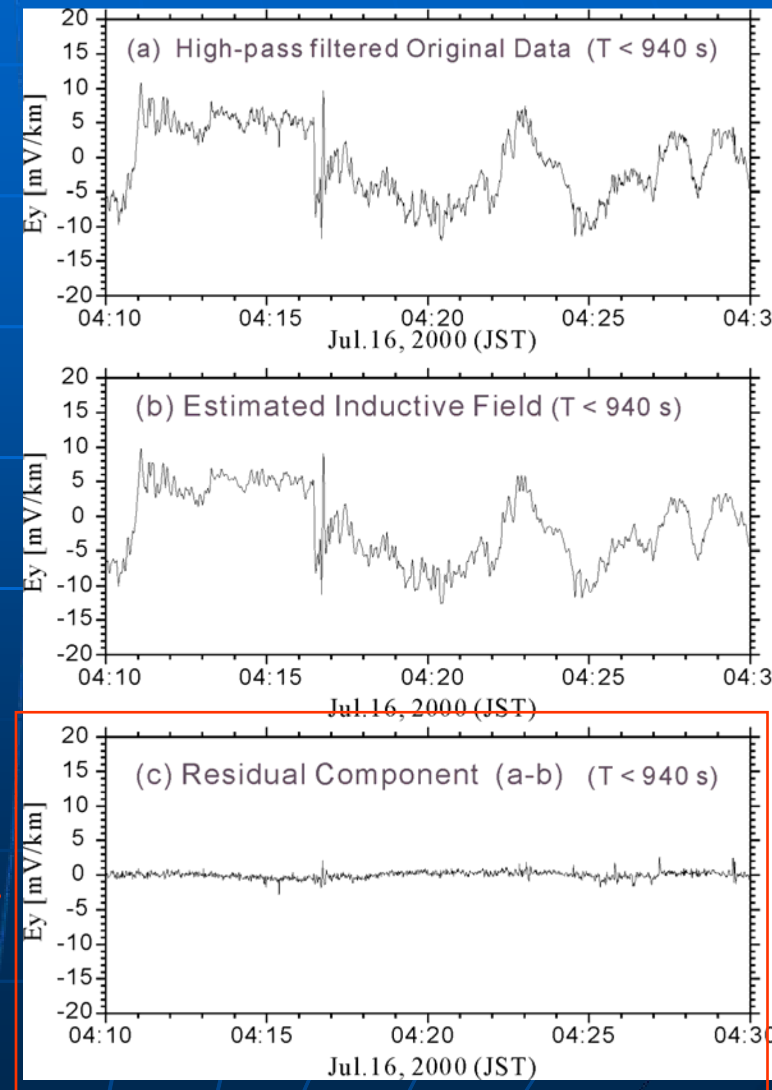


Result of Electric Components

NS (Ex) Comp.



EW (Ey) Comp.

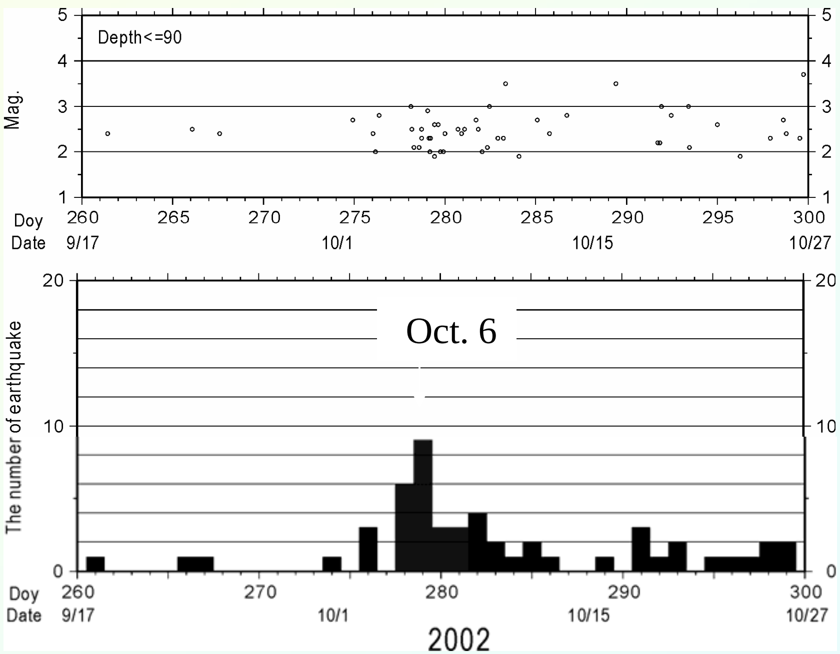


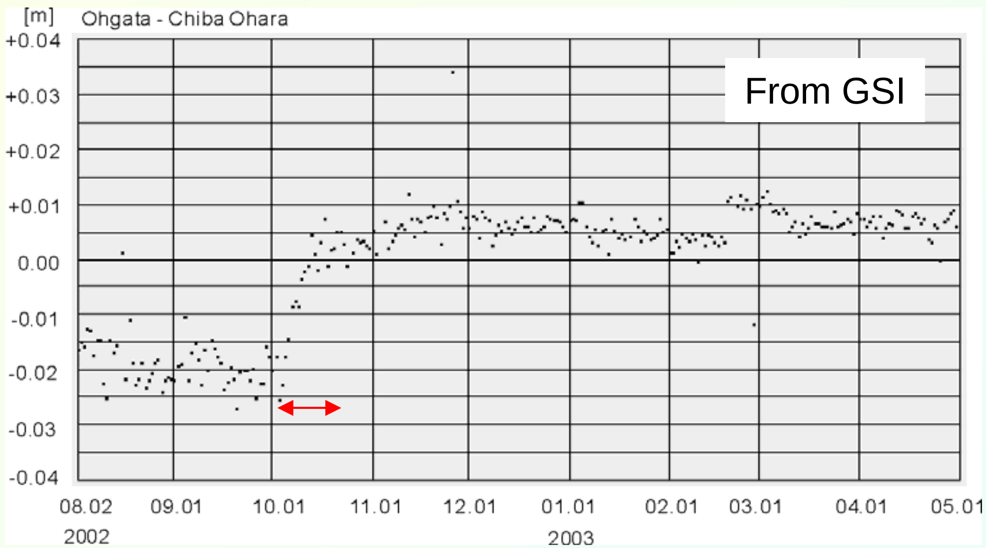
Possible EM changes at Boso Stations

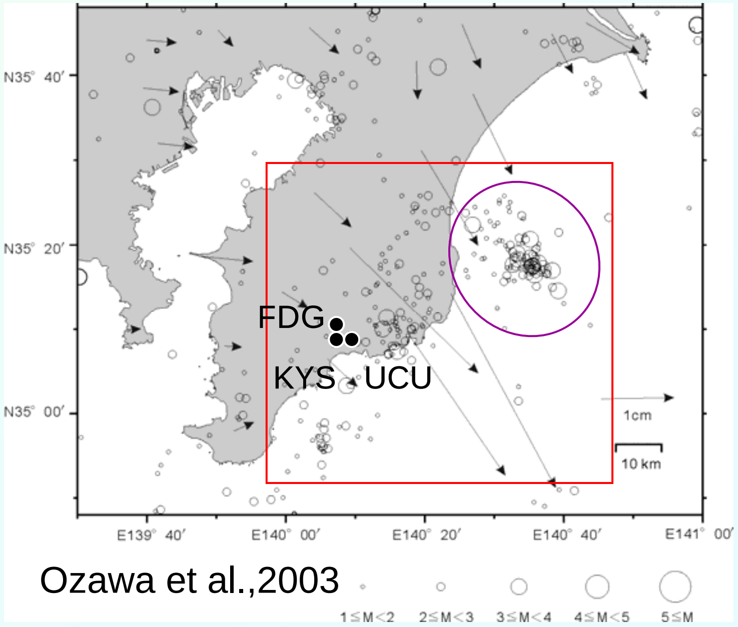
2002Boso Slow Slip event

In early October, 2002, Slow slip occurred at Boso area in Japan. The surface displacement is about 1-2 cm in the south-east direction. The underground displacement is estimated about 10 cm at maximum and Mw =6.5.

From JMA



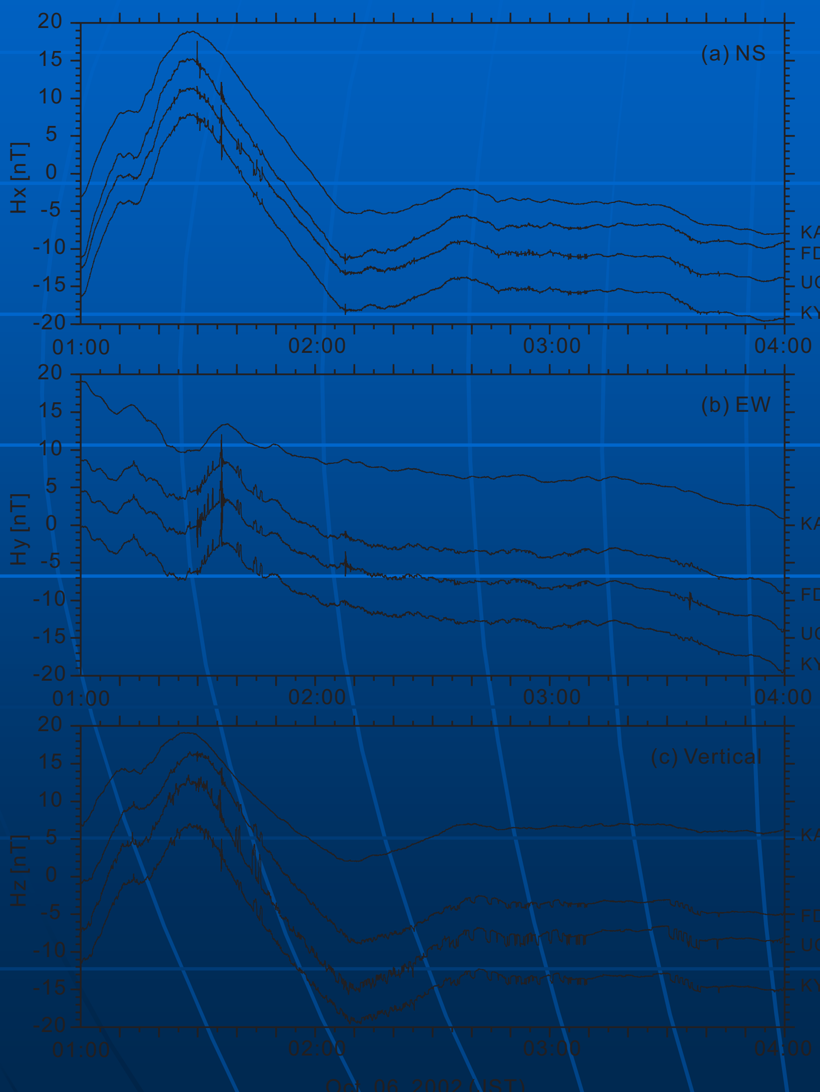


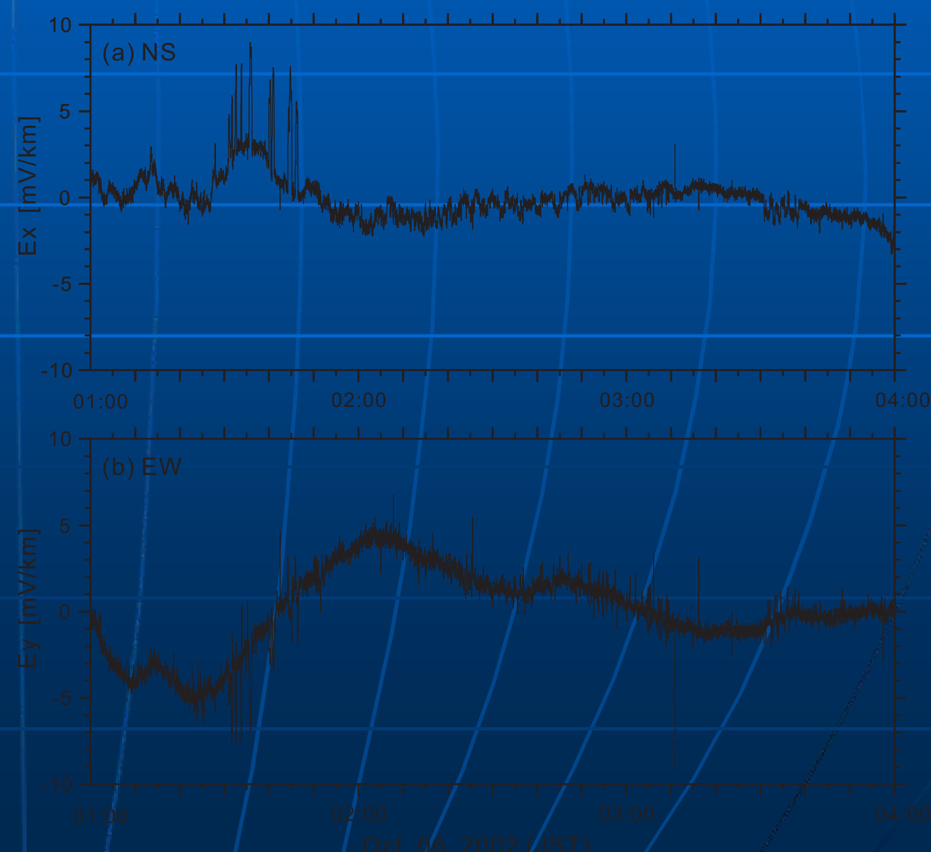


Ozawa et al.,2003

Relative displacement between Ohara-Ogata during Septenber 1 and December 2, 2002.

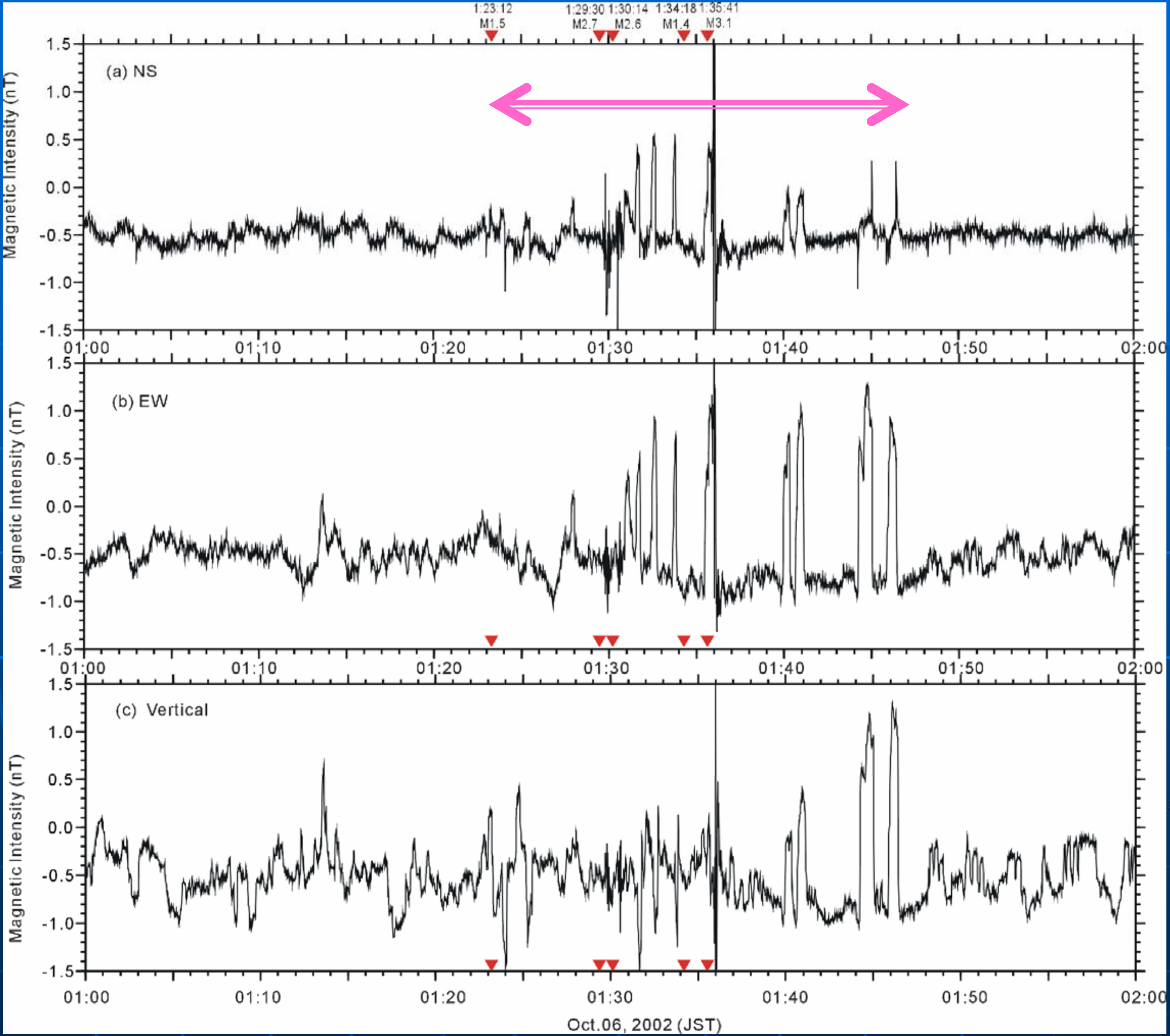
Unusual Electromagnetic changes observed Boso stations on October 6,2002.





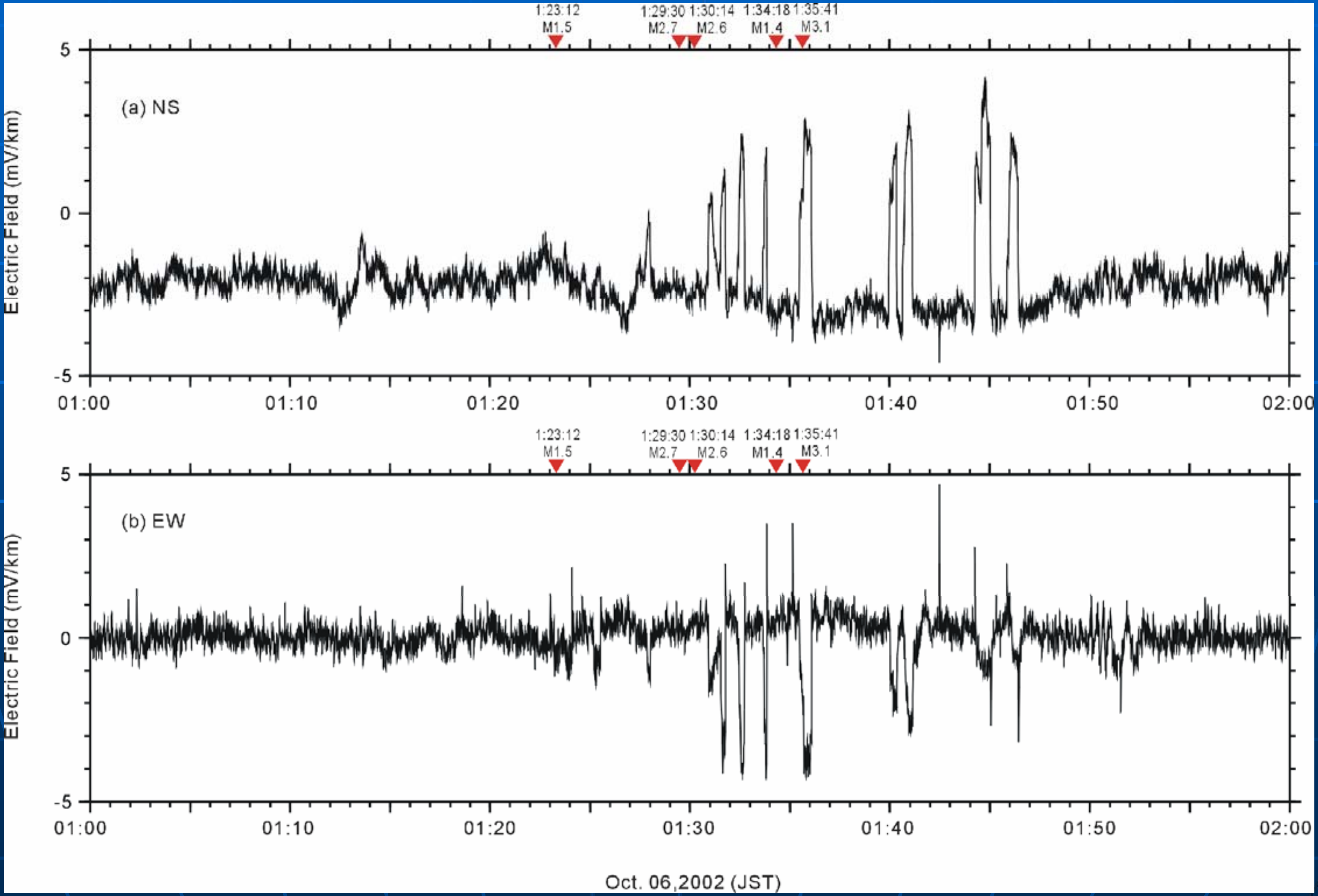
Magnetic Fields (KYS)

