Apply low-cost acceleration sensors to the Earthquake Early Warning Systems in Taiwan

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Contents

Introduction

Background

The Micro Electro Mechanical System (MEMS) acceleration sensors have been well developed (Holland, 2003).

Because the MEMS sensors are inexpensive and easily to be installed, it is possible to construct an extremely dense seismic network economically.

A home seismometer was developed by adopting the MEMS acceleration sensors in Japan (Horiuchi et al., 2009).

The Self-organizing Seismic Early Warning Information Network (SOSEWIN) system was implemented by the MEMS acceleration sensors in Istanbul. (Fleming et al., 2009)

The Quake-Catcher Network (QCN) has been implemented in the United States, the Europe and the Chile (Cochran et al., 2009; Chung et al., 2011).

Motivation

Taiwan is situated between the Philippine Sea Plate and the Eurasia Plate. Because many large and destructive earthquakes occurred, to develop an Earthquake Early Warning (EEW) system is essential.

The EEW system has been well developed in Taiwan (Wu and Teng, 2002; Hsiao et al., 2009; Hsiao et al., 2011).

The system is capable of issuing an earthquake report within 20 sec of its occurrence with good magnitude estimations.
(Hsiao et al., 2009).

However, the dense seismic network could shorten the response time and provide more precise values of the Peak Ground Acceleration (PGA).

The MEMS sensors provide us a solution to install dense seismic network.

Features of the low-cost strong-motion sensor

MEMS Acceleration Sensors

The Palert acceleration sensor

Low-cost
Easy to install

Dynamic range : 16 bit
Sampling rate: 100 Hz
Sensitivity : ± 2g

Features of the Palert Acceleration Sensor

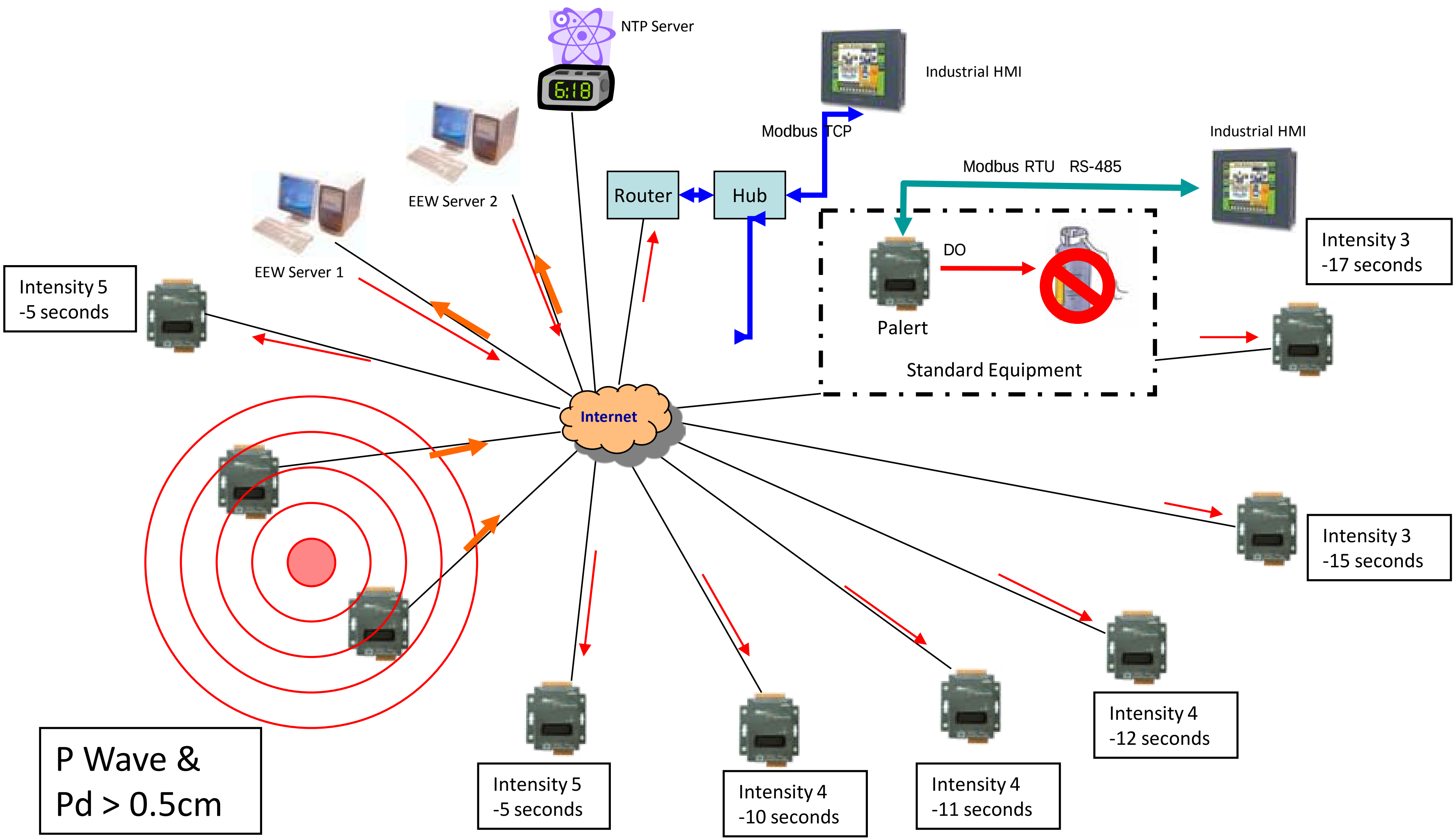
<Continuous Mode>

- 100 samples per second
- 3 channels (UD, EW, NS) in acceleration
- 1 channel (UD) in displacement (Pd)

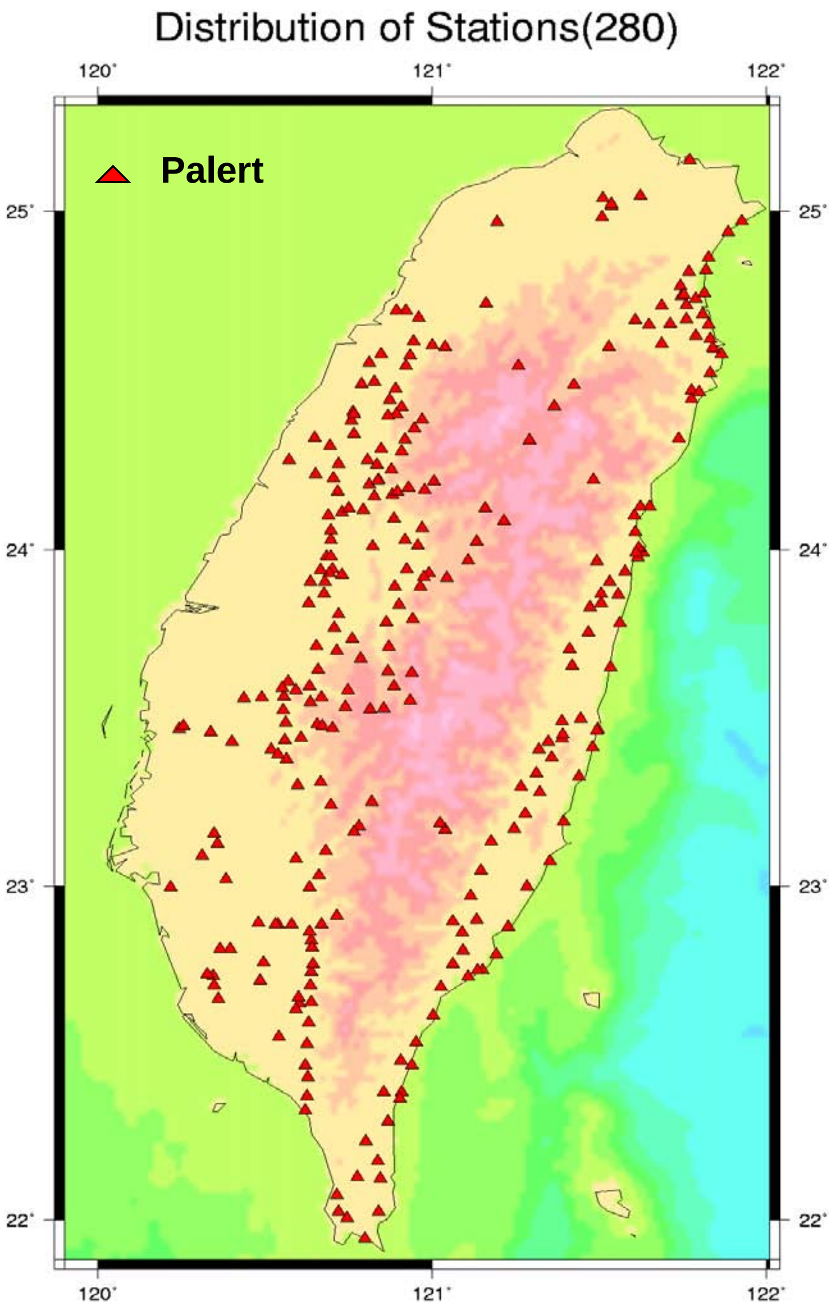
<Triggered Mode>

- Threshold to the peak amplitudes of displacement, velocity and acceleration

Palert EEW Networking System



Seismic Network and real-time data acquisition



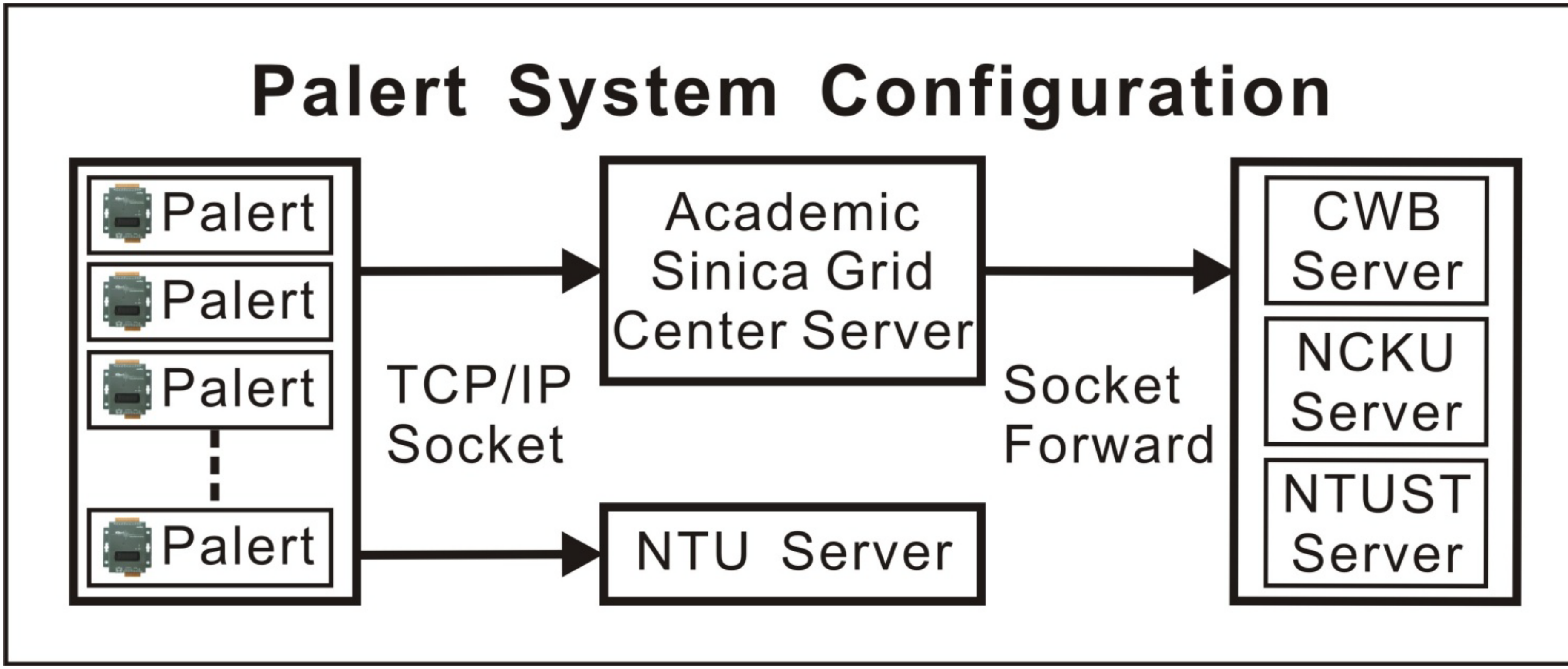
Palert Seismic Network

Total of 280 stations as of 2013 Dec.

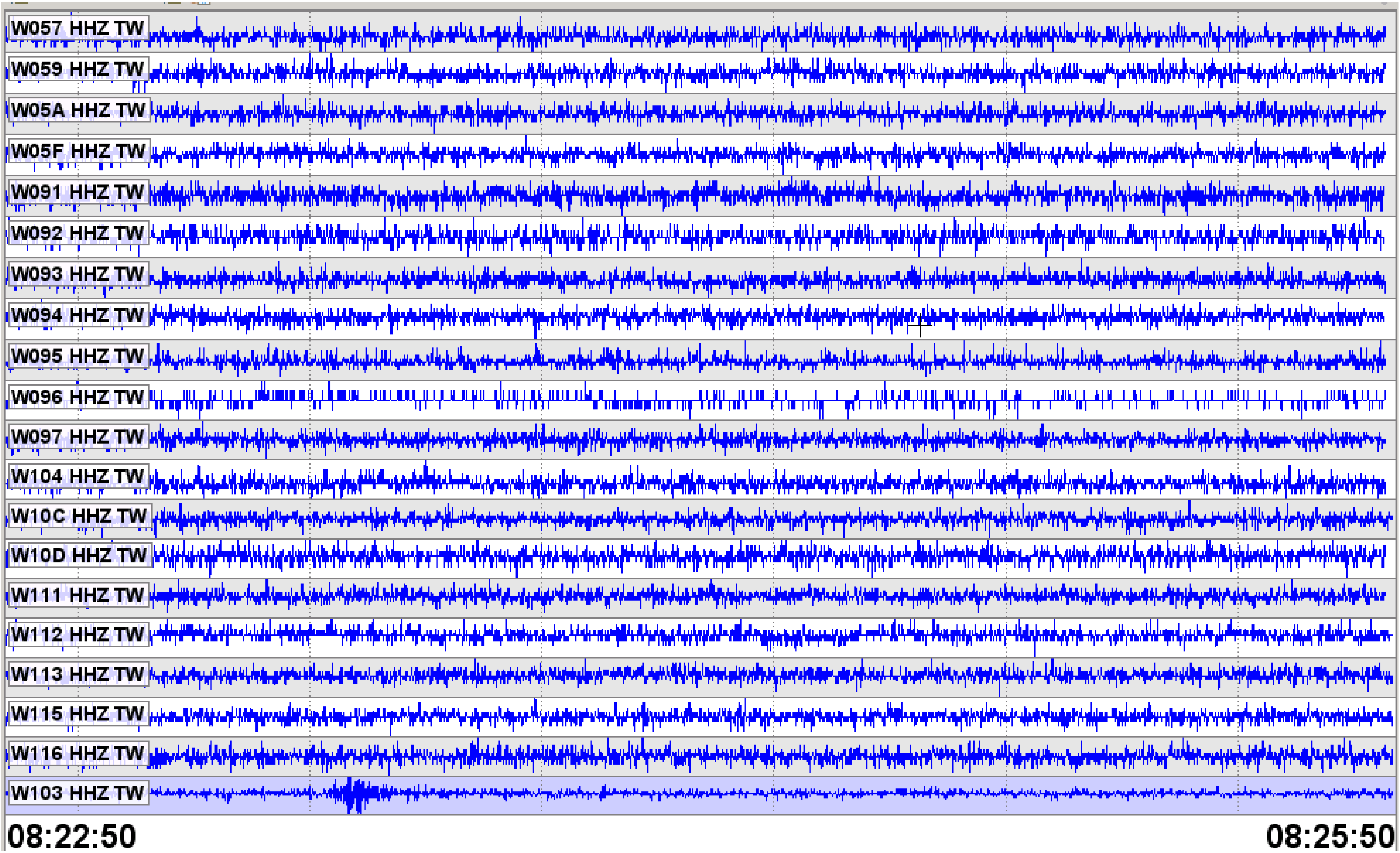
Most of stations were installed in the elementary schools.

Palert sensors were install either on wall or on pillars.

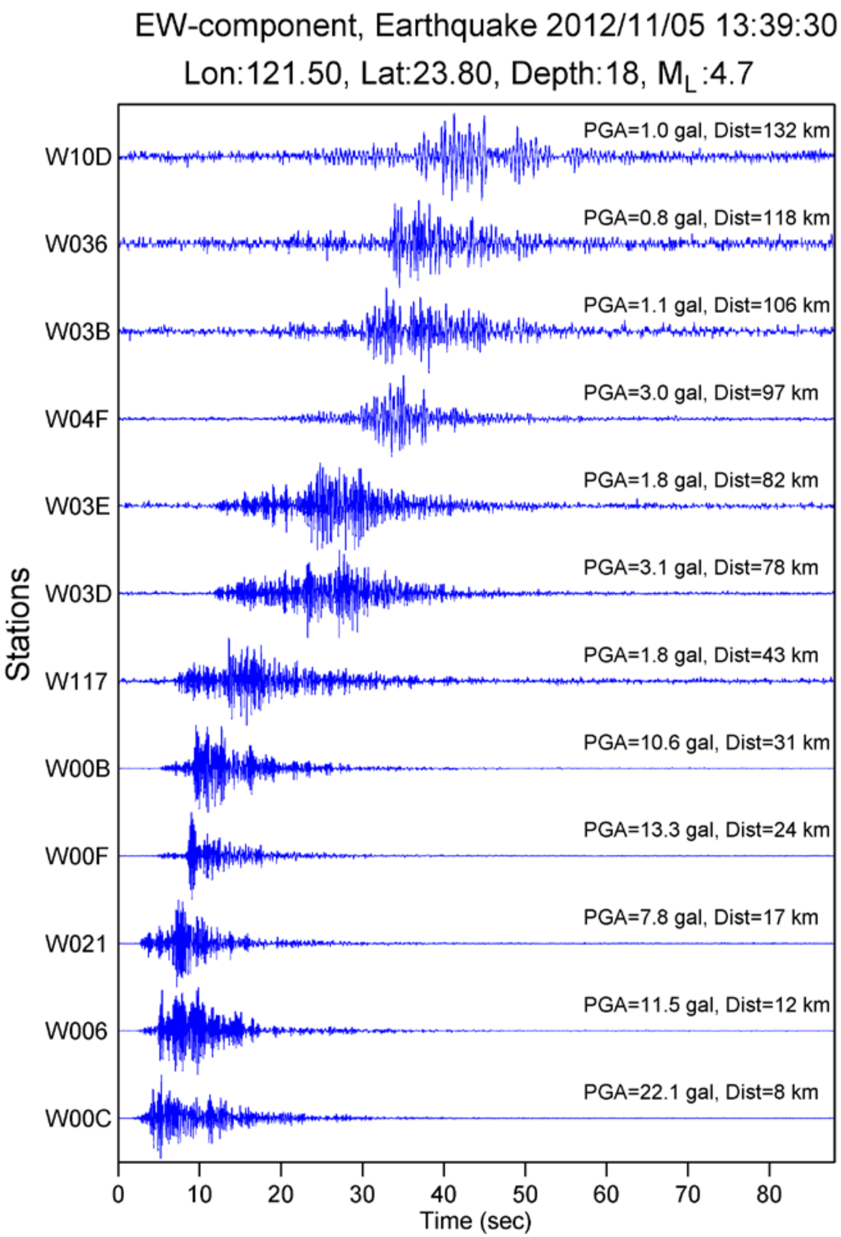
Palert sensors are connected to the data processing center for detecting earthquakes and disseminating warnings.

