Singular spectral analysis and principal component analysis of ULF geomagnetic data; reduction of global noises and possible changes associate with the 2000 Izu Islands Earthquake swarm in Japan

Katsumi Hattori and Daishi Kaida

Graduate School of Science,

Chiba University, Japan

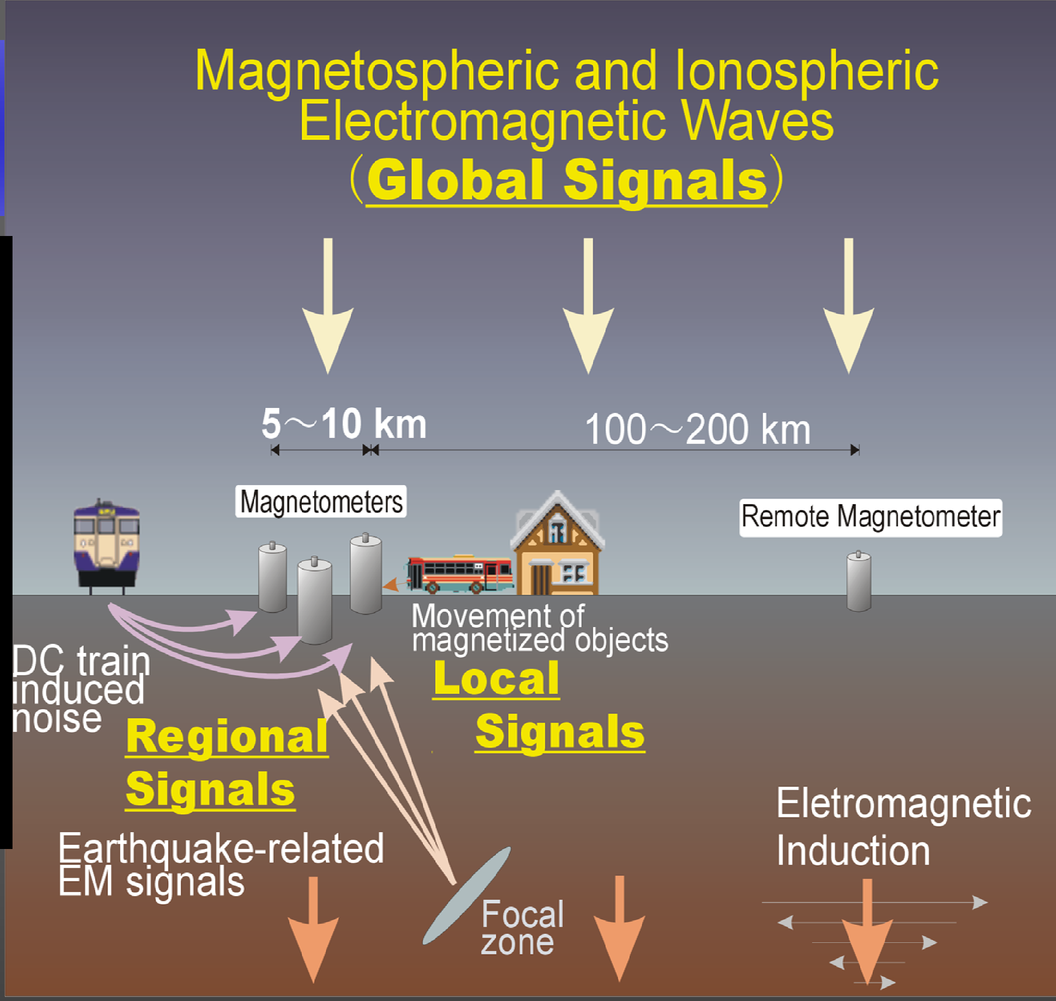
1-1. Background

ULF Geomagnetic data include

1. geomagnetic pulsations (originated from solar-terrestrial intereaction)
global variation with spatial resolution several hundreds km

2. artificial noises （DC-driven train noises etc.） a few tens km

3. Variation from crustal activities such as earthquakes and volcanic activities



In order to monitor or identify crustal activity-related signals from ULF magnetic data , it is important

how to discriminate

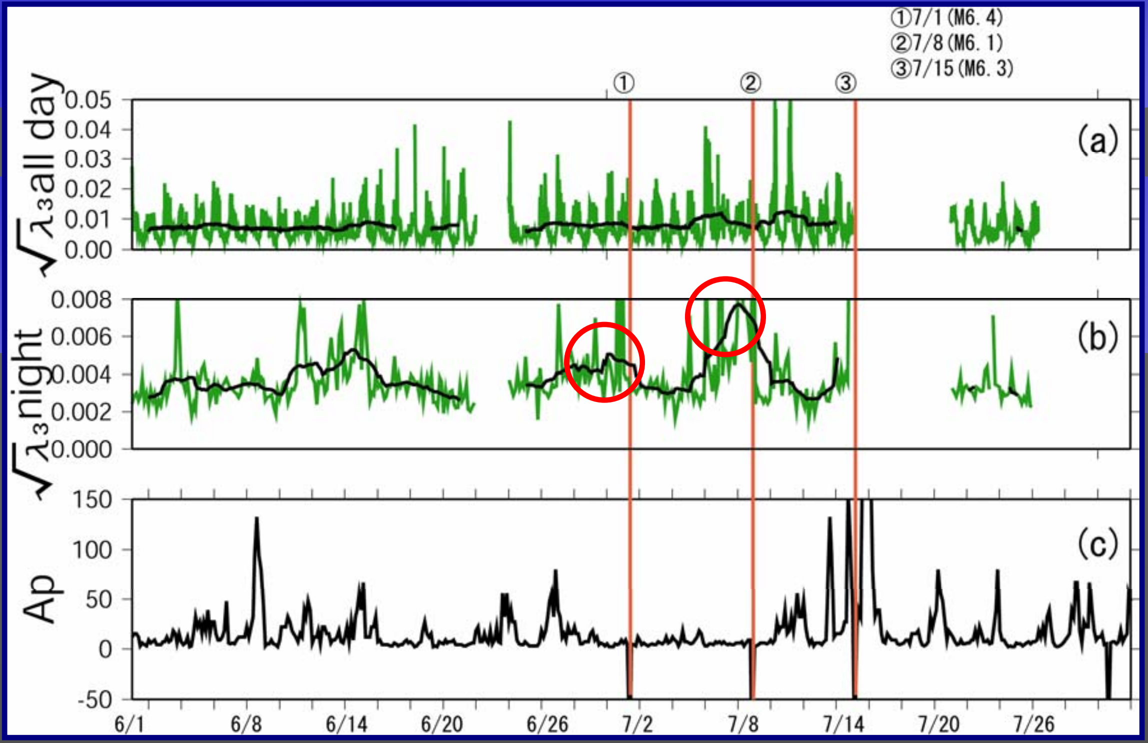
1. Geomagnetic pulsations
2. Artificial noises

1-2. Previous study of Principal Component analysis for the 2000 Izu Islands swarm

Hattori et. al. (PCE 2004)

3 station data with inter-sensor distance of 5 km

sampling rate 12.5 Hz
narrow band pass filter with center frequency at 0.01 Hz



1st Principal Component ⇒ geomagnetic pulsations
2nd Principal Component ⇒ artificial noises **are dominant**
3rd Principal Component ⇒ earthquake-related signals

Problem

The contribution of 3rd principal component is less than 6 %.

1-3. Present study

In order to overcome the difficulties in previous analysis

(1) Reduce the most intense variation in ULF geomagnetic pulsations with using the singular spectral analysis.

(2) Perform principal component analysis for the 2000 Izu Islands swarm in Japan.

2-1. Station map and EQs

Reference site

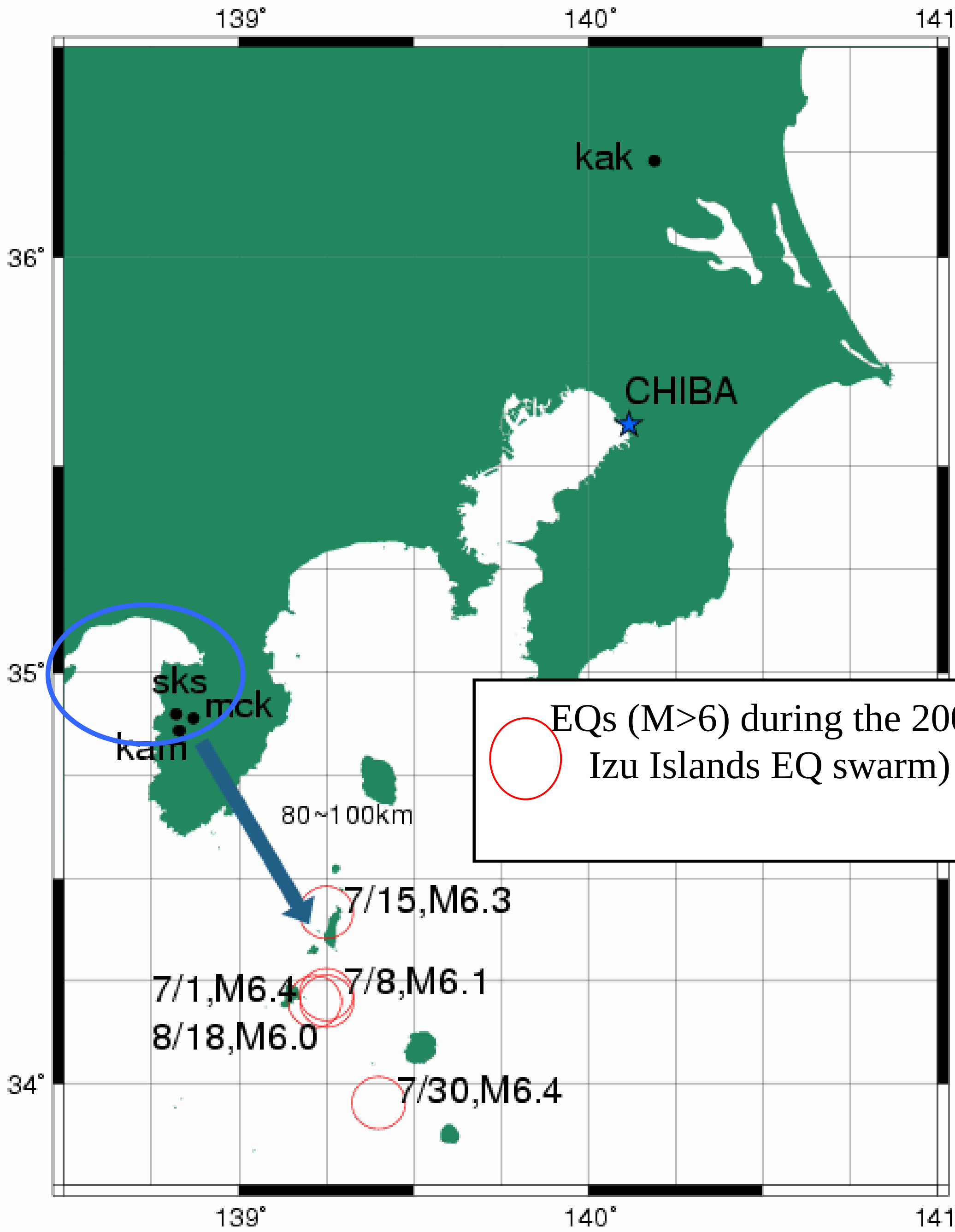
JMA Kakioka Observatory (kak)

1 Hz sampling

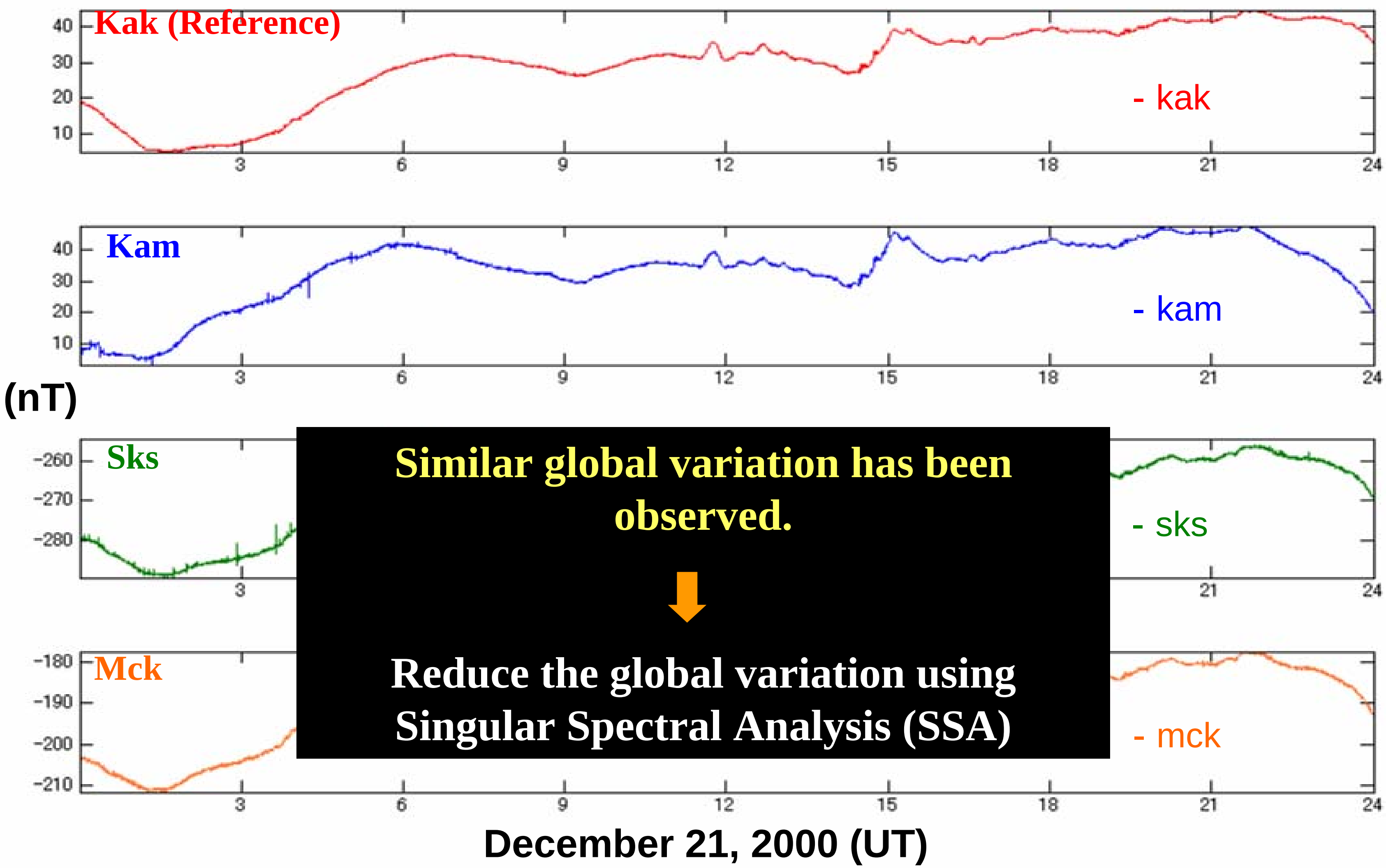
Izu network station

Kamo (kam), Seikoshi (sks), and Mochikoshi (mck)
1 Hz sampling data

station	lat.	long.
kak	36.23°	140.19°
kam	34.86°	138.83°
sks	34.90°	138.82°
mck	34.89°	138.87°



2-2. Observed data



Similar global variation has been observed.

⬇

Reduce the global variation using Singular Spectral Analysis (SSA)

3-1. Singular Spectral Analysis (SSA)

chiba-u geophysics

SSA is a kind of time series analysis.
Extract periodicities from the time series data with use of singular value decomposition without any models.