KYS 01:00 – 02:00



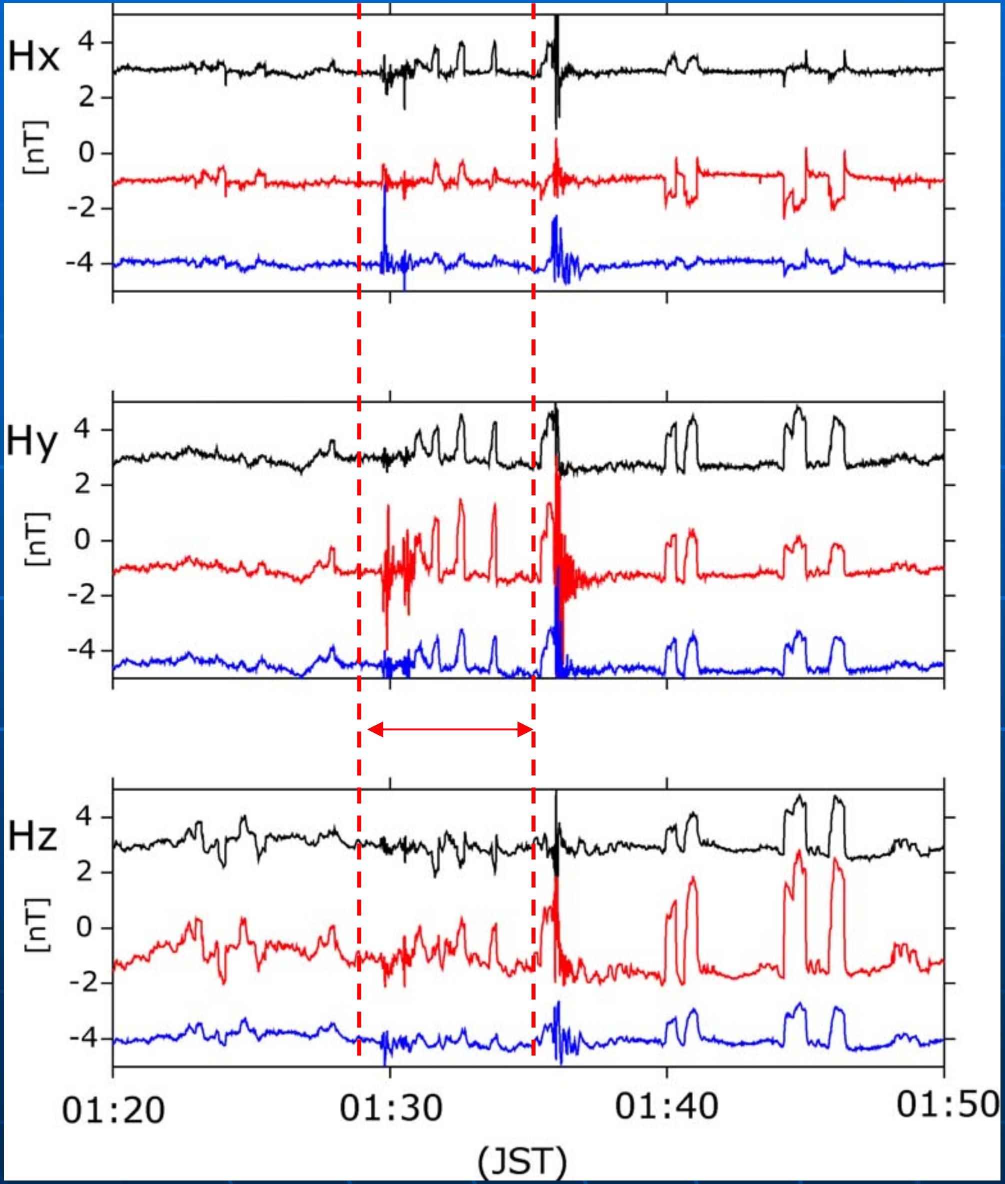
Electric potential difference(KYS)

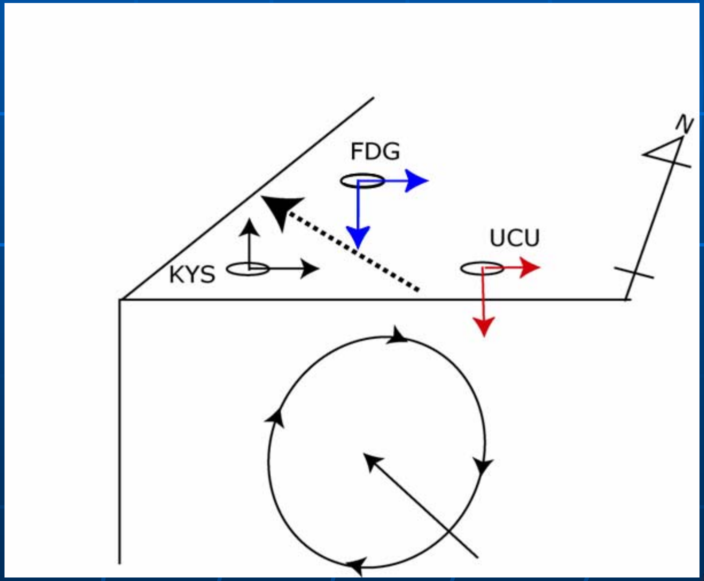
KYS 01:00 – 02:00



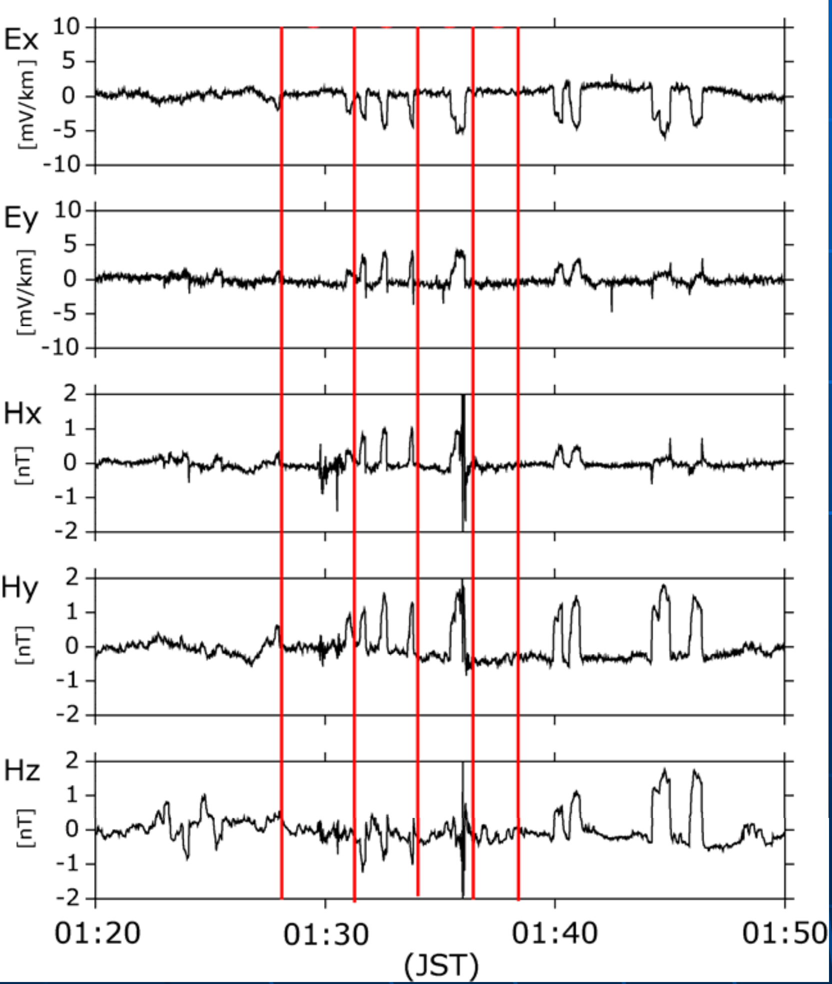
Possible current estimated from polarity of magnetic fields change (1)

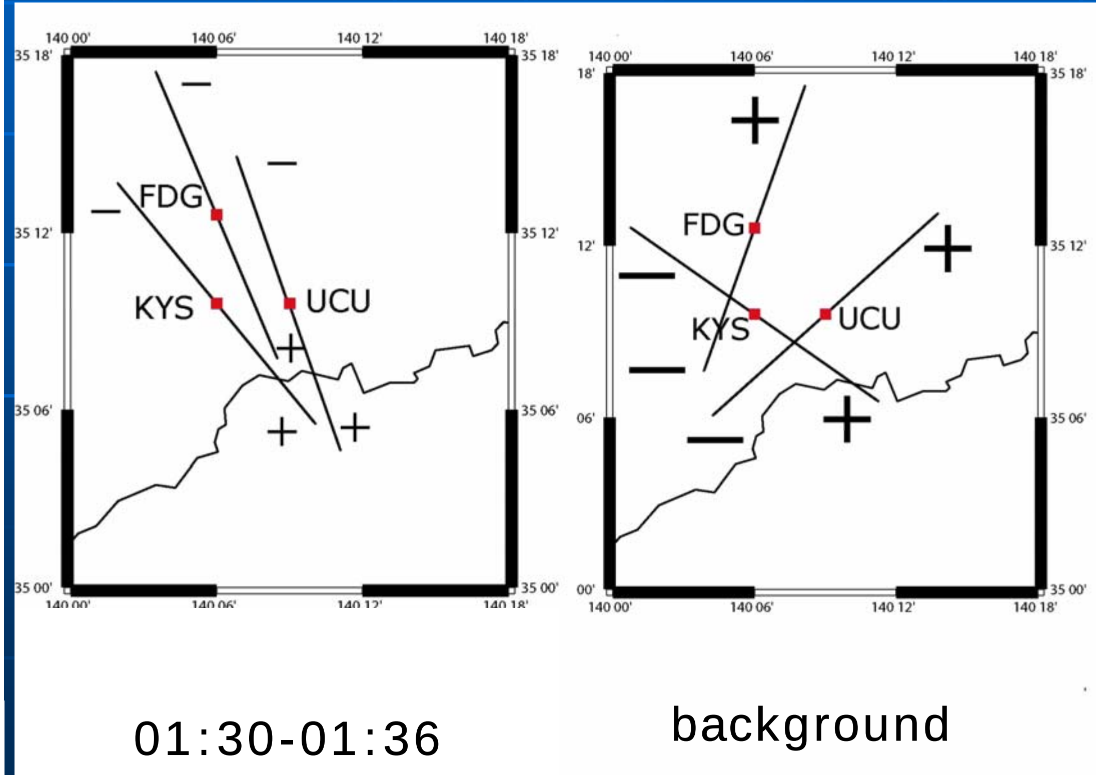
01:30 - 01:36 on October 6, 2002





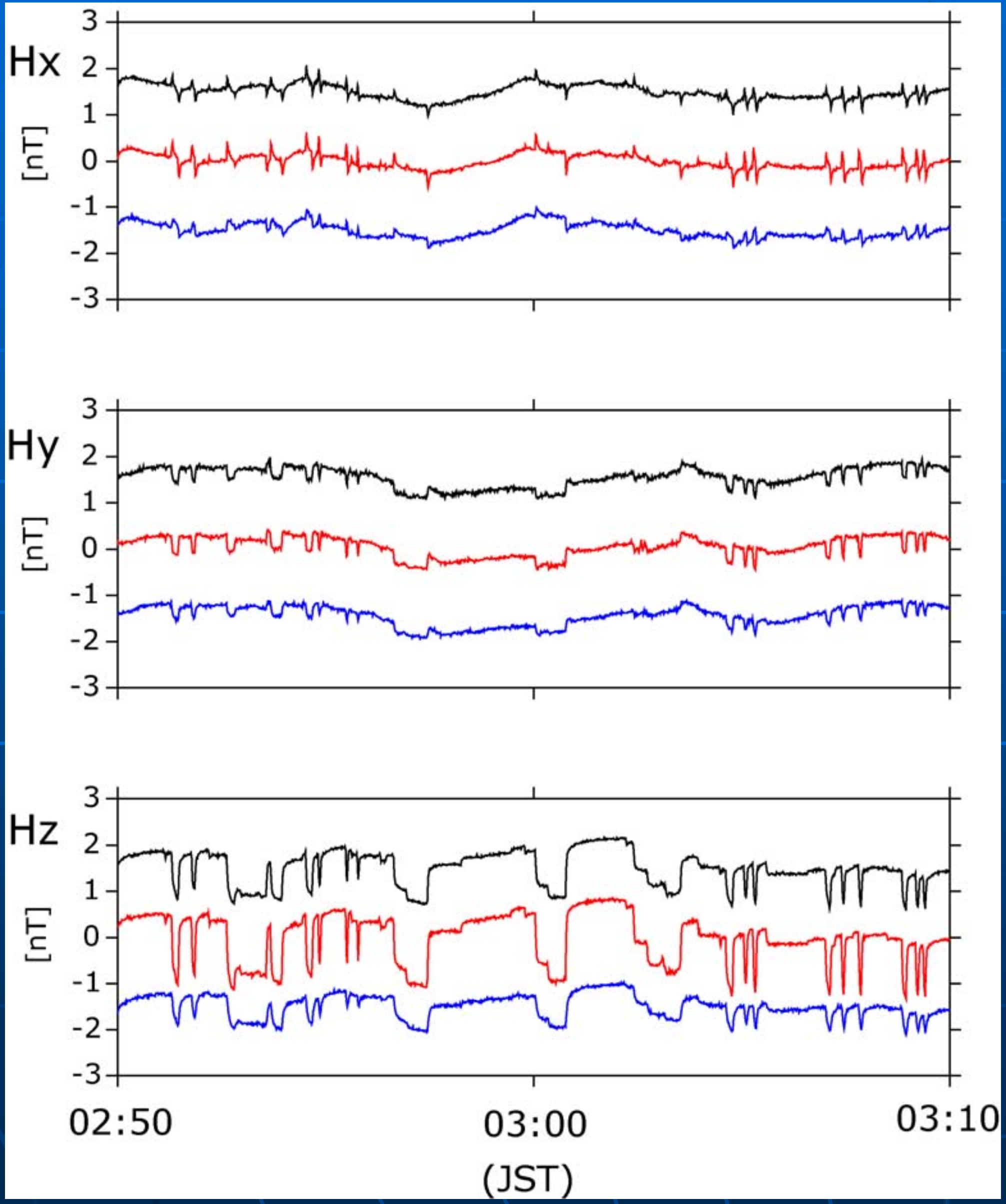
Gradient of geoelectric field

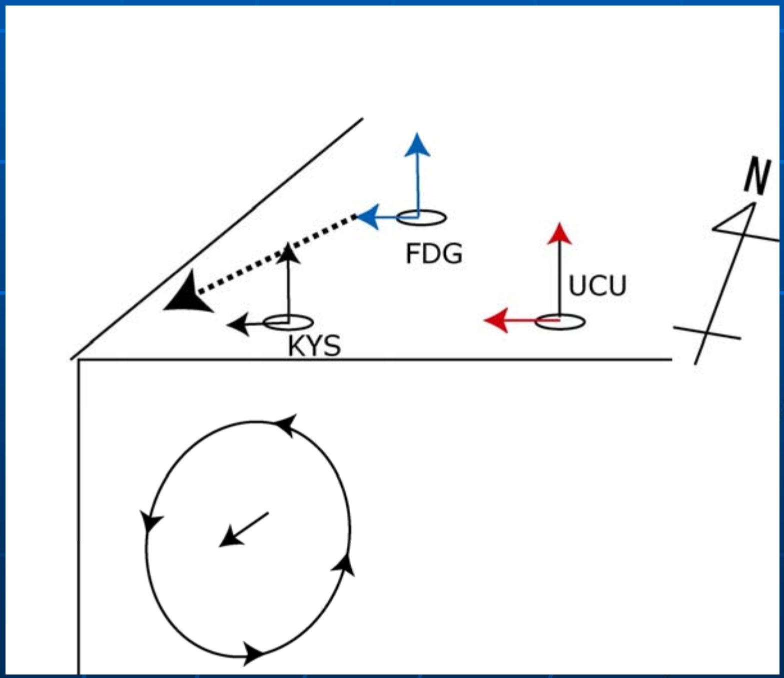




Possible current estimated from polarity of magnetic fields change (2)