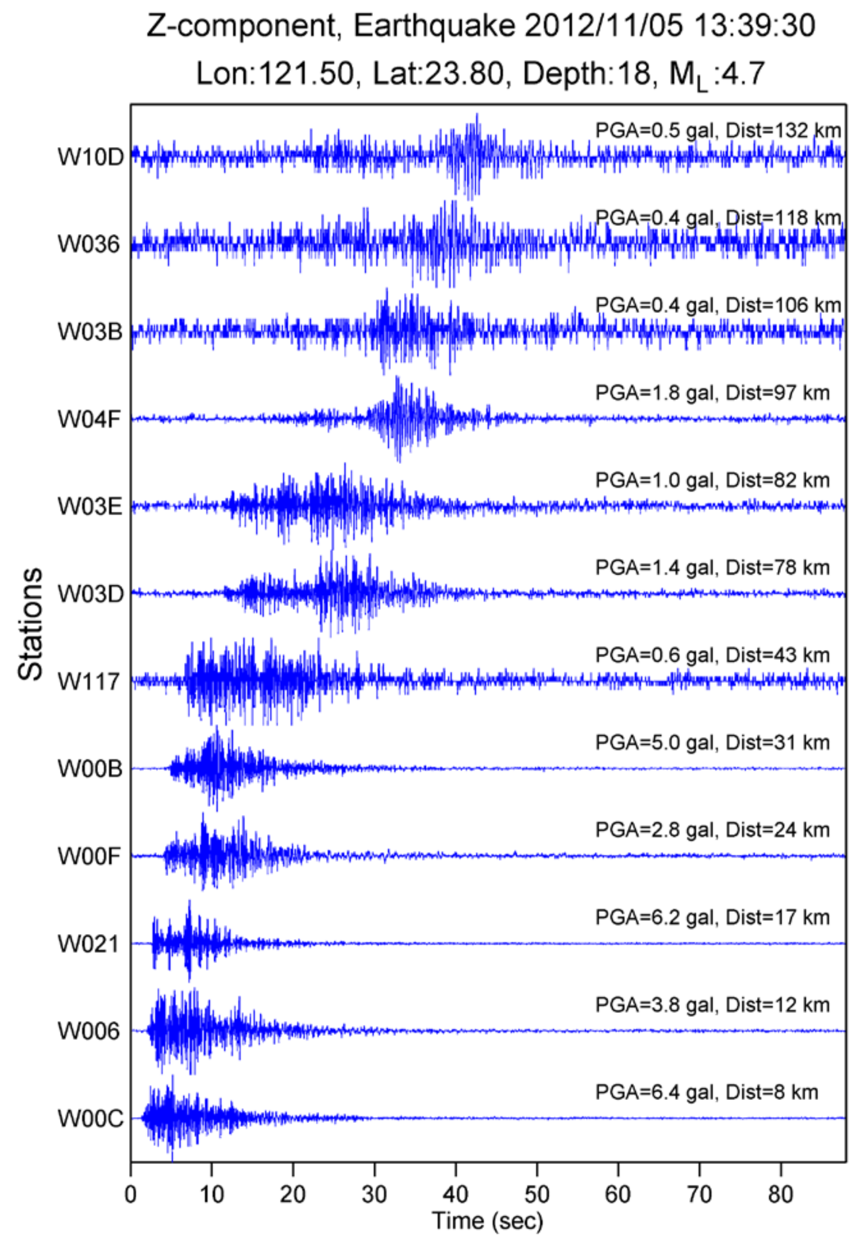

Palert System Configuration
Palert
Palert
Palert
Palert
TCP/IP
Socket
Academic
Sinica Grid
Center Server
NTU Server
Socket
Forward
CWB
Server
NCKU
Server
NTUST
Server

Continuous Real-Time Data Streams

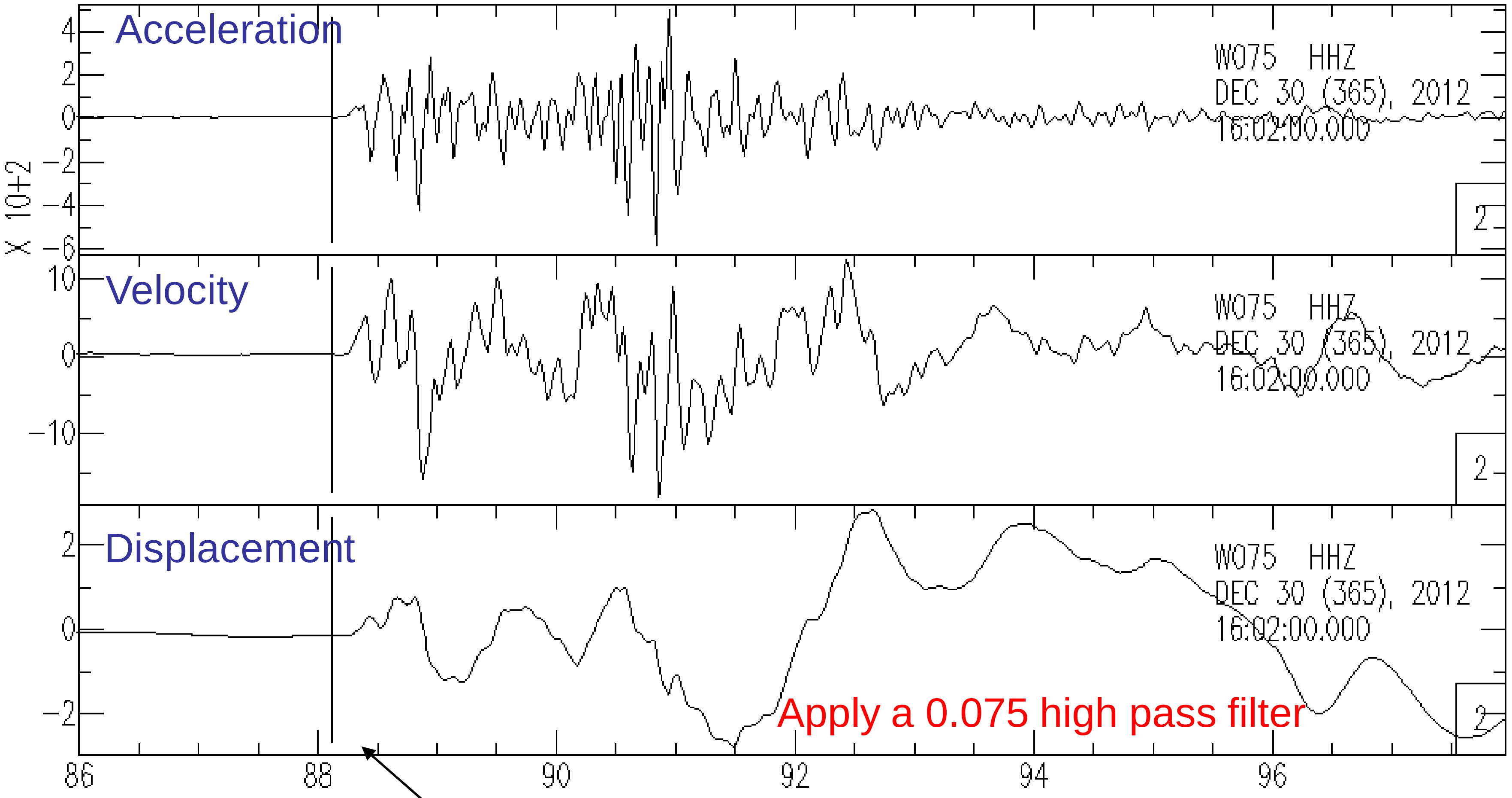


Waveforms from the Palert Seismic Network





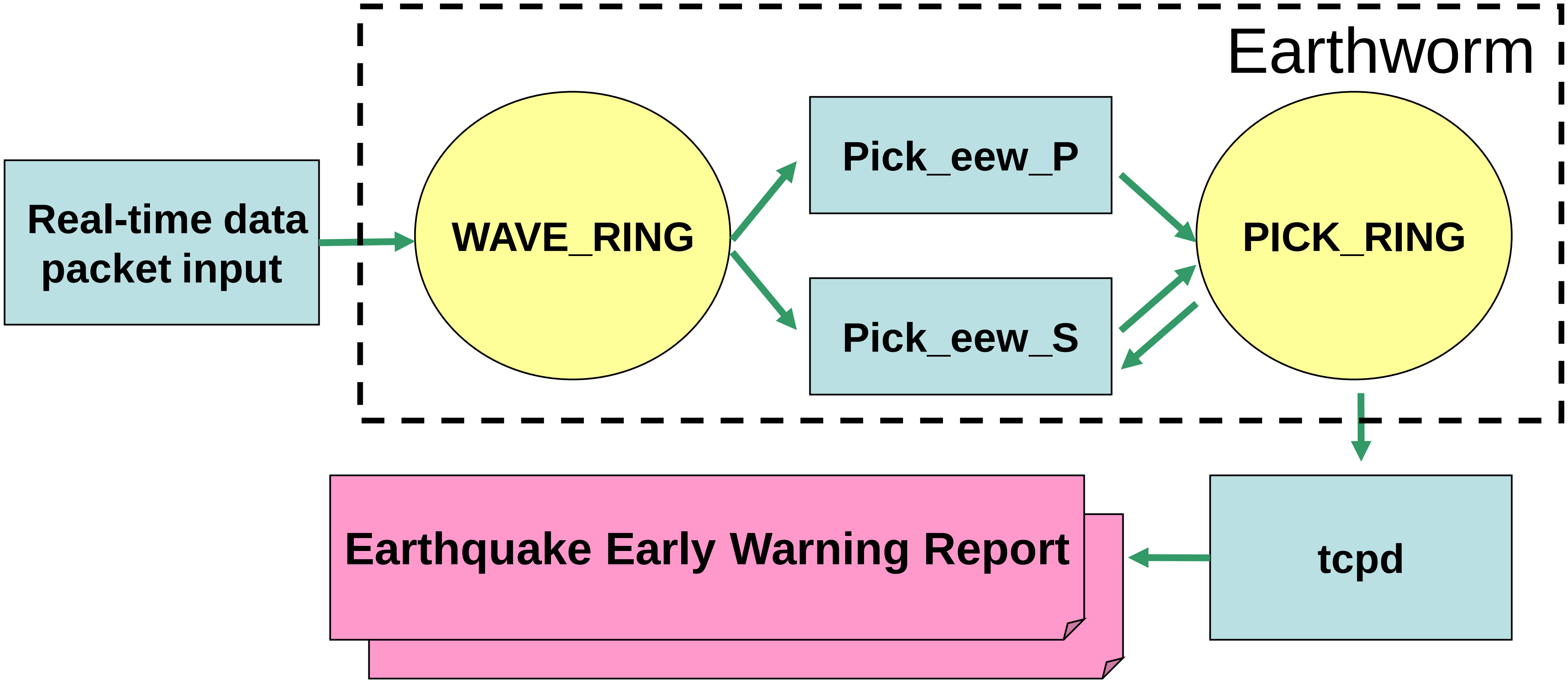
High Quality Data

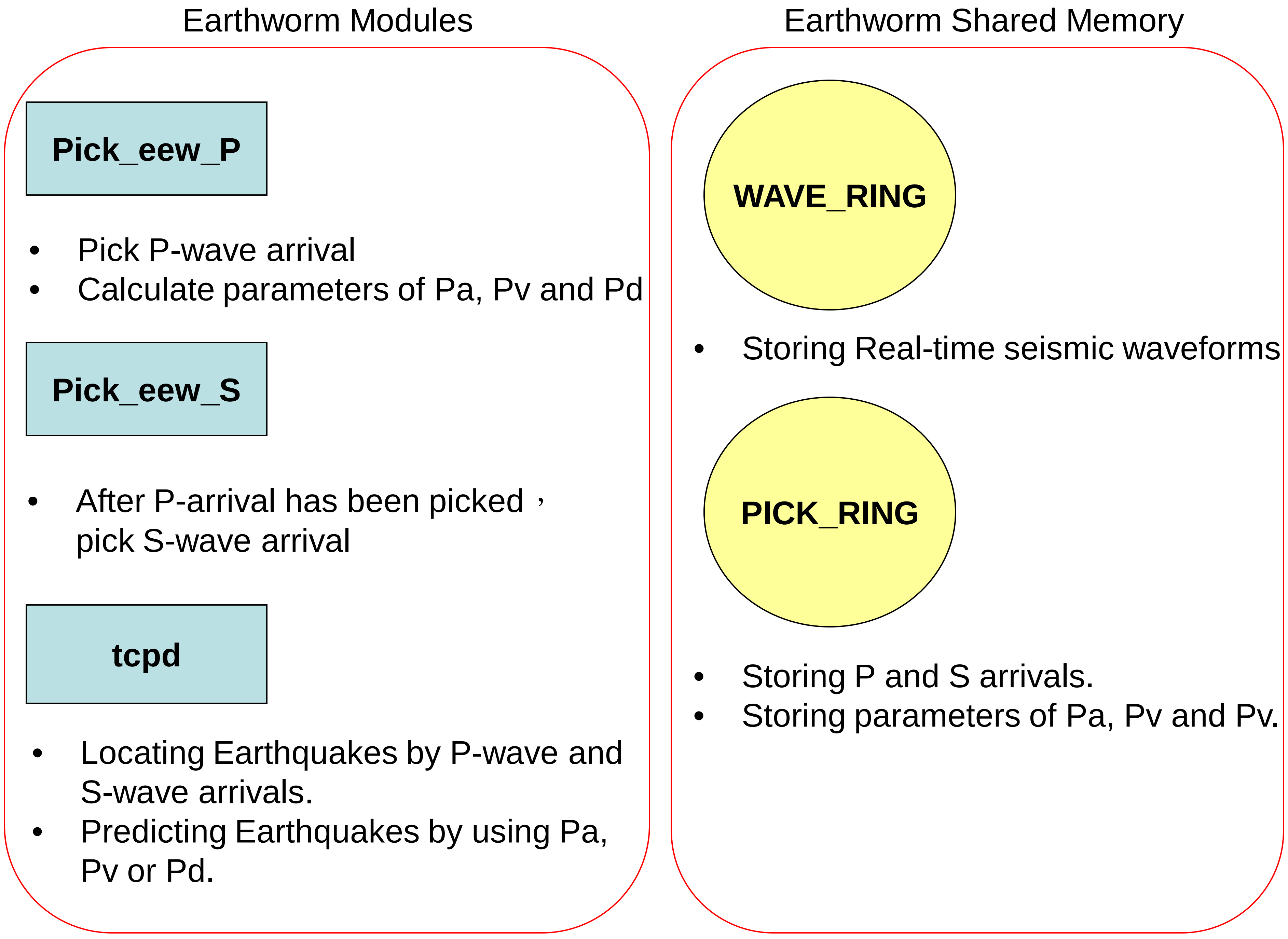


P-wave arrival

Architecture of real-time data processing

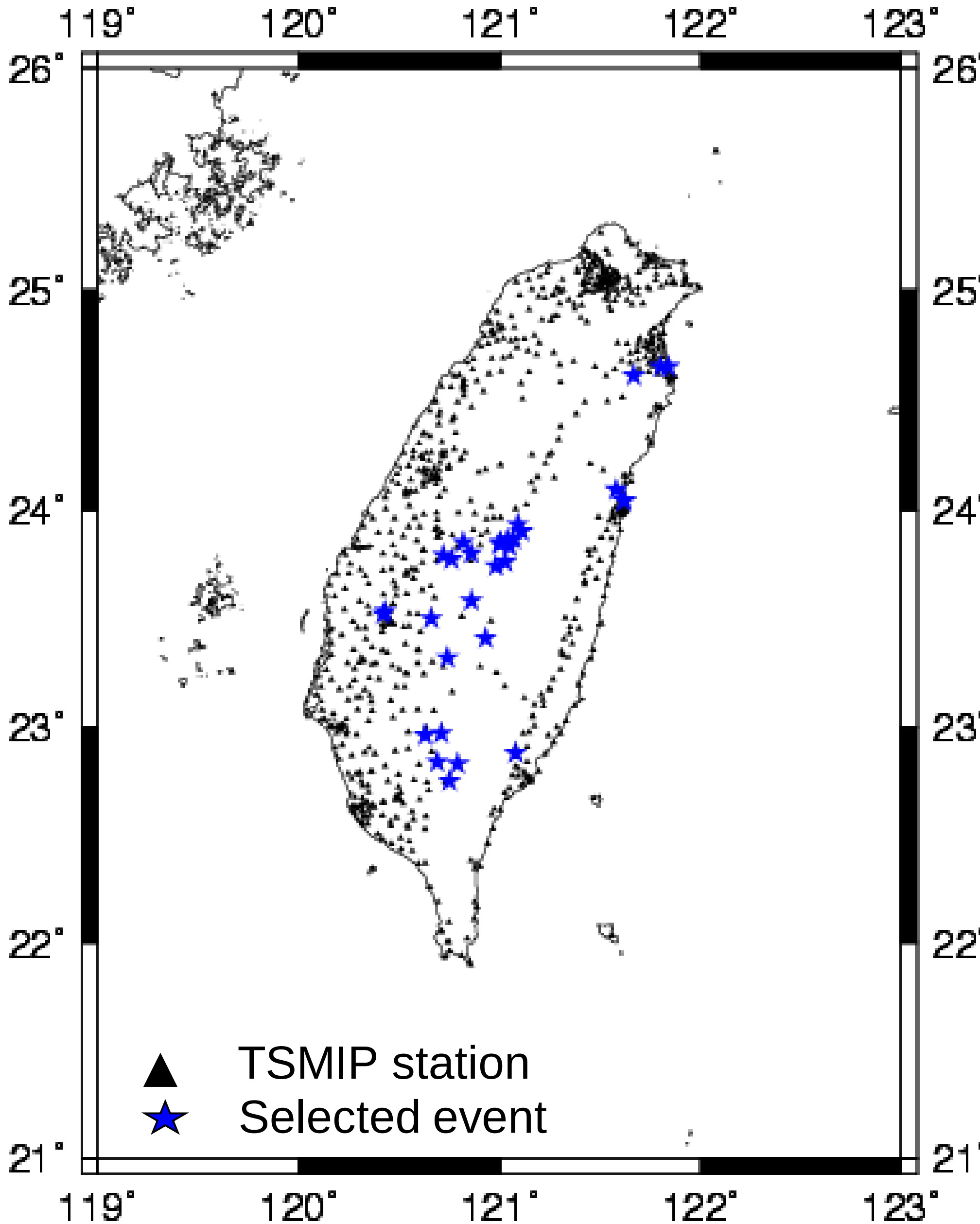
Earthquake Early Warning procedure




Earthworm Modules
Earthworm Shared Memory
Pick_eew_P
• Pick P-wave arrival
• Calculate parameters of Pa, Pv and Pd
Pick_eew_S
• After P-arrival has been picked， pick S-wave arrival
tcpd
• Locating Earthquakes by P-wave and S-wave arrivals.
• Predicting Earthquakes by using Pa, Pv or Pd.
WAVE_RING
• Storing Real-time seismic waveforms
PICK_RING
• Storing P and S arrivals.
• Storing parameters of Pa, Pv and Pv.