SSA has an advantage against wavelet analysis and fourier analysis in pulse detection and so on

Procedure of SSA

3-1. Singular Spectral Analysis (SSA)

1st Step

Time series data $\{x_j\} = x_1, x_2 \cdots x_N$

1-1. Created the Matrix (kXL) from time series data

$$X = \begin{matrix} x_1 & x_2 & x_3 & \cdots & x_L \\ x_2 & x_3 & x_4 & \cdots & x_{L+1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_k & x_{k+1} & x_{k+2} & \cdots & x_N \end{matrix}$$

L : Window Length

1-2. Compute covariance matrix S of X

$$S = X^T X = \begin{pmatrix} x_1 & x_2 & \cdots & x_k \\ x_2 & x_3 & \cdots & x_{k+1} \\ x_3 & x_4 & \cdots & x_{k+2} \\ \vdots & \vdots & \ddots & \vdots \\ x_L & x_{L+1} & \cdots & x_N \end{pmatrix} \begin{pmatrix} x_1 & x_2 & x_3 & \cdots & x_L \\ x_2 & x_3 & x_4 & \cdots & x_{L+1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_k & x_{k+1} & x_{k+2} & \cdots & x_N \end{pmatrix}$$

2^{nd} Step

2-2. Singular Decomposition (Eigen valus decomposition) of S matrix

$$S = U \Lambda U^{-1}$$

Eigenvalue Λ

Eigenvector U

$$\Lambda = \begin{pmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_L \end{pmatrix}$$

$$U = \begin{pmatrix} u_1 & u_2 & \cdots & u_L \end{pmatrix} = \begin{pmatrix} u_{11} & u_{21} & \cdots & u_{L1} \\ u_{12} & u_{22} & \cdots & u_{L2} \\ \vdots & \vdots & \ddots & \vdots \\ u_{1L} & u_{2L} & \cdots & u_{LL} \end{pmatrix}$$

2-2. Compute V matrix

$$V = \frac{X^T U}{\sqrt{\Lambda}} = \begin{pmatrix} v_{11} & v_{21} & \cdots & v_{L1} \\ v_{12} & v_{22} & \cdots & v_{L2} \\ v_{13} & v_{23} & \cdots & v_{L3} \\ \vdots & \vdots & \ddots & \vdots \\ v_{1k} & v_{2k} & \cdots & v_{Lk} \end{pmatrix}$$

$\Rightarrow$

$$X = U \sqrt{\Lambda} V^T$$

3^{rd} Step reconstruction

3-1. Reconstruction of Matrix X using principal components

$$X = U\sqrt{\Lambda}V^T$$

$$= u_1\sqrt{\lambda_1}v_1^T + u_2\sqrt{\lambda_2}v_2^T + \cdots + u_L\sqrt{\lambda_L}v_L^T$$

$$= X^1 + X^2 + \cdots + X^L$$

i th matrix X^i

$$X^i = \begin{pmatrix} x_{11}^i & x_{21}^i & x_{31}^i & \cdots & x_{L1}^i \\ x_{12}^i & x_{22}^i & x_{32}^i & \cdots & x_{L2}^i \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{1k}^i & x_{2k}^i & x_{3k}^i & \cdots & x_{Lk}^i \end{pmatrix}$$

4^{th} Step diagonal averaging

4-1. Reconstruction of ith principal Component of $G_1^i \sim G_n^i$ from X^i

$$G_1^i = x_{11}^i$$

$$G_2^i = (x_{12}^i + x_{21}^i)/2$$

$$G_3^i = (x_{13}^i + x_{22}^i + x_{31}^i)/3$$

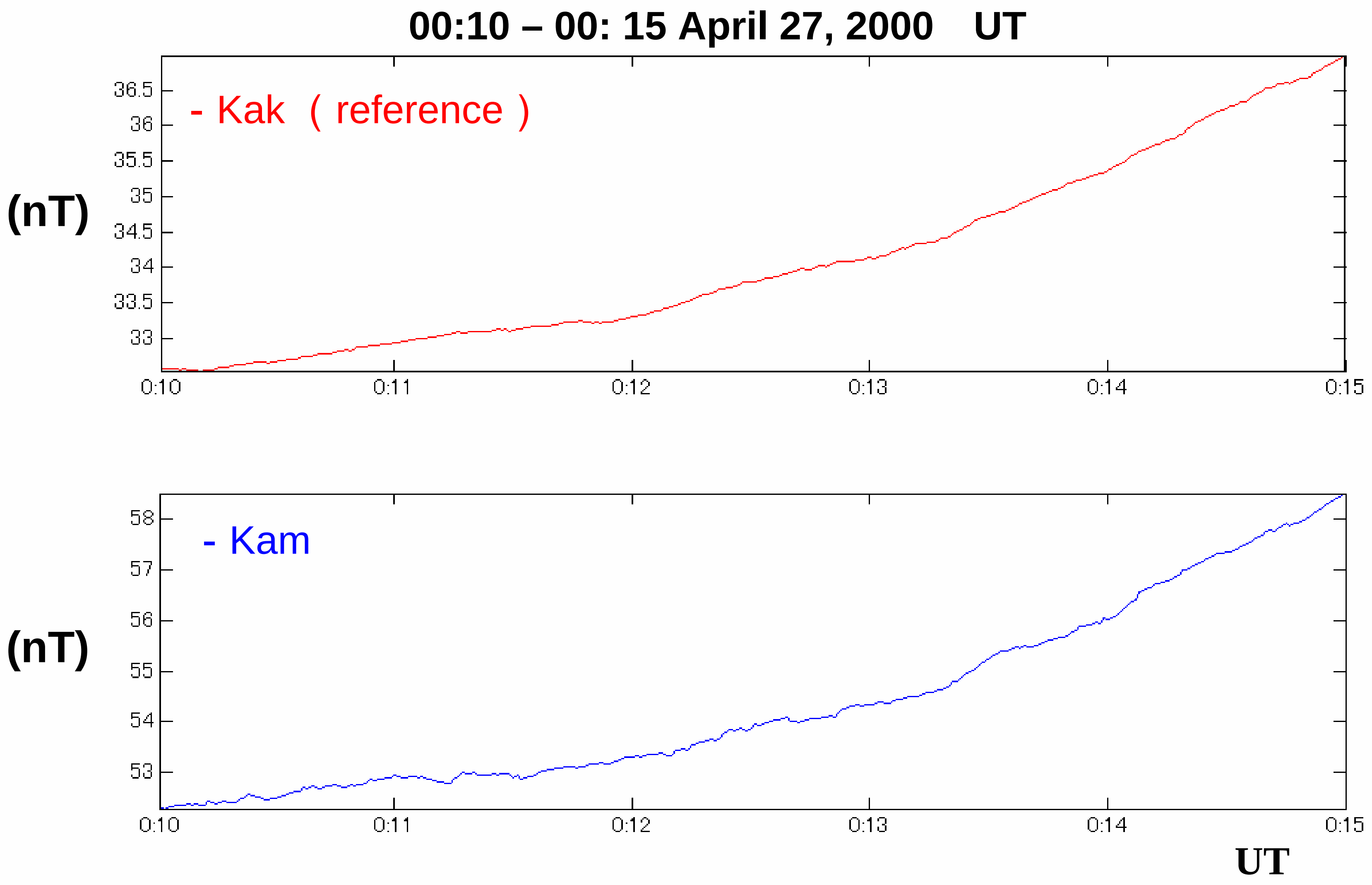
$$\vdots$$

$$G_{N-1}^i = (x_{L-1,K}^i + x_{L,K-1}^i)/2$$

$$G_N^i = x_{LK}^i$$

$$\Rightarrow \left\{G_j^i\right\} = G_1^i, G_2^i \cdots G_N^i$$

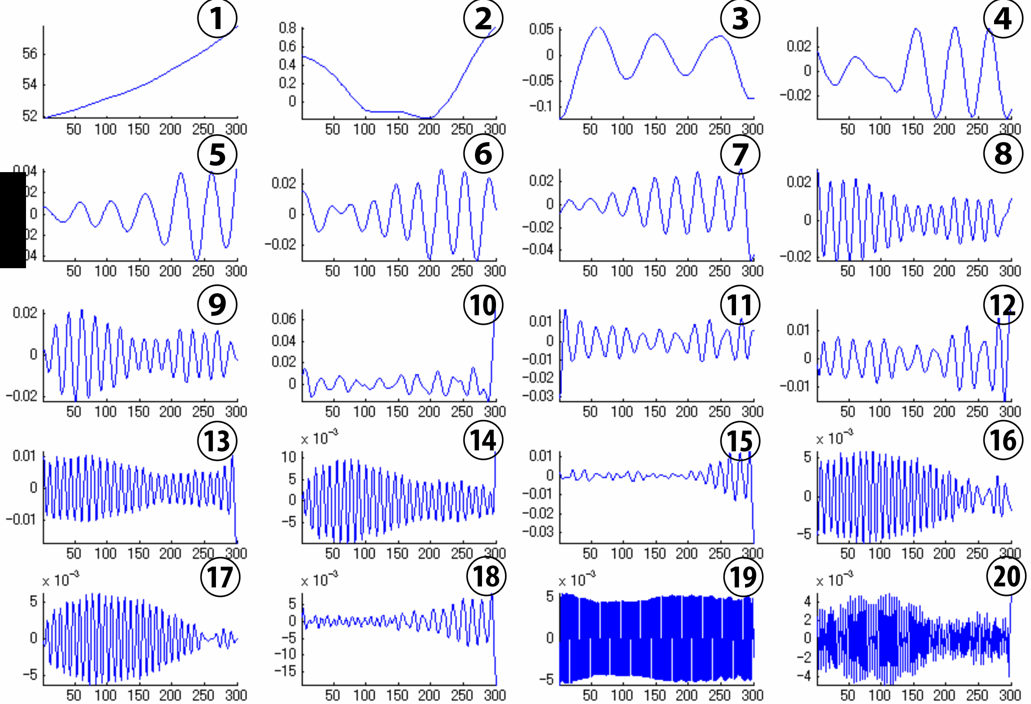
4-1. Global noise reduction with using SSA



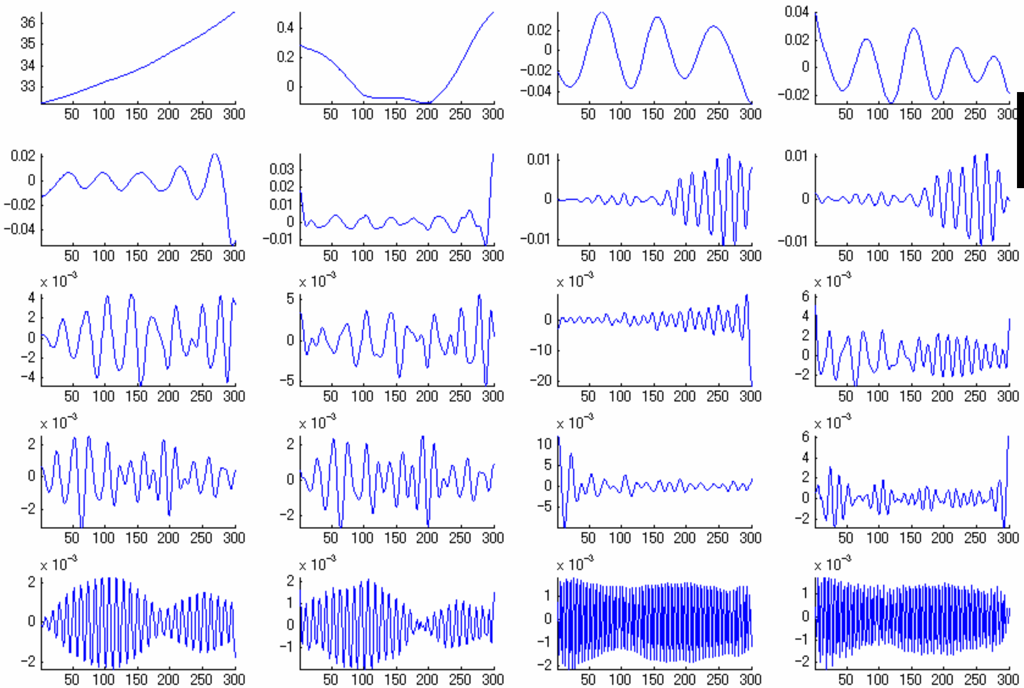
➡ **Apply SSA**

Result of SSA

kam



Reconstructed 1 - 20th principal components by SSA (L=100)

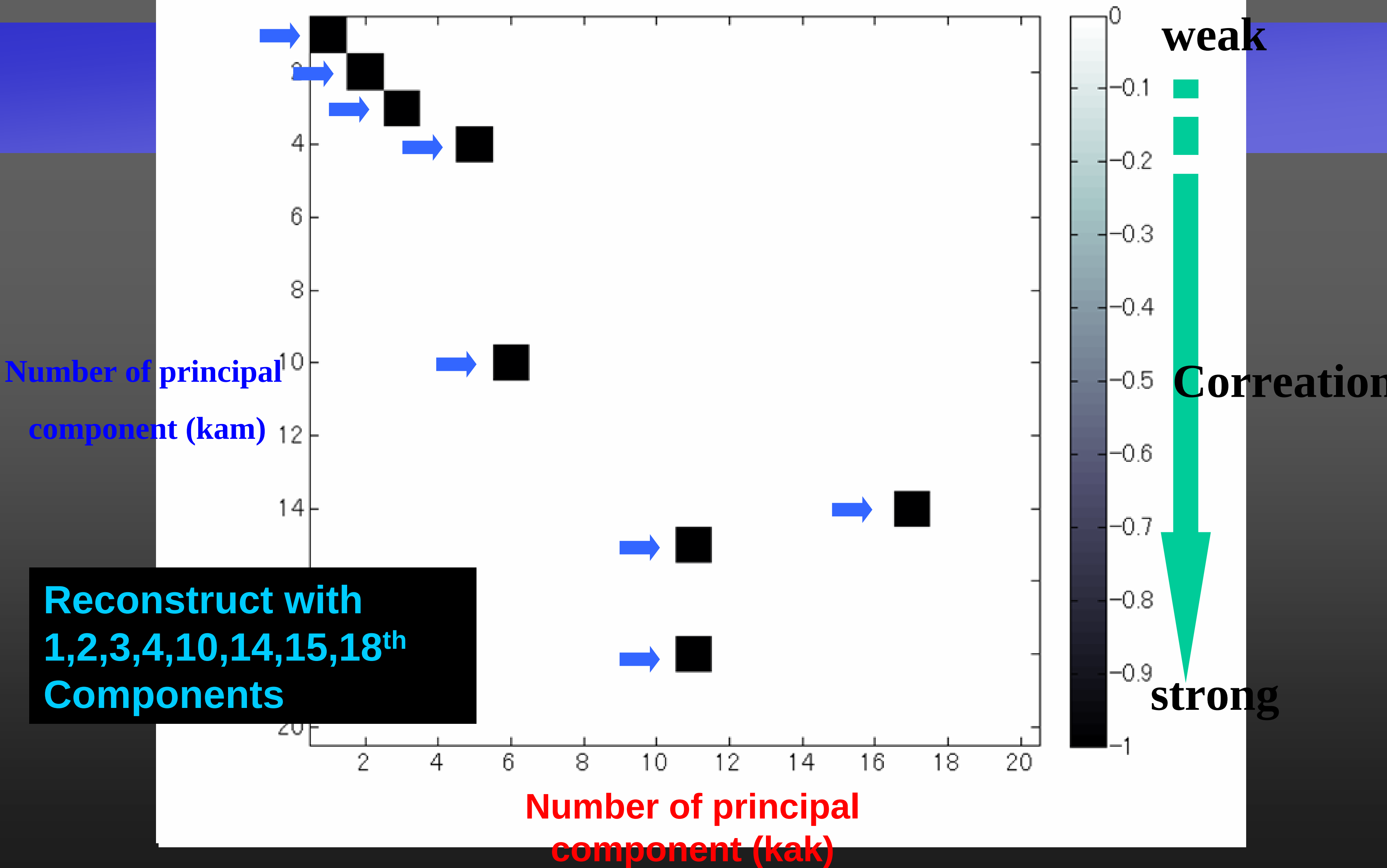


kak (reference)