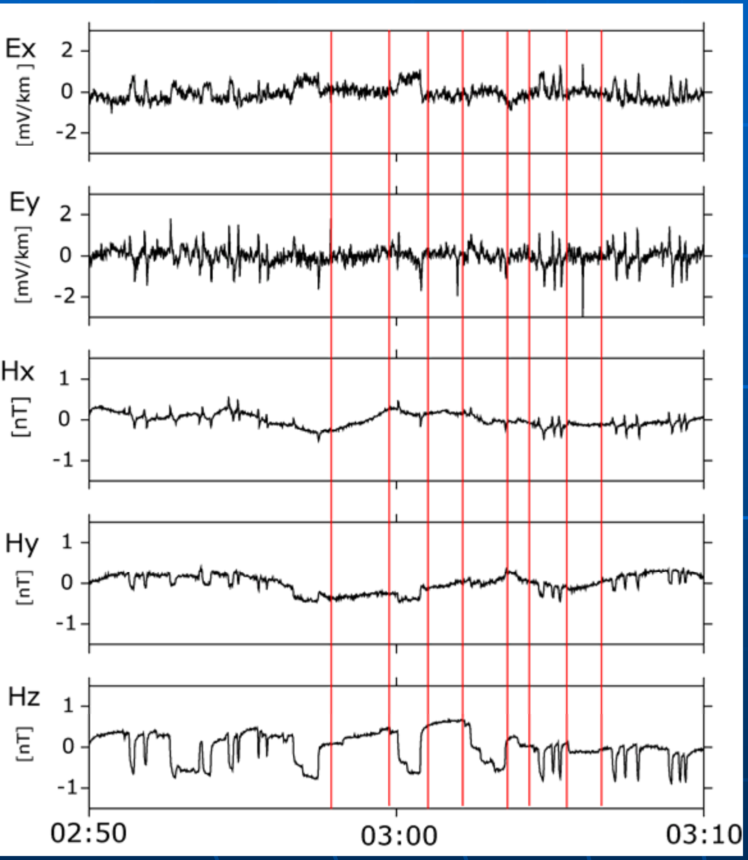
03:00 - 03:10 on October 6, 2002

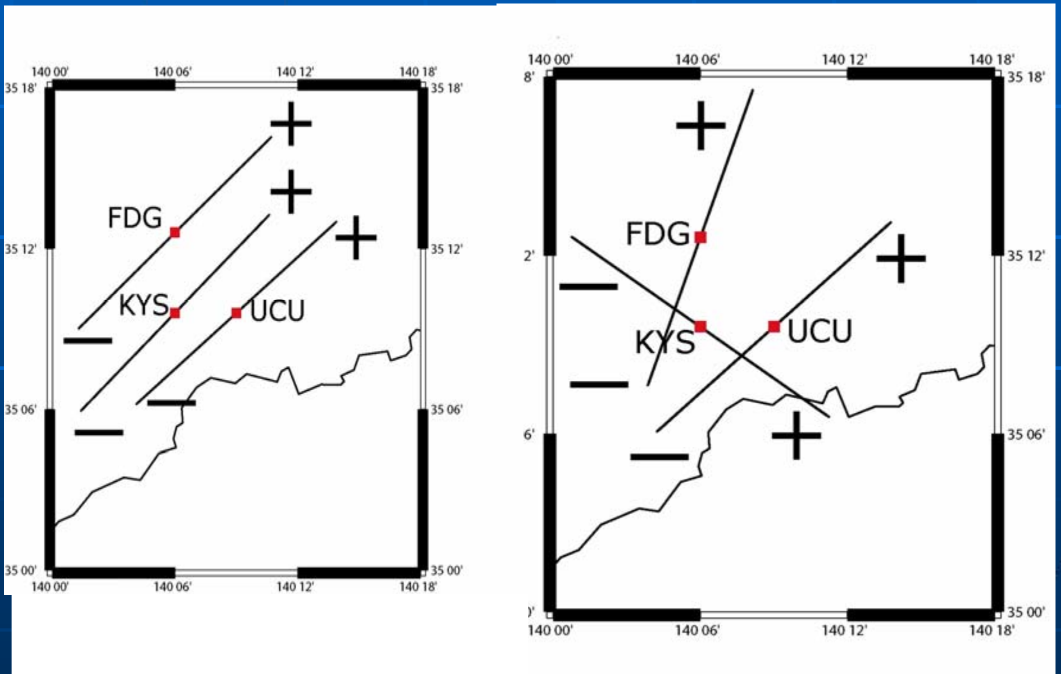




Gradient of geoelectric field

02:50-03:10



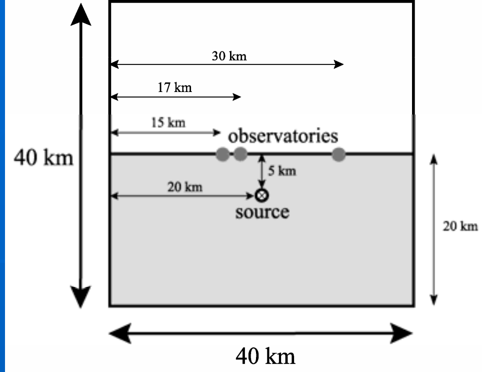


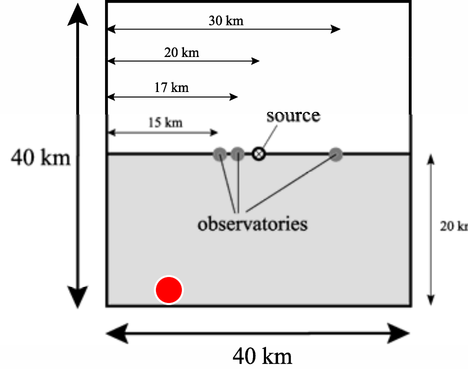
03:00-03:10

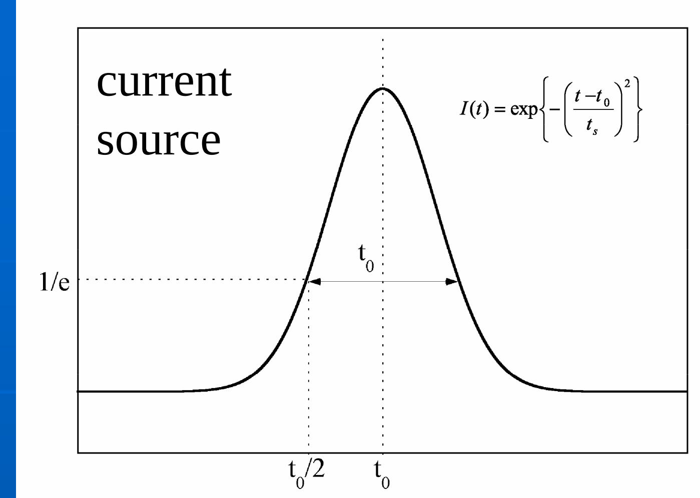
background

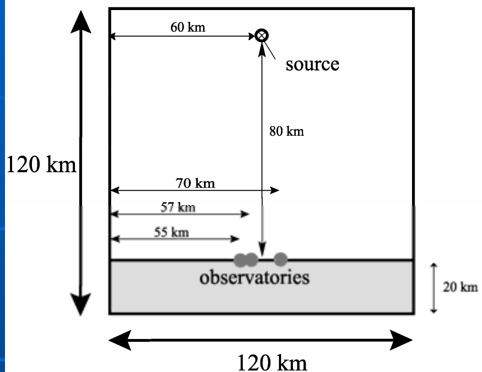
Simulation of signal propagation

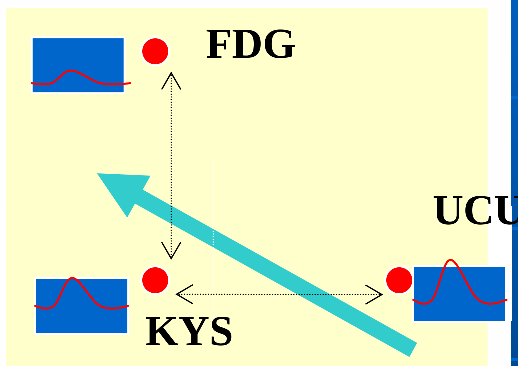
- 2D FDTD simulation has been performed to investigate the EM propagation from the assumed line current source.
- For the simulation, realistic parameters (underground conductivity, ionosphere) have been chosen.
- A line current source in the ionosphere, on the surface, in the subsurface are examined.

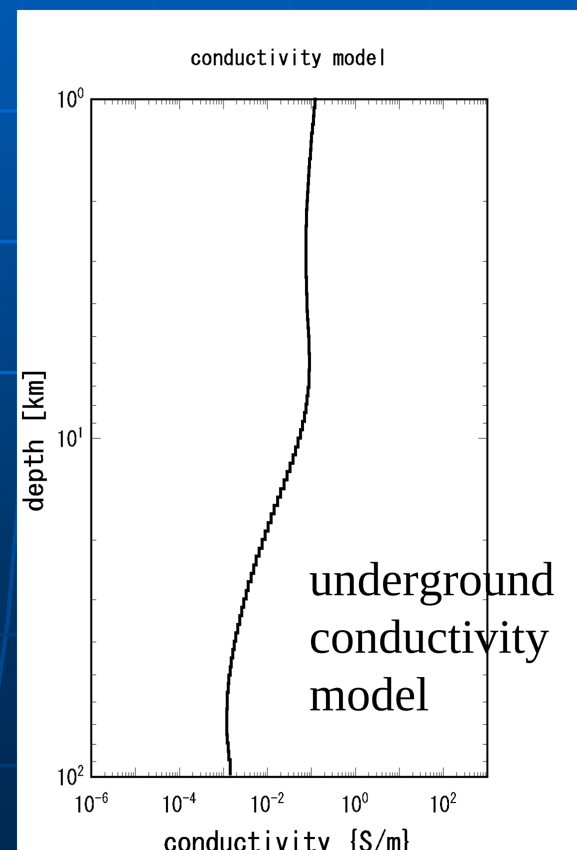

40 km
30 km
17 km
15 km
observatories
5 km
20 km
source
20 km
40 km

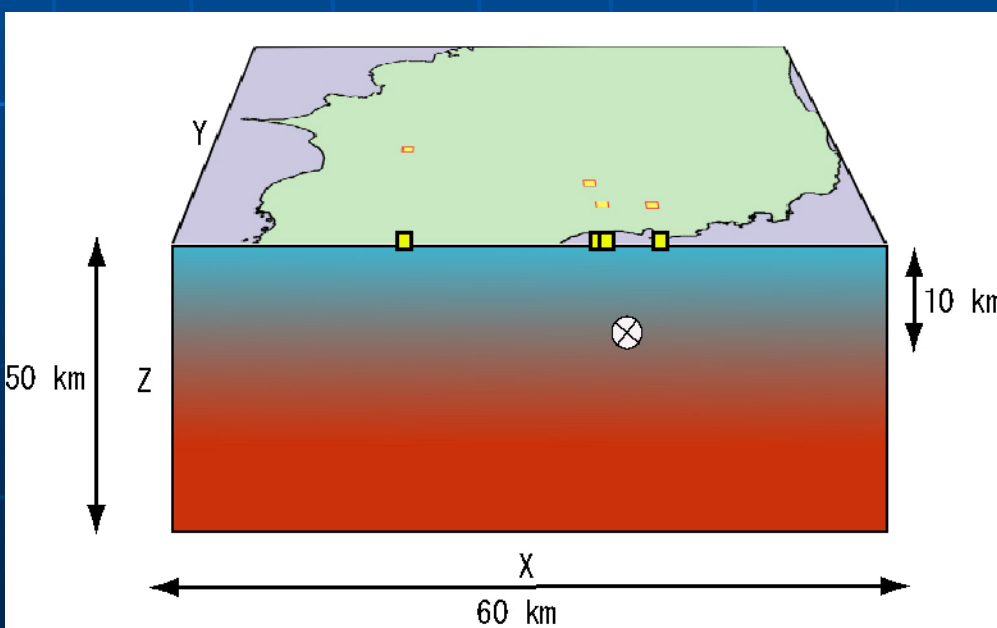

40 km
30 km
20 km
17 km
15 km
source
observatories
20 km
40 km


current
source
$I(t) = \exp\left\{-\left(\frac{t-t_0}{t_s}\right)^2\right\}$
1/e
t_0
$t_0/2$
t_0


120 km
60 km
source
80 km
70 km
57 km
55 km
observatories
20 km
120 km


FDG
UCU
KYS

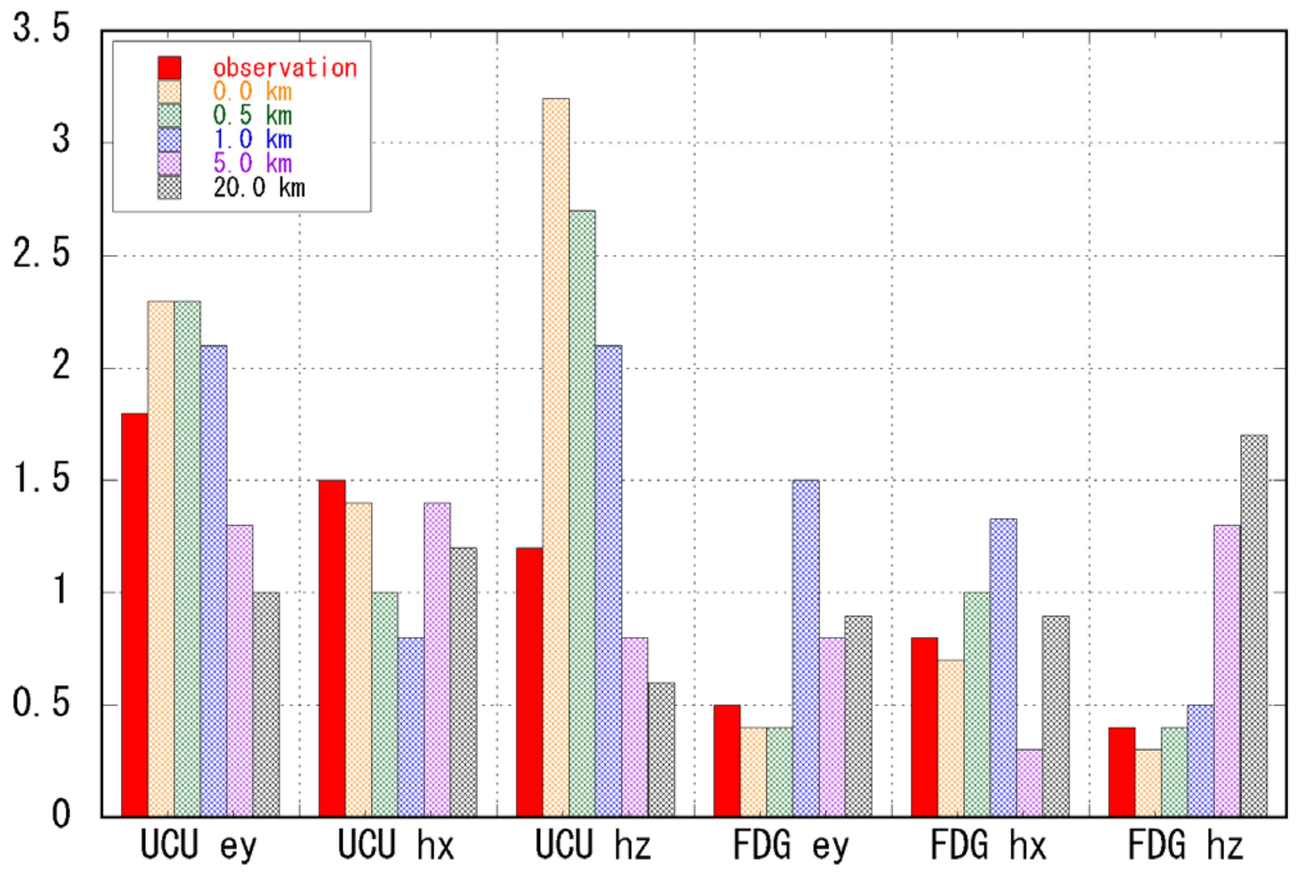

conductivity model
10^0
10^1
10^2
depth [km]
10^{-6}
10^{-4}
10^{-2}
10^0
10^2
conductivity {S/m}
underground
conductivity
model


Y
10 km
50 km
Z
X
60 km

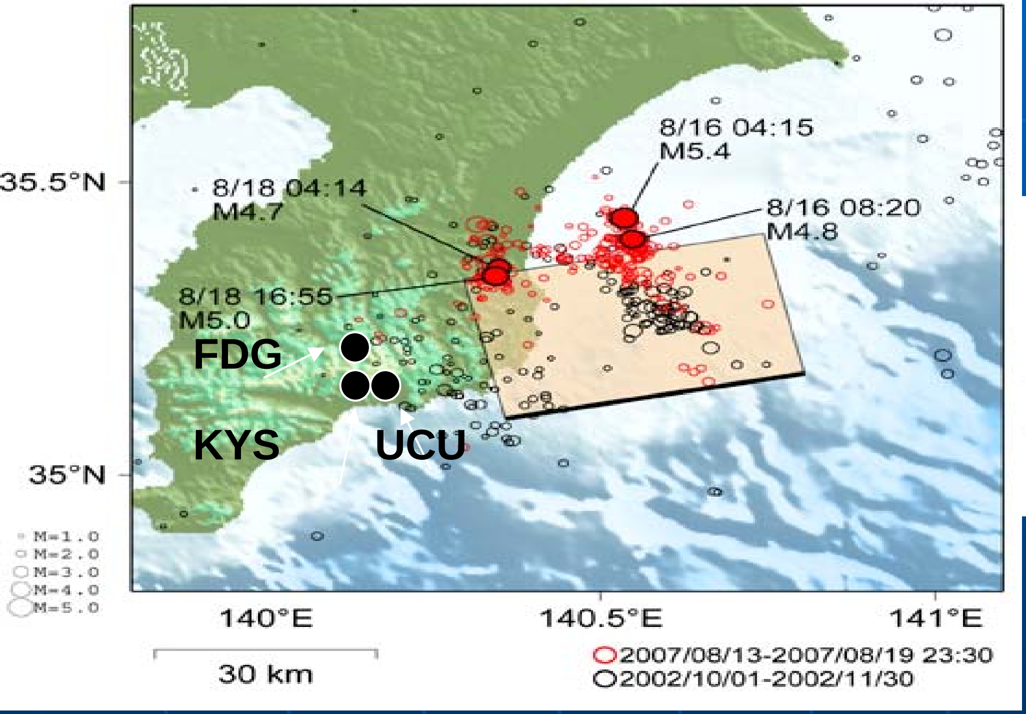
Simulation Results

- Ionospheric source
  ➔ Not good in polarization
- Surface source
  ➔ Not good in for propagation distance (amplitude)
- Only shallow lithospheric source
  ➔ almost satisfy the observed characteristics

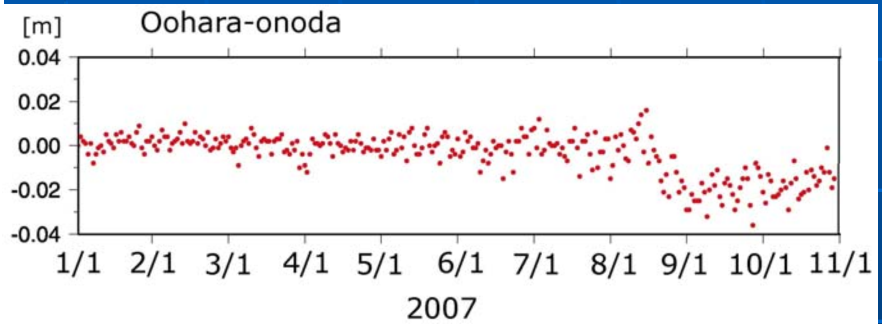
Amplitude ratio relative to KYS



Slowslip event in August 2007 (the 2nd slowslip event)

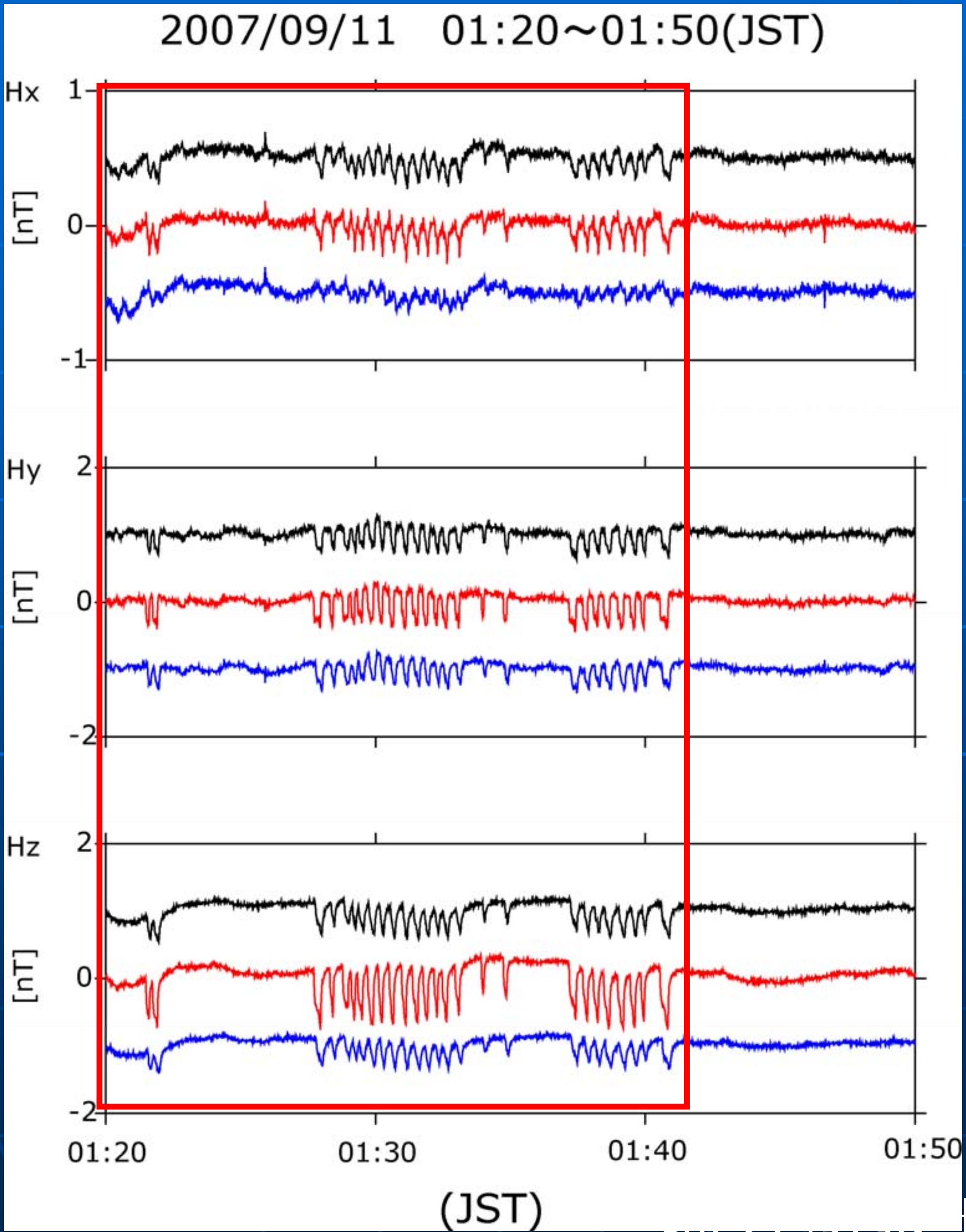


Displacement (GPS)

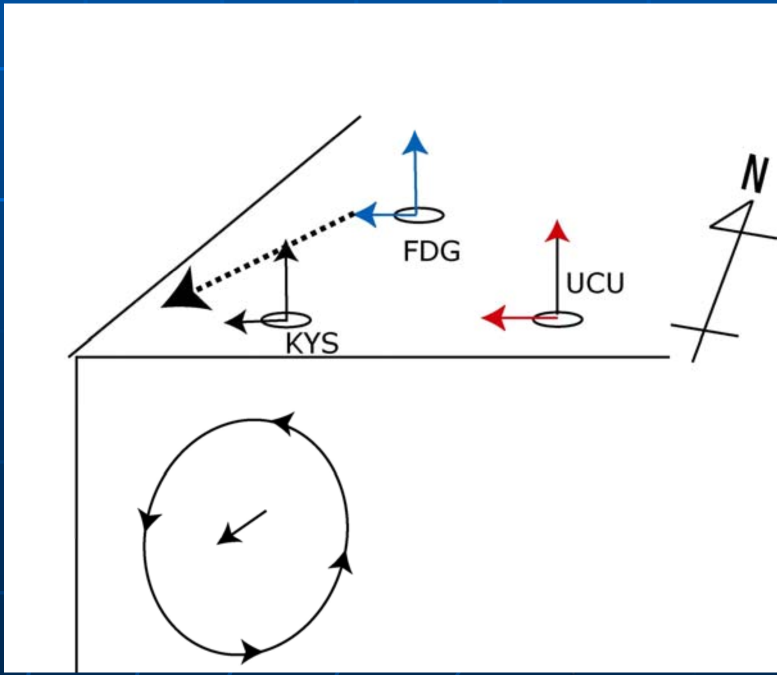


from home page of Hi-net @NIED, Japan

Possible current estimated from polarity of magnetic fields change (3)