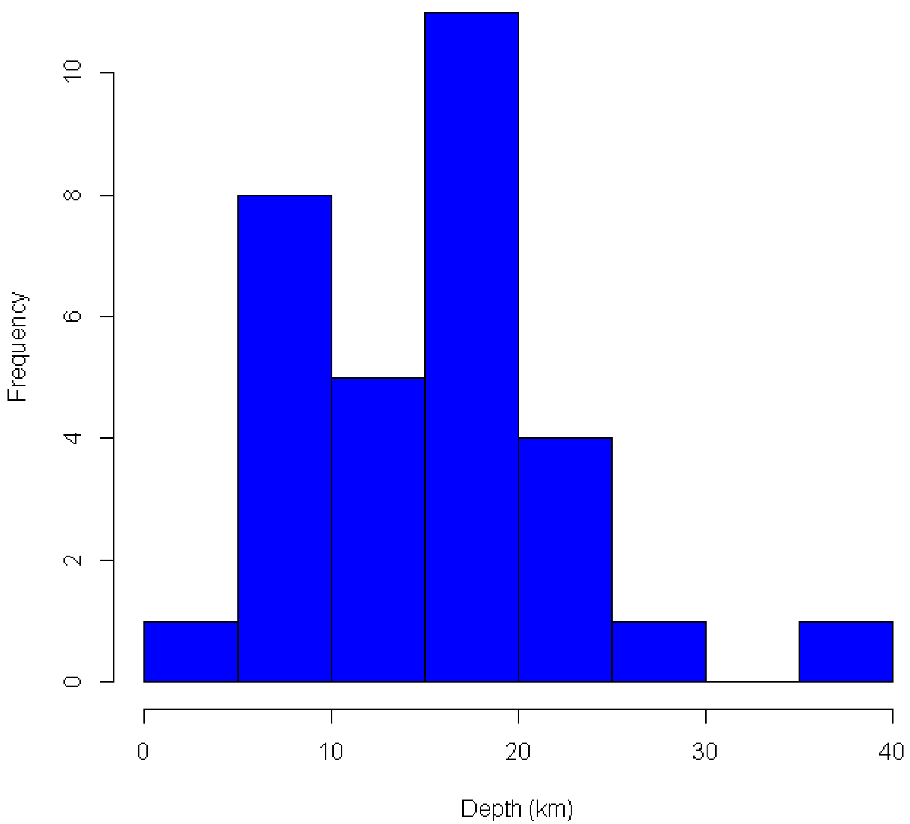
Determination of earthquake magnitude

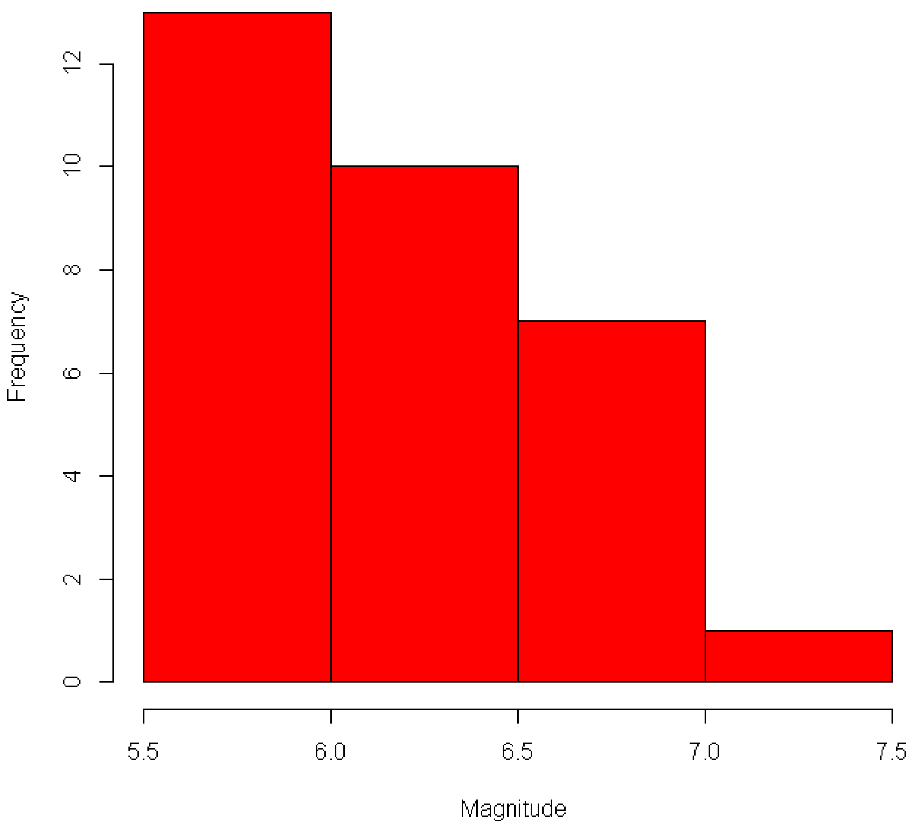
TSMIP Seismic network



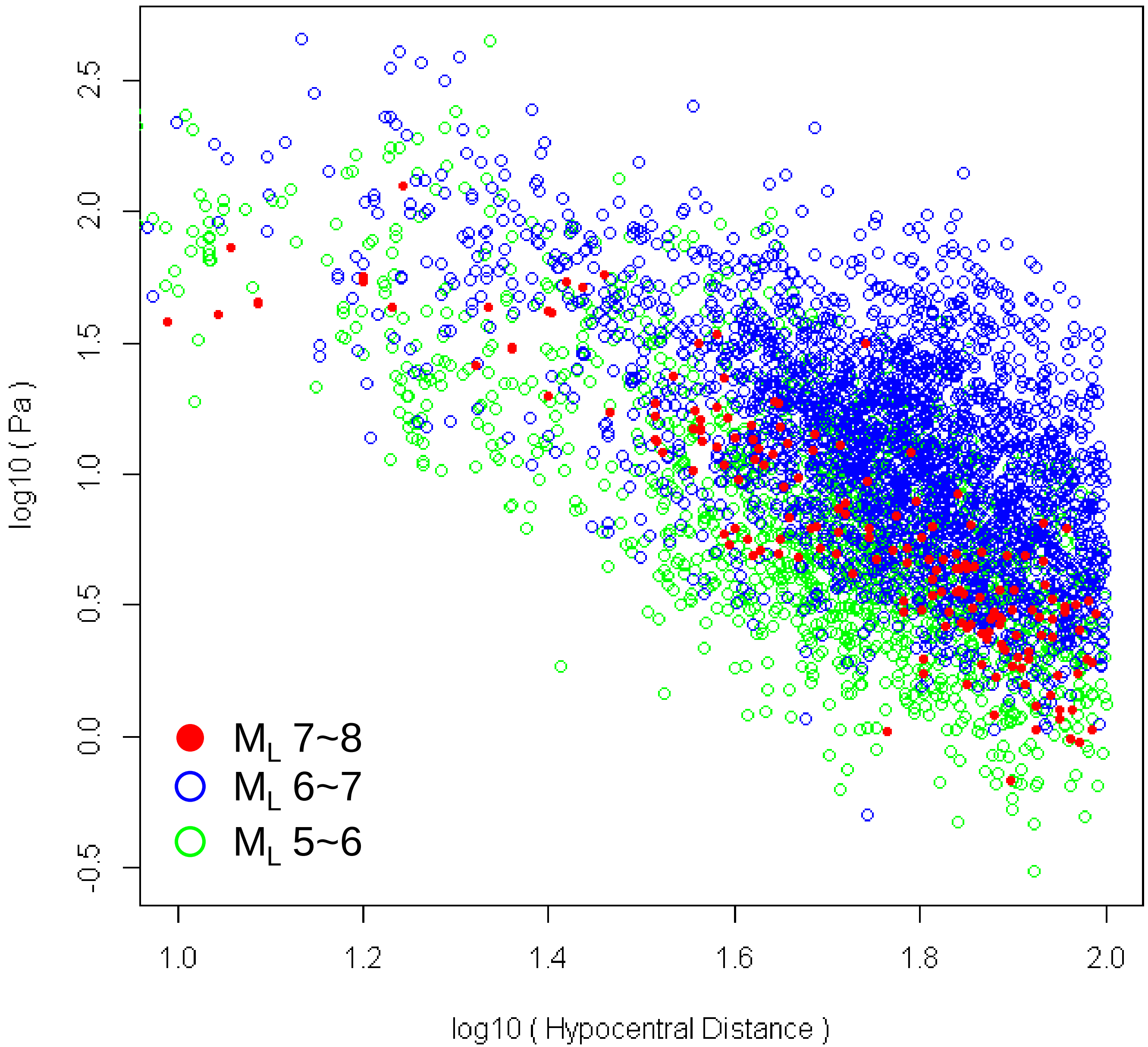
Data

Date : 1995 ~ 2012
Depth : 0 ~ 40 km
M_L : > 5.5

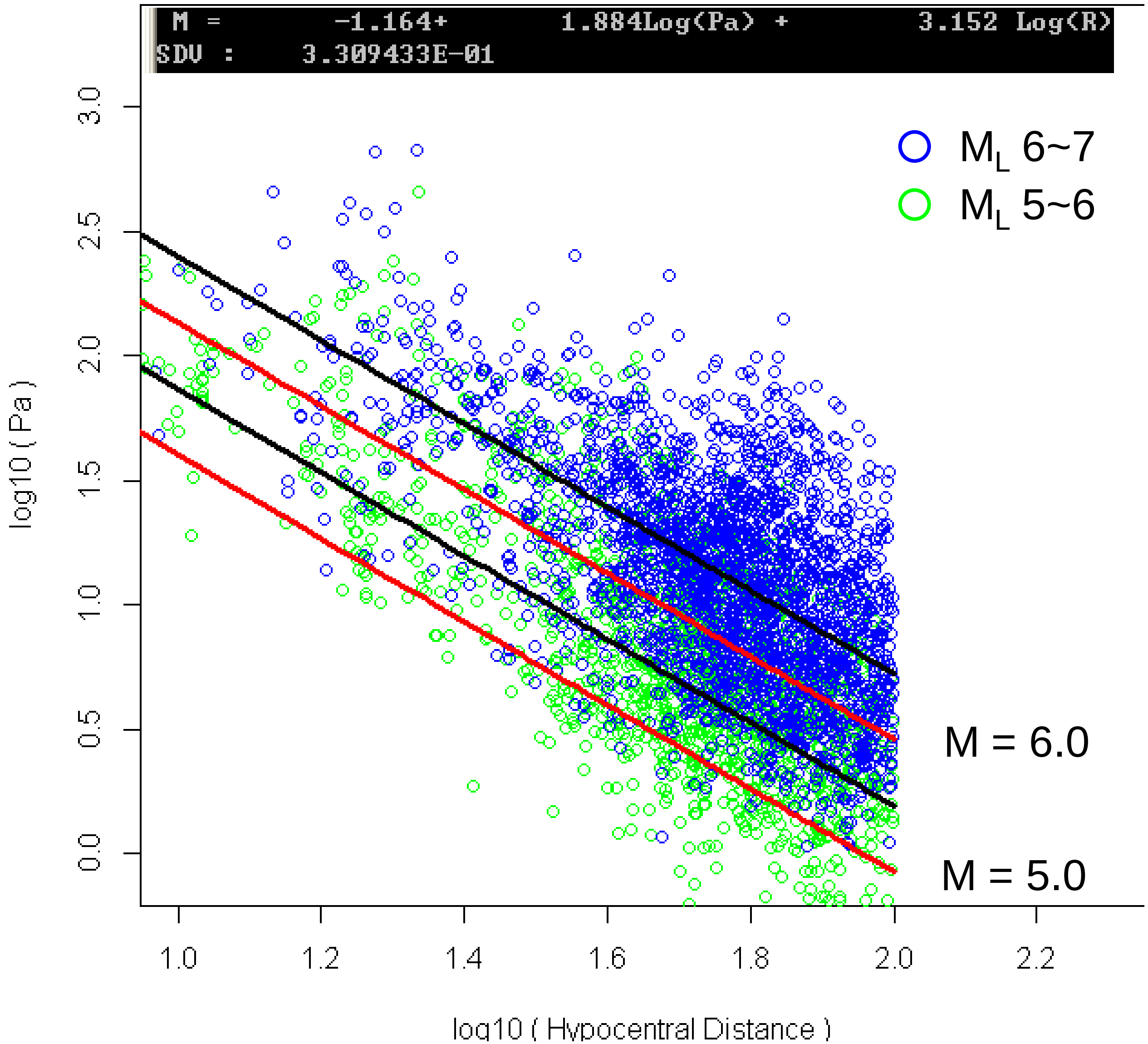




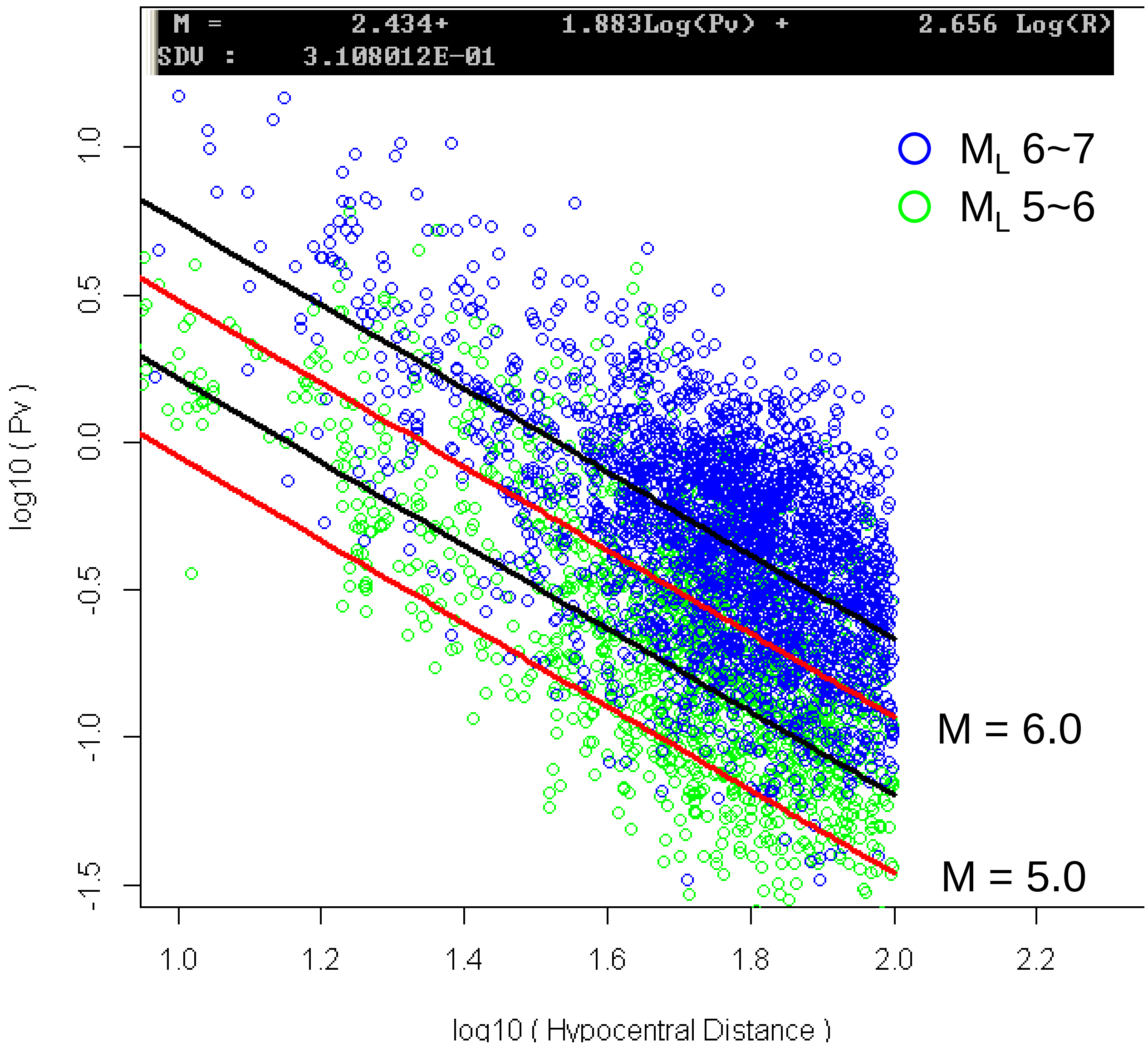
Magnitude Under Determine in the Chi-Chi Earthquake



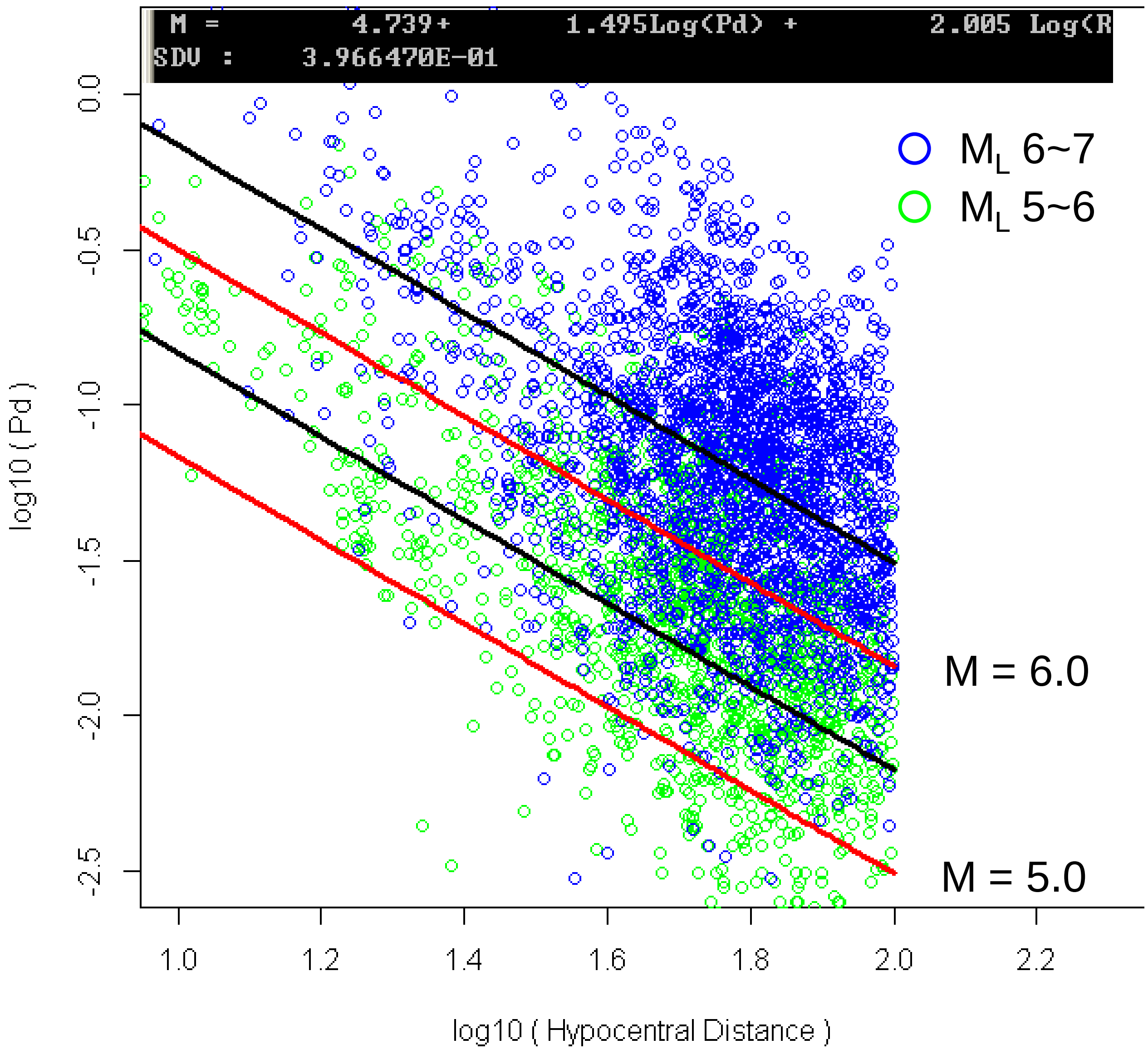
$$\log10(Pa) = 0.618 + 0.531*M - 1.673 * \log10(R)$$



log10(Pv) = -1.293 + 0.531*M - 1.411 * log10(R)



log10(Pd) = -3.170 + 0.669*M - 1.342 * log10(R)