Extract common variations

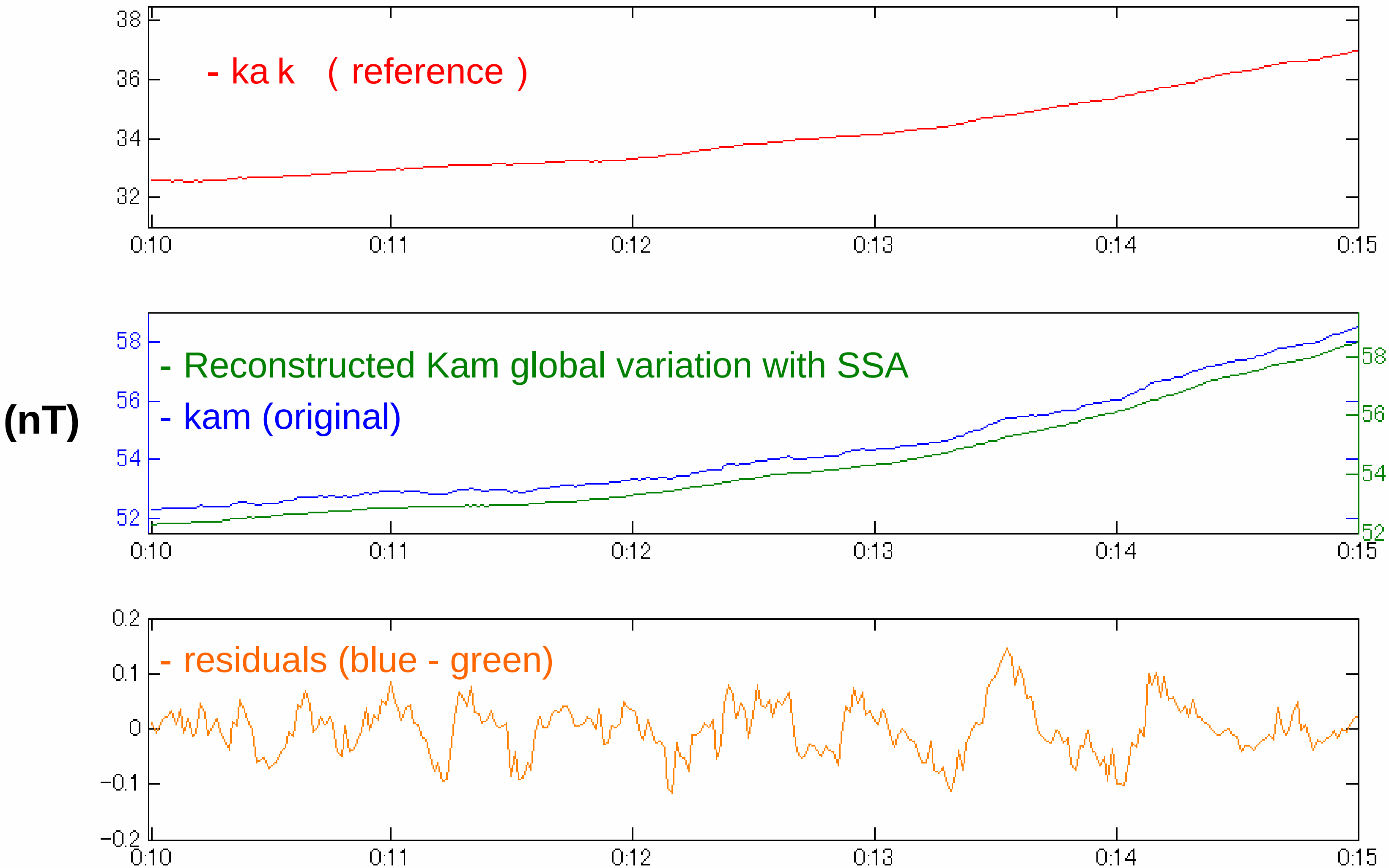
Investigate the correlation among components

Global noise reduction with SSA



Reconstruct with 1,2,3,4,10,14,15,18th Components

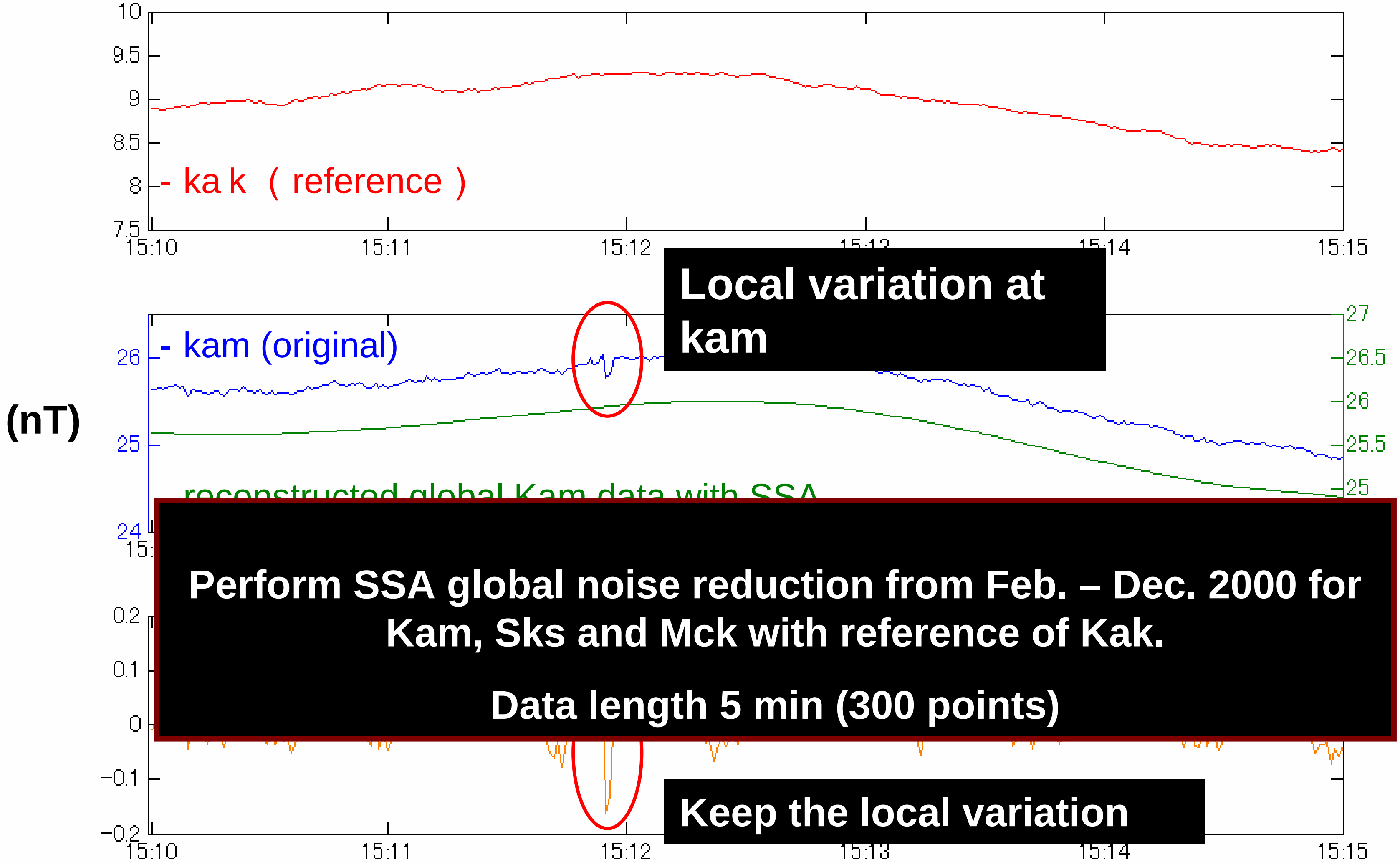
Result of global noise reduction with SSA



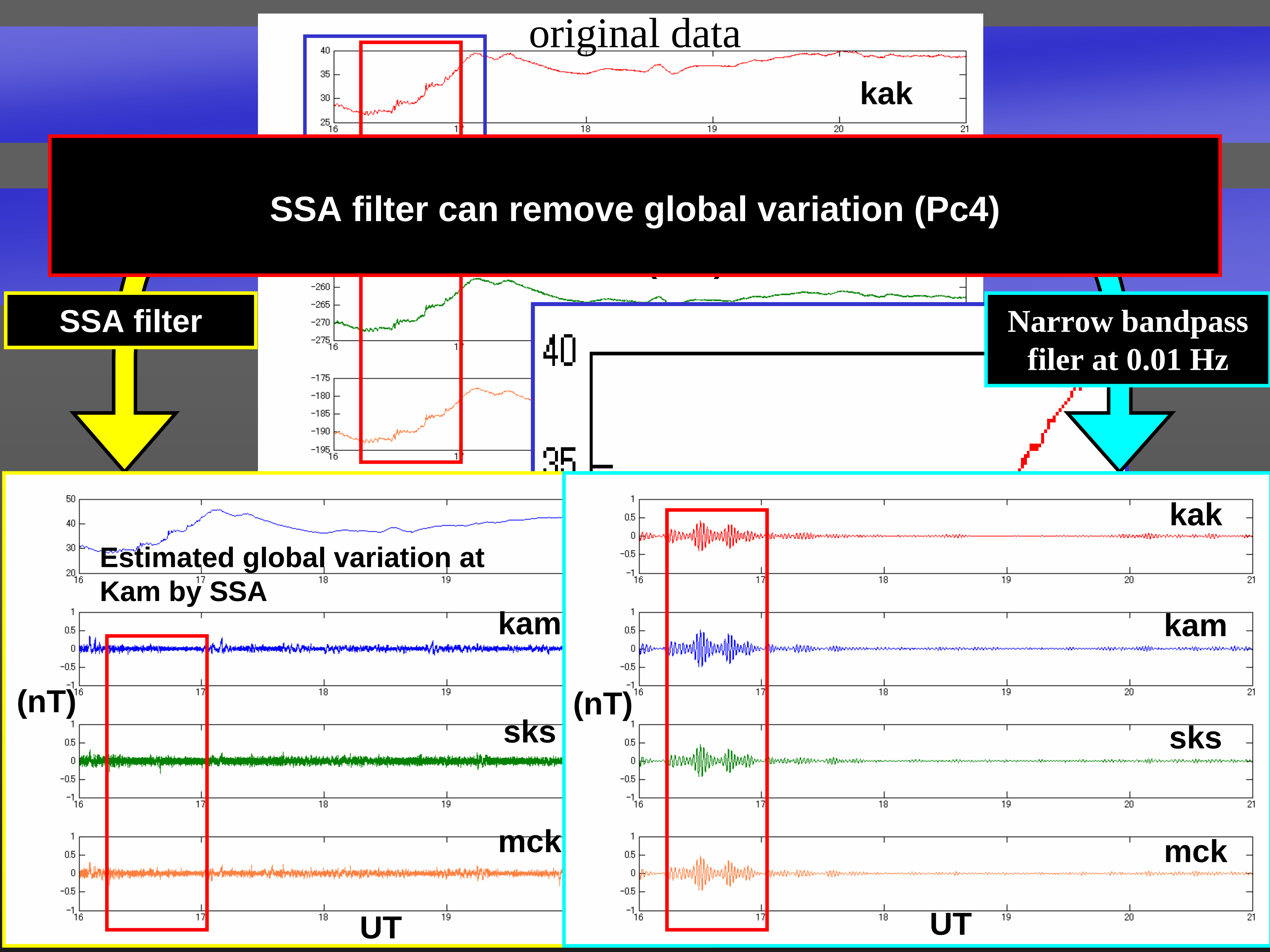
00:10 – 00:15 April 27, 2000 UT

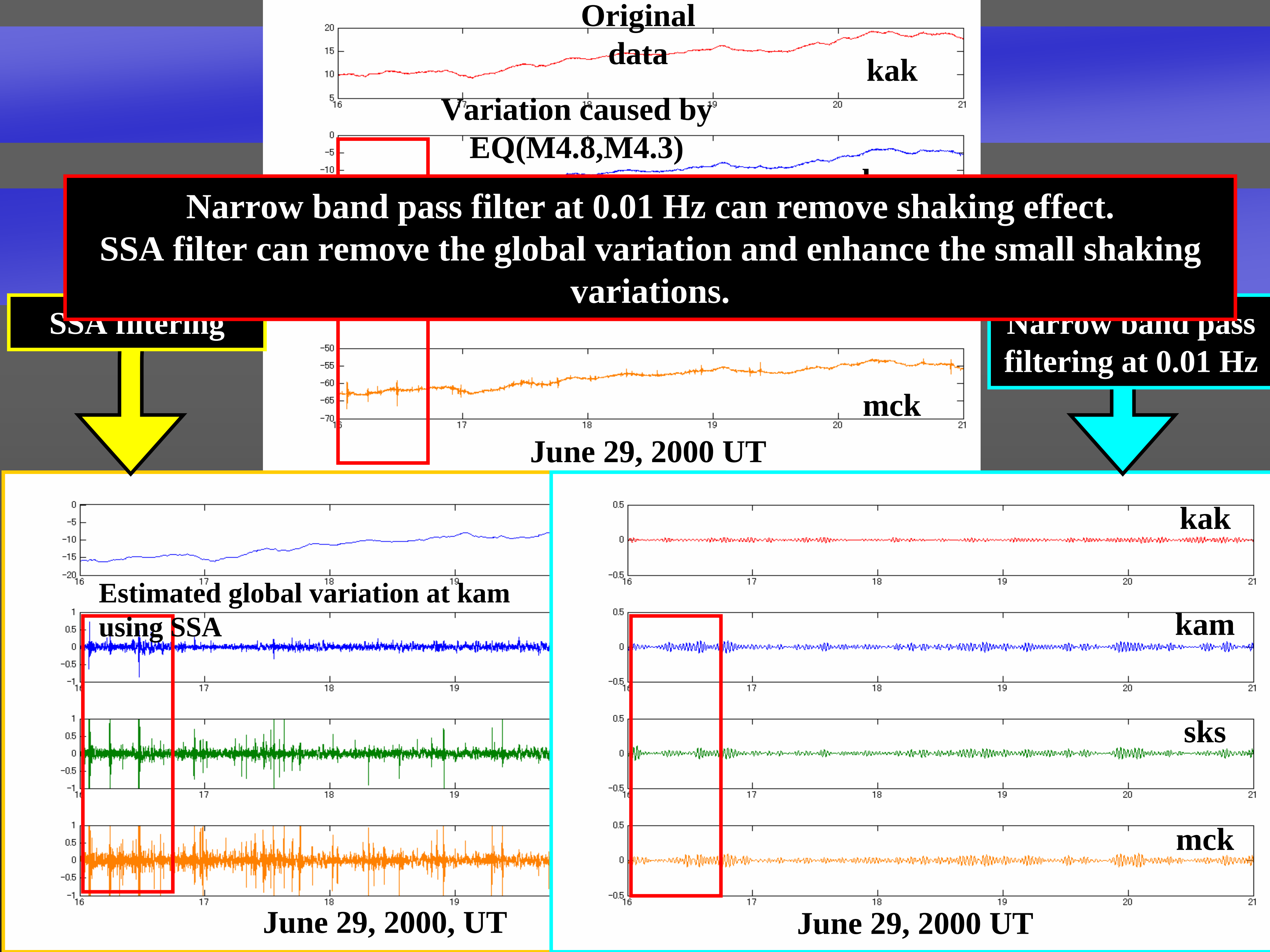
Result of global noise reduction with SSA

(In the case of local variation existence at Kam data)