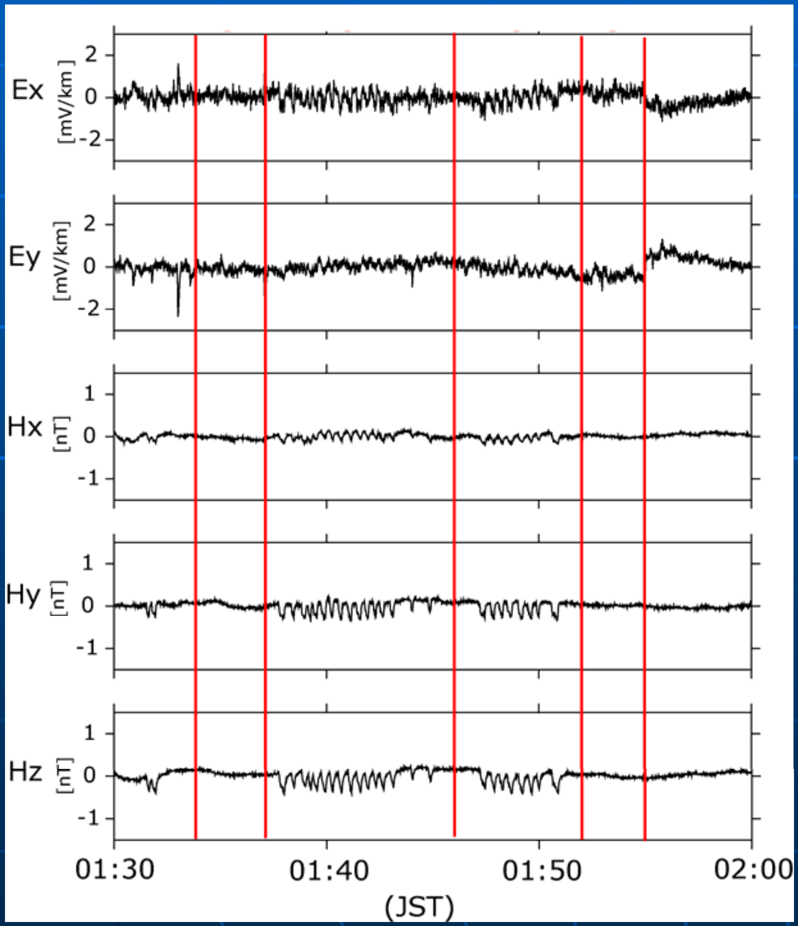


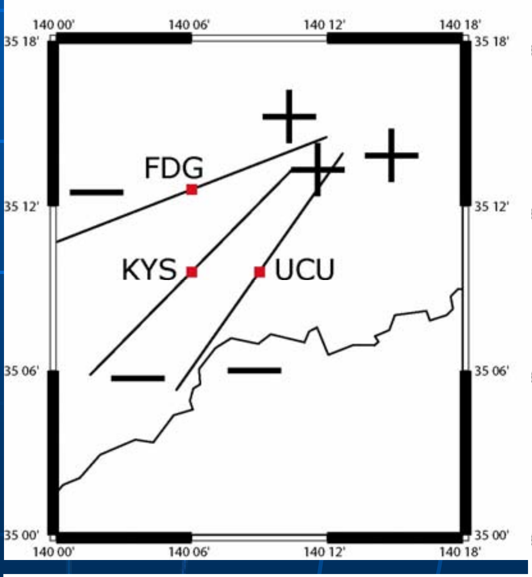
01:20 - 01:50 on September 11, 2007 (just after slowslip event)

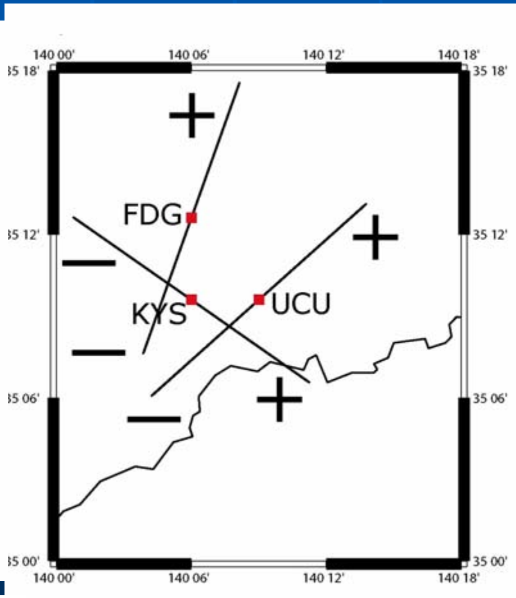


Gradient of geoelectric field

01:20-01:50







01:39-01:45
01:47-01:52

background

Summary of noise reduction with ISTF

- ISTF with wavelet transform is effective for identify and eliminate signals originated from external magnetic variations (T<940 sec) for both geomagnetic and geoelectric potential difference data.

- Application to the unusual data observed on October 6, 2002 and Sptember 11, 2008 at Boso Peninsula shows the high capability to analyze details.

- The results of these events are highly suggestive of the existence of electrokinetic effects under the ground near the stations. The 2D FDTD simulation results also support above results, if a line current source exists. It is the first time to capture so clear signals in situ observation.

Conclusion

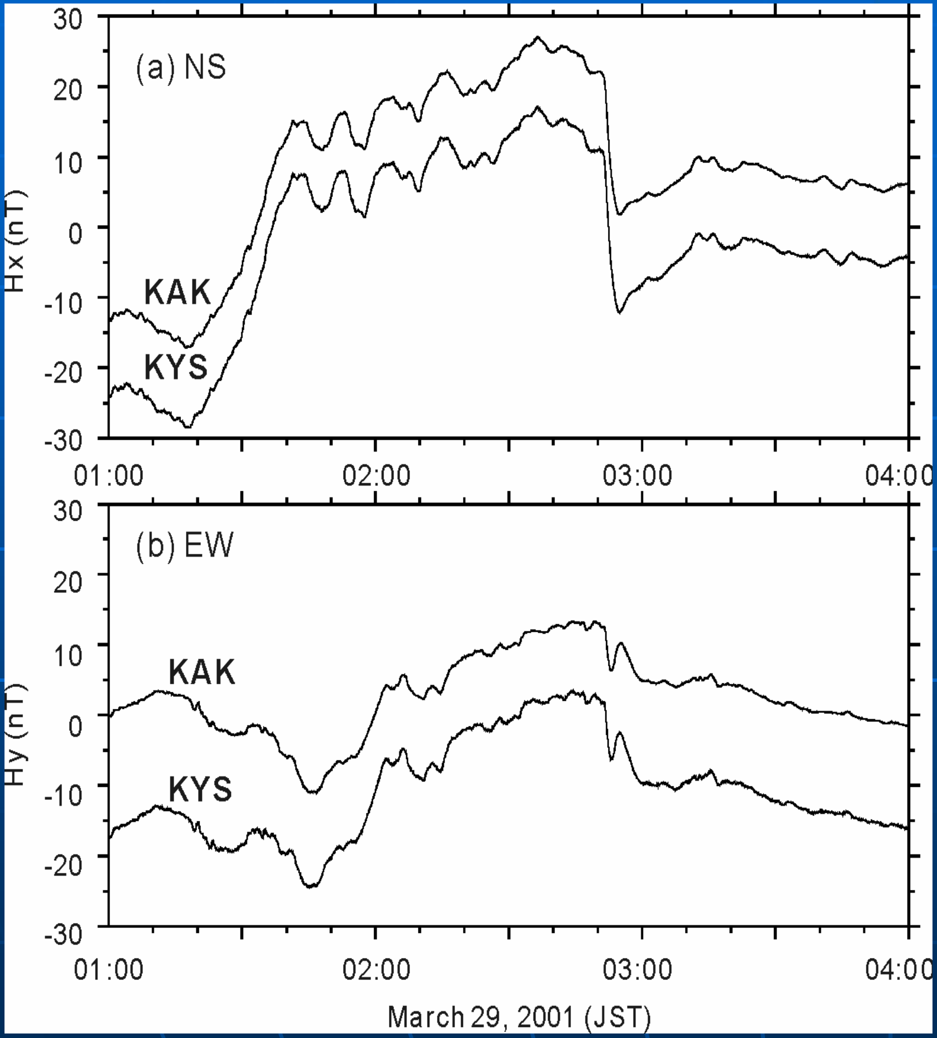
- The proposed ISTF method with wavelet transform is effective for both monitoring of underground structure changes and the global noises (upper-atmospheric sources such as geomagnetic pulsaions) reduction.
- The ISTFs seem to have a variation with the strain change in Izu stations.
- The electric-kinetic channels seem to exist under/near Boso stations and activate at the time of slowslip.

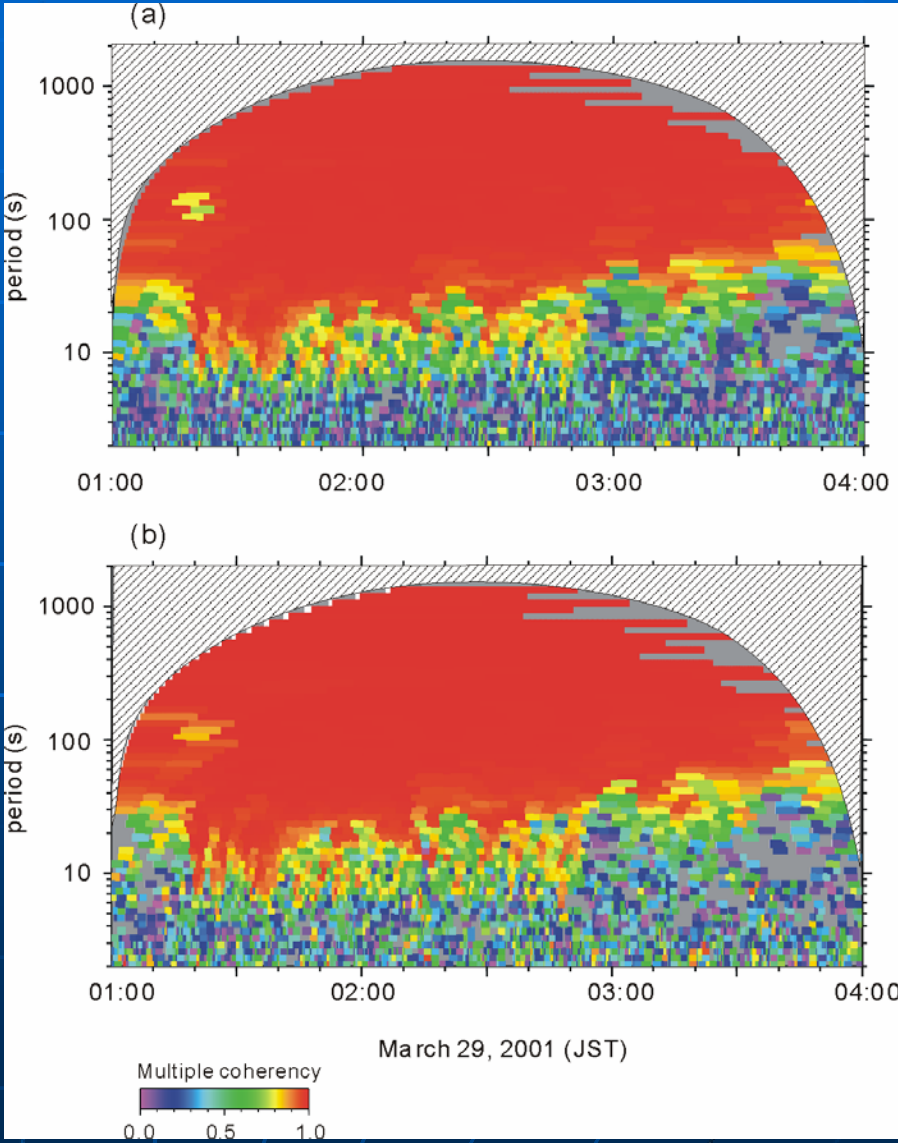
Acknowledgement

The authors would like to express thanks to Japan Meteorological Agency (JMA) for geomagnetic data at Kakioka Observatory, strain data at Toi station, and seismic catalog.

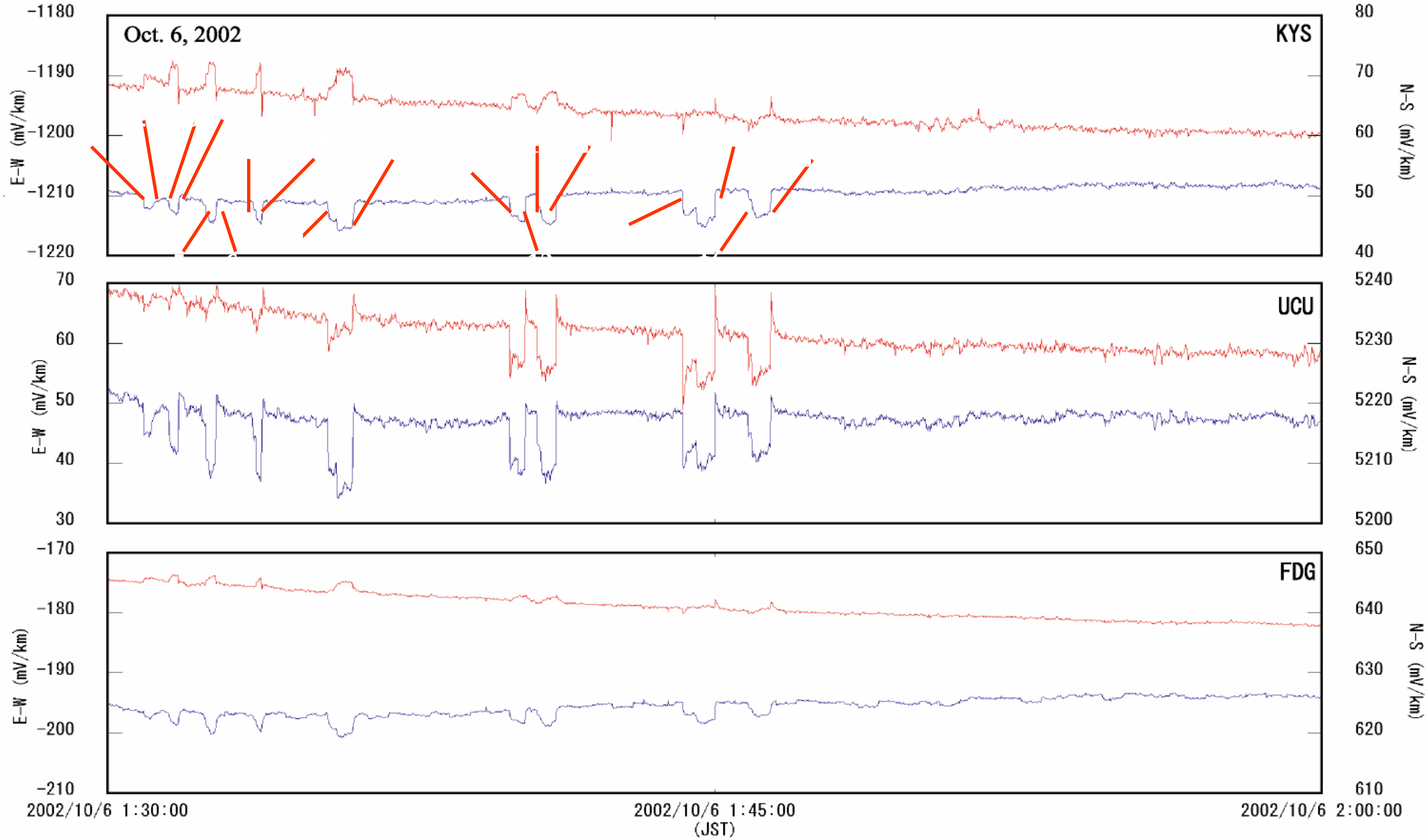
Thank you for your attention !!

Example of Multiple coherency (magnetic fields)