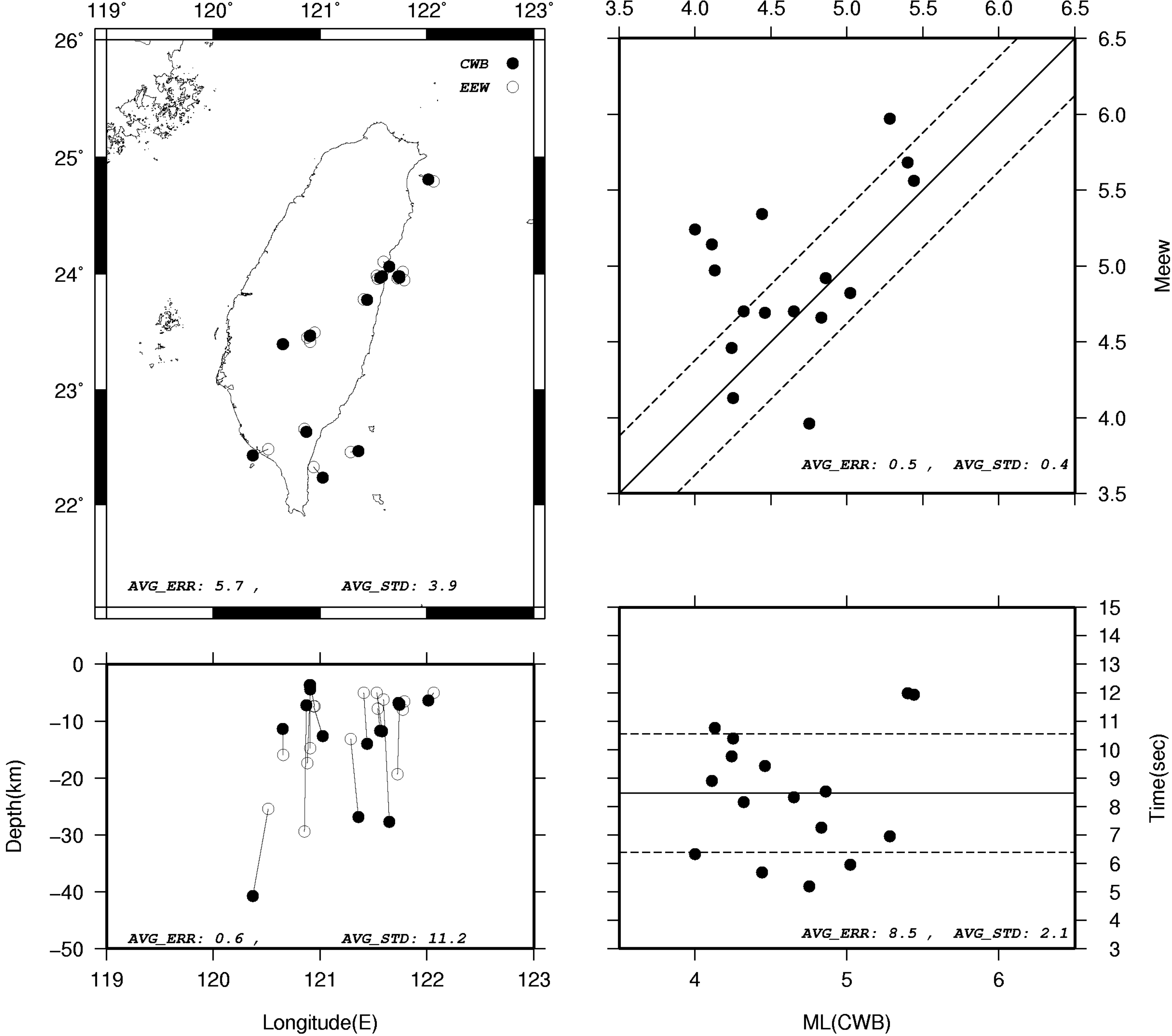


Off-line test of EEW system
from 25,Oct. 2012 to 03,Jan. 2013

2012,1025
~
2013,0103

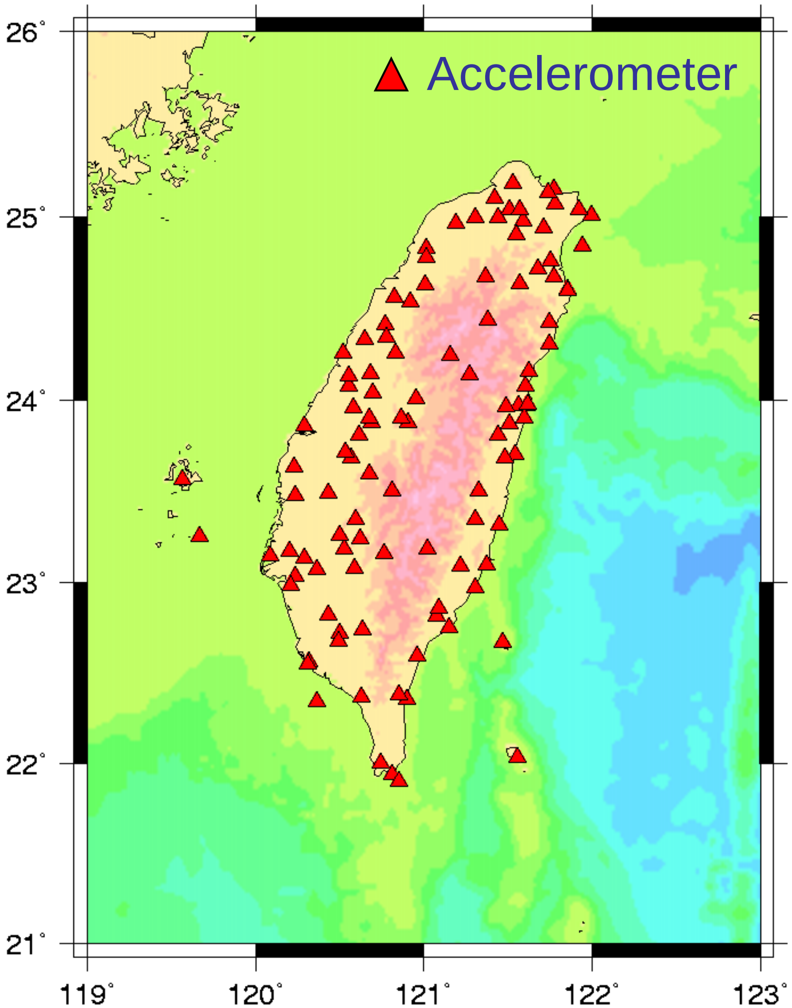
16 events

$M_L > 4.0$

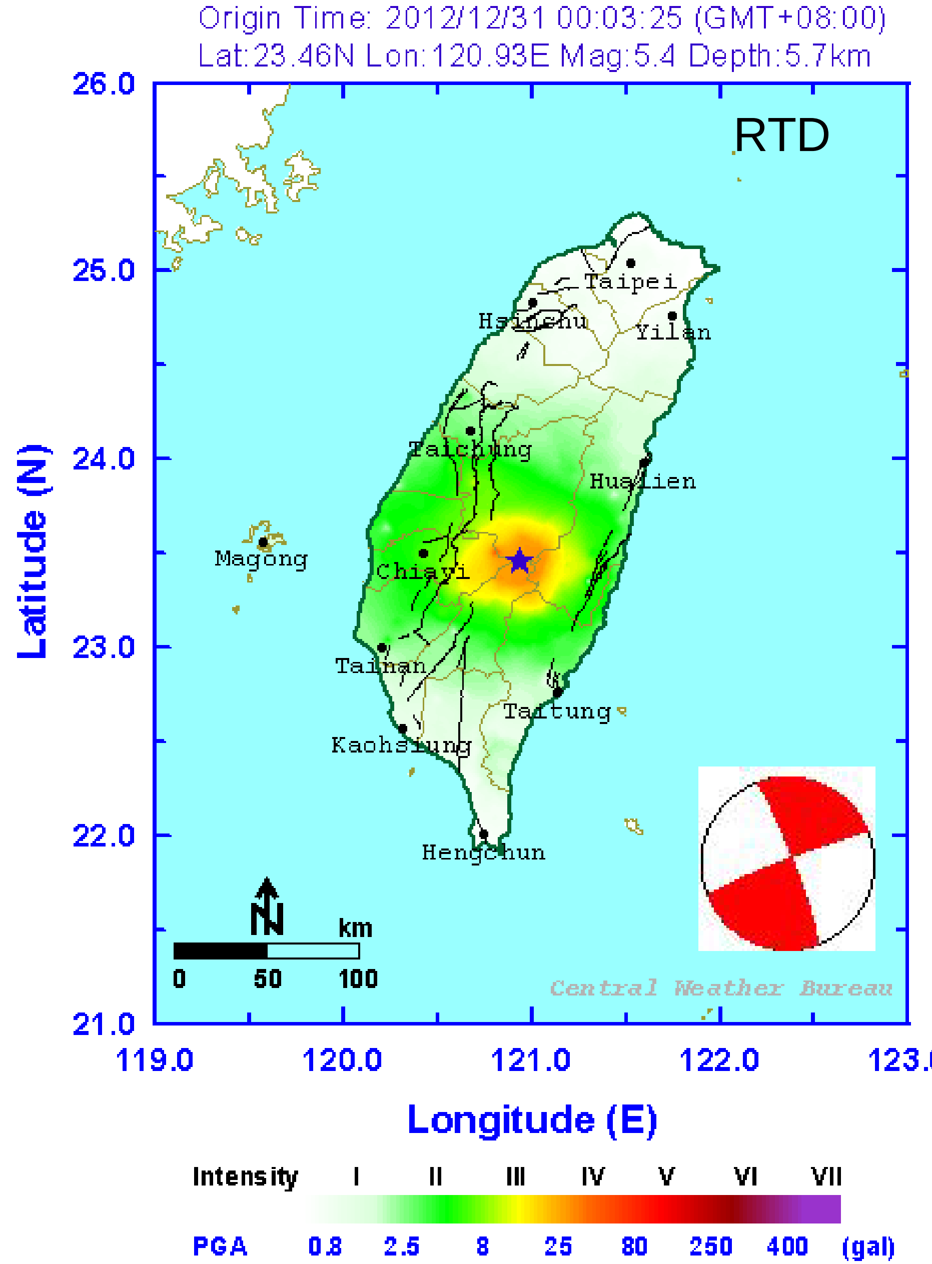


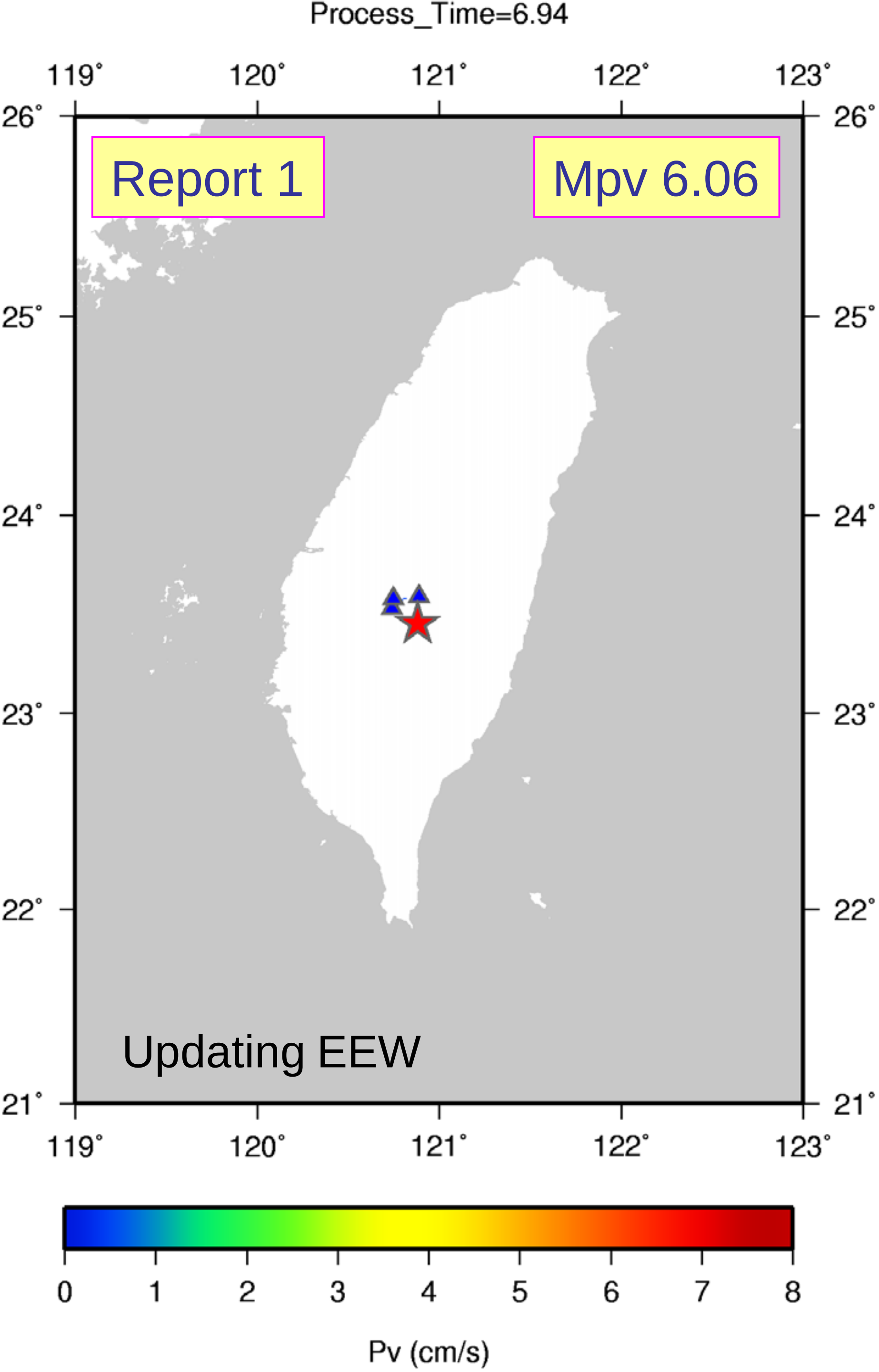
Case Study – 2012.Dec.30 , ML 5.4

RTD Network 110 Stations



SMART24A
Sampling rate: 100 sps
24-bits，±2g

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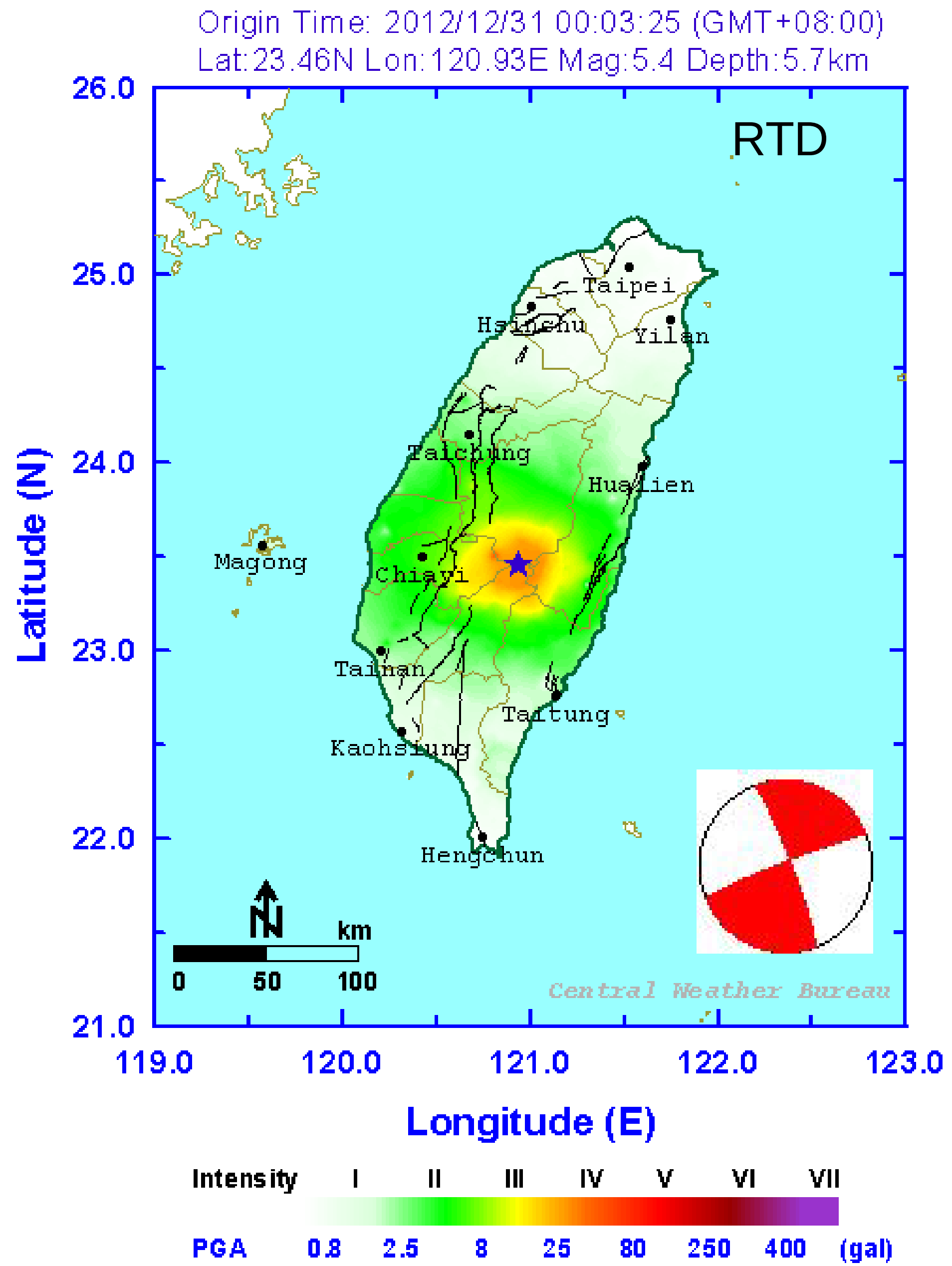
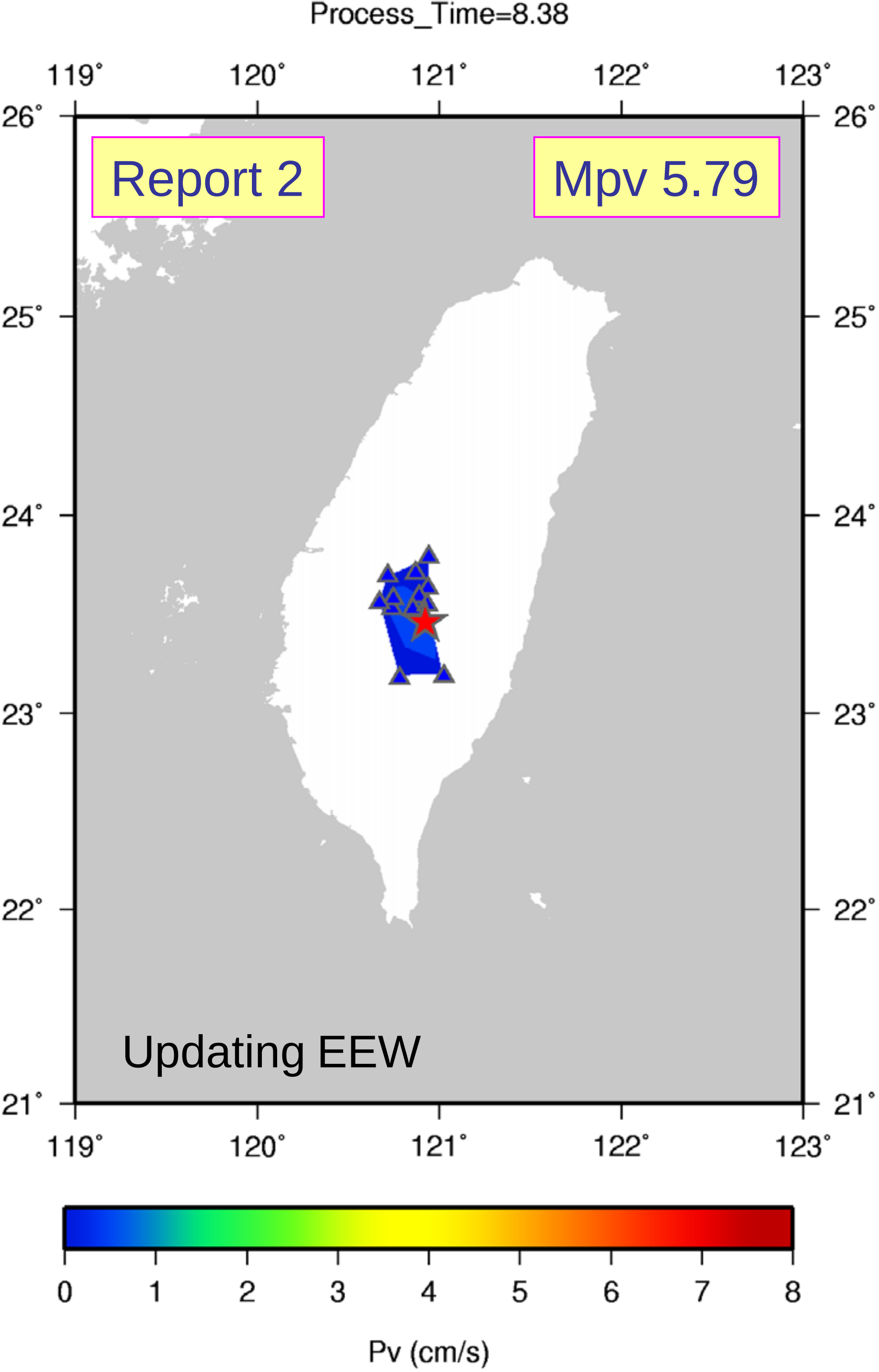
Report 1
Mpv 6.06
Updating EEW
Pv (cm/s)


Origin Time: 2012/12/31 00:03:25 (GMT+08:00)
Lat:23.46N Lon:120.93E Mag:5.4 Depth:5.7km
RTD
Latitude (N)
Longitude (E)
Taipei
Hsinchu
Yilan
Taichung
Hualien
Magong
Chiayi
Tainan
Taitung
Kaohsiung