15:10 – 15:15 April 27, 2000 UT


original data
kak
SSA filter can remove global variation (Pc4)
SSA filter
Narrow bandpass filer at 0.01 Hz
Estimated global variation at Kam by SSA
kam
sks
mck
(nT)
UT
kak
kam
sks
mck
(nT)
UT


Original data
kak
Variation caused by EQ(M4.8,M4.3)
Narrow band pass filter at 0.01 Hz can remove shaking effect.
SSA filter can remove the global variation and enhance the small shaking variations.
SSA filtering
Narrow band pass filtering at 0.01 Hz
mck
June 29, 2000 UT
Estimated global variation at kam using SSA
June 29, 2000, UT
kak
kam
sks
mck
June 29, 2000 UT

5-1. Principal Component Analysis (PCA) after filtering

① narrow band pass filter centered at 0.01Hz （remove shaking effects）

② SSA filter （Reduction of global variation）

③ SSAfilter＋narrow band 0.01Hz filter

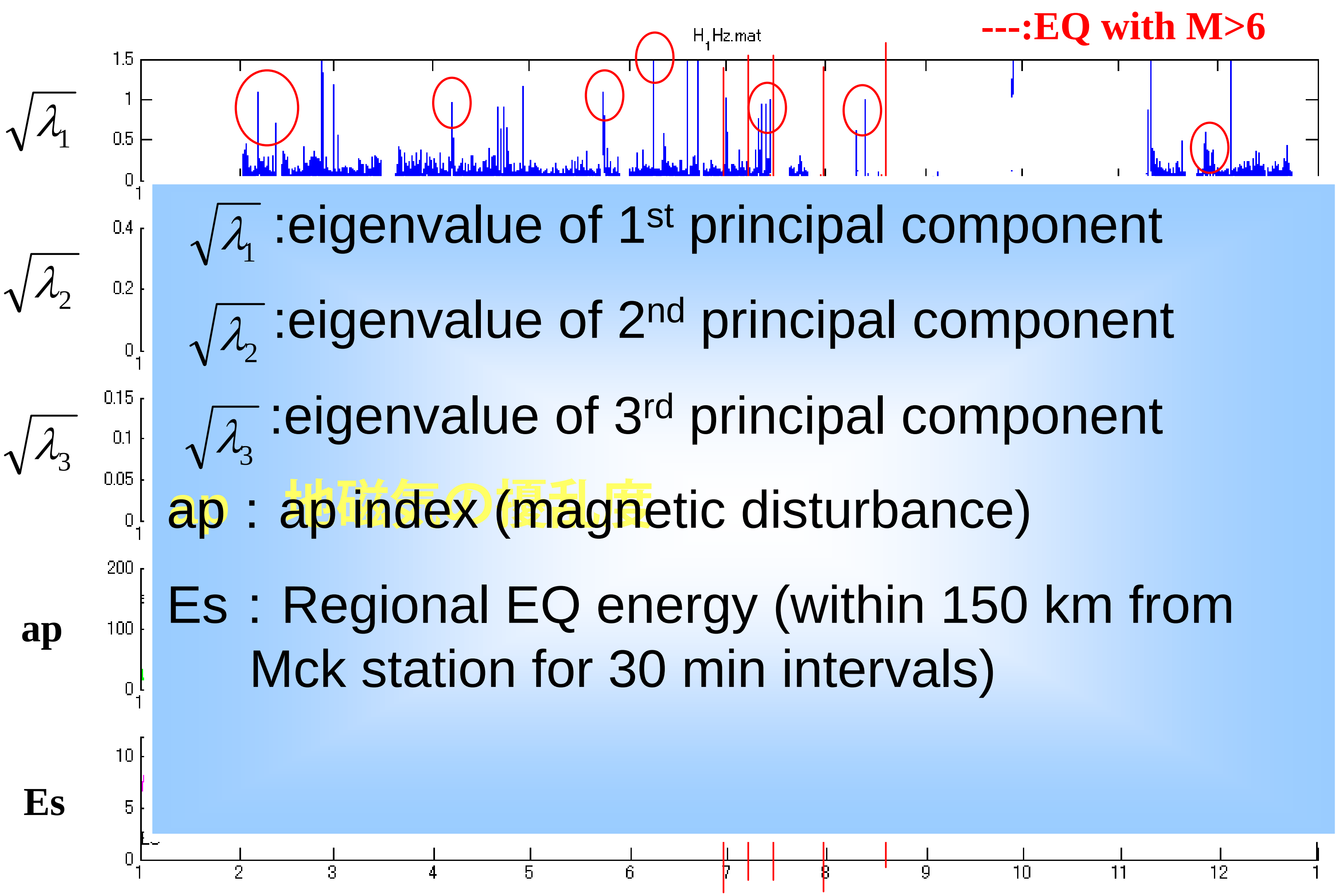
↓

Midnight data (UT15-19)

(less artificial noise period)

Perform PCA

(1) Result of narrow bandpass filter at 0.01 Hz (eigenvalue variation)



$\sqrt{\lambda_1}$:eigenvalue of 1st principal component

$\sqrt{\lambda_2}$:eigenvalue of 2nd principal component

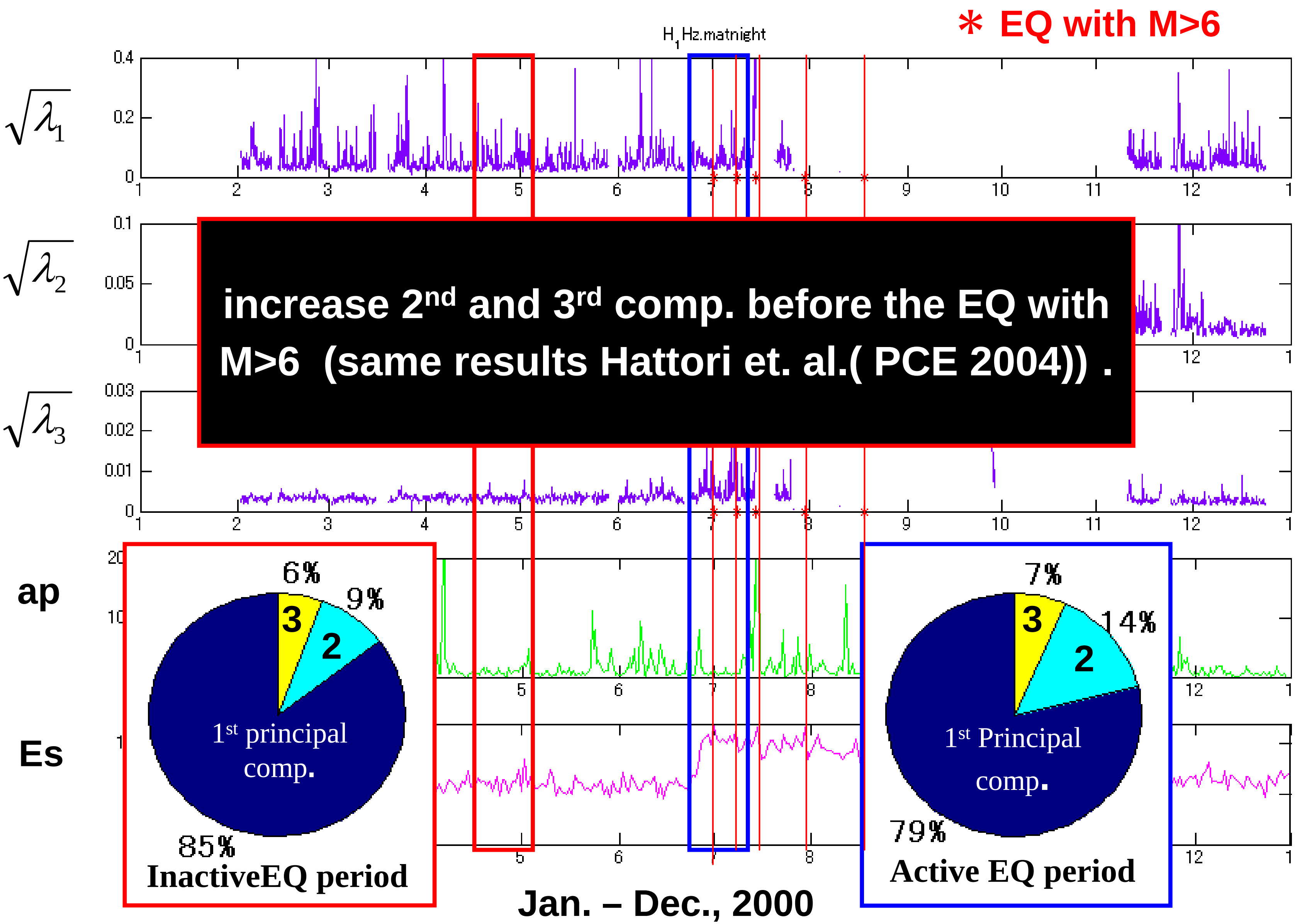
$\sqrt{\lambda_3}$:eigenvalue of 3rd principal component

ap : ap index (magnetic disturbance) 地磁気の擾乱度

Es : Regional EQ energy (within 150 km from Mck station for 30 min intervals)

January – December, 2000

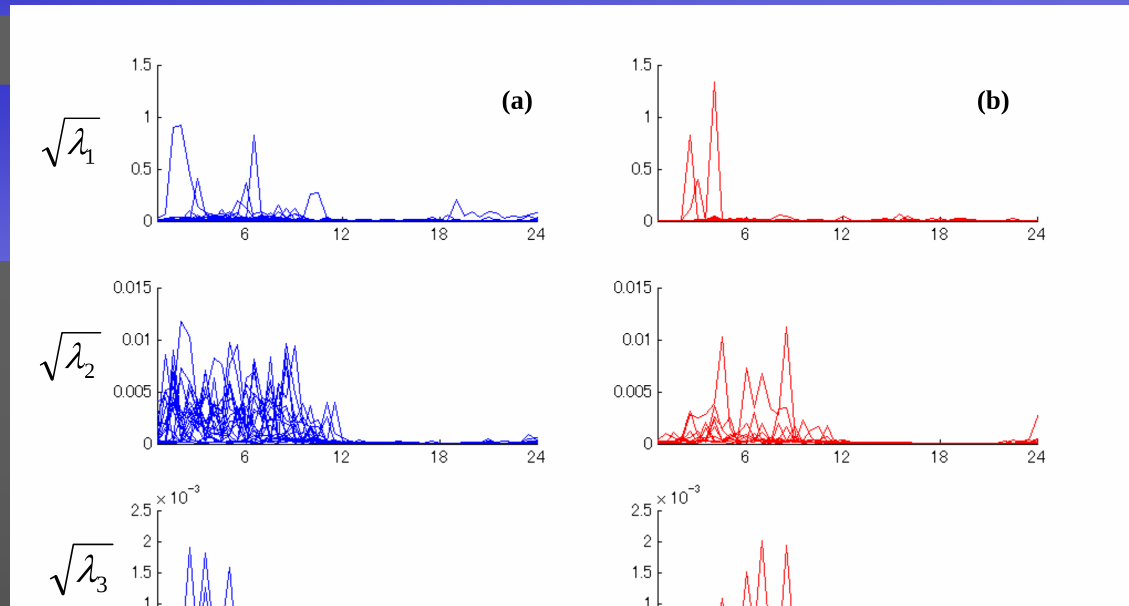
(1) Results of narrow bandpass filter at 0.01 Hz (eigenvalue) (nighttime data)



increase 2nd and 3rd comp. before the EQ with M>6 (same results Hattori et. al.(PCE 2004)) .

(1) Result of narrow bandpass filter at 0.01Hz
(artificial noise effect)

Variation of principal components intensity in April 2000.
(a) Weekdays
(b) Weekend and holidays



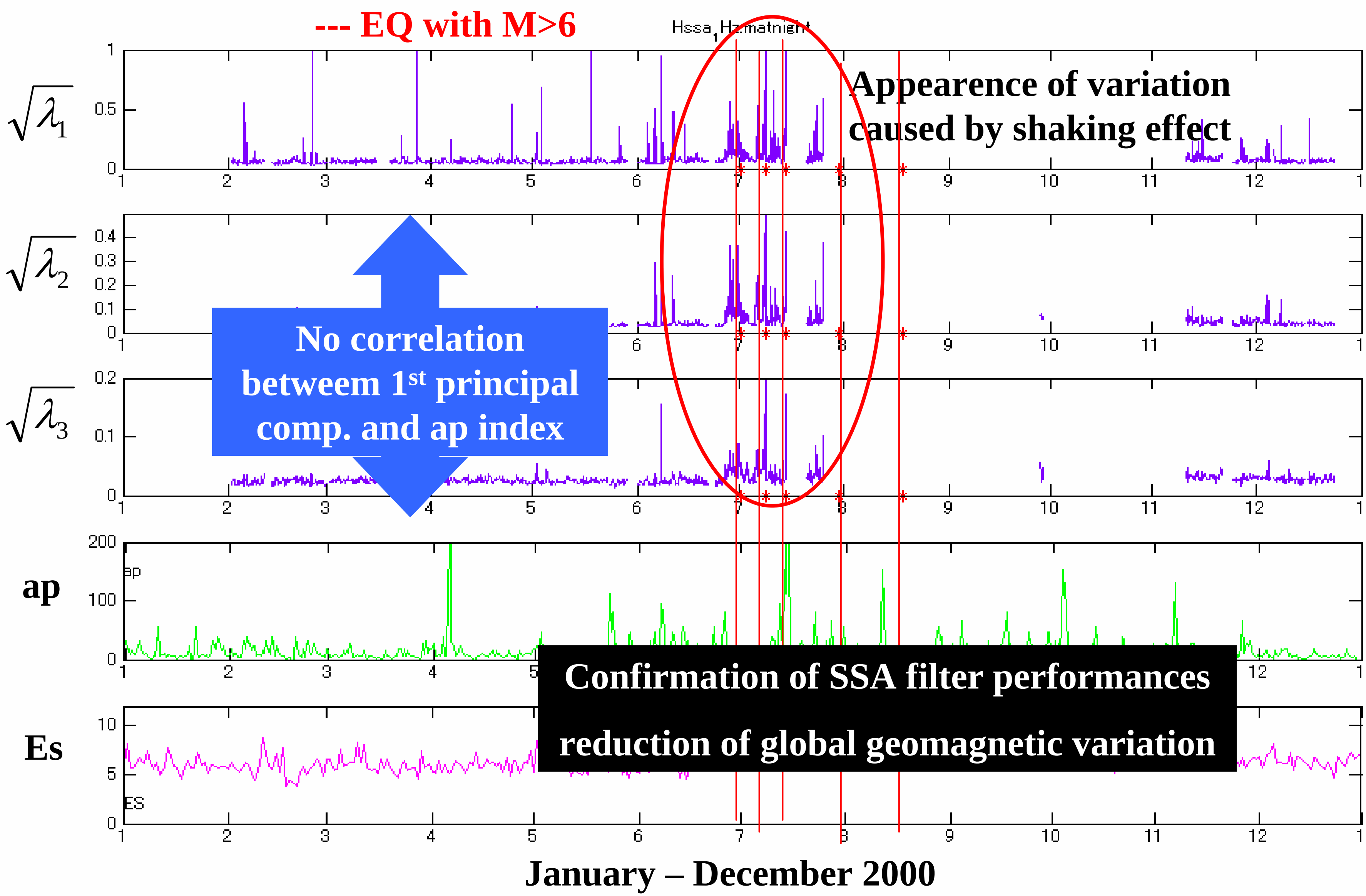
2nd principal comp. : influence by artificial noises is large.

Nighttime data : contamination is less.