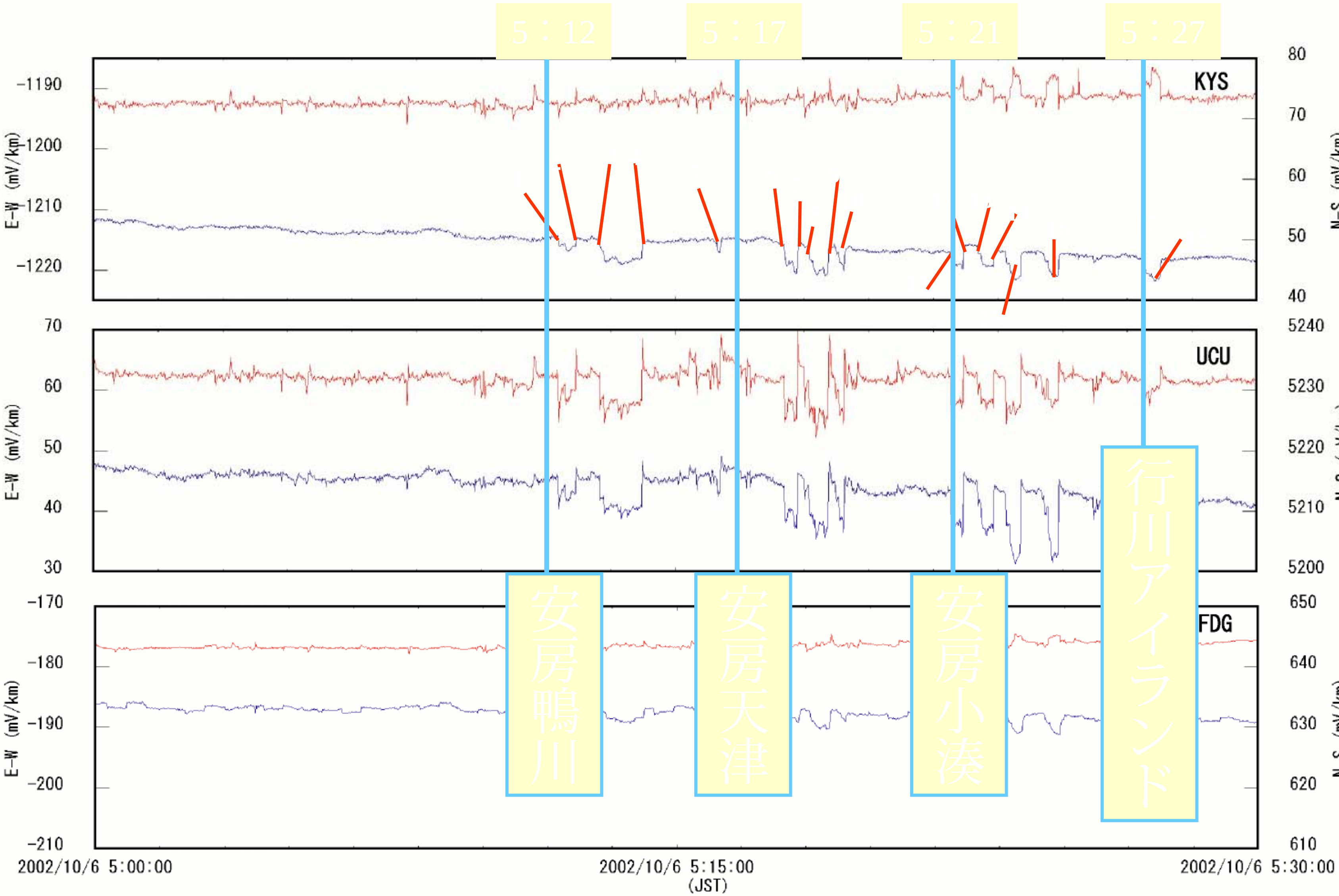


異常シグナルの見かけ到来方向を求める



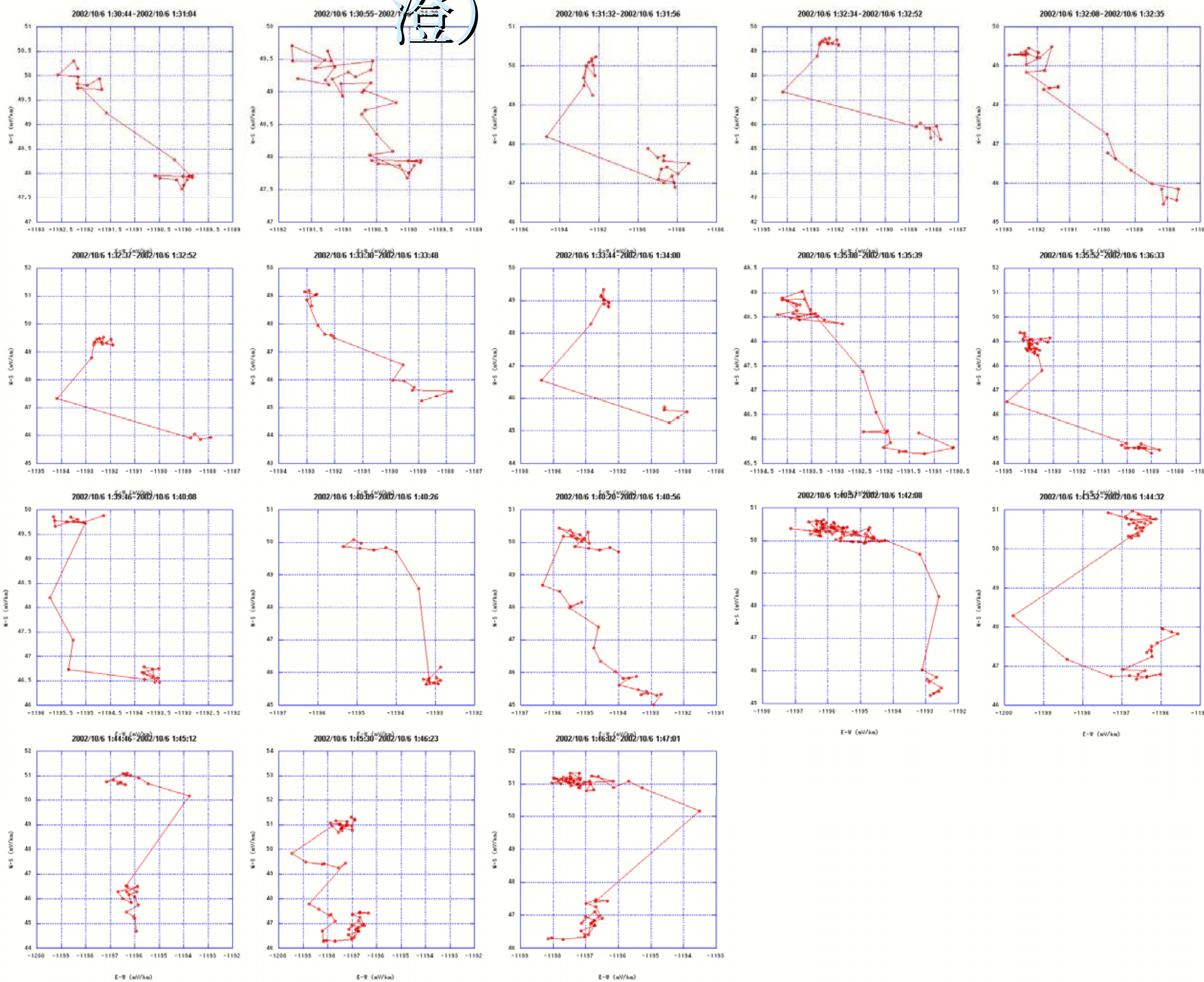
Electric field variations obtained at array stations in Boso Peninsula (KYS, UCU, FDG) for interval of 01:30 to 02:00 on Oct. 6, 2002. N-S component (blue line), E-W component (red line).

鉄道ノイズの見かけ到来方向を求める

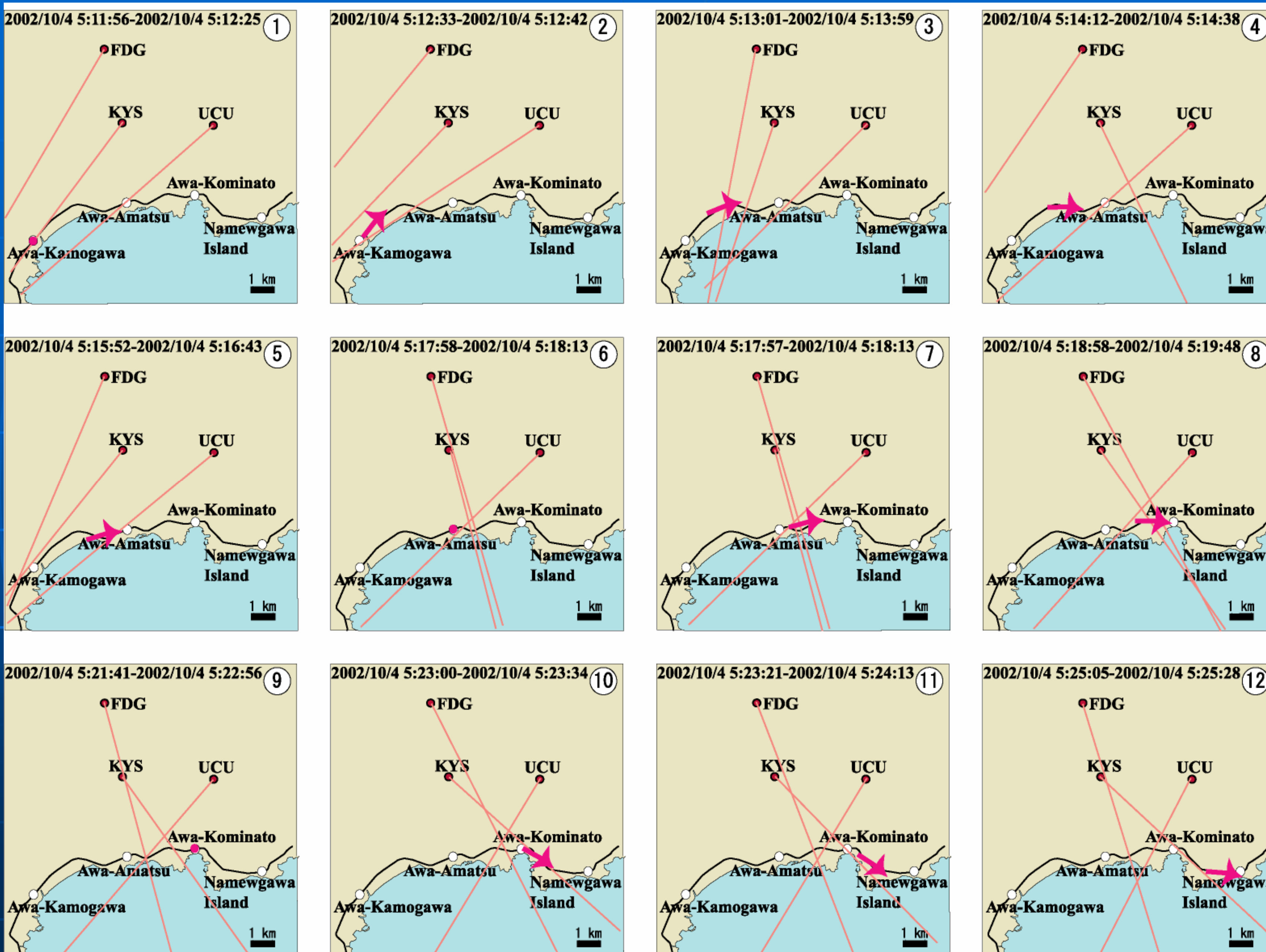


Examples of electric noise variations obtained at array stations in Boso Peninsula (KYS, UCU, FDG) for interval of 05:00 to 05:30 on Oct. 6, 2002.
N-S component (blue line), E-W component (red line).

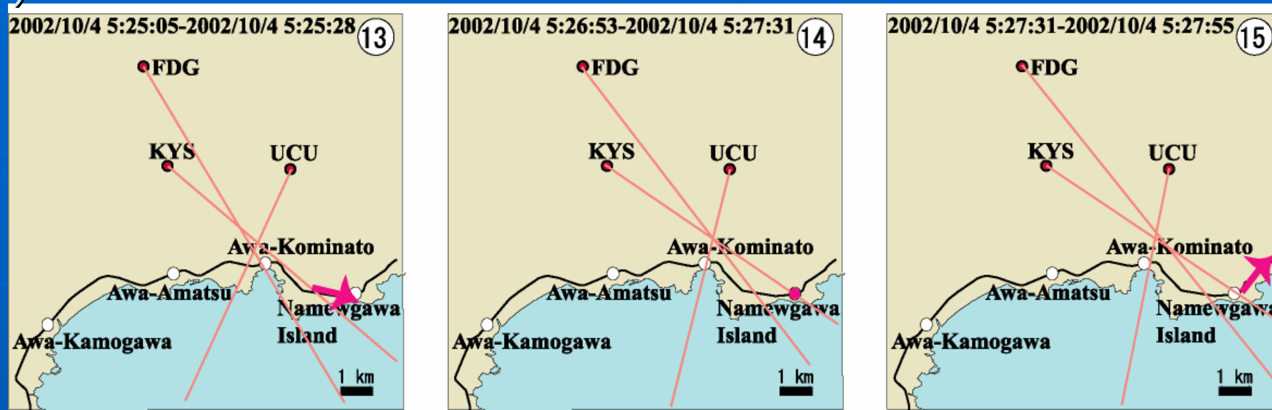
X-Y（東西，南北）への投影例（清澄）



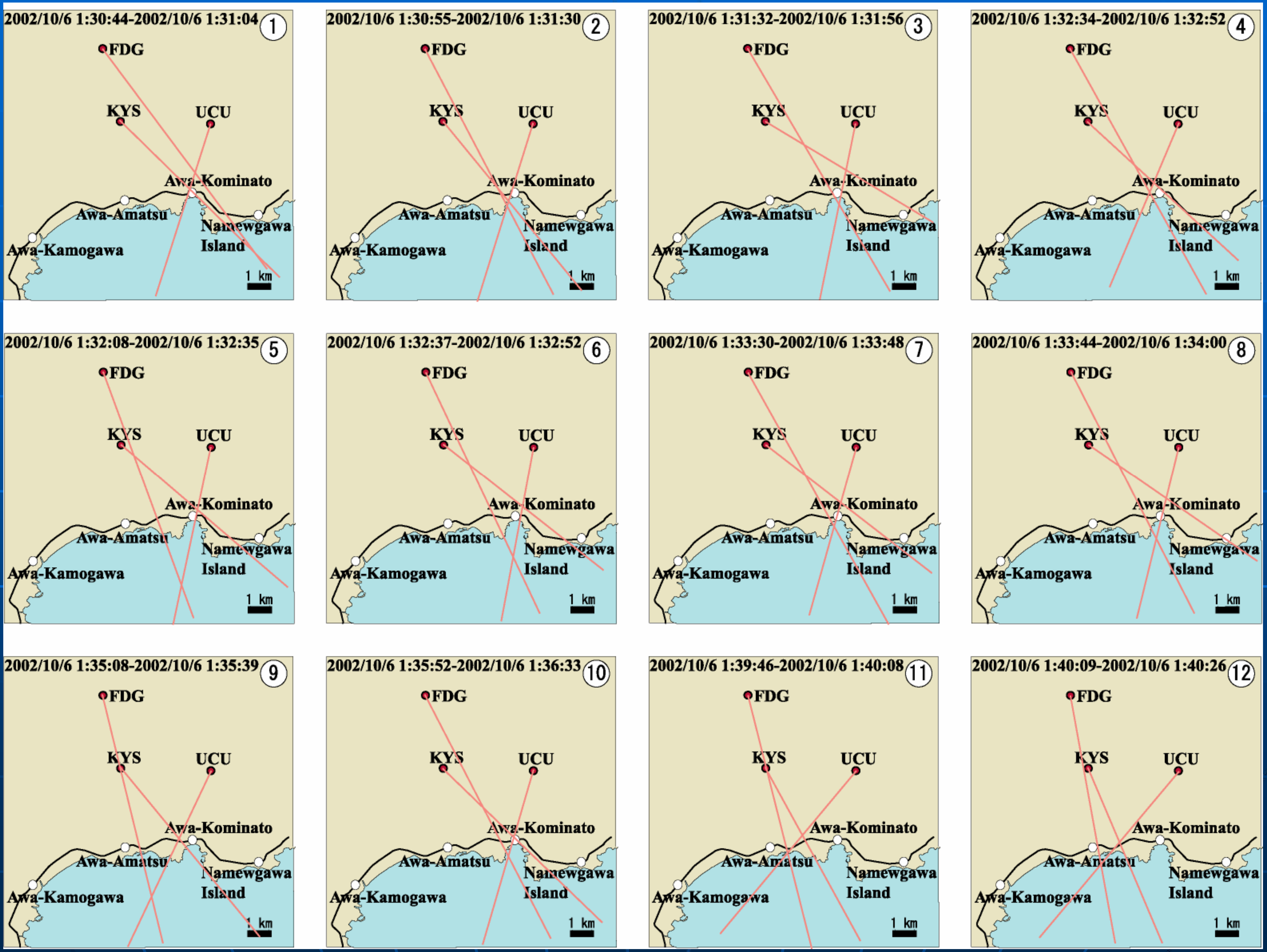
鉄道ノイズ (2002.10.4)



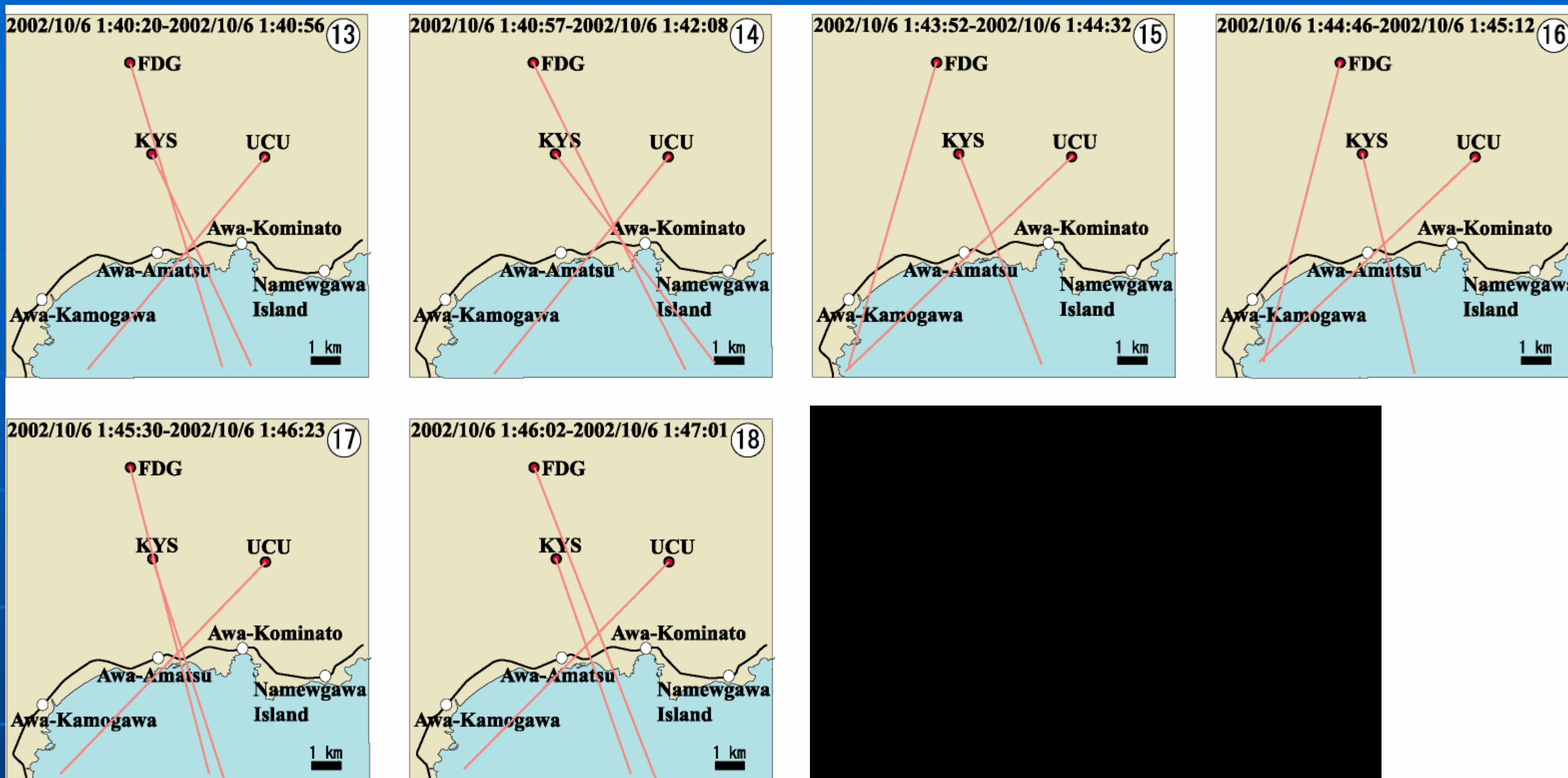
鉄道ノイズ
(2002.10.4)



2002.10.6 Anomaly_1



2002.10.6 Anomaly_2

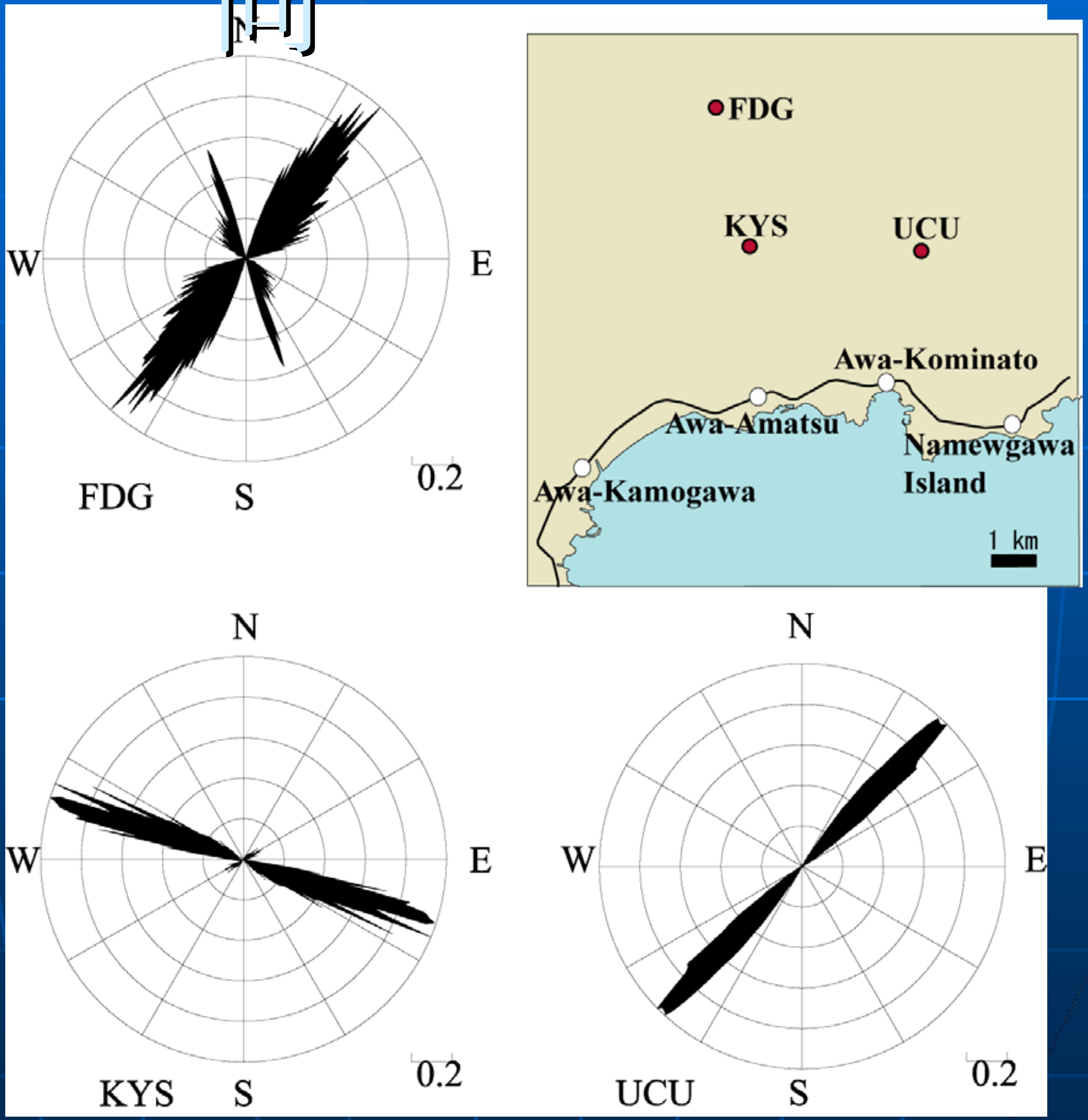


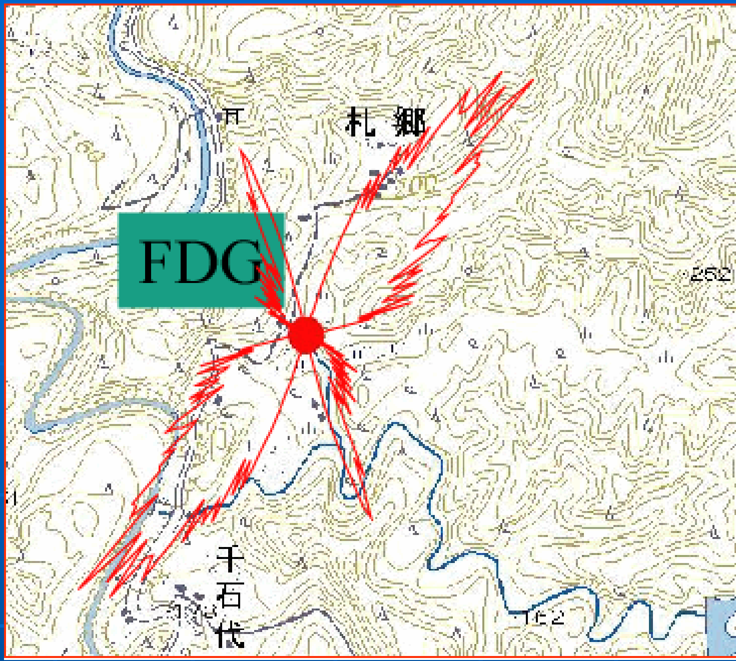
バックグランドノイズ到来方向

0:00-4:00 の間で
00分〜01分
10分〜11分
20分〜21分
30分〜31分
40分〜41分
50分〜51分

各データ（1分=60データ）について， E-W方向, N-S 方向に投影した電場データを使用.