Hengchun
Central Weather Bureau
Intensity I II III IV V VI VII
PGA 0.8 2.5 8 25 80 250 400 (gal)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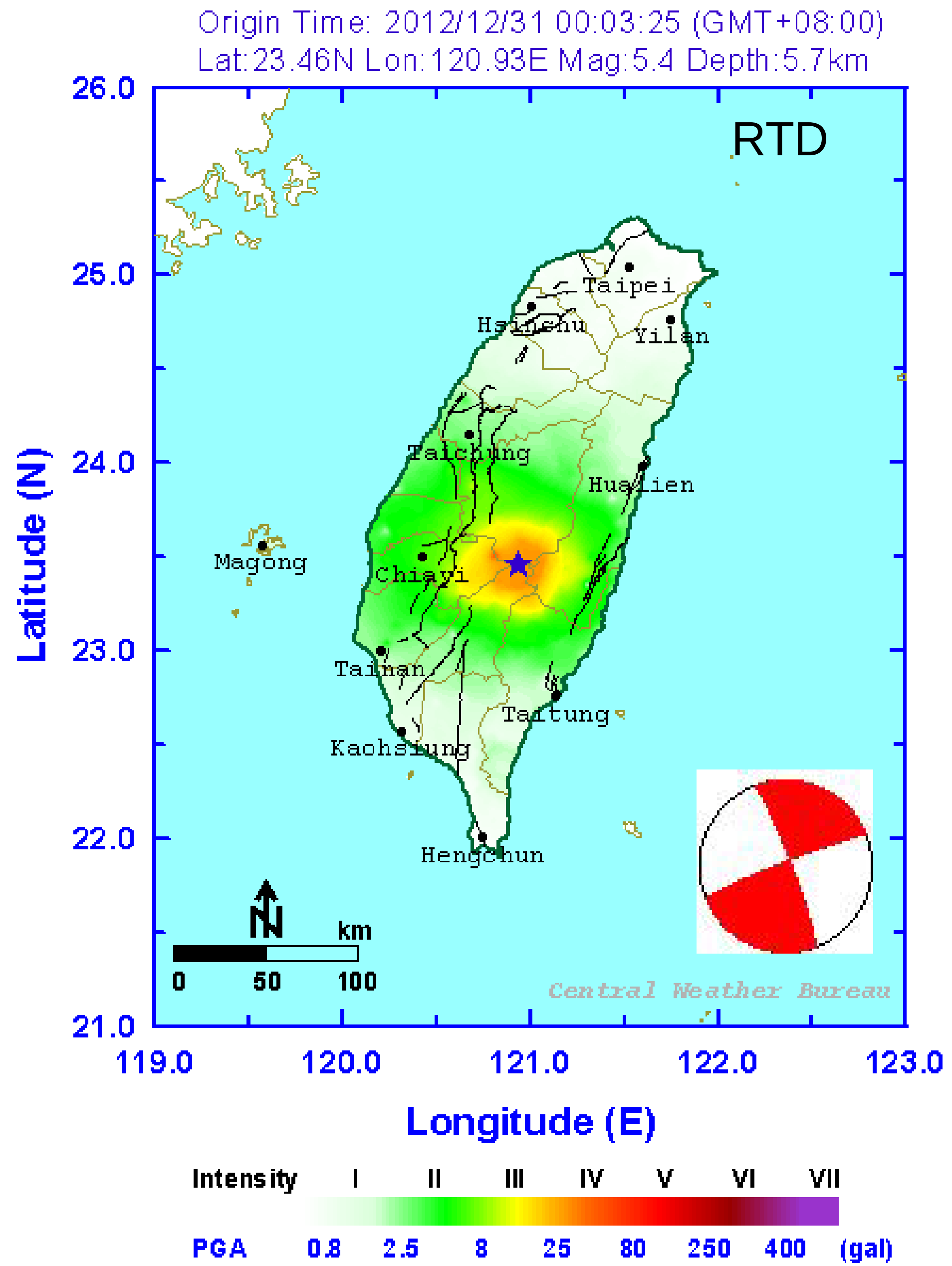
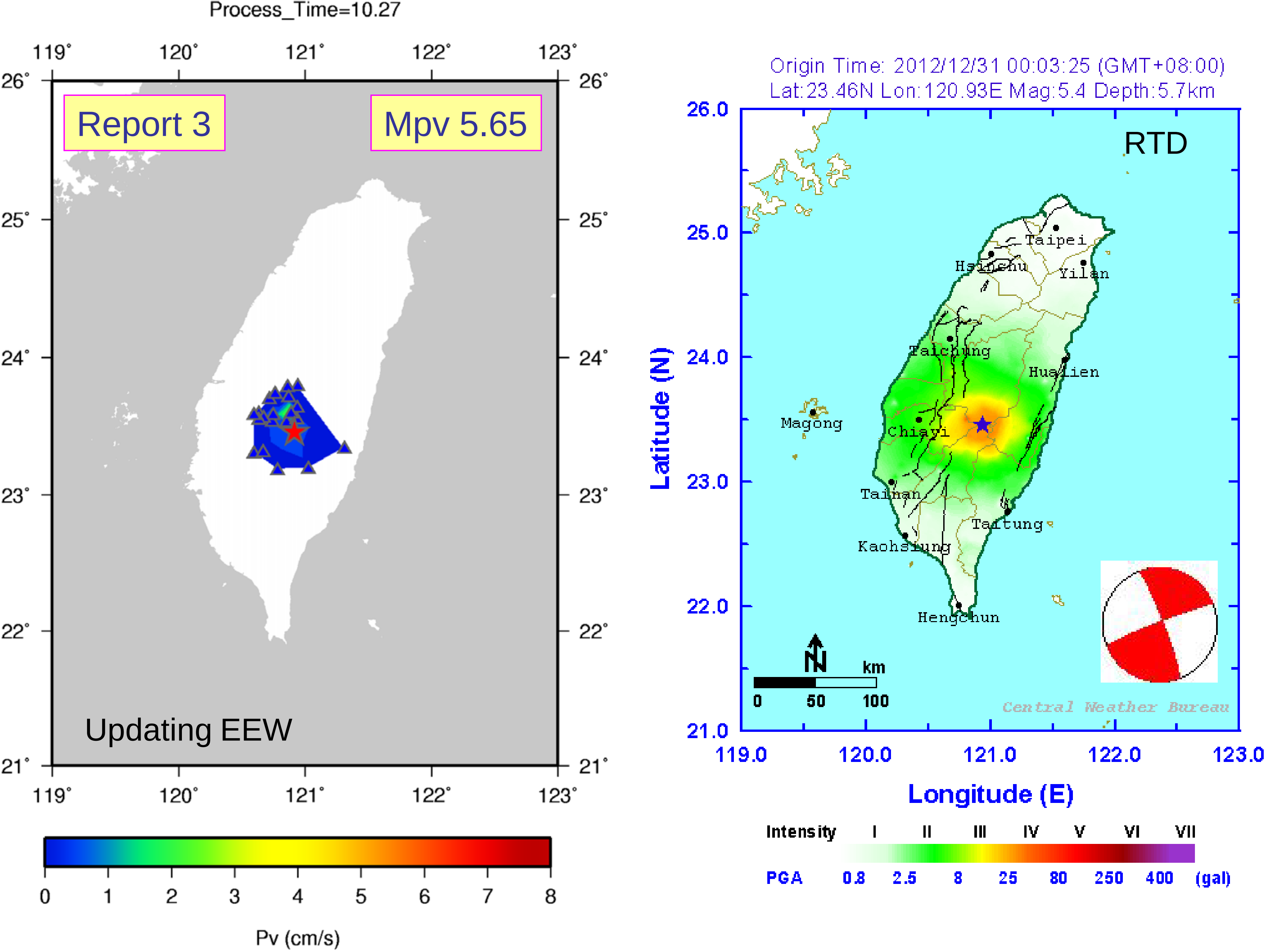
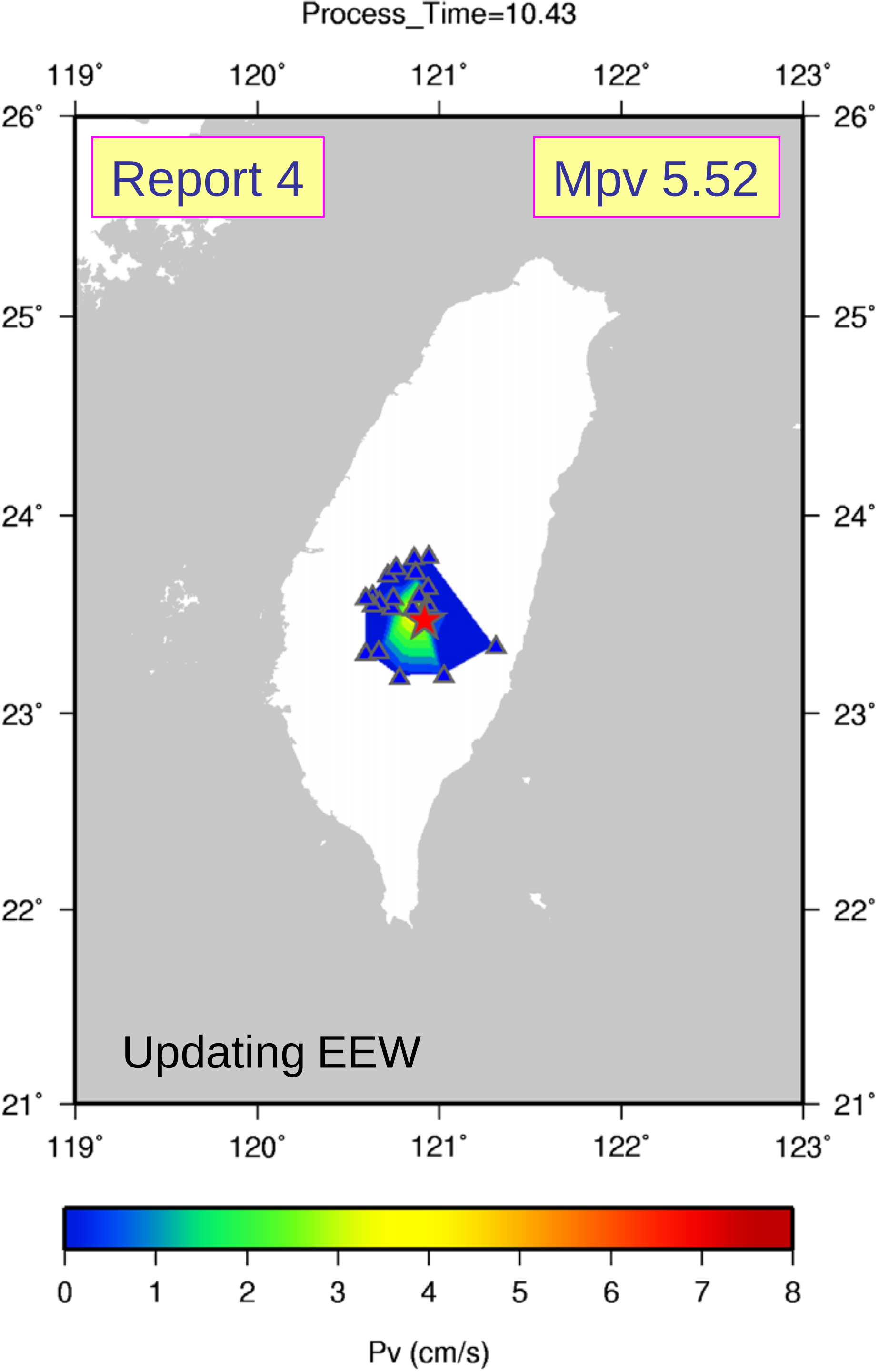
Report 2
Mpv 5.79
Updating EEW
119° 120° 121° 122° 123°
26° 25° 24° 23° 22° 21°
0 1 2 3 4 5 6 7 8
Pv (cm/s)


Origin Time: 2012/12/31 00:03:25 (GMT+08:00)
Lat:23.46N Lon:120.93E Mag:5.4 Depth:5.7km
RTD
Taipei
Hsinchu
Yilan
Taichung
Hualien
Magong
Chiayi
Tainan
Taitung
Kaohsiung
Hengchun
N
km
0 50 100
Central Weather Bureau
Latitude (N)
26.0 25.0 24.0 23.0 22.0 21.0
119.0 120.0 121.0 122.0 123.0
Longitude (E)
Intensity I II III IV V VI VII
PGA 0.8 2.5 8 25 80 250 400 (gal)