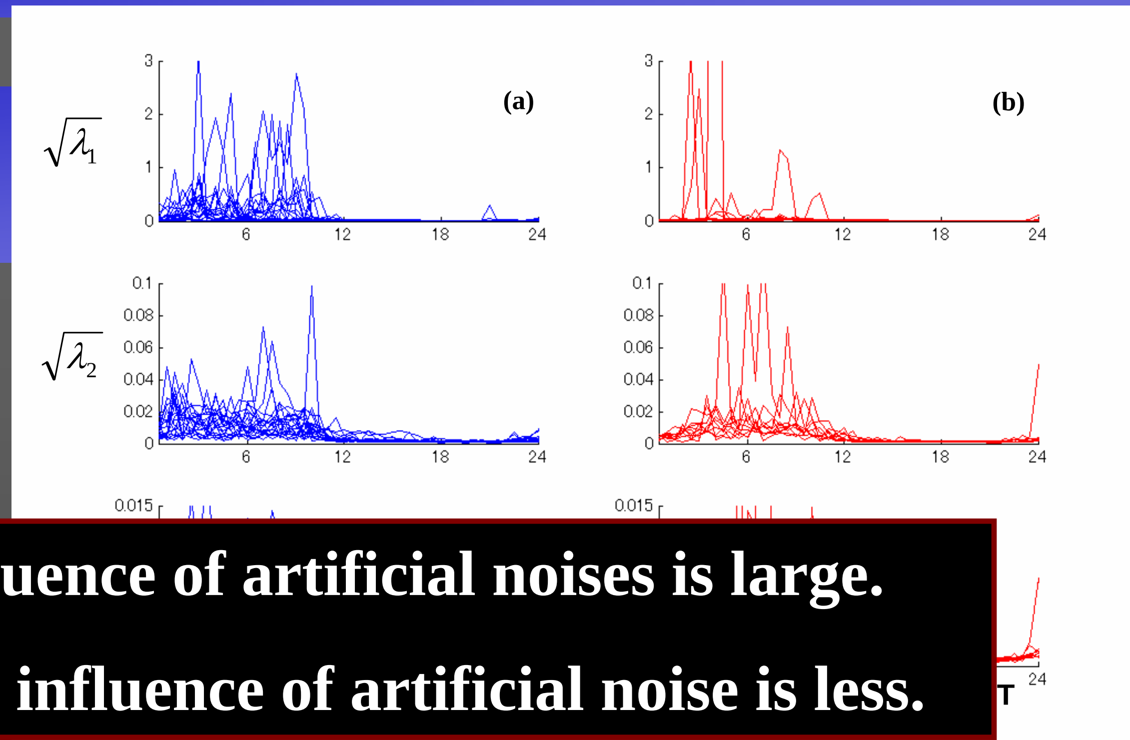
	D/N	D/N(weekdays)	D/N(weeekend)	W/H	W/H(daytime)	W/H(nighttime)
1st comp.	5.6	4.4	2.8	1.6	1.9	1.2
2nd comp.	34.9	36.4	10.9	3.5	3.4	1
3rd comp.	14.4	9.6	10.5	1.3	1.1	1.2

D/N: ratio between daytime and nighttime
W/H: ratio between weekdays and weekend/ holidays

(2) Result of SSA filter (variation of nighttime eigenvalues)



(2) Results of SSA filter (artificial noise effect)



Variation of intensity of principal components in April 2000.
(a) weekdays
(b) we

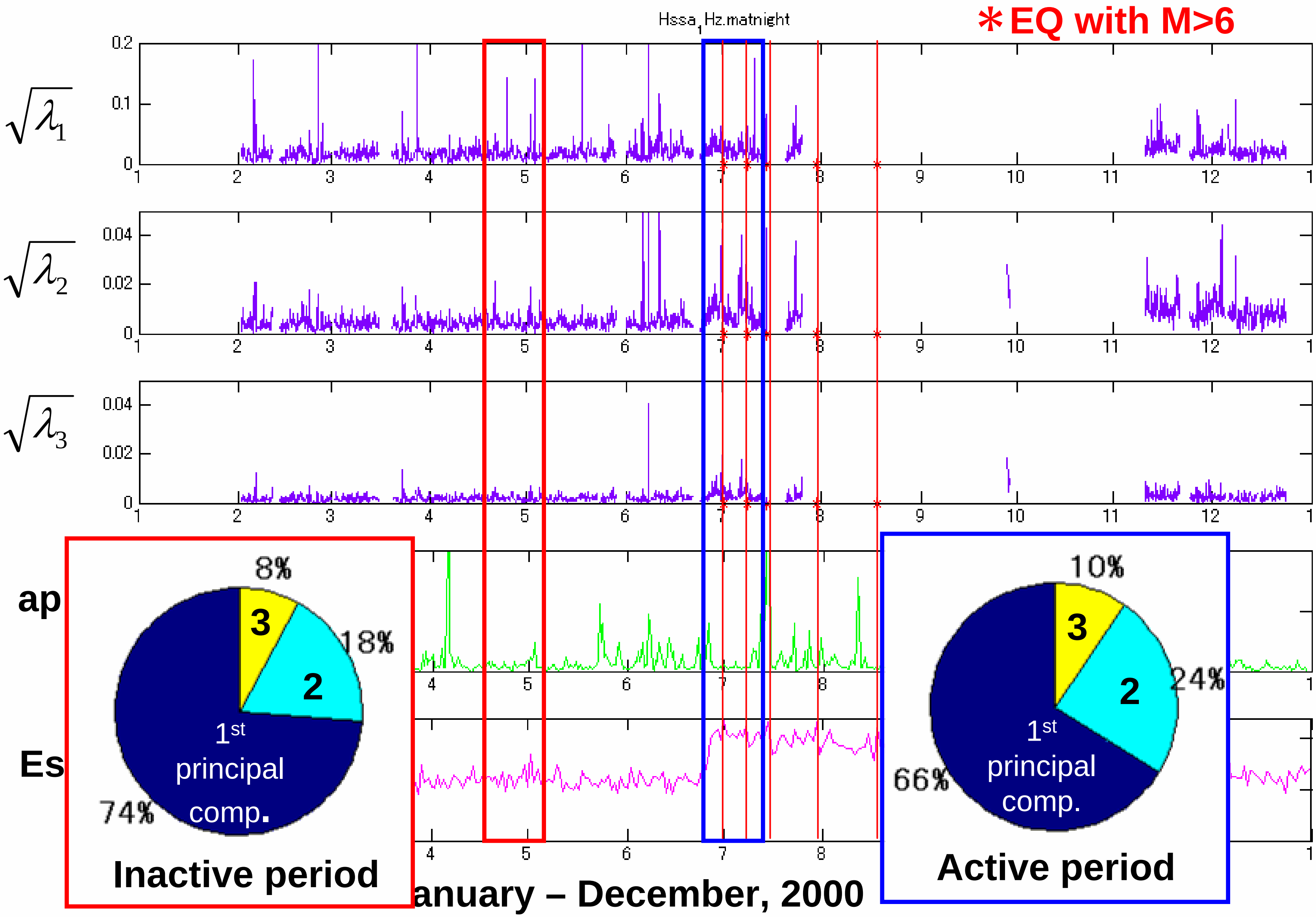
1st Comp. : influence of artificial noises is large.

Nighttime data : influence of artificial noise is less.

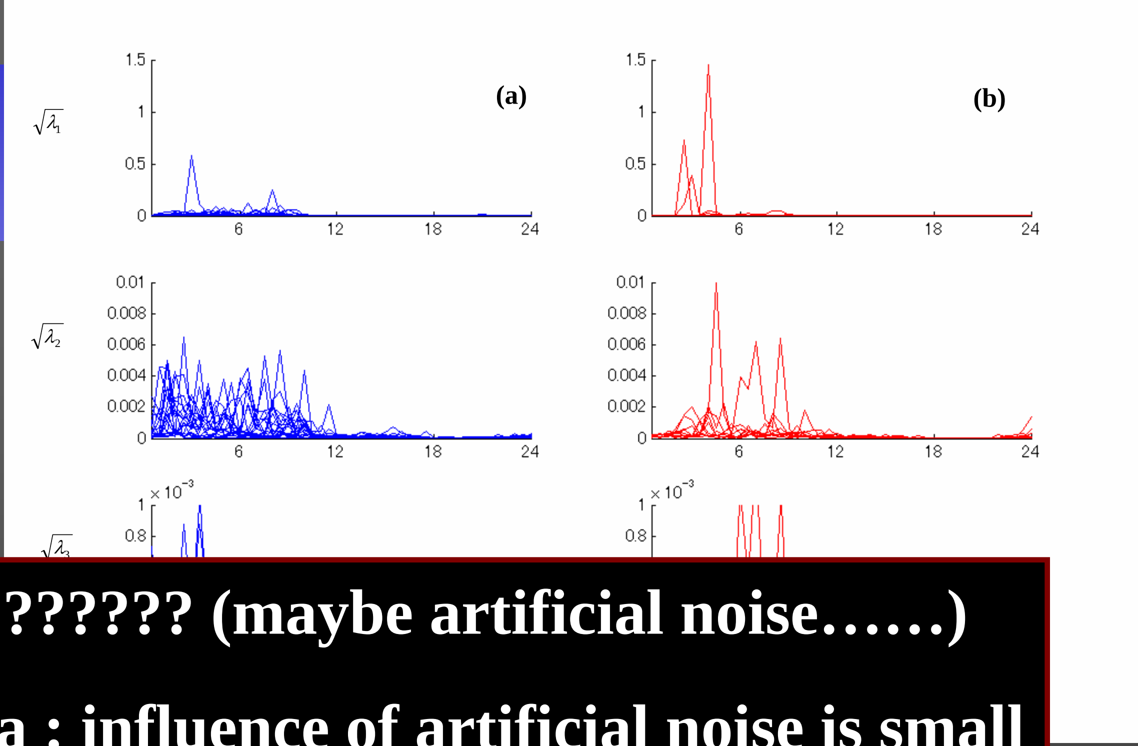
	D/N	D/N(weekdays)	D/N(weeekend)	W/H	W/H(daytime)	W/H(nighttime)
1st comp.	10	4.4	12.2	2.2	2.8	1
2nd comp.	8.7	8.3	8.8	1.2	1.1	1
3rd comp.	4.5	4.4	4.5	1.2	1.1	1.1

D/N: ratio between daytime and nighttime
W/H: ratio between weekdays and weekend/holidays

(3) Results of SSA filter + narrow bandpass filter at 0.01Hz
(variation of eigenvalues at nighttime)



(3) Results of SSA filter + narrow bandpass filter at 0.01Hz influence of artificial effect)



Variation of intensity of principal components in April 2000.
(a) weekdays
(b) weekend and holidays

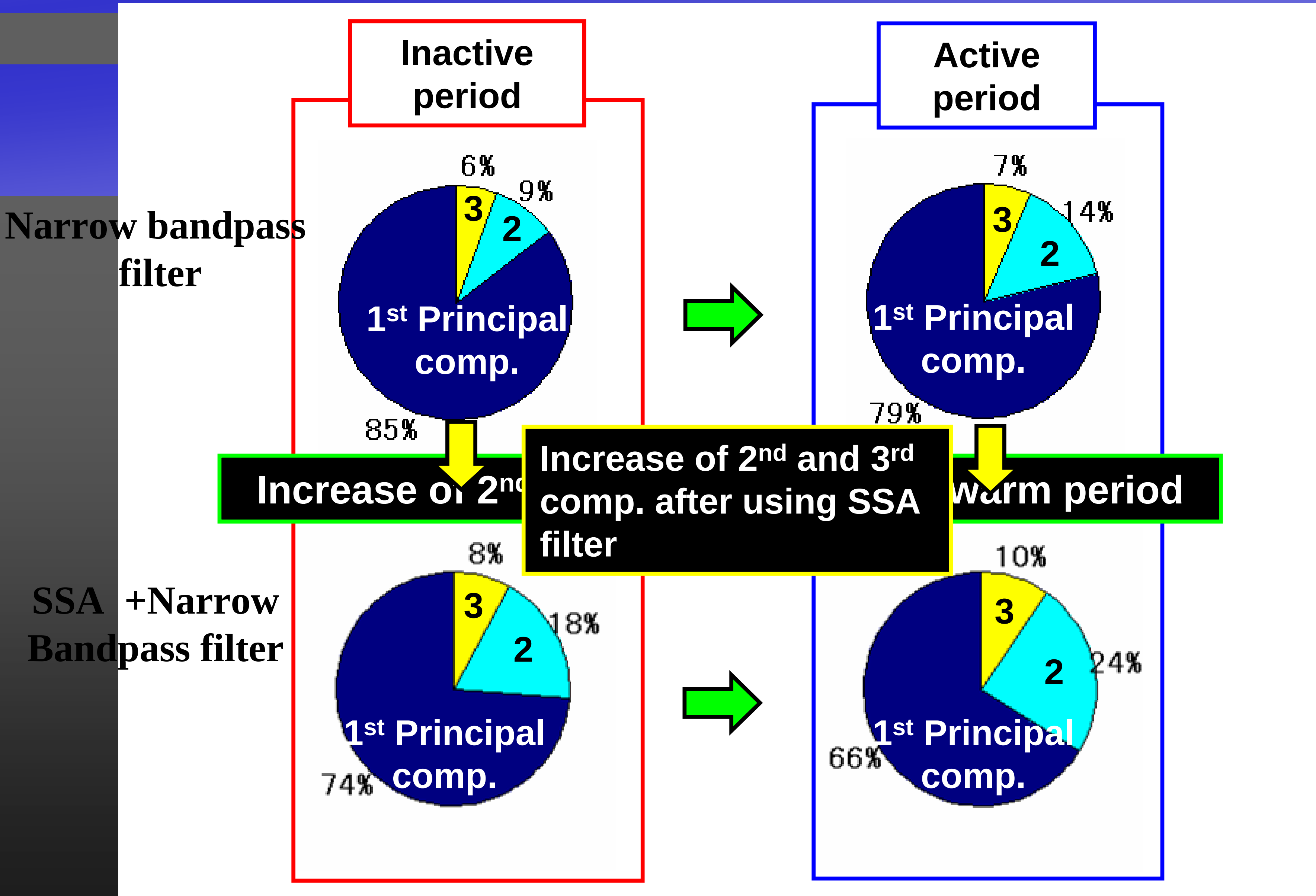
1st comp. : ??????? (maybe artificial noise……)

Nighttime data : influence of artificial noise is small

	D/N	D/N(weekdays)	D/N(weeekend)	W/H	W/H(daytime)	W/H(nighttime)
1st comp.	4.7	3.1	5.3	1.6	1.8	1.1
2nd comp.	13.1	8.9	14.7	2	1.7	1
3rd comp.	12	11.7	12.2	1.2	1.1	1.1

D/N: ratio between daytime and nighttime
W/H: ratio between weekdays and weekend/holidays

6. Summary



Inactive period
Active period
Narrow bandpass filter
SSA +Narrow Bandpass filter
6%
9%
3
2
1st Principal comp.
85%
7%
14%
79%
8%
18%
74%
10%
24%
66%
Increase of 2nd and 3rd comp. after using SSA filter