2成分の分布から傾きと相関係数の絶対値を求めた.





The estimated direction of the usual background noise.

FDTD法

マックスウェルの方程式

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} \quad (2)$$

（1）を中心差分を用いて時間に関して離散化する．

$$\nabla \times \mathbf{E}^{n} = \mu \frac{\mathbf{H}^{n+1/2} - \mathbf{H}^{n-1/2}}{\Delta t} \quad \rightarrow \quad \mathbf{H}^{n+1/2} = \mathbf{H}^{n-1/2} - \frac{\Delta t}{\mu} \nabla \times \mathbf{E}^{n}$$

時刻n+1/2を現在としたとき，現在の**H**は過去の**H**と，その場所の**E**のローテーションから計算できる．

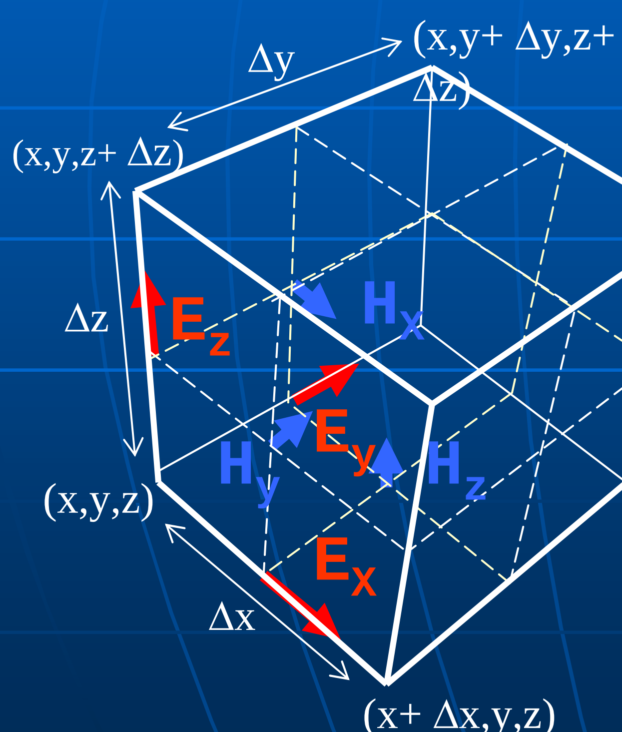
同様に（２）も離散化するが，このときはn+1/2を基準として行う．

$$\nabla \times \mathbf{H}^{n+1/2} = \varepsilon \frac{\mathbf{E}^{n+1} - \mathbf{E}^{n}}{\Delta t} + \mathbf{J}^{n+1/2} \quad \rightarrow \quad \mathbf{E}^{n+1} = \mathbf{E}^{n} + \frac{\Delta t}{\varepsilon} \nabla \times \mathbf{H}^{n+1/2} - \mathbf{J}^{n+1/2}$$

空間について離散化

$$\mathbf{E}=\begin{bmatrix} E_x(i+1/2,y,k) \\ E_y(i,j+1/2,k) \\ E_z(i,j,k+1/2) \end{bmatrix}$$

$$\mathbf{H}=\begin{bmatrix} H_x(i,j+1/2,k+1/2) \\ H_y(i+1/2,j,k+1/2) \\ H_z(i+1/2,j+1/2,k) \end{bmatrix}$$



各成分は互いに少しだけずれた位置に配置させる．（Yee格子）

Hのy成分は以下のように表すことができる．

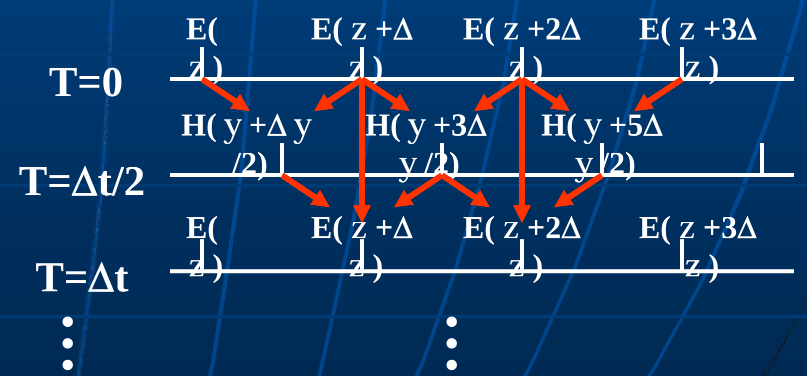
$$\mathbf{H}_y^{n+1/2}(x,y+\Delta y/2,z+\Delta z/2)=\mathbf{H}_x^{n-1/2}(x,y+\Delta y/2,z+\Delta z/2)-\frac{\Delta t}{\mu}\nabla\times\mathbf{E}_x^{n}(x+\Delta x/2,y,z)$$

$$=\mathbf{H}_y^{n-1/2}(x,y+\Delta y/2,z+\Delta z/2)-\frac{\Delta t}{\mu}\left\{\frac{\partial E_z^n}{\partial y}(x,y+\Delta y/2,z+\Delta z/2)-\frac{\partial E_y^n}{\partial z}(x,y+\Delta y/2,z+\Delta z/2)\right\}$$

$$=\mathbf{H}_y^{n-1/2}(x,y+\Delta y/2,z+\Delta z/2)-\frac{\Delta t}{\mu}\frac{E_z^n(x,y+1,z+\Delta z/2)-E_z^n(x,y,z+\Delta z/2)}{\Delta y}$$

$$+\frac{\Delta t}{\mu}\frac{\partial E_y^n(x,y+\Delta y/2,z+1)-E_y^n(x,y+\Delta y/2,z)}{\Delta z}$$

電界と磁界を交互に計算される(leap-frogアルゴリズム)



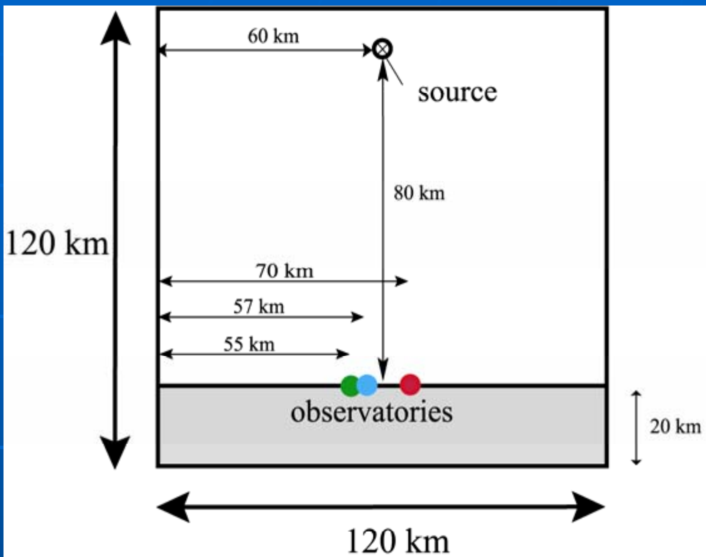
2次元FDTDモデル

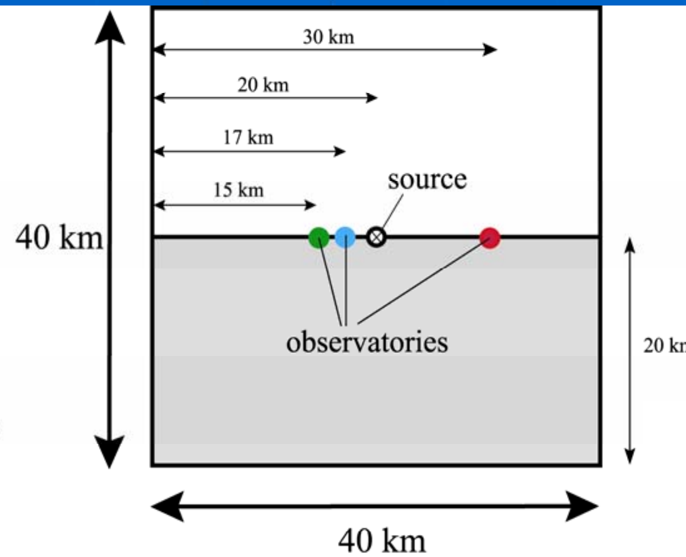
セル幅：1km×1km

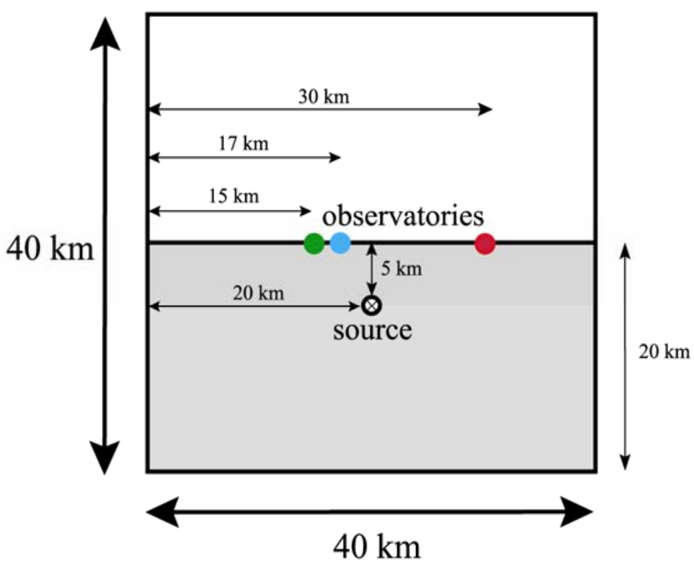
解析領域が地上80kmを超える場合は、

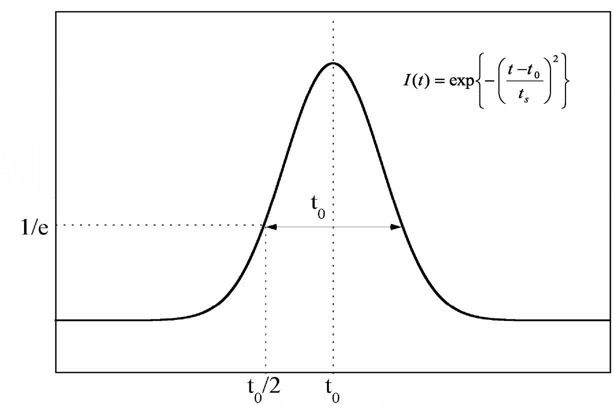
電離層伝導度モデルを適用。

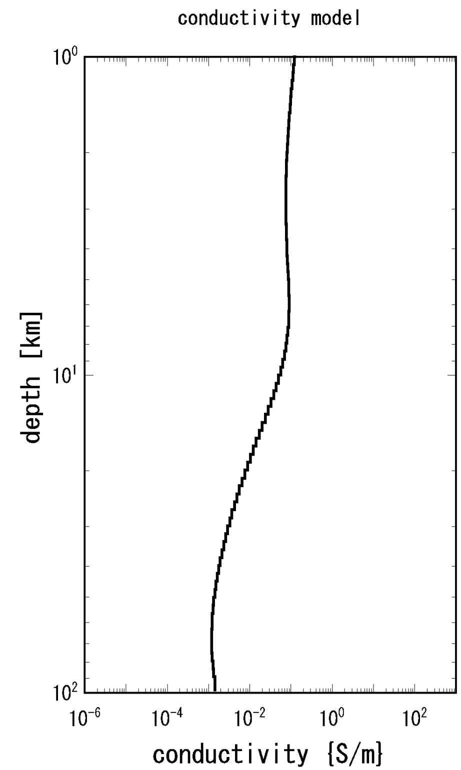
地中にはMTによって得られた1次元比抵抗構造を適用



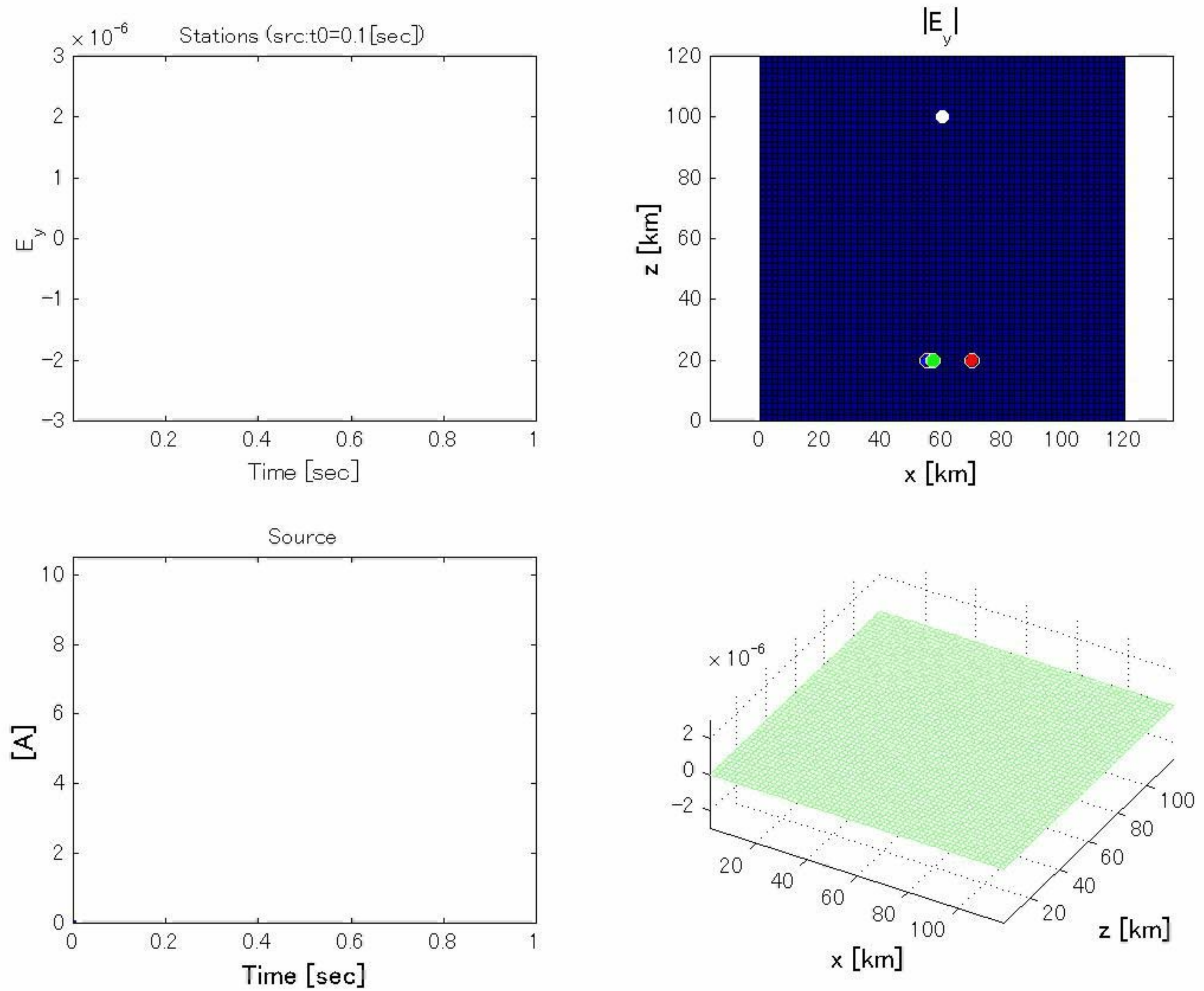








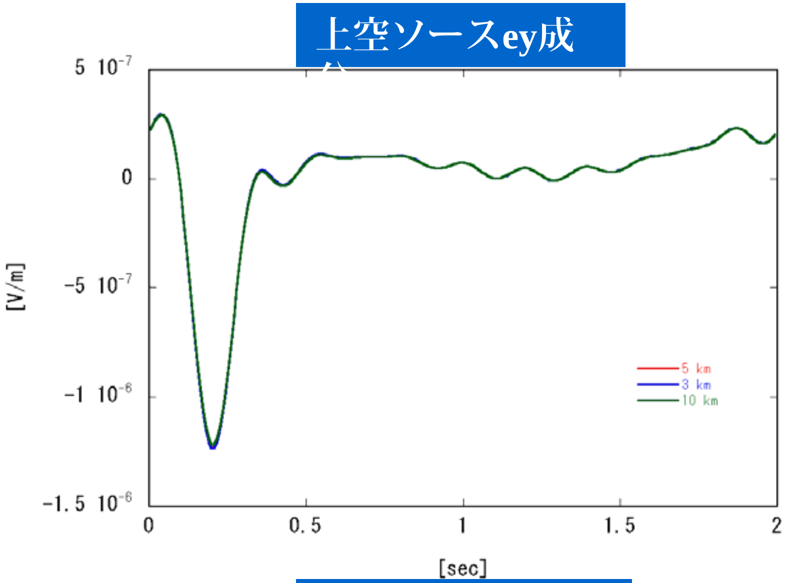
A　電離層起源

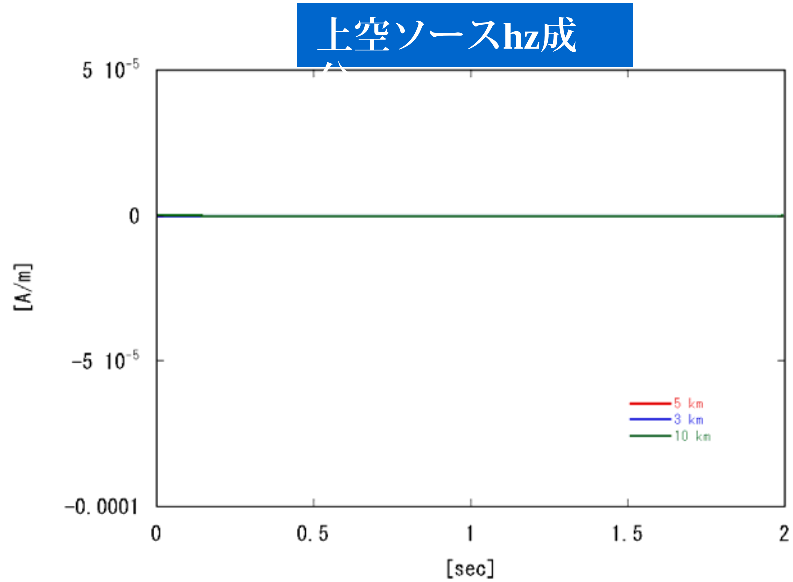


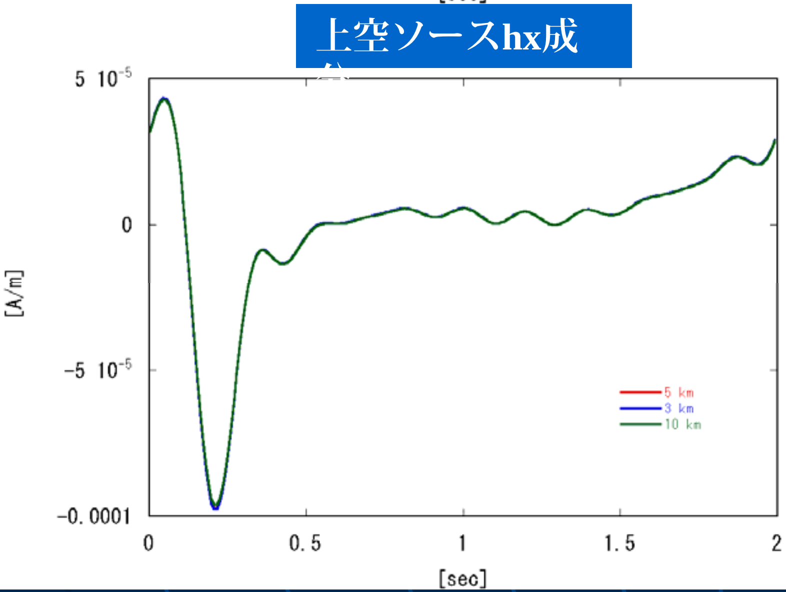
Stations (src:t0=0.1[sec])
× 10^-6
Ey
Time [sec]
|Ey|
z [km]
x [km]
Source
[A]
Time [sec]
× 10^-6
x [km]
z [km]