Process_Time=10.27
Report 3
Mpv 5.65
Updating EEW
Pv (cm/s)
0 1 2 3 4 5 6 7 8
Origin Time: 2012/12/31 00:03:25 (GMT+08:00)
Lat:23.46N Lon:120.93E Mag:5.4 Depth:5.7km
RTD
Taipei
Hsinchu
Yilan
Taichung
Hualien
Magong
Chiayi
Tainan
Taitung
Kaohsiung
Hengchun
km
0 50 100
Central Weather Bureau
Latitude (N)
Longitude (E)
Intensity I II III IV V VI VII
PGA 0.8 2.5 8 25 80 250 400 (gal)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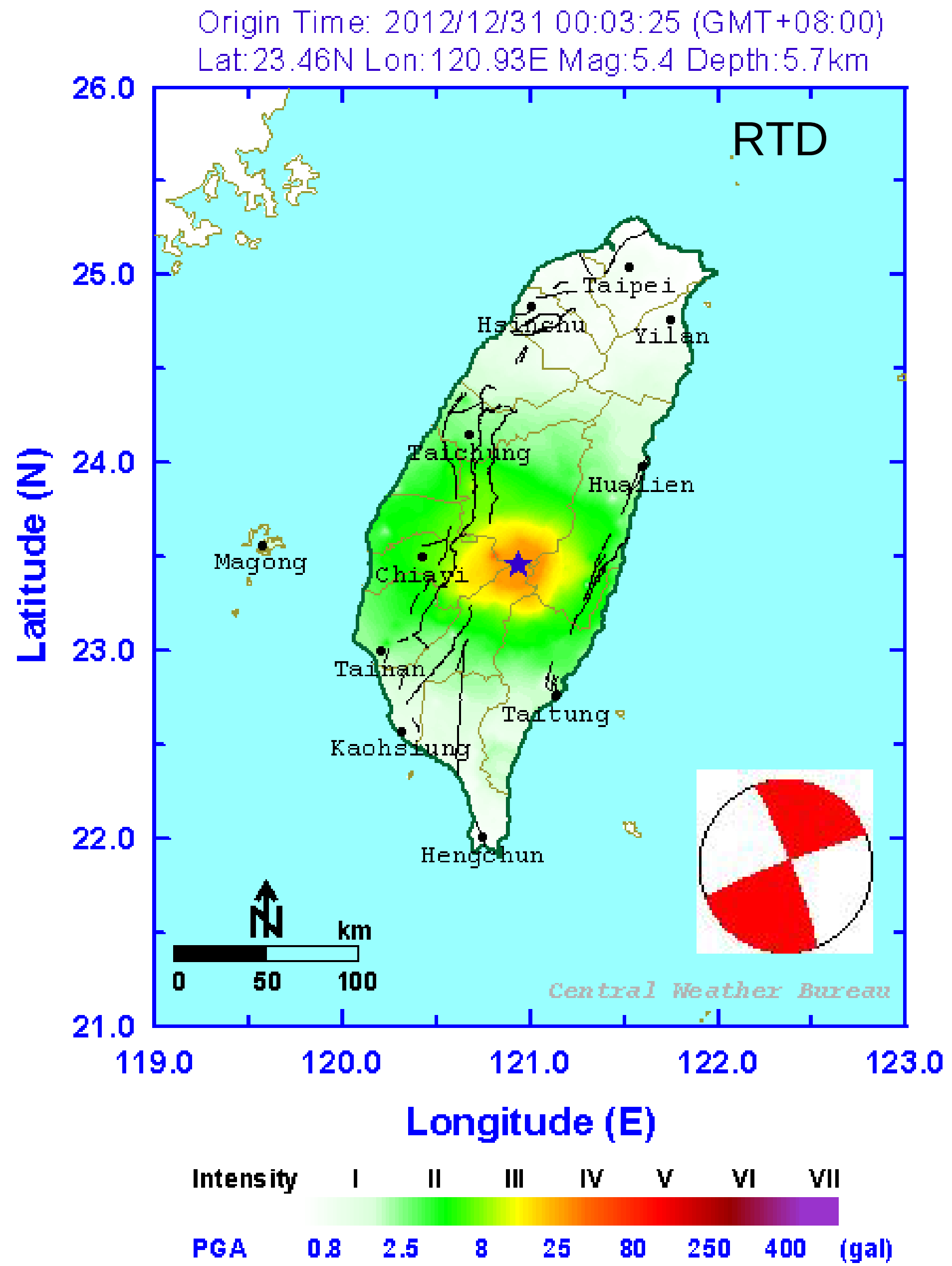
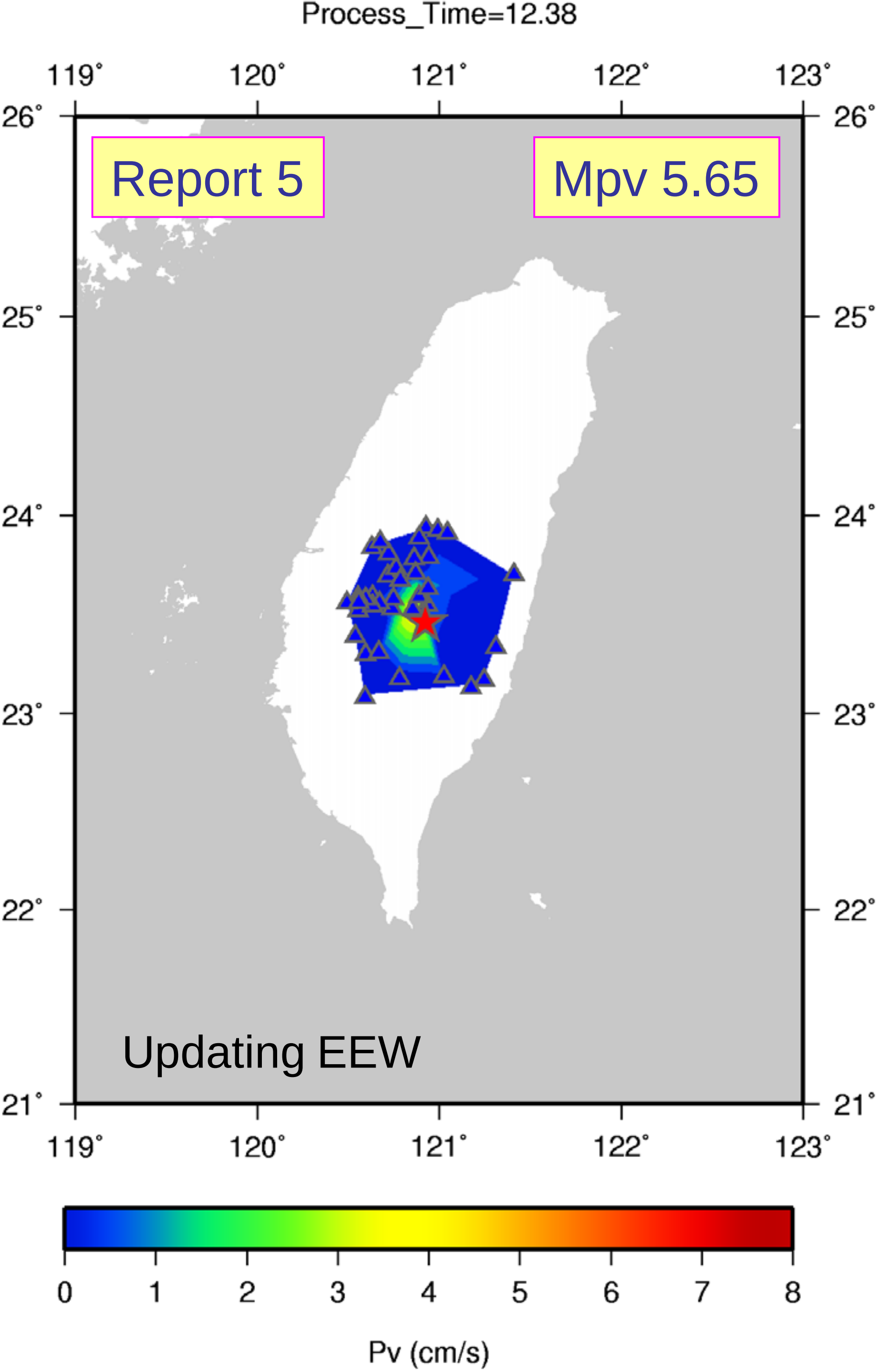
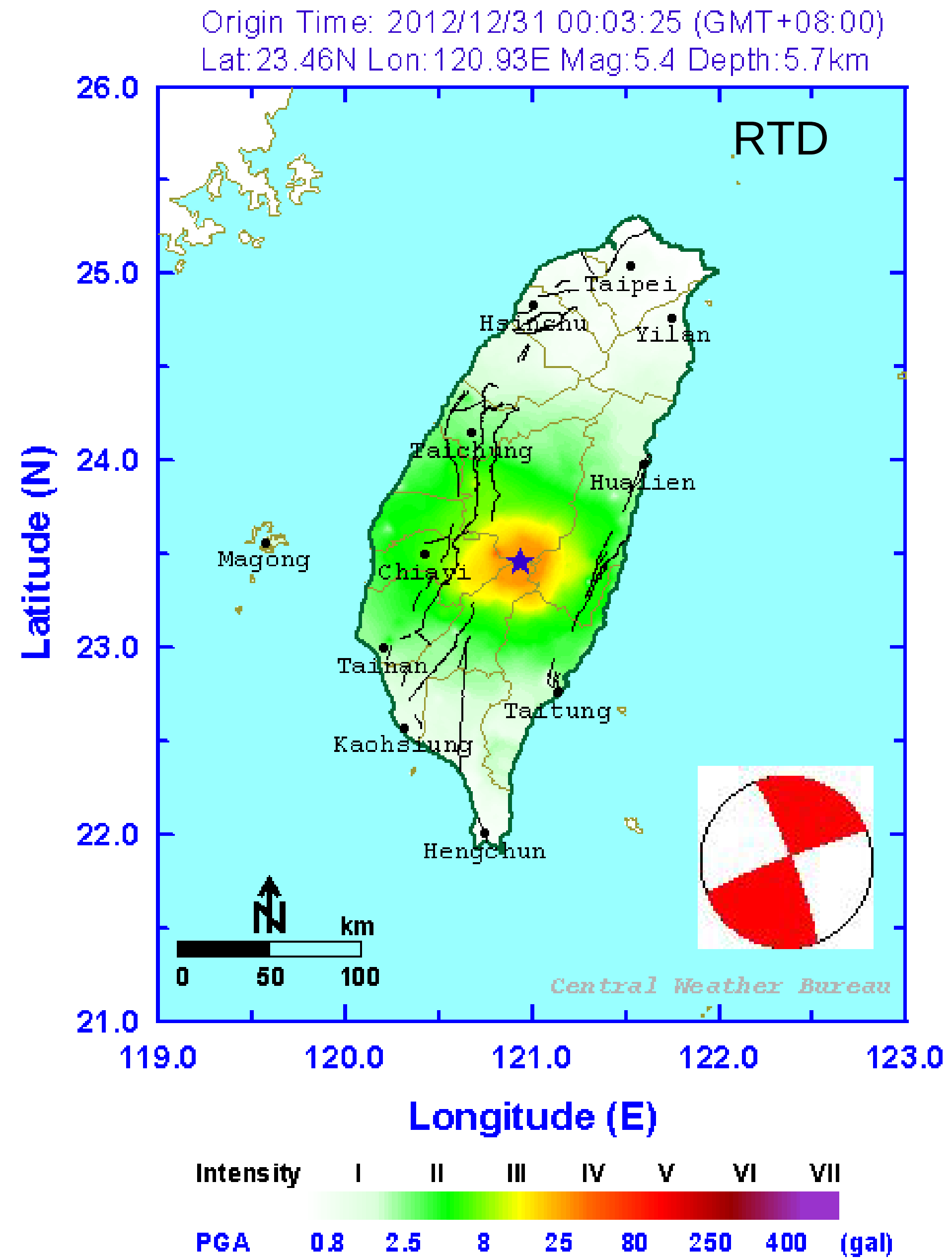
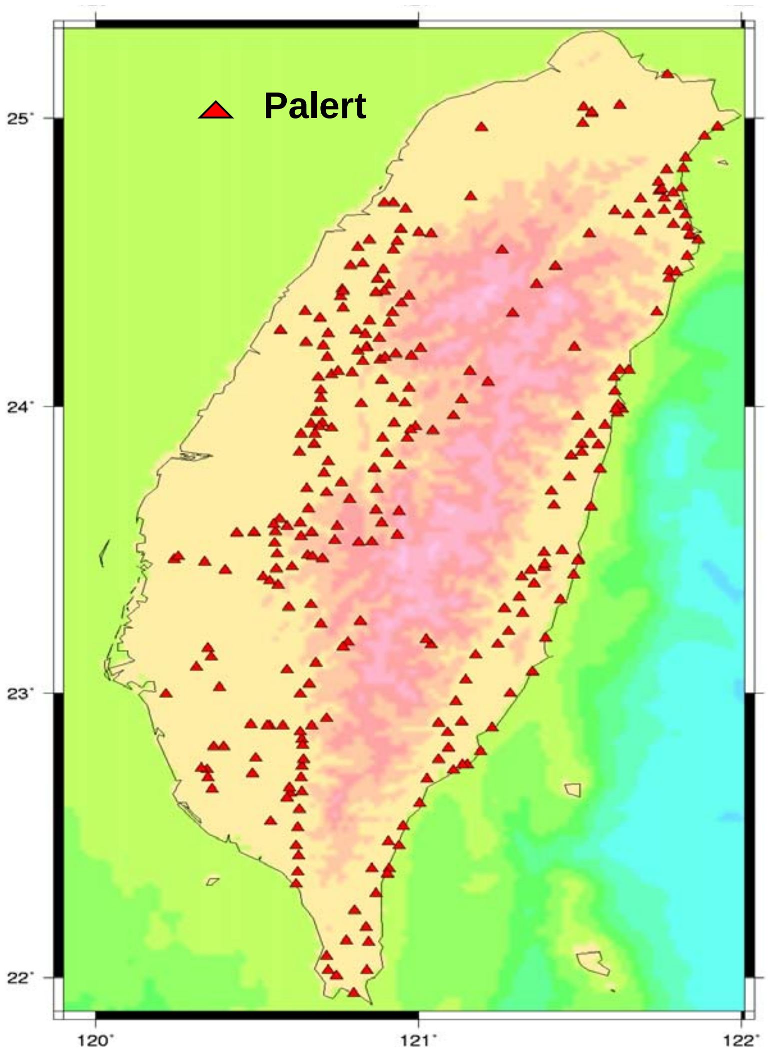
Report 4
Mpv 5.52
Updating EEW
119° 120° 121° 122° 123°
26° 25° 24° 23° 22° 21°
0 1 2 3 4 5 6 7 8
Pv (cm/s)


Origin Time: 2012/12/31 00:03:25 (GMT+08:00)
Lat:23.46N Lon:120.93E Mag:5.4 Depth:5.7km
RTD
Taipei
Hsinchu
Yilan
Taichung
Hualien
Magong
Chiayi
Tainan
Taitung
Kaohsiung
Hengchun
km
0 50 100
Central Weather Bureau
Latitude (N)
26.0 25.0 24.0 23.0 22.0 21.0
119.0 120.0 121.0 122.0 123.0
Longitude (E)
Intensity I II III IV V VI VII
PGA 0.8 2.5 8 25 80 250 400 (gal)

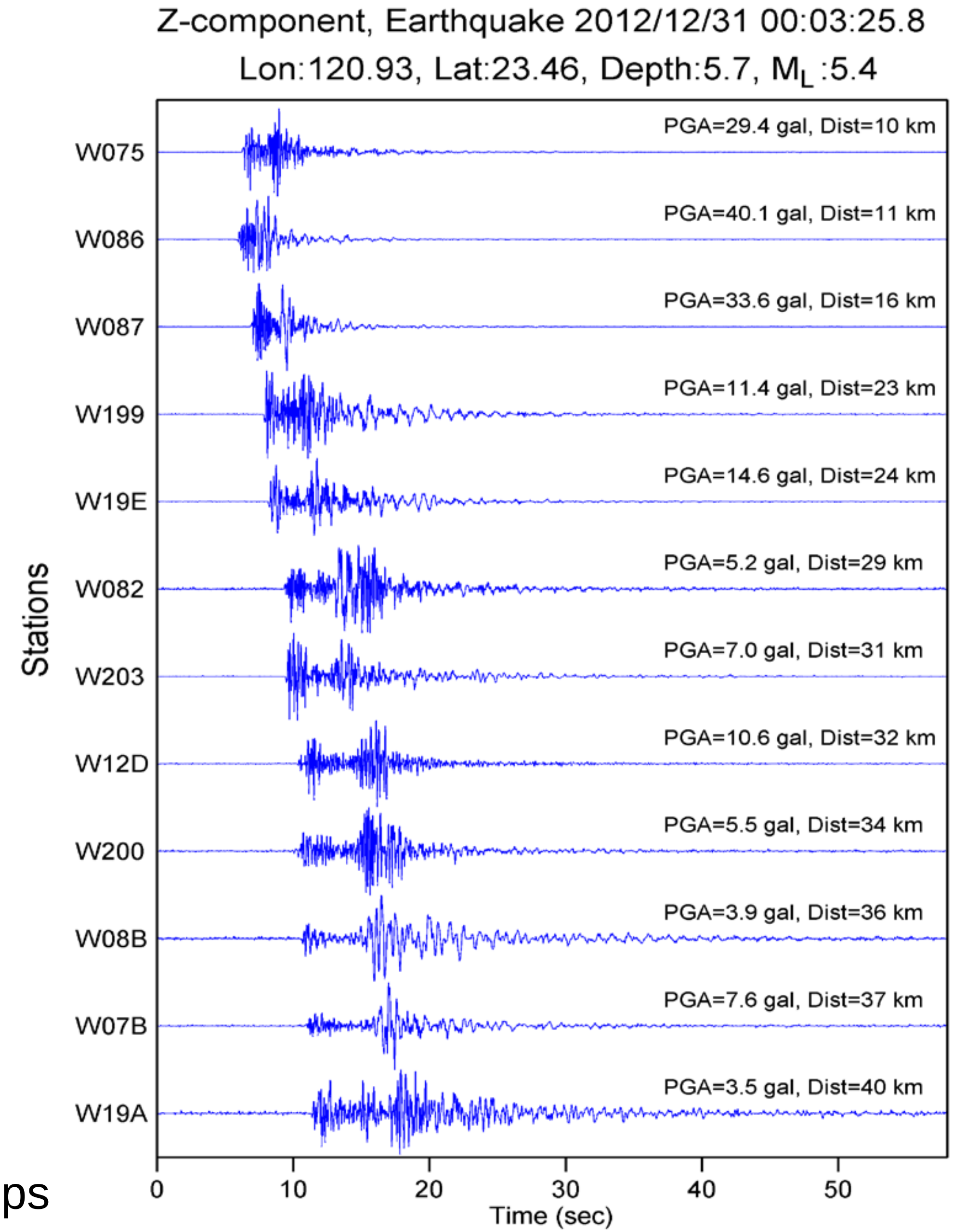

Process_Time=12.38
Report 5
Mpv 5.65
Updating EEW
119° 120° 121° 122° 123°
26° 25° 24° 23° 22° 21°
0 1 2 3 4 5 6 7 8
Pv (cm/s)


Origin Time: 2012/12/31 00:03:25 (GMT+08:00)
Lat:23.46N Lon:120.93E Mag:5.4 Depth:5.7km
RTD
Taipei
Hsinchu
Yilan
Taichung
Hualien
Magong
Chiayi
Tainan
Taitung
Kaohsiung
Hengchun
N
km
0 50 100
Central Weather Bureau
26.0 25.0 24.0 23.0 22.0 21.0
Latitude (N)
119.0 120.0 121.0 122.0 123.0
Longitude (E)
Intensity I II III IV V VI VII
PGA 0.8 2.5 8 25 80 250 400 (gal)