6. Summary

chiba-u geophysics

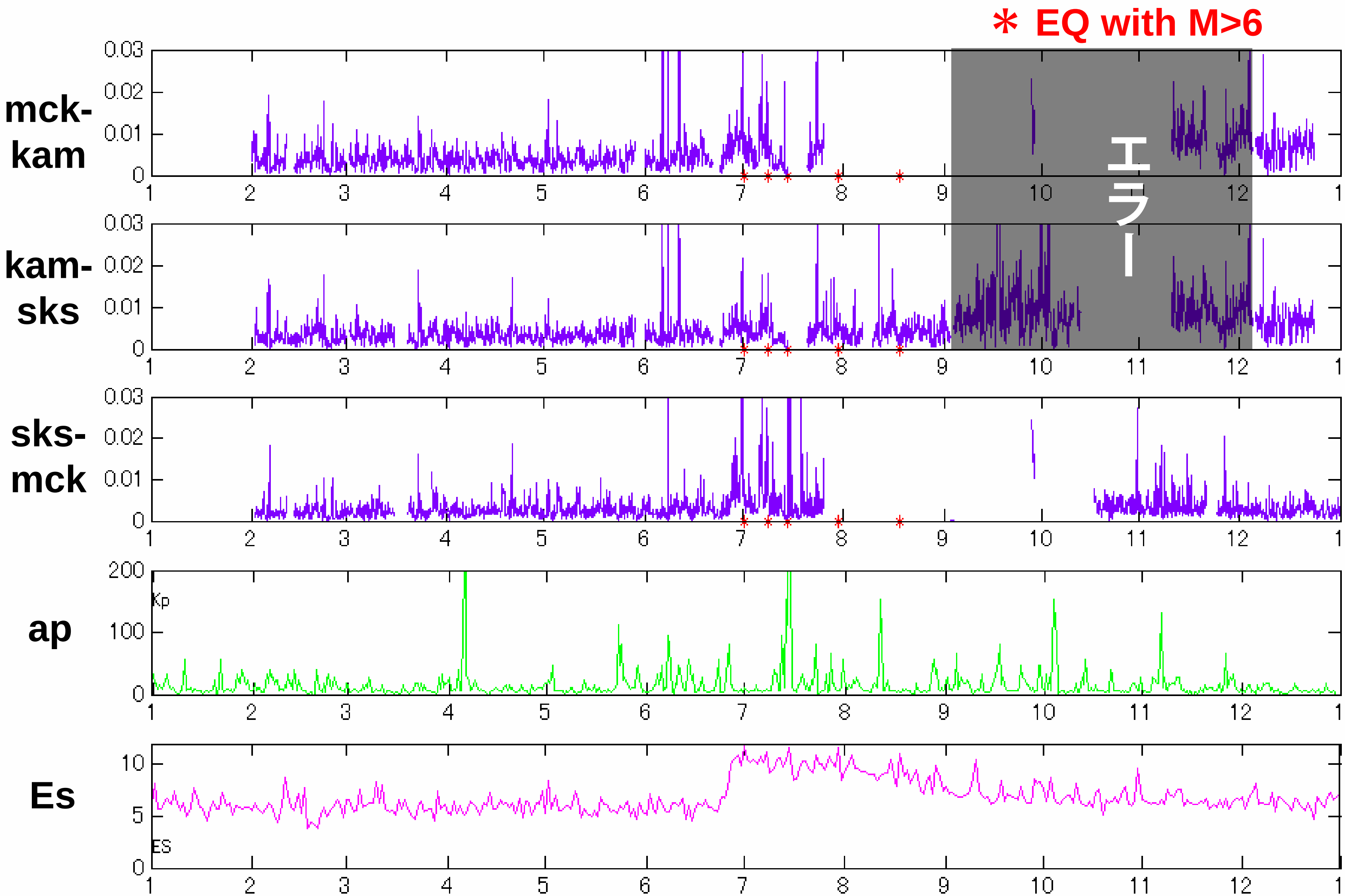
		Narrow bandpass filter at 0.01Hz	SSA filter	SSA+ narrow bandpass filter at 0.01Hz
1st comp.	active	geomagnetic pulsations	shaking effects	?
	inactive	geomagnetic pulsations	daytime: artificial noises	?
2nd comp.	active	EQ- related variation	shaking effects	EQ- related variation
	inactive	daytime: artificial noises	?	?
3rd comp	active	EQ- related variation	shaking effects	EQ- related variation
	inactive	?	?	?

6. Conclusion

1. **Realize a global noise reduction with SSA approach using an adequate reference data.**
2. **Success to improve the PCA performance using SSA filter and narrow bandpass filter with centered frequency of 0.01 Hz.**
3. **Confirm the performance of PCA with two station data after reduce the global variations.**

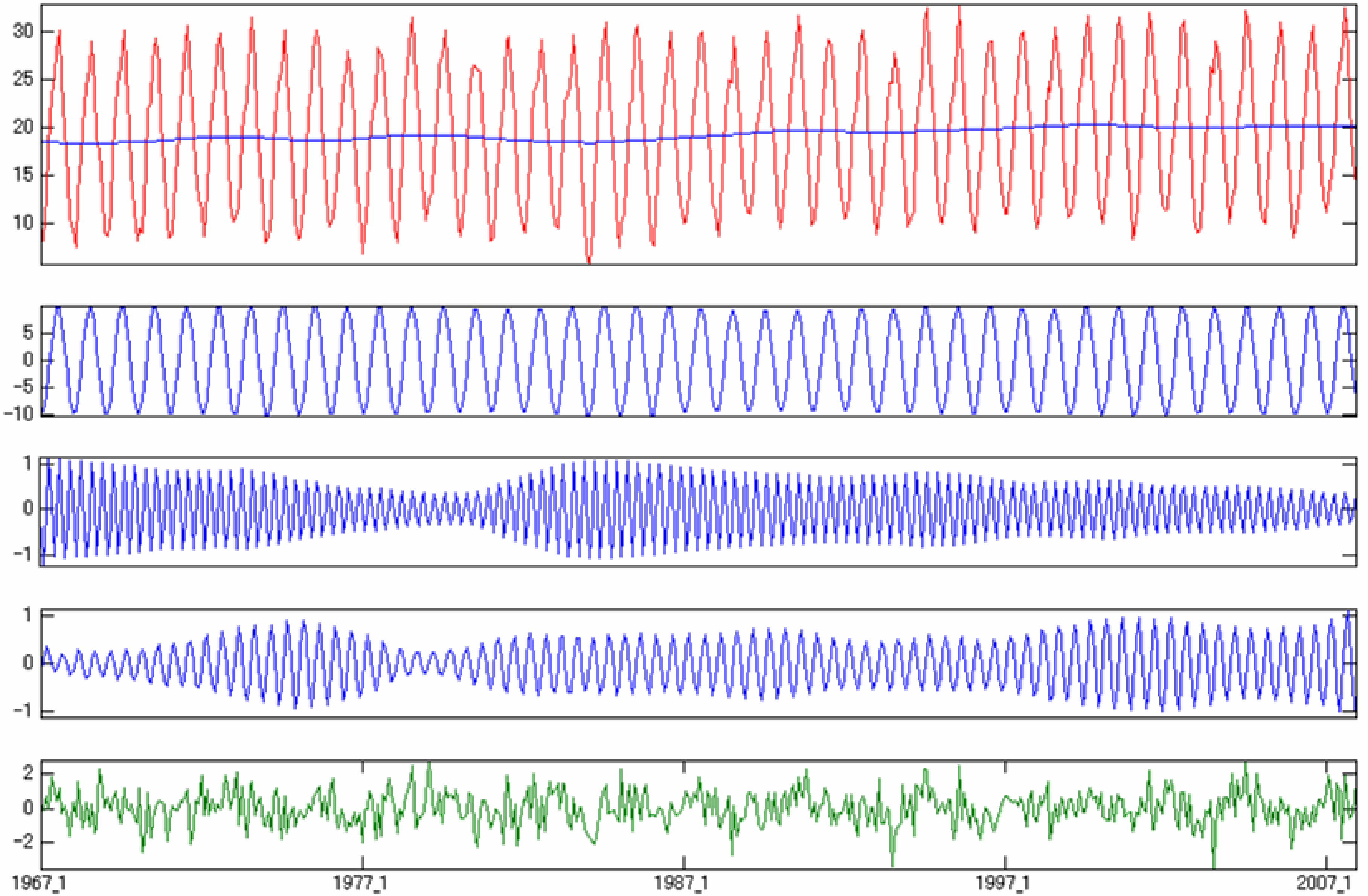
Thank you for attention.

Variation of 2nd principal comp. with 2 station data using SSA filter and narrow bandpass filter at 0.01 Hz (nighttime data)



January –December, 2000

Example of SSA （ monthly average temperature at Chiba from 1967 to 2007 ）



7. 2観測点のデータを用いたPCA

Serita et. al.(2005) は 3 観測点の水平南北成分のデータのPCAにより

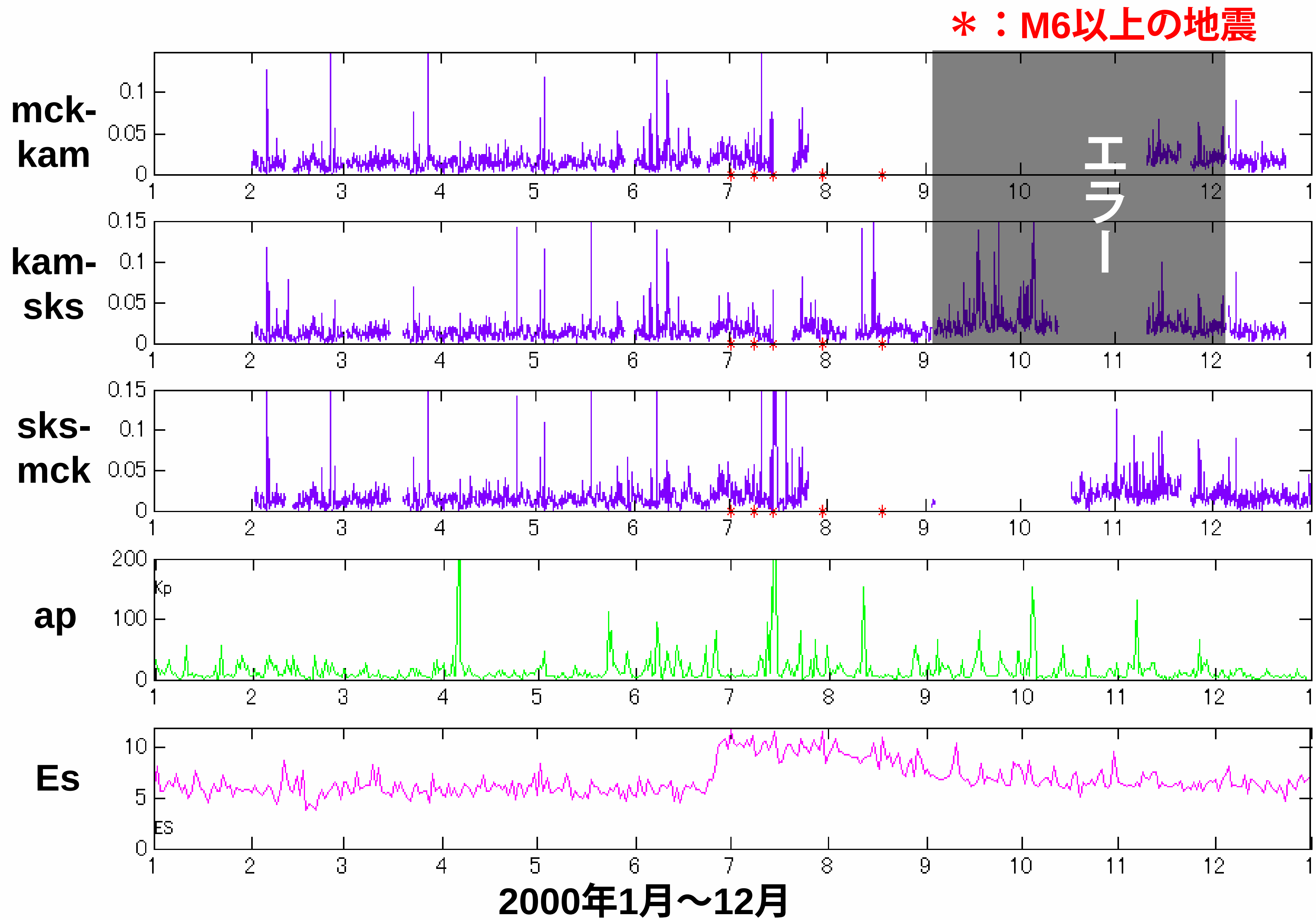
第１主成分　⇒　地磁気脈動　（太陽起源の信号）
第２主成分　⇒　人工ノイズ
第３主成分　⇒　地震前兆信号　が多く含まれると報告した。

SSAフィルタによって地磁気脈動を除去

第１主成分　⇒　人工ノイズ
第２主成分　⇒　地震前兆信号

SSAフィルタ適用後の時系列にPCAを適用する場合、
2 観測点のみのデータで地震前兆信号が抽出可能？？？

第1主成分の固有値の変動　～夜間のみ～



8. まとめ2

chiba-u　geophysics

伊豆の3観測点のデータにリファレンスを柿岡としたSSAフィルタを適用した。その結果の2観測点のデータを用いた主成分解析を行った。

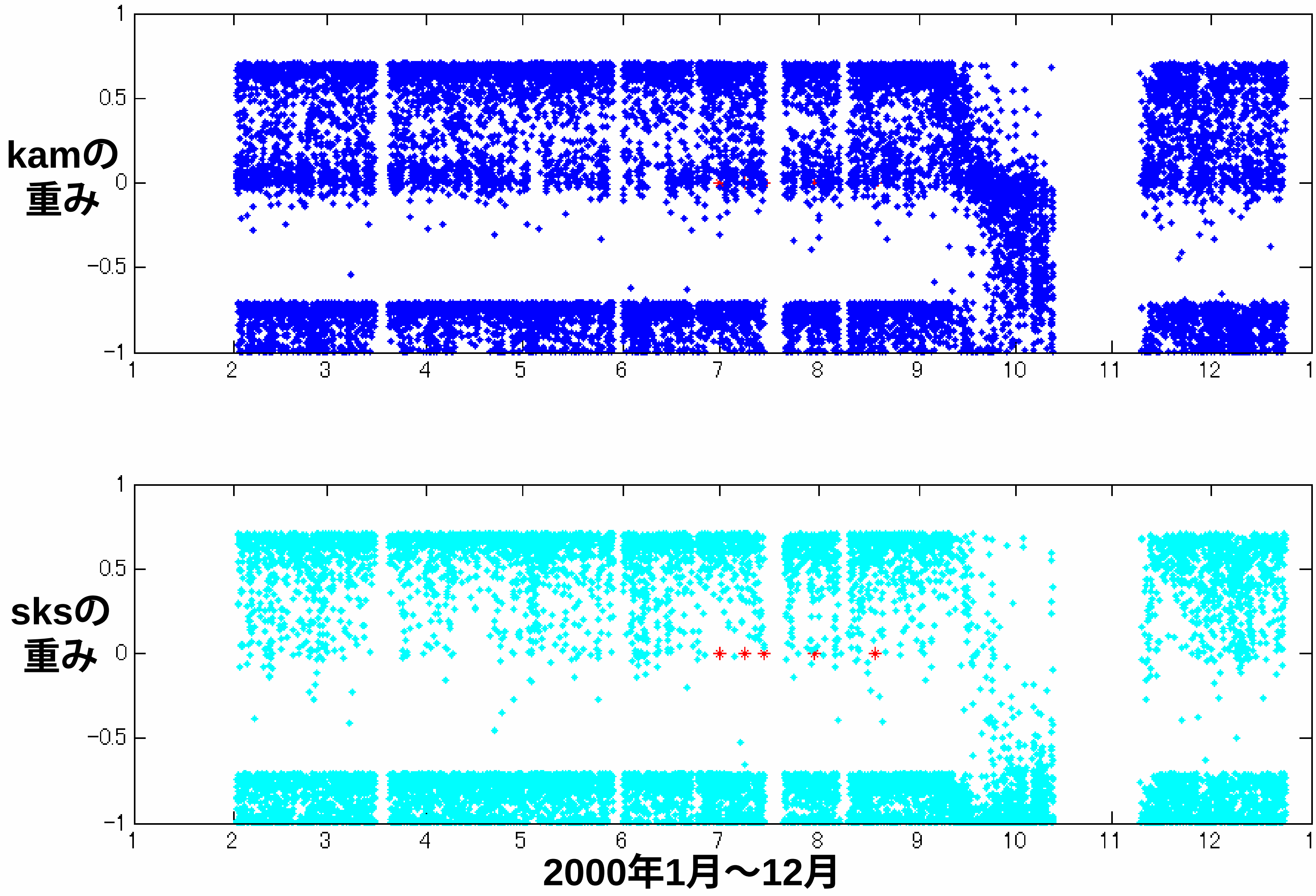
mck-kam, kam-sks, sks-mckの3パターンの結果を検討した。