←地表

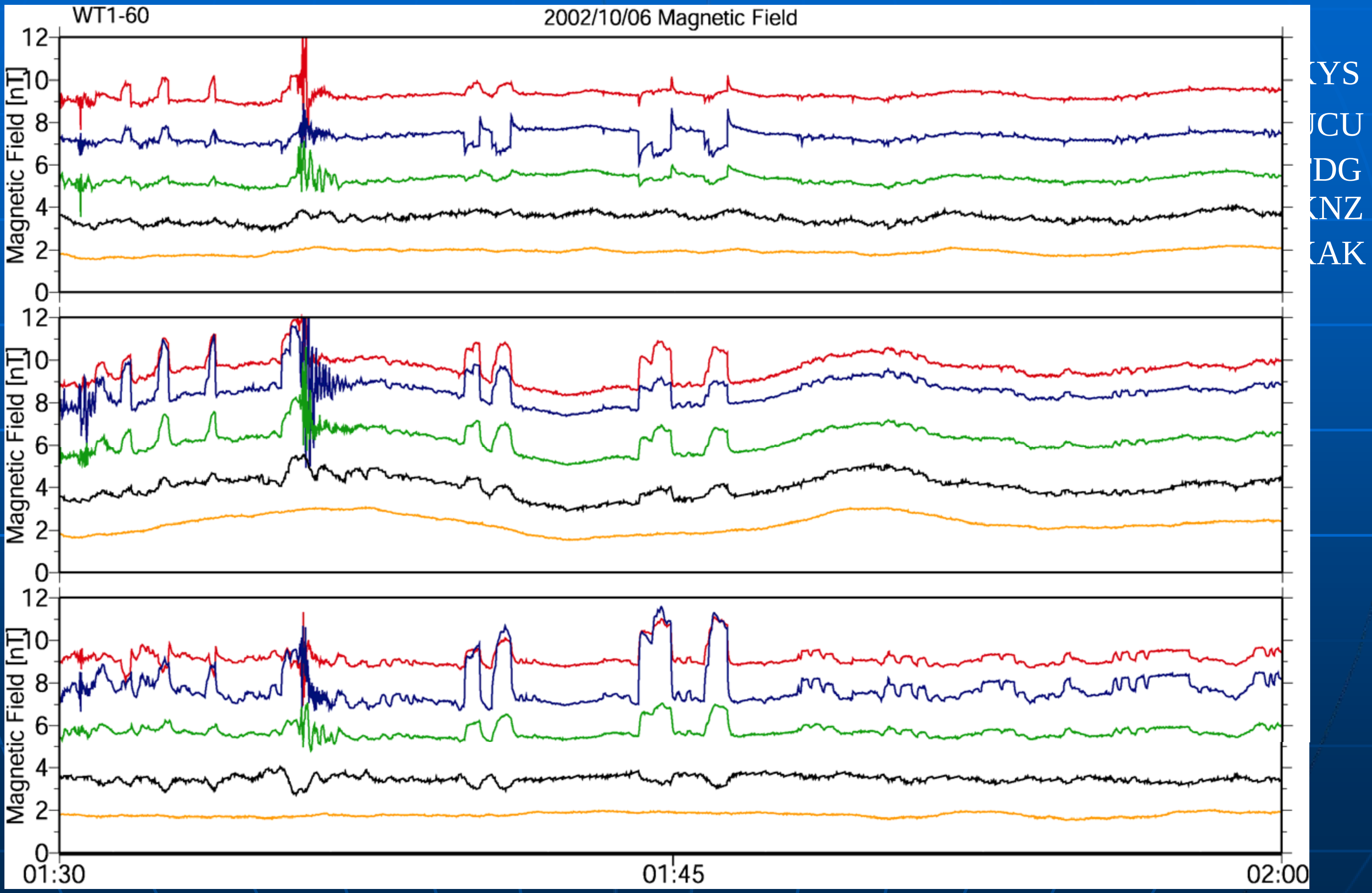
電離層起源では各観測点位置によるey,hxの振幅に違いは見られなくなる



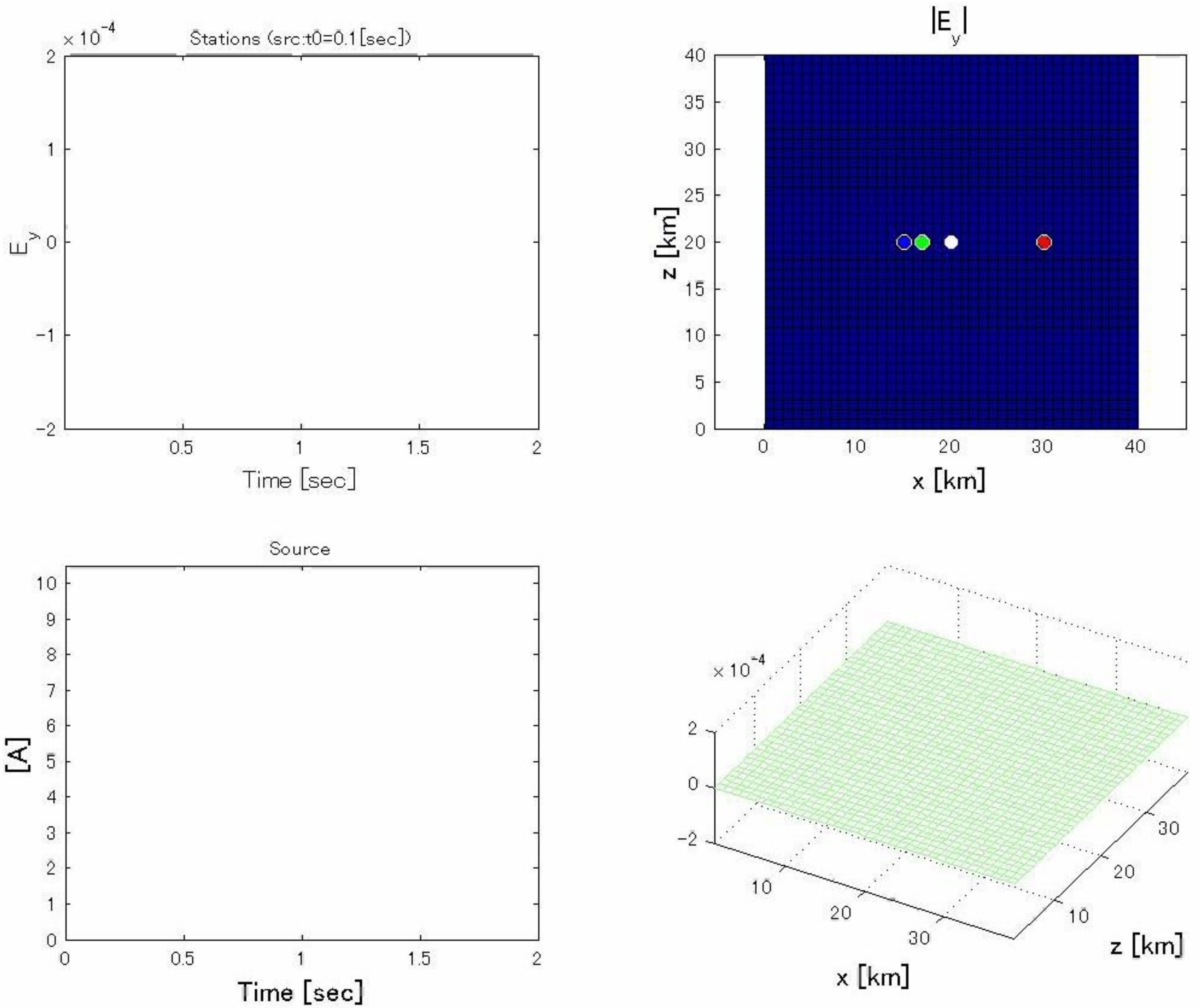




磁場異常変化　2002/10/5
各観測点ごと振幅に違いがある



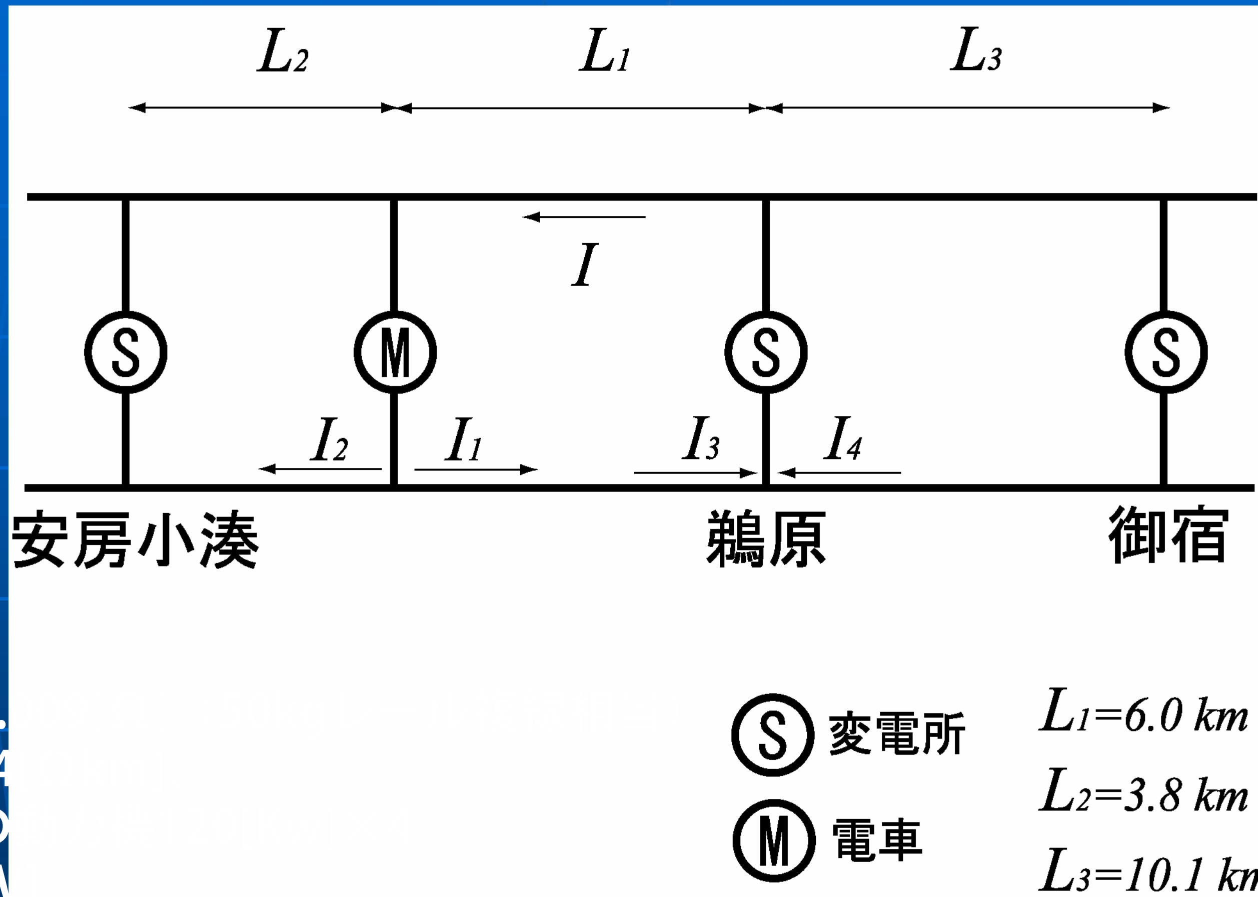
B　地表起源



Stations (src:t0=0.1[sec])
× 10^-4
E_y
Time [sec]
|E_y|
z [km]
x [km]
Source
[A]
Time [sec]
× 10^-4
x [km]
z [km]

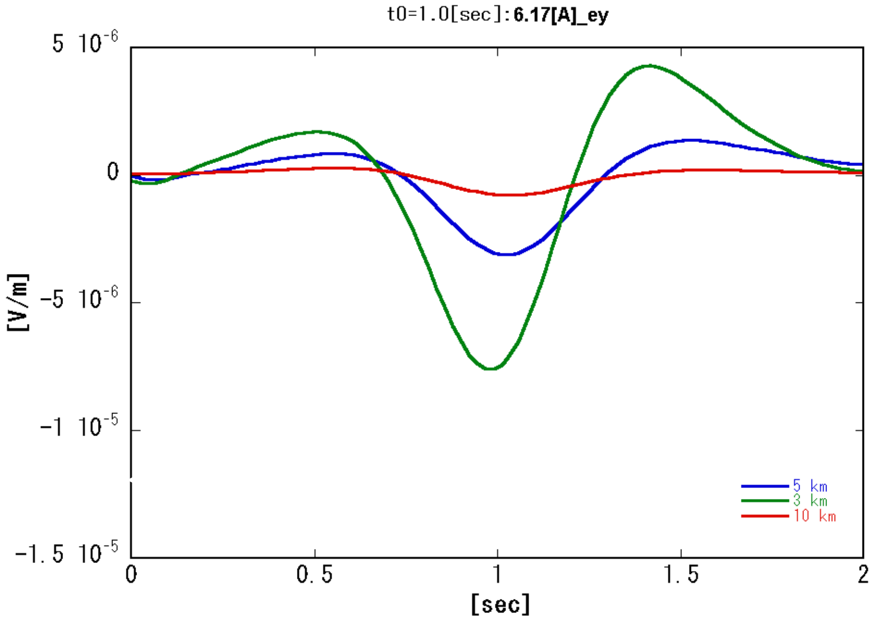
←地表

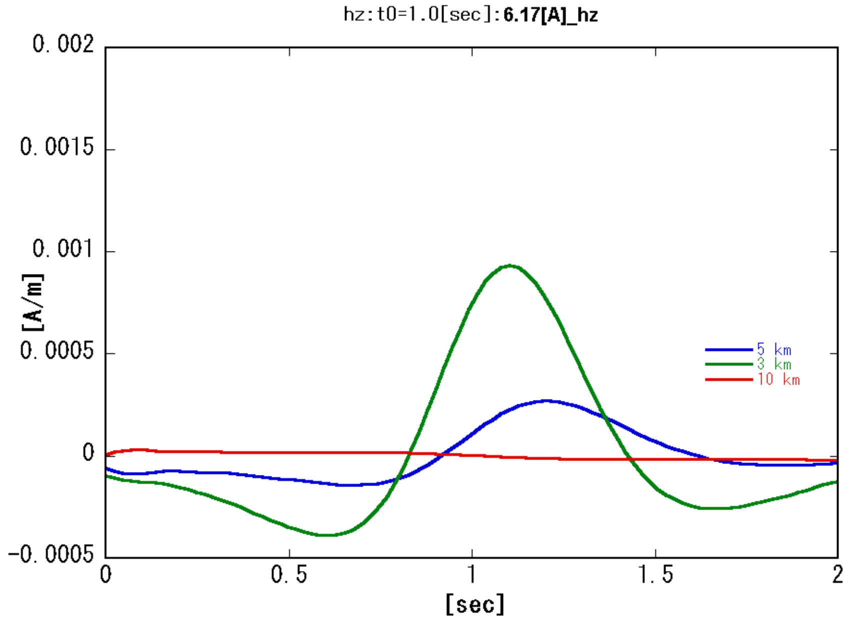
外房線の　き電回路

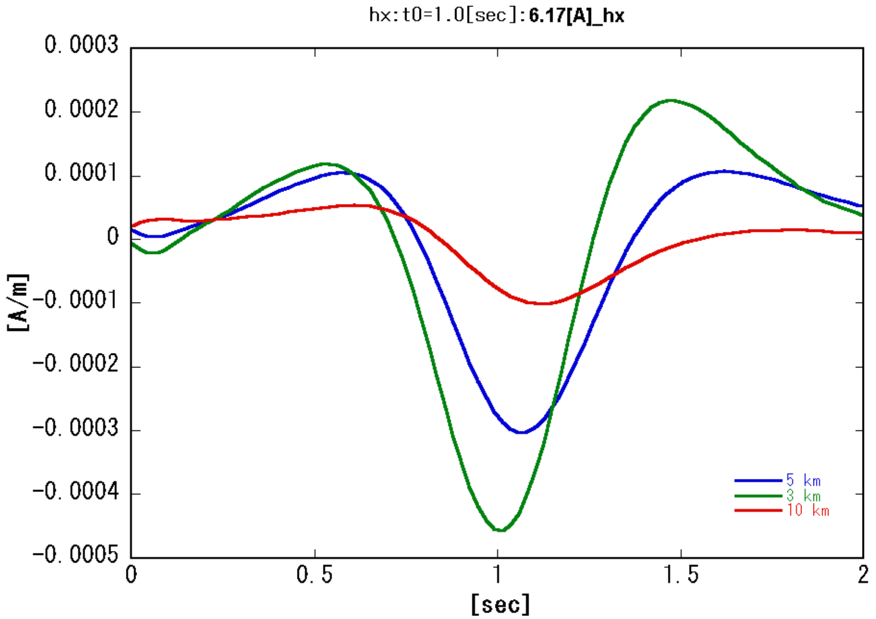


レール抵抗r=0.
漏れ抵抗ω=1.4
外房線の電車の
き電電圧1500[V
からIをもとめ計算を行うと、漏れ電流はおよそ6 [A]となった

安房小湊駅付近に線電流源を仮定し、FDTDを実施







緑：3km (UCU)

青：5km (KYS)

赤：10km (FDG)

各観測点における観測された電車ノイズの電場、磁場振幅
（5時22分安房小湊着発電車）。

EH、MHはそれぞれ電場、磁場の水平合力成分を表している。

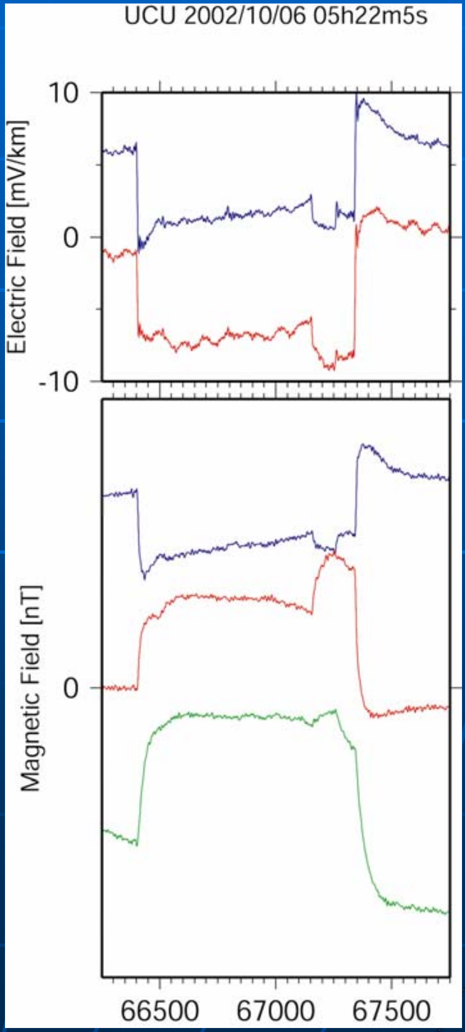
KYS			horizontal force				
electric EW	1.8	[mV/ km]	EH	3.85	[mV/ km]	(3.85E-06	[V/ m])
electric NS	-3.4	[mV/ km]					
magnetic X	0.5	[nT]	MH	0.54	[nT]	(4.29E-04	[A/ m])
magnetic Y	0.2	[nT]					
magnetic Z	0.745	[nT]				(5.93E-04	[A/ m])

UCU							
electric EW	-6.5	[mV/ km]	EH	9.55	[mV/ km]	(9.55E-06	[V/ m])
electric NS	-7	[mV/ km]					
magnetic X	-0.84	[nT]	MH	0.86	[nT]	(6.88E-04	([A/ m])
magnetic Y	0.204	[nT]					
magnetic Z	1.769	[nT]				(1.41E-03	[A/ m])