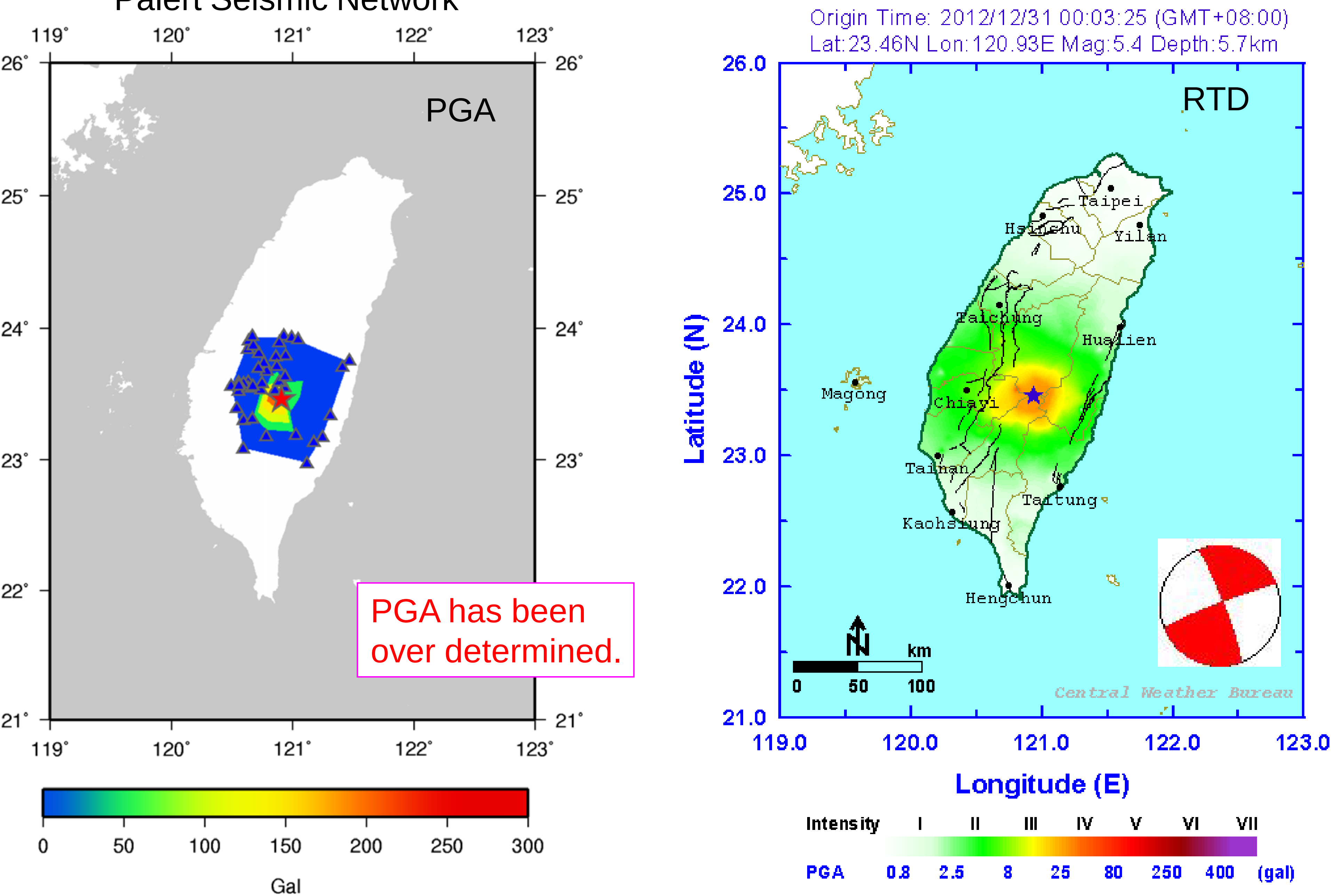
Palert Seismic Network (280)



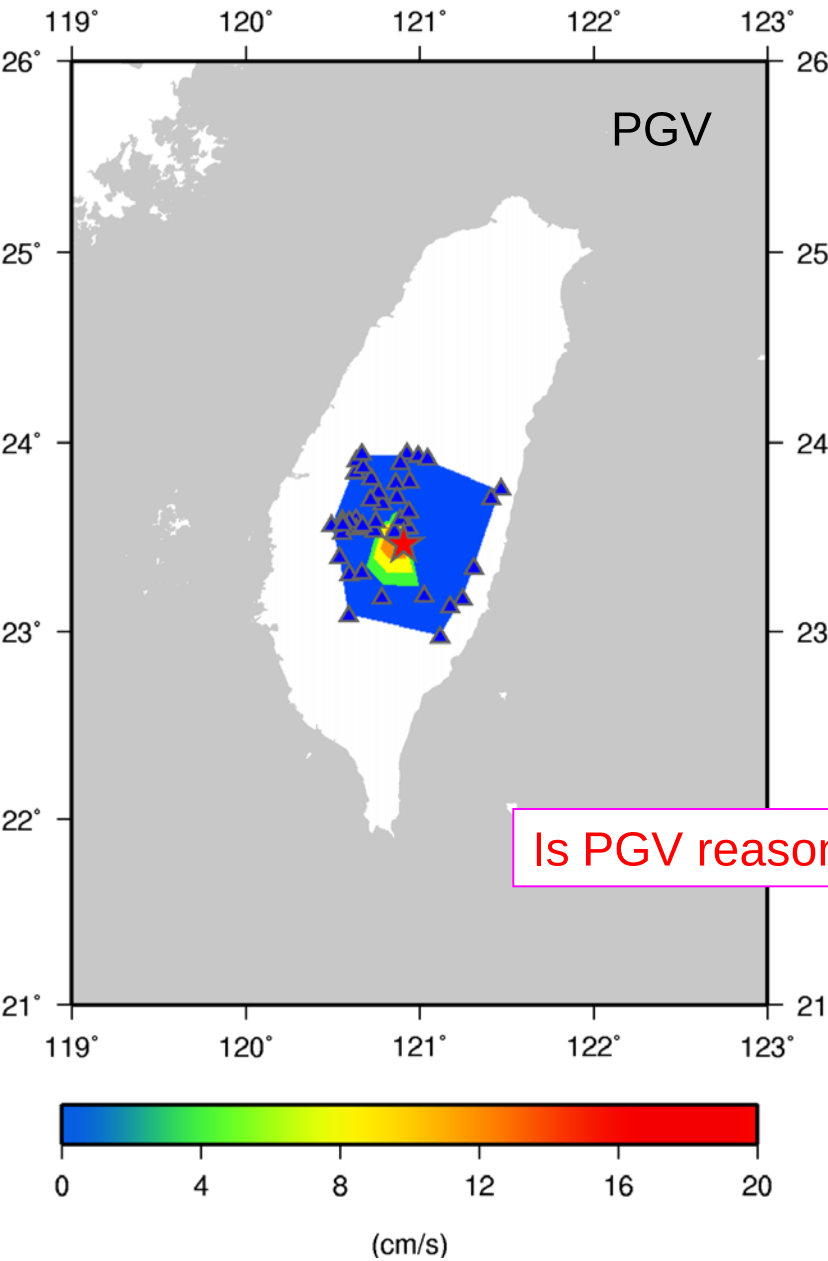
Palert
Sampling rate: 100 sps
16-bits，±2g



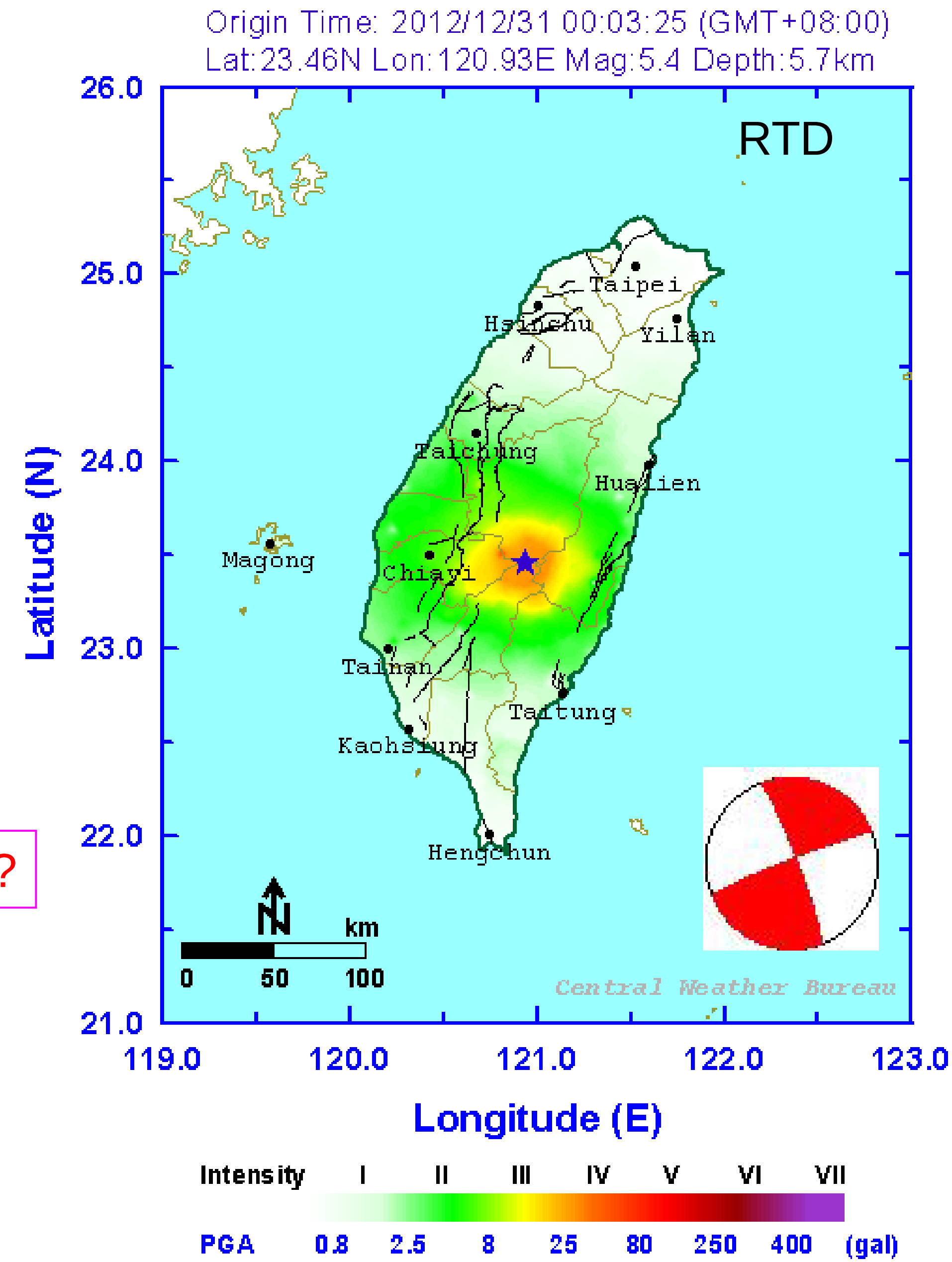
Palert Seismic Network



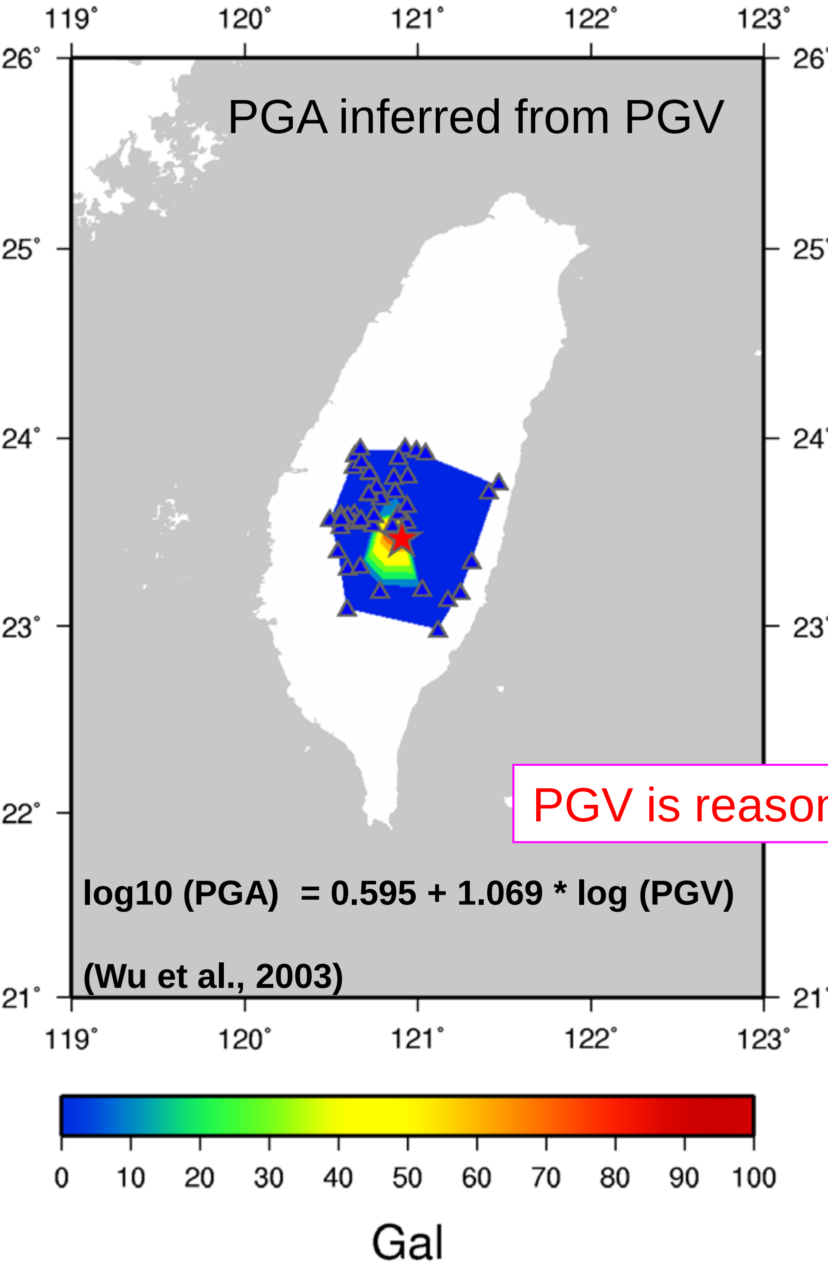
Palert Seismic Network



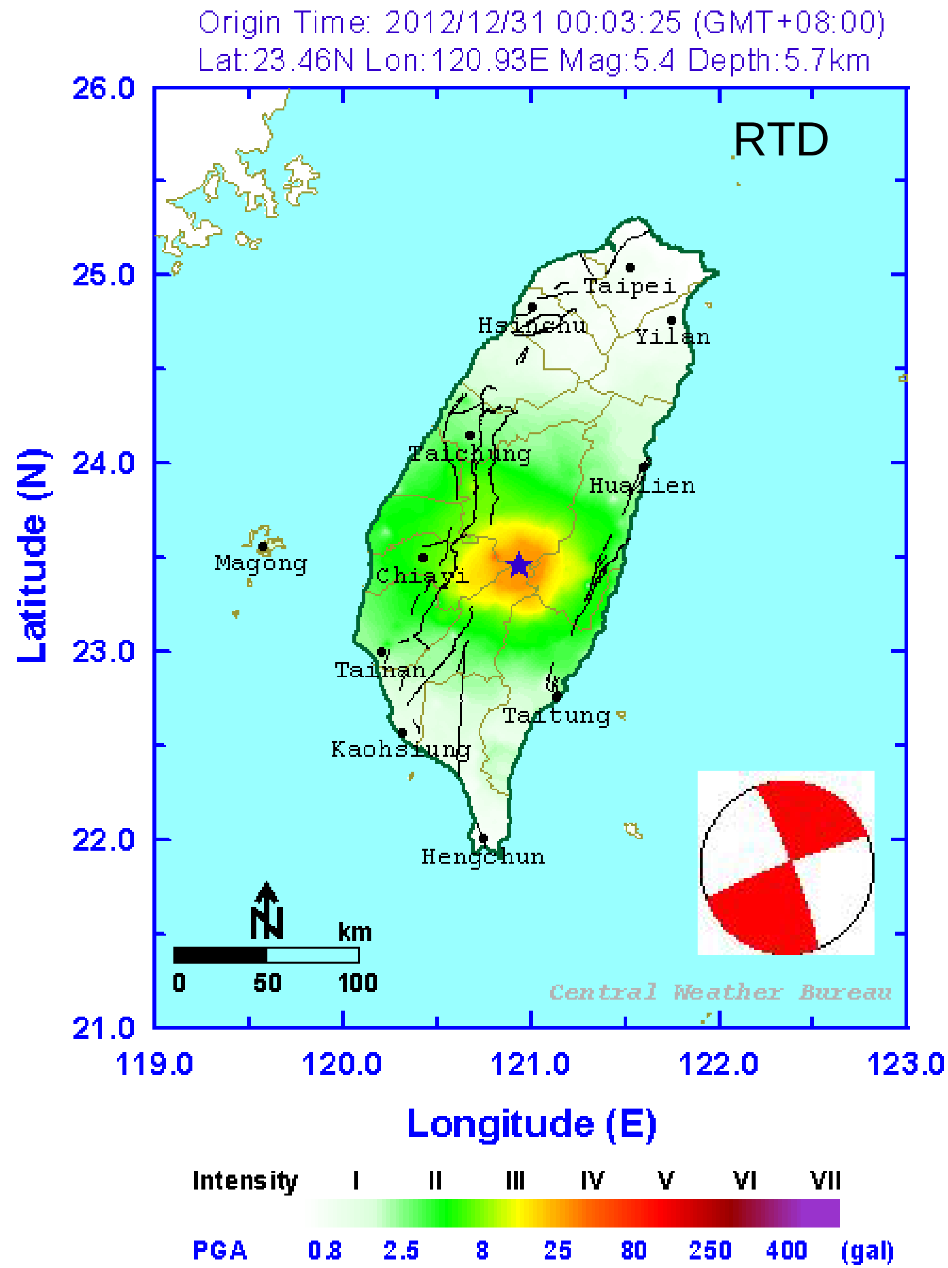
Is PGV reasonable ?