第2主成分に連続的な上昇が見られた。
第1主成分にもわずかに上昇が見られた。

⇩

1観測点が欠測で3観測点のPCAが適用できなかった場合でも、
2観測点の主成分解析で補うことができる可能性がある。

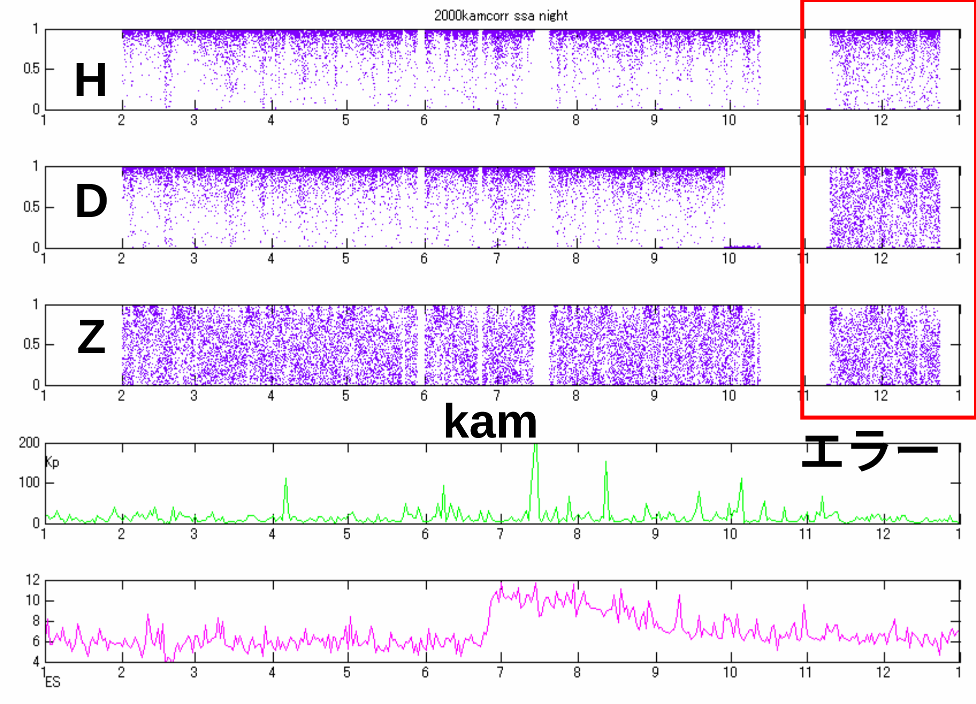
2観測点で観測を行う場合、設置・メンテナンス等のコストの面でも有利

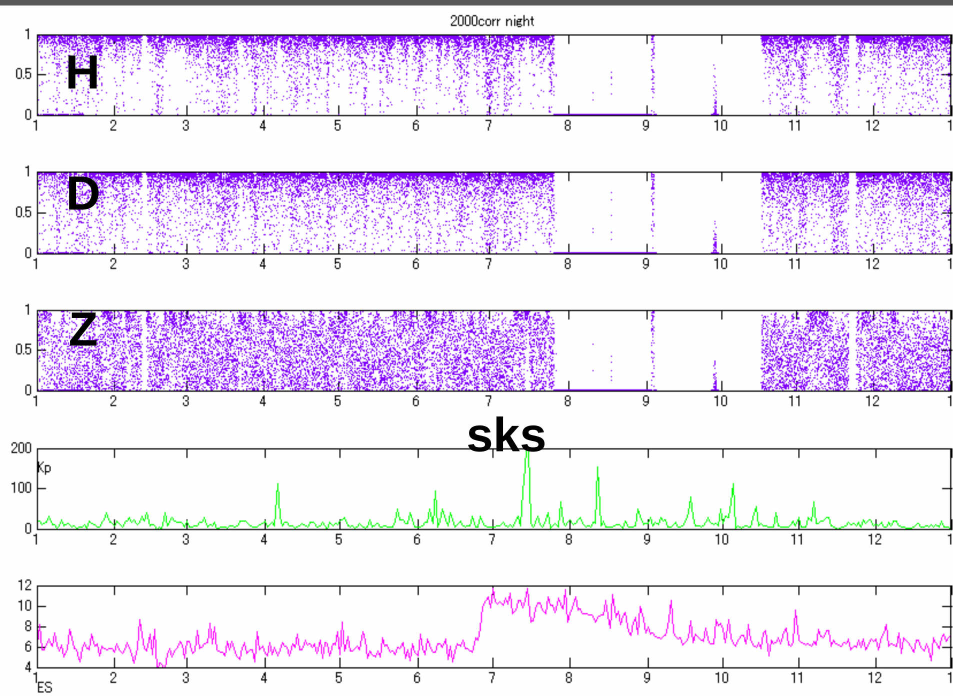

kamの
重み
sksの
重み
1
0.5
0
−0.5
−1
1 2 3 4 5 6 7 8 9 10 11 12 1
2000年1月～12月

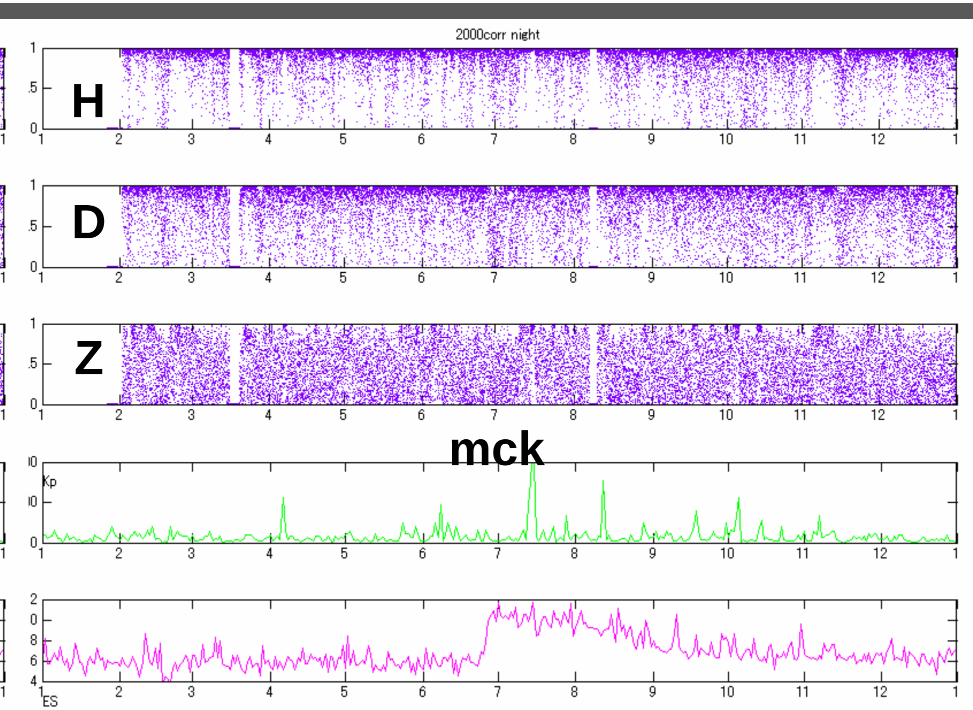
相関

chiba-u geophysics

伊豆観測点
(kam,sks,mck)と
柿岡(kak)の相関
(夜間)







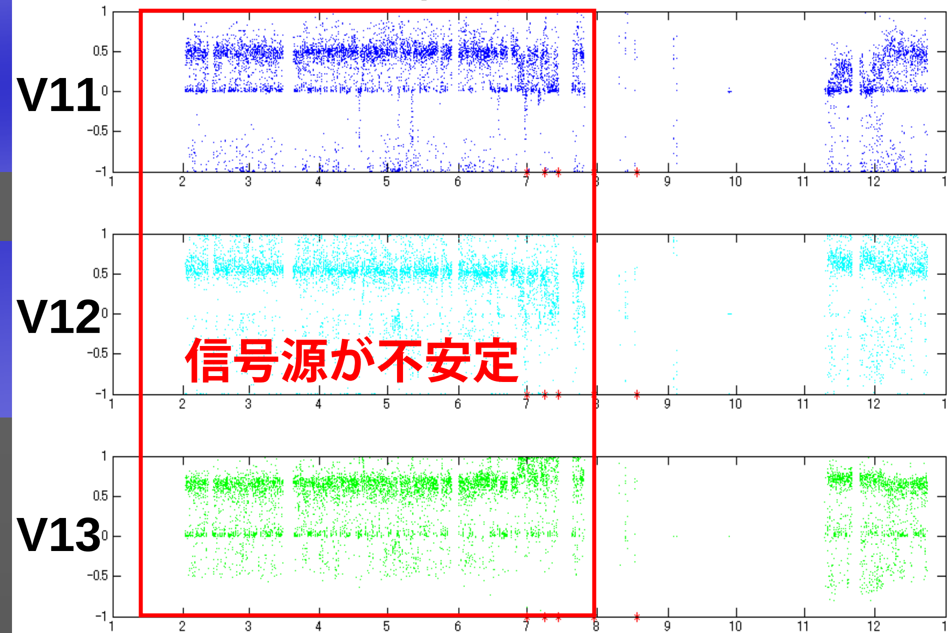
固有ベクトルの変動

V11：kamの重み
V12：sksの重み
V13：mckの重み

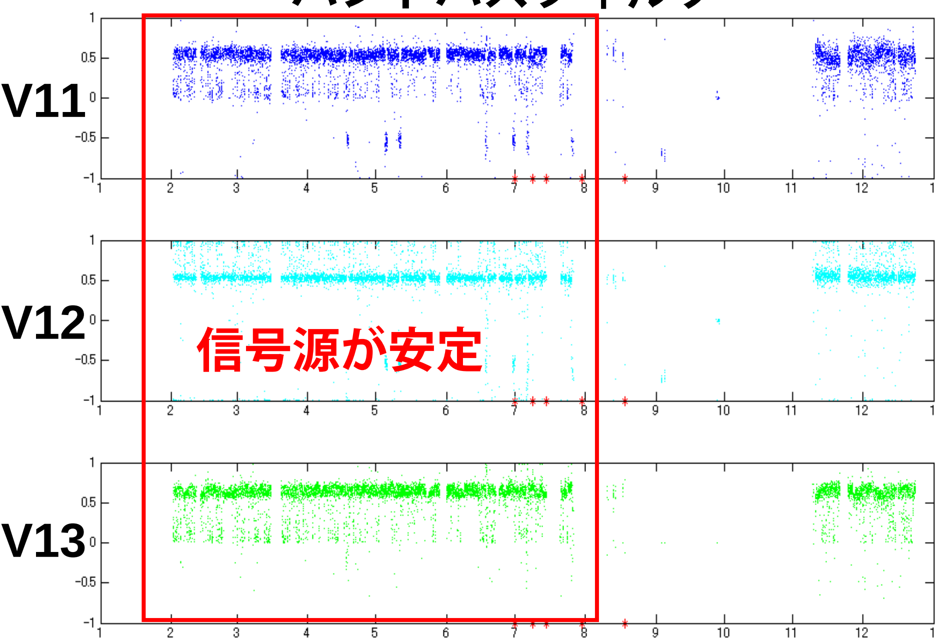
$$1 = \sqrt{V_{11}{}^2 + V_{12}{}^2 + V_{13}{}^2}$$

$$Z_1 = V_{11} X_{kam} + V_{12} X_{sks} + V_{13} X_{mck}$$

SSAフィルタ

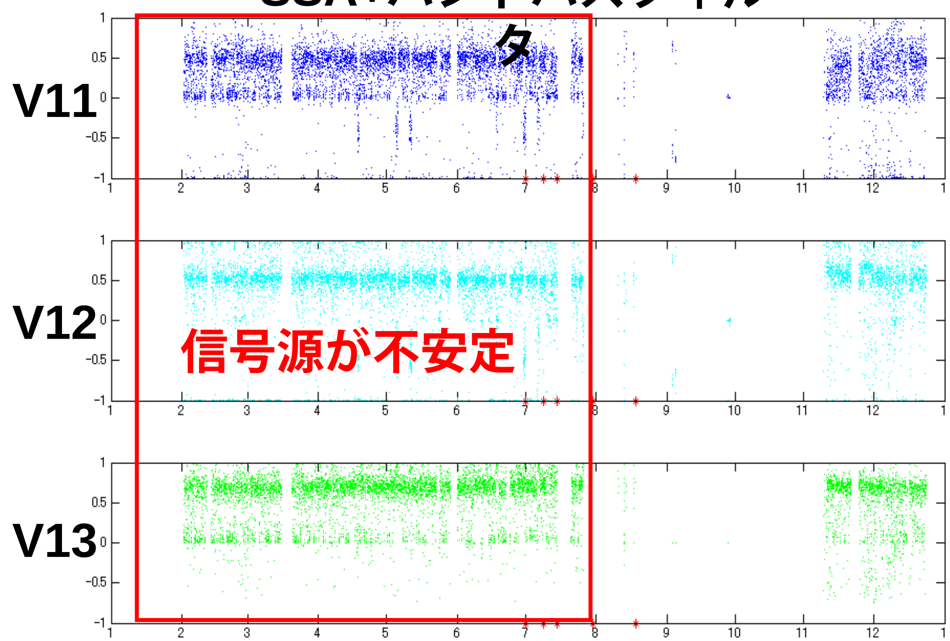


バンドパスフィルタ



2000年

SSA+バンドパスフィルタ



2000年

7. 今後の課題

chiba-u　geophysics

今回は1Hzサンプリングのデータを使用した。

↓

房総観測点の12.5Hzのデータをリファレンスとし、伊豆観測点のデータにSSAフィルタを適用し、
主成分解析を適用。

6. まとめ２

①0.01Hzバンドパスフィルタを適用した時系列
②SSAフィルタを適用した時系列
③両方を適用した時系列
にそれぞれPCA(主成分解析)を適用した。

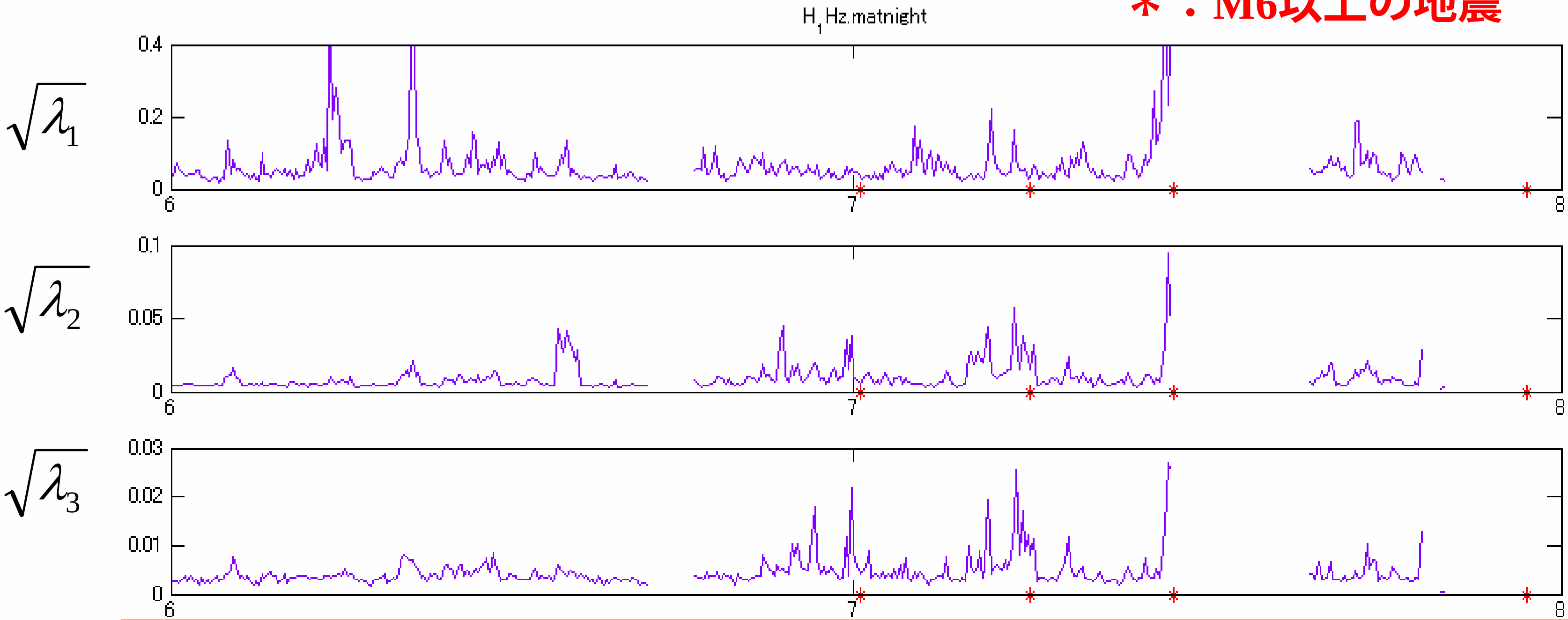
①の場合、地磁気脈動の影響が強いことが確認できた。
②の場合、地磁気脈動の影響は概ね除去できたが、
地震波による磁力計の揺れが卓越した。
③の場合、地震数日前に１～３の主成分の上昇が見られた。