FDG							
electric EW	0.79	[mV/ km]	EH	1.5	[mV/ km]	(1.50E-06	[V/ m])
electric NS	-1.28	[mV/ km]					
magnetic X	-0.14	[nT]	MH	0.17	[nT]	(1.35E-04	[A/ m])
magnetic Y	0.103	[nT]					
magnetic Z	0.634	[nT]				(5.05E-04	[A/ m])

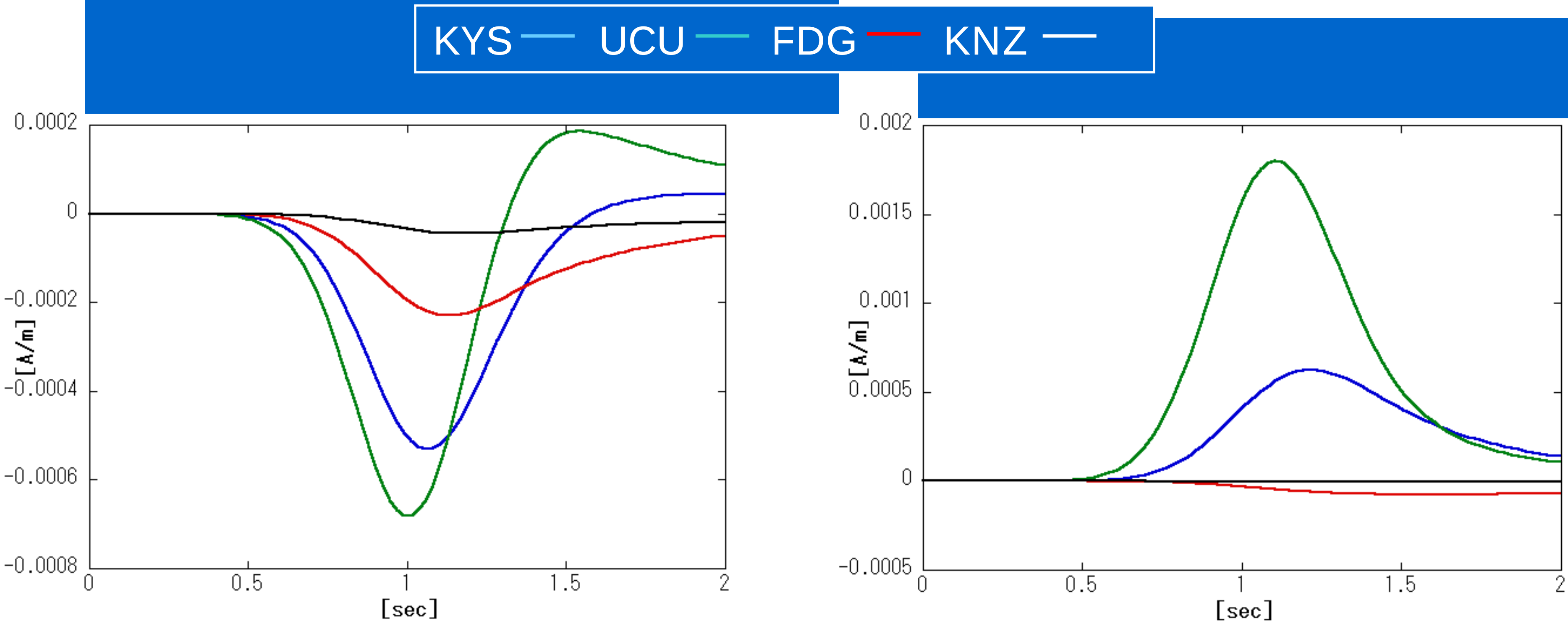
sim	5 km	3km	10 km	25 km
ey	1	2.446	0.248	0.045
hx	1	1.506	0.332	0.052
hz	1	3.450	-0.060	-0.009

obs	KYS	UCU	FDG	KNZ
electric H	1	2.481	0.390	
magnetic H	1	1.593	0.315	0.000
magnetic Z	1	2.374	0.851	0.000



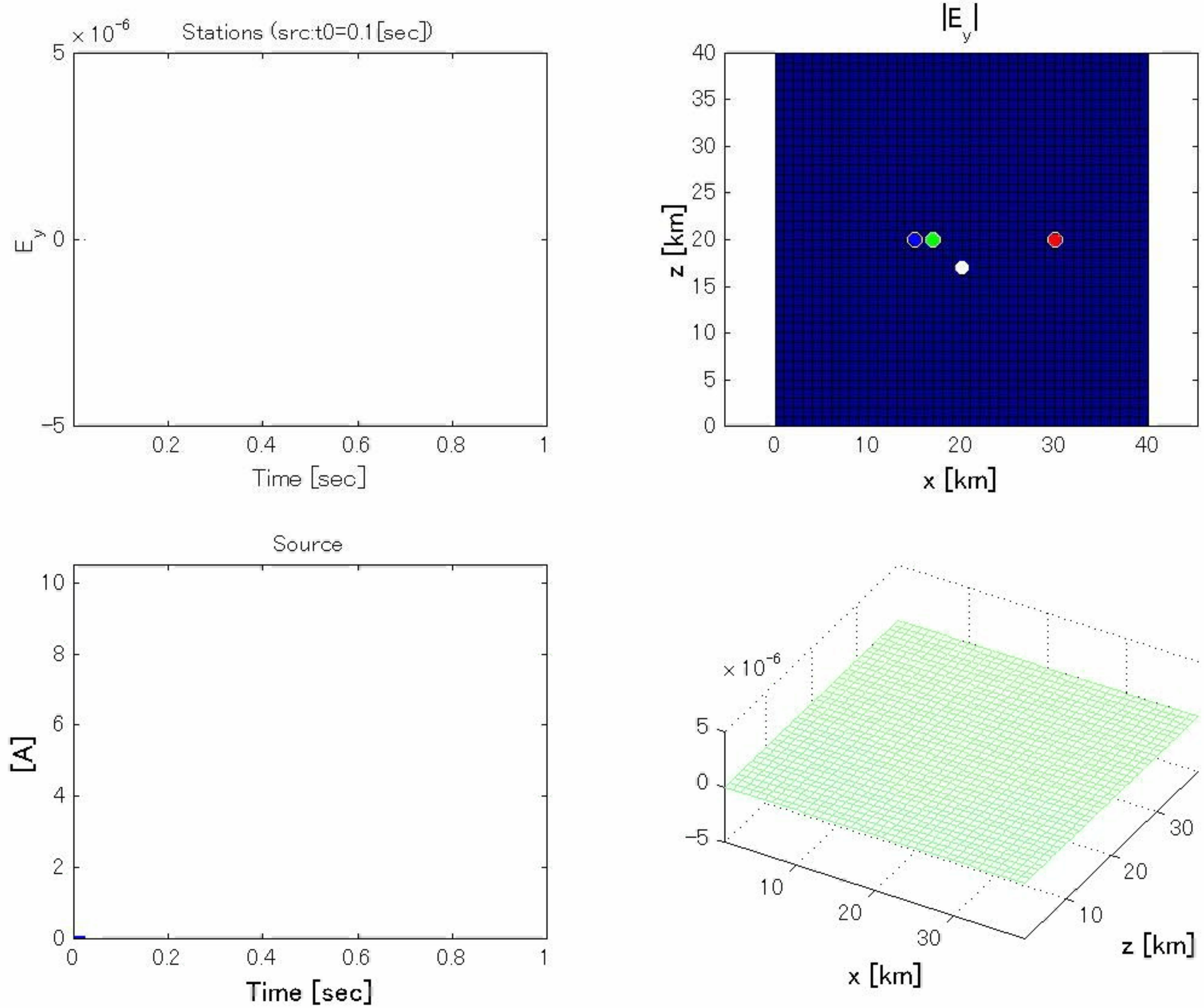
シミュレーションで得られた各電磁場成分の観測点間の振幅比（sim）と、実際の観測点で得られた電車ノイズの観測点間の振幅比(obs)。

KNZ(鉄道から約25km)で見積もられる電磁場（hx,hz）



異常変動は小湊付近の電車によるものではない

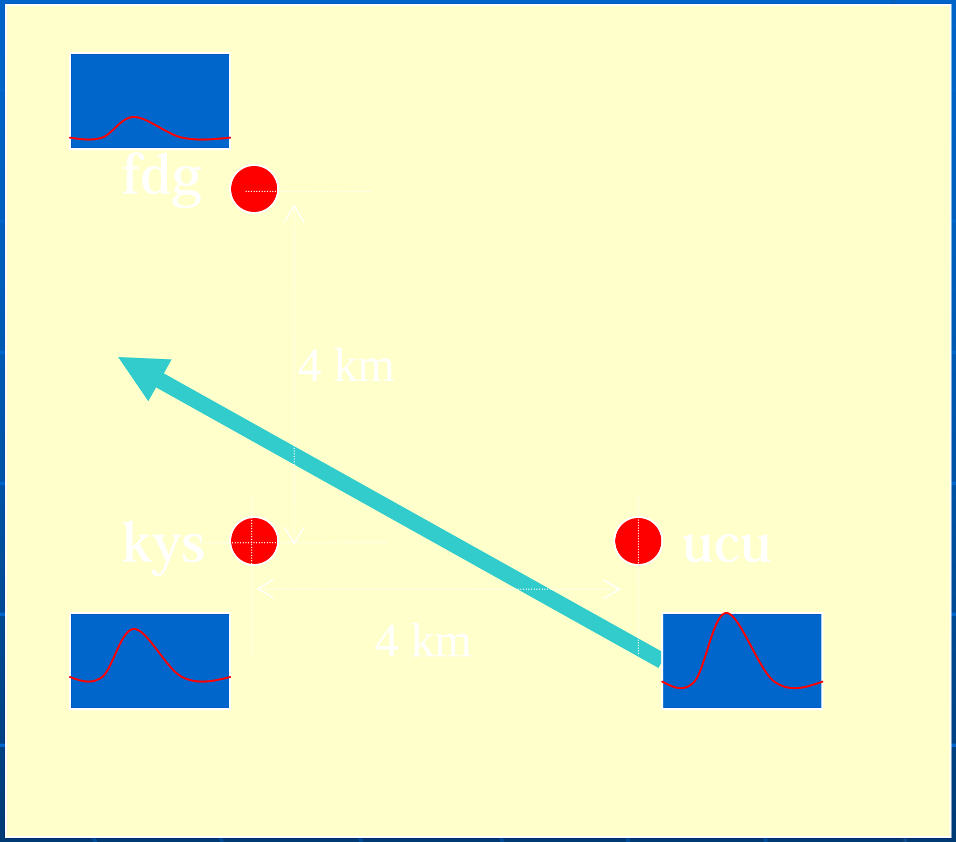
C　地下起源



× 10^-6
Stations (src:t0=0.1[sec])
5
0
−5
Ey
0.2
0.4
0.6
0.8
1
Time [sec]
|Ey|
40
35
30
25
20
15
10
5
0
z [km]
0
10
20
30
40
x [km]
Source
10
8
6
4
2
0
[A]
0
0.2
0.4
0.6
0.8
1
Time [sec]
× 10^-6
5
0
−5
10
20
30
x [km]
10
20
30
z [km]

←地表

観測点網の中を線電流が流れると仮定

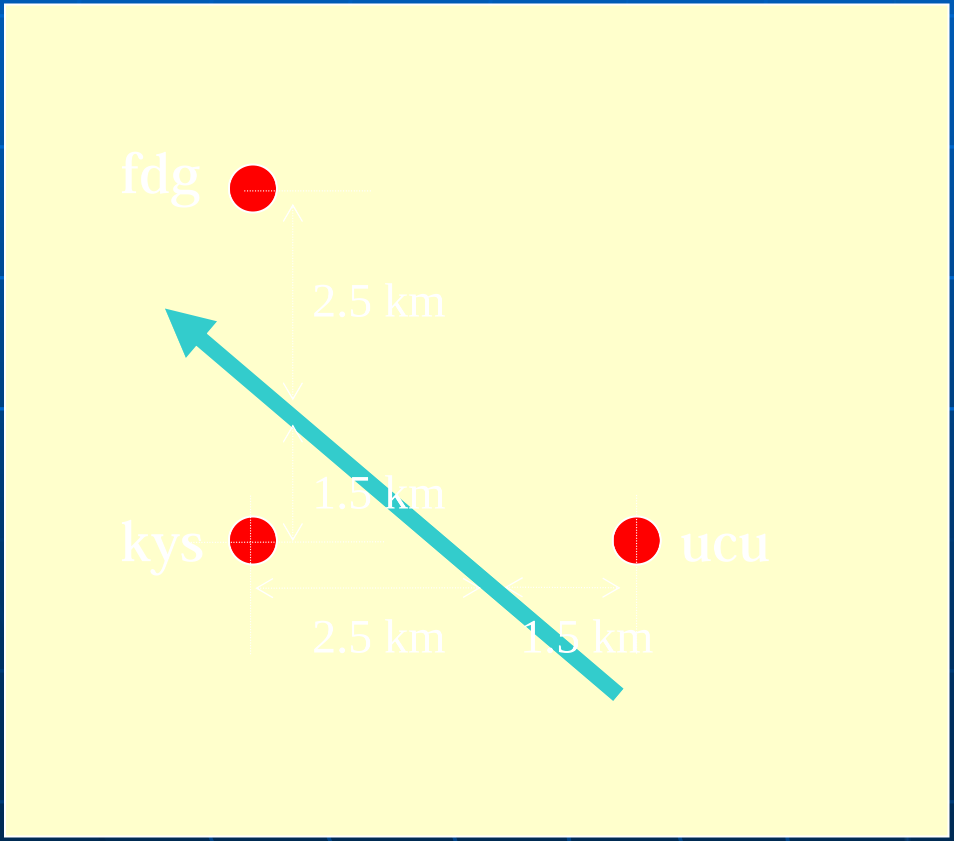


シミュレーション結果から
各観測点での電磁場の
振幅の割合について比較

線電流源の深さ、
観測点からの距離を変えて
得られる振幅の比率を求めた。

実際の観測から求めた振幅比

obs	KYS	UCU	FDG
electric H	1.0	1.8	0.5
magnetic H	1.0	1.5	0.8
magnetic Z	1.0	- 1.2	- 0.4



線電流源深さ0km（地表）

	KYS	UCU	FDG
ey	1.0	2.3	0.4
hx	1.0	1.4	0.7
hz	1.0	3.2	0.3

線電流源深さ0.5km

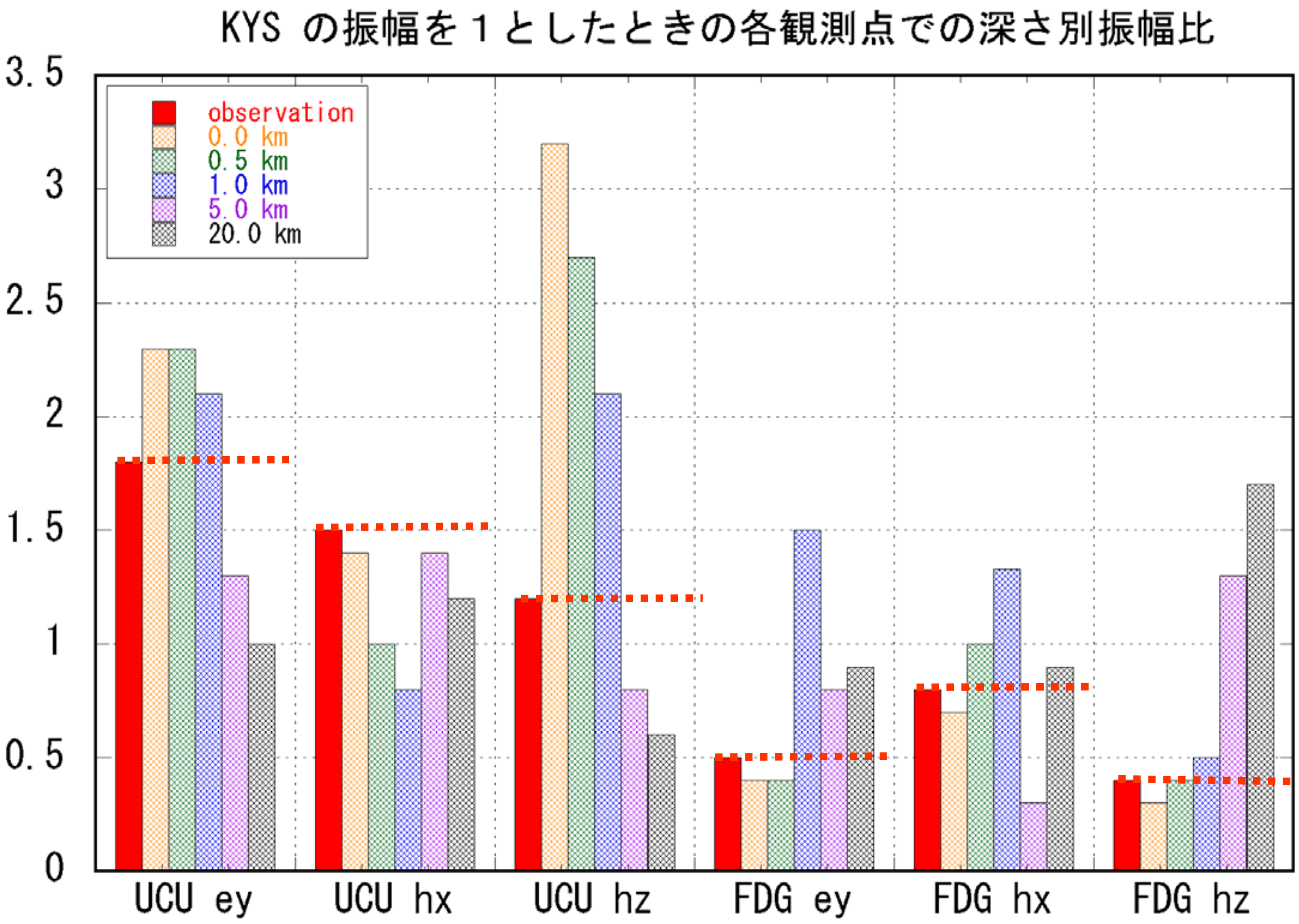
	KYS	UCU	FDG
ey	1.0	2.3	0.4
hx	1.0	1.0	1.0
hz	1.0	2.7	0.4

線電流源深さ1.0km

	KYS	UCU	FDG
ey	1.0	2.1	0.5
hx	1.0	0.8	1.3
hz	1.0	2.1	- 0.5

線電流源深さ5.0km

	KYS	UCU	FDG
ey	1.0	1.8	0.6
hx	1.0	0.8	1.2
hz	1.0	1.3	0.7



KYS の振幅を１としたときの各観測点での深さ別振幅比
3.5
3
2.5
2
1.5
1
0.5
0
observation
0.0 km
0.5 km
1.0 km
5.0 km
20.0 km
UCU ey
UCU hx
UCU hz
FDG ey
FDG hx
FDG hz

2次元FDTDまとめ

FDTD法を用いて、上空、地表、地下に波源を置いたときの地表における電磁場を計算した。（電離層モデル、MT結果）ソース位置の違いによる定性的な見積もりが可能となった

- 電離層起源のシグナル
  - 異常変動は説明できない
- 電車ノイズ　（地表）
  - 波源を安房小湊駅付近（線電流源）と仮定し、漏れ電流を計算した。
    - 各観測点において計算された電磁場の値は現実のノイズの値に近い。
    - 安房小湊駅付近で発生するノイズは、KNZまでは届かない。
- 地下起源のシグナル
  - 異常変動のソースを線電流と仮定した場合、その深さは0〜1km程度か。

４.総括

房総半島南部にハイサンプリング（50Hz）のULF電磁場観測点を構築した（KYS,UCU,FDG　電磁場5成分）。

2002年10月6日未明に異常な変動を3点同時に観測した。

特徴として

（１）電場ベクトルの変動から電車ノイズとは異なる。

（２）磁場変動からソースは観測点近傍の地下にあることが示唆された。

観測点網周辺の地下電気伝導度構造を調査し、2次元FDTD法によるシミュレーションを行った。

総括２

ソース位置の違いによるシミュレーション

•ソースが上空にある場合

⇒各観測点同時で、振幅も同じ。

•ソースが地表にある場合（電車ノイズ）

⇒電車ノイズは鹿野山まで付近までは到達しない。

•ソースが地下にある場合

⇒異常変動のソースは浅い場所でなければならない。

→地下0.5-1km付近の地下水移動に伴う界面導電現象等

間欠的な流動の発生により複数の電磁場変動。

観測波形の調査を行い、観測点周辺での電磁環境の推定を行った。それらを元に方位探査による信号の弁別や、観測されうる電磁信号のシミュレーションを行うことができた。