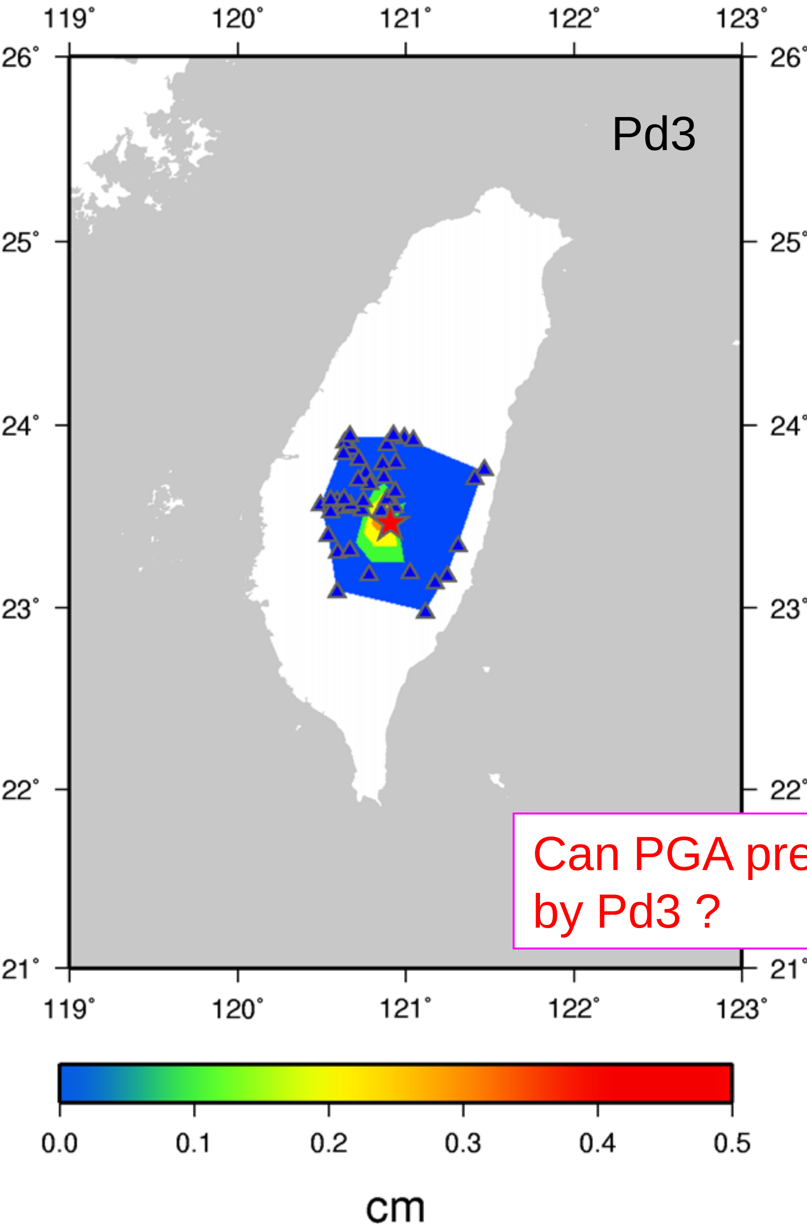
Palert Seismic Network

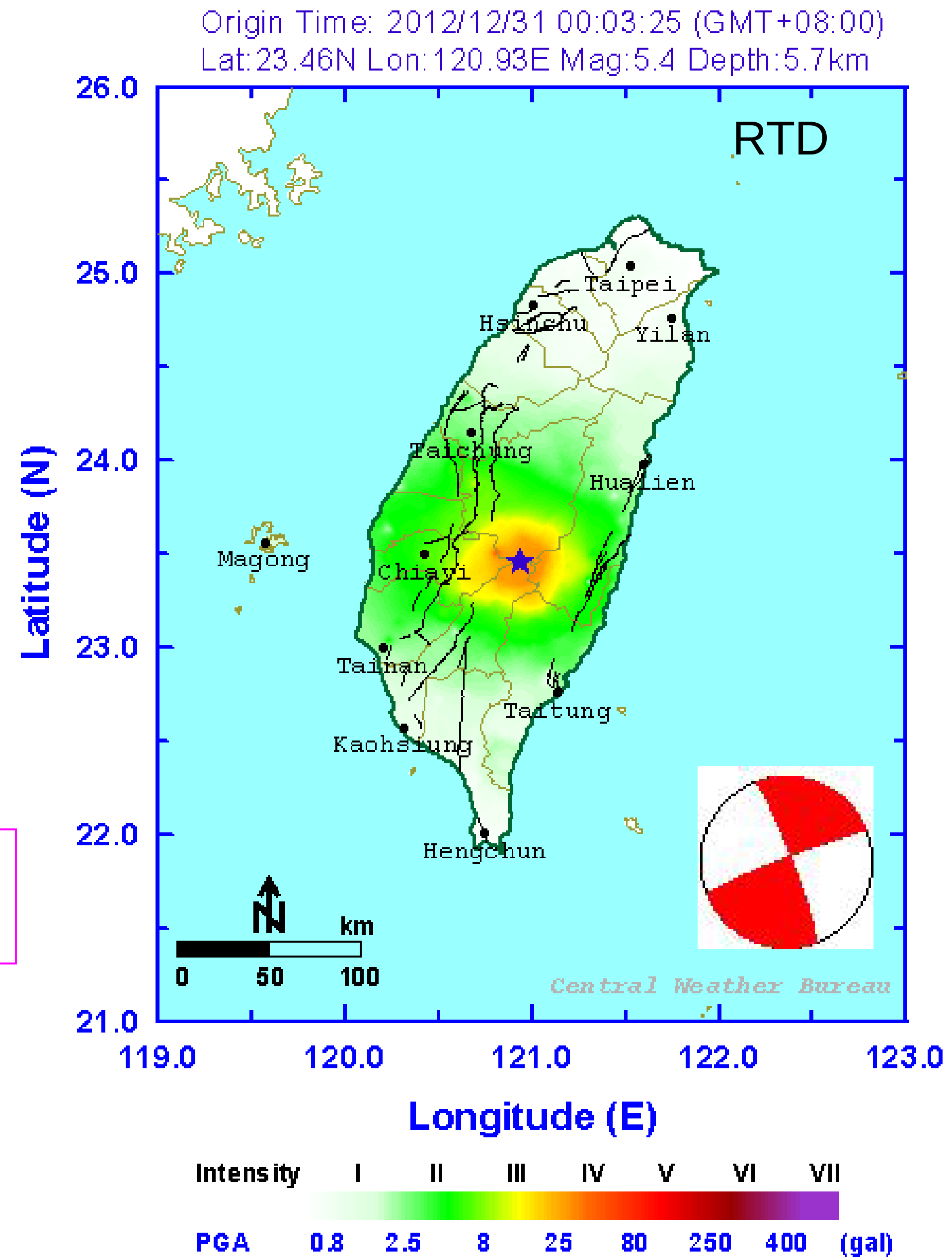


PGV is reasonable.

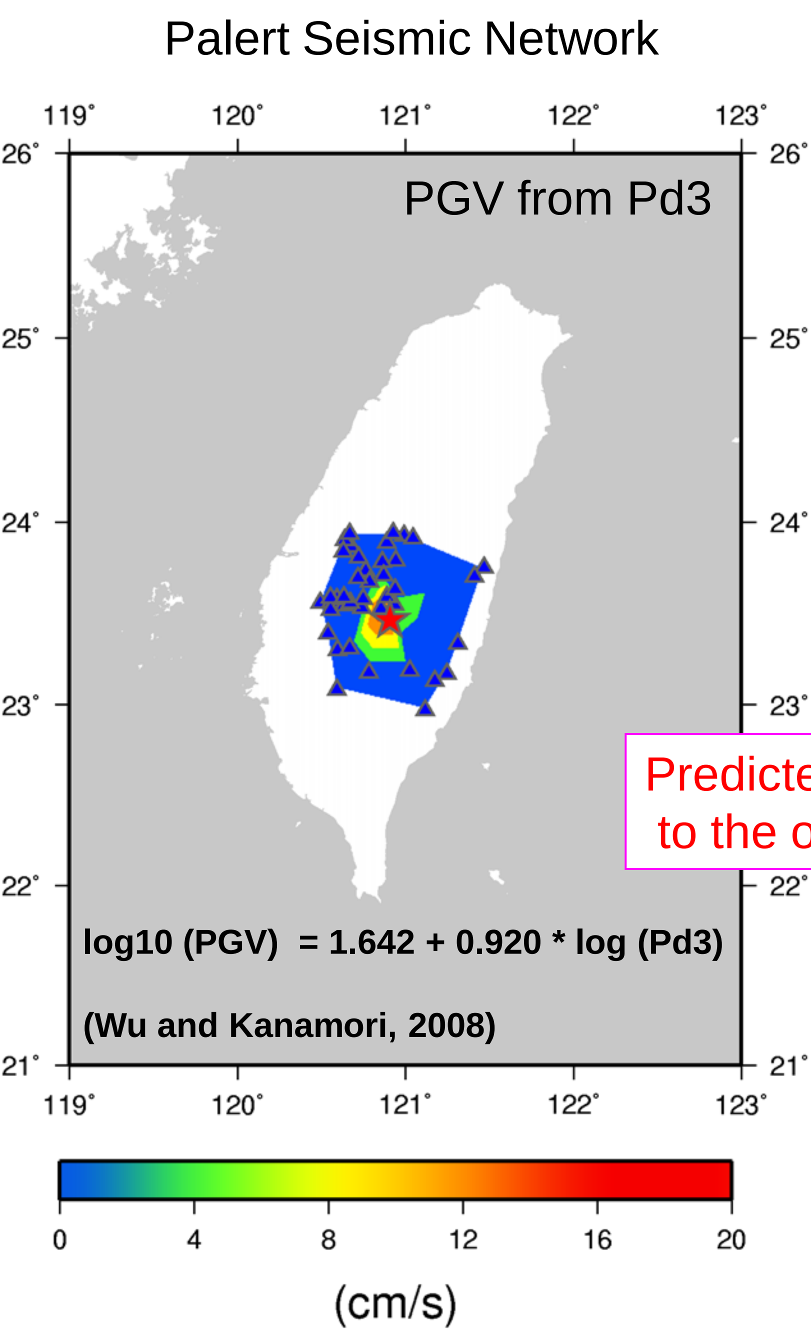


Palert Seismic Network

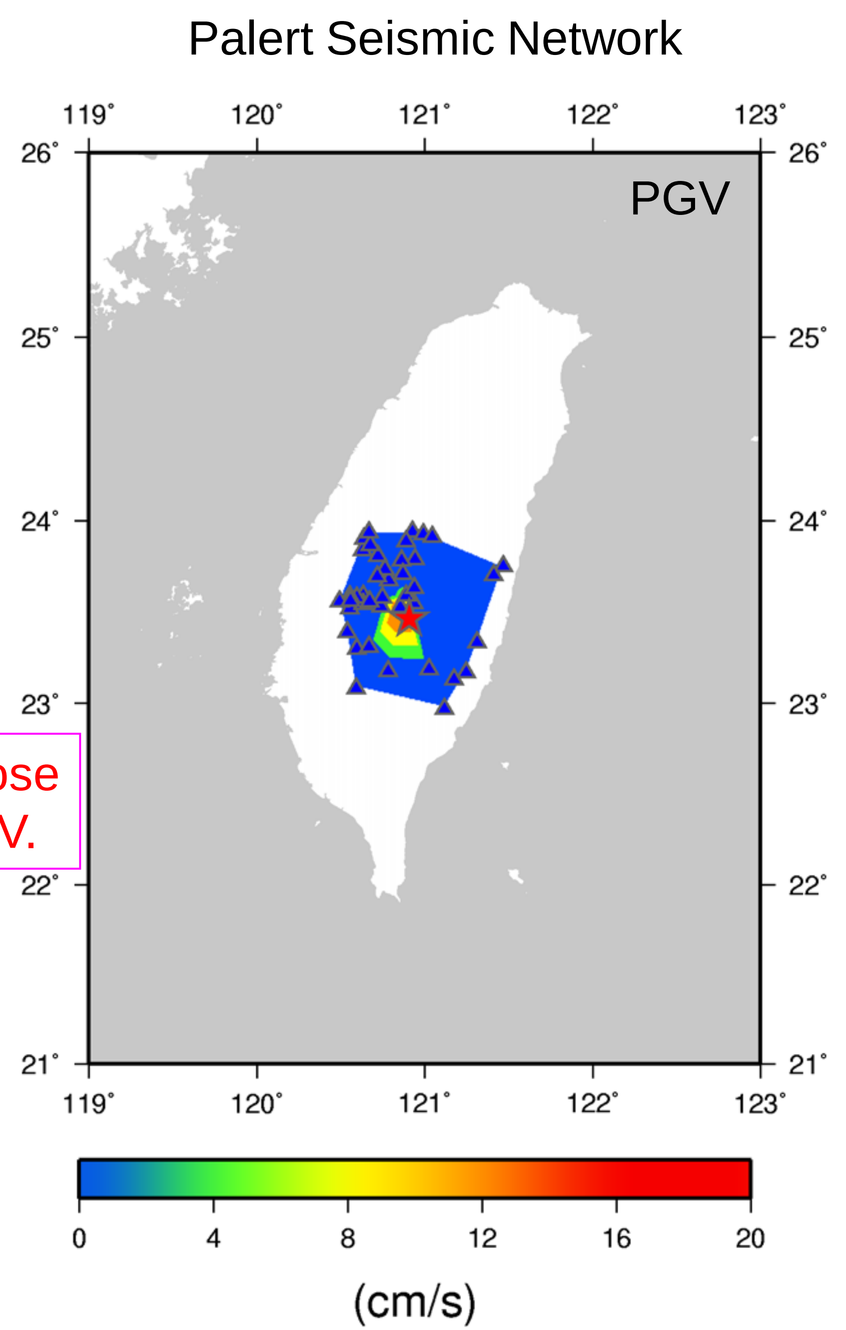




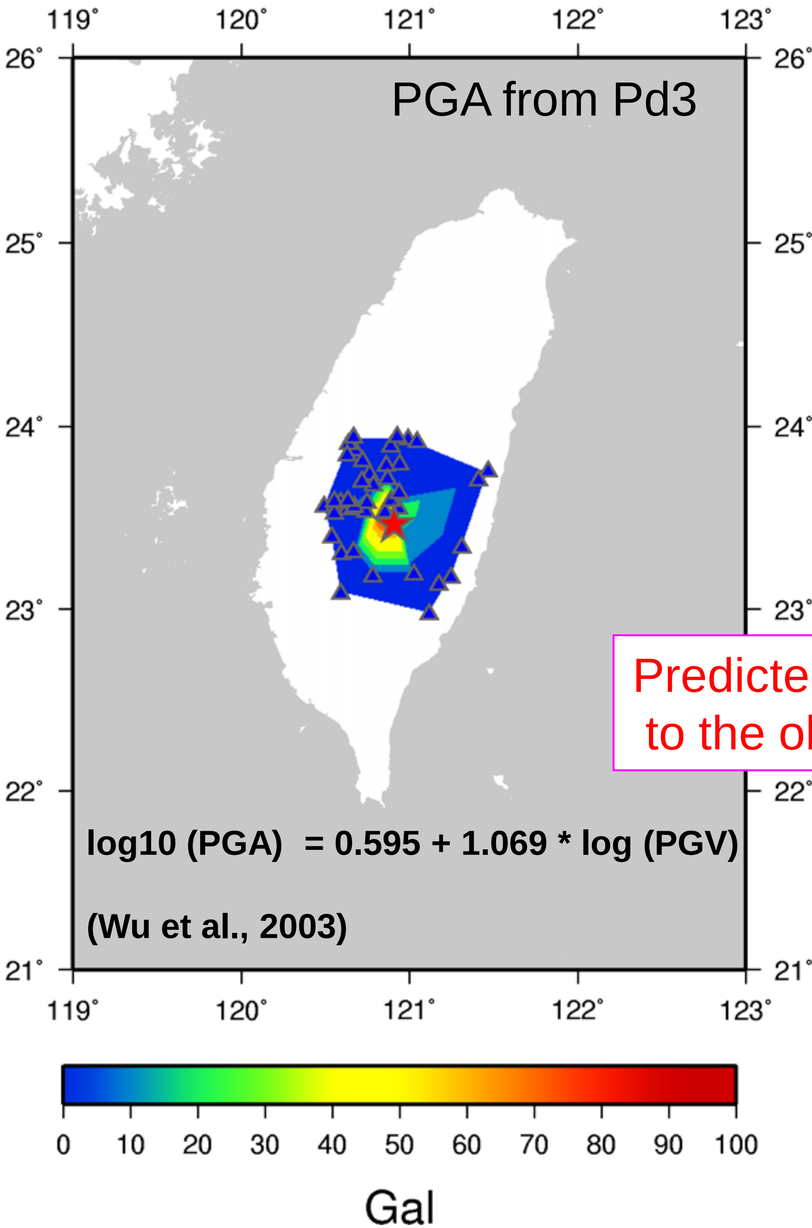
Can PGA predicted by Pd3 ?



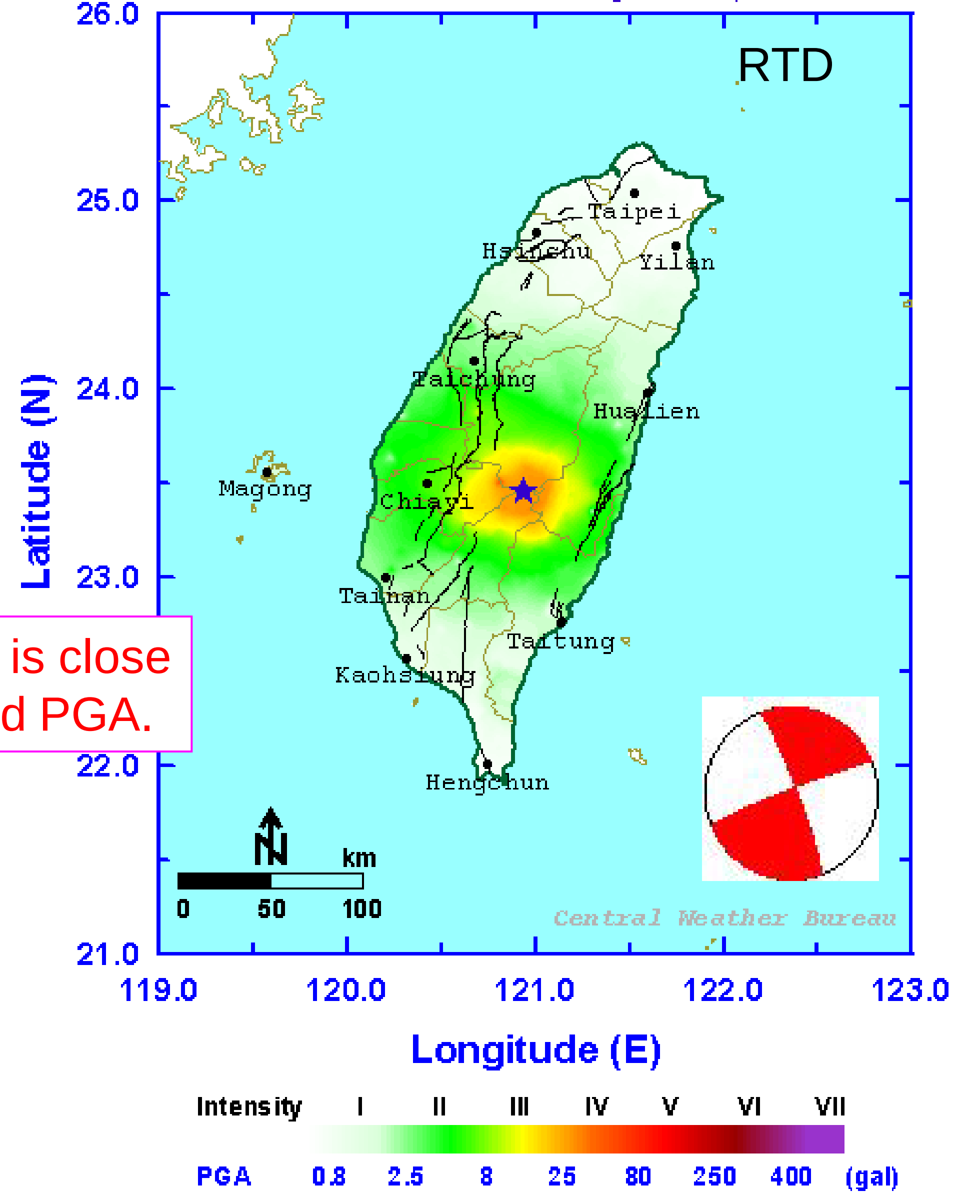
Predicted PGA is close to the observed PGV.



Palert Seismic Network



Predicted PGA is close to the observed PGA.



Summary

Palert PGV and pd3 are consistent with th PGA from The traditional seismic network.

Palert