①の場合の寄与率は約5%
③の場合の寄与率は約20%　と上昇が見られた。

SSAフィルタによって影響力のある太陽起源の信号を除去することができ、
地震に関する信号の数学的優位性を持たせることができたと言える。

① 0.01Hzフィルタのみ　～6,7月夜間の固有値の変動

＊：M6以上の地震



ap

Es

芹田らの結果と調和的。

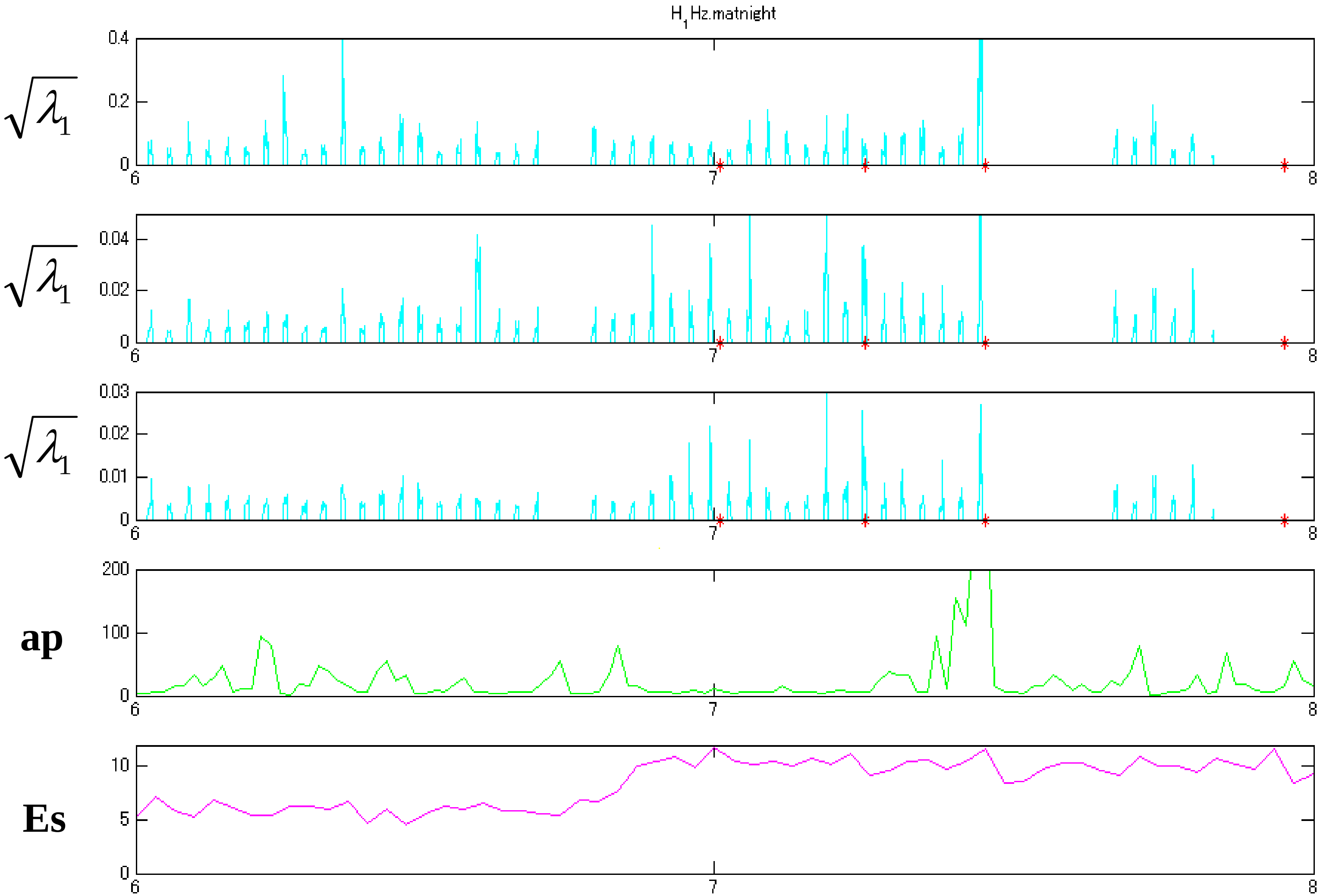
$$第３主成分の寄与率 = \frac{\sqrt{\lambda_3}}{\sqrt{\lambda_1}+\sqrt{\lambda_2}+\sqrt{\lambda_3}} \cong 0.0566 \cong 5.6\%$$

0

6　7　8

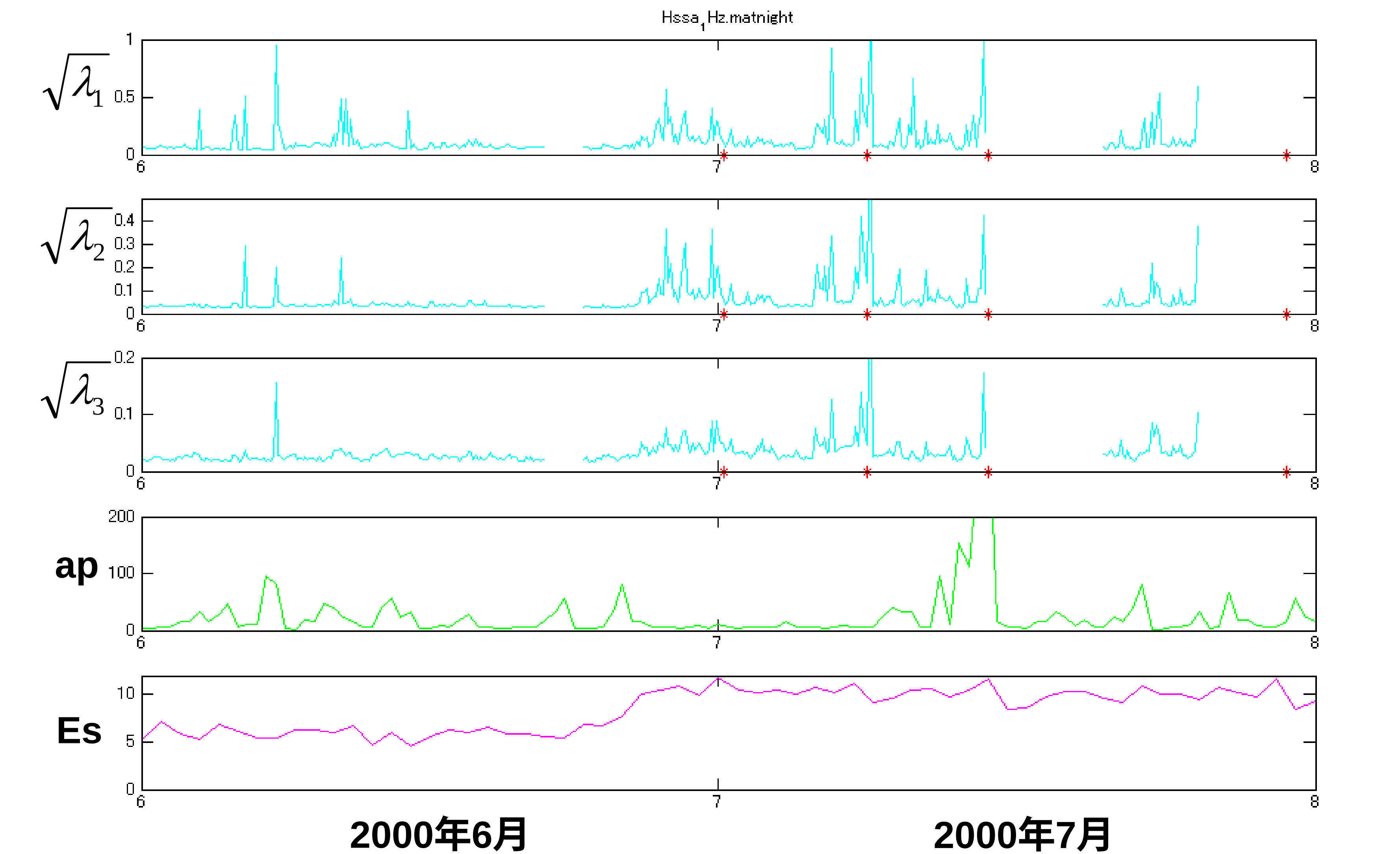
2000年6月　**2000年7月**

固有値の変動



2000年6月～7月

② SSAフィルタのみ　～6,7月夜間の固有値の変動～



chiba-

主成分解析（ＰＣＡ）の手順

３０分ごとのデータマトリクス

$$X = (x_{ij})_{i,j=1}^{k,N} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & x_{1N} \\ x_{21} & x_{22} & x_{23} & \cdots & x_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{k1} & x_{k2} & x_{k3} & \cdots & x_{kN} \end{bmatrix}$$

N=1800(1Hz×60秒×30分)

K=3(kam,sks,mck)

共分散行列

$$R = \frac{1}{N} X^{*T} X^{*}$$

$$R = V \Lambda V^{-1}$$

chib

固有値Λ　　　　　　　　　固有ベクトルV

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_k \end{bmatrix}$$

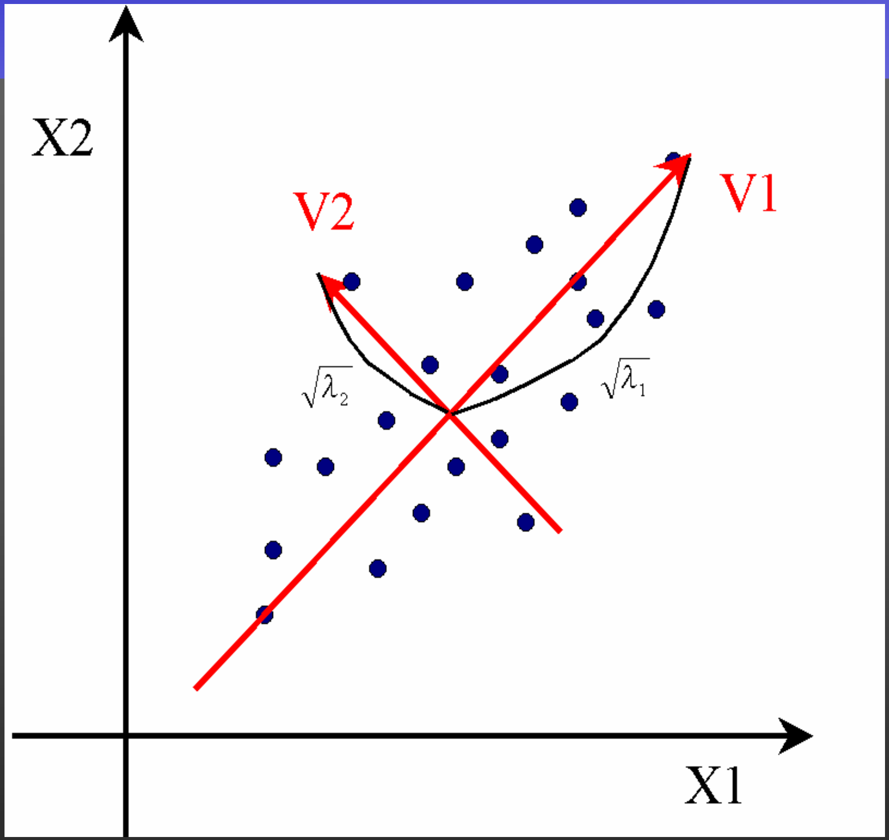
$$V = \begin{bmatrix} V_{11} & V_{21} & \cdots & V_{k1} \\ V_{12} & V_{22} & \cdots & V_{k2} \\ \vdots & \vdots & \ddots & \vdots \\ V_{1k} & V_{2k} & \cdots & V_{kk} \end{bmatrix}$$

主成分の波形は以下の式で再現される

$$Z_i = V_{i1} X_{kam} + V_{i2} X_{sks} + V_{i3} X_{mck}$$

主成分解析概念図（2次元）

chiba-u　geophysics



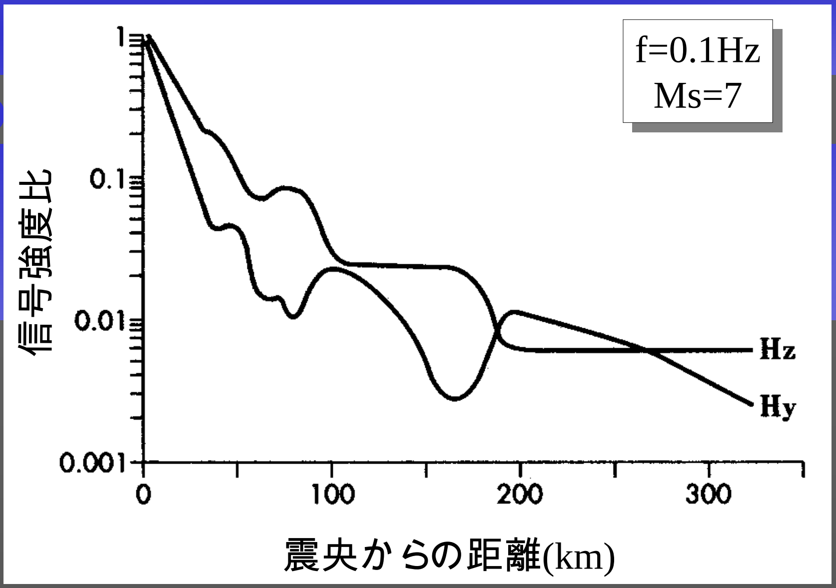
X1 = 身長
X2 = 体重

λ1 = 体の大きさ
λ2 = 肥満の度合い

常磐線（取手駅以北）と水戸線は、観測に悪影響の少ない交流電化と、既存の直流電化区間を相互に走れる交直流電車の技術ができるまでは、長らく非電化で運転されていた。また、首都圏新都市鉄道つくばエクスプレス線の守谷駅以北は開業当初から交流電化であり、さらに関東鉄道常総線と関東鉄道竜ヶ崎線はコストの問題もありいまだに非電化のまま運行している

ウィキペディアより

chiba-u geop



	型	周期(秒)	波形			型	周期(秒)	波形
Pc	Pc1	0.2～5			Pi	Pi1	1～40	不規則な
	Pc2	5～10				Pi2	40～150	減衰波形
	Pc3	10～45	規則的な			Pi3	150～	(irregular)
	Pc4	45～150	連続波形					
	Pc5	150～600	(continuous)					
	Pc6	600～						
		地磁気脈動の国際的分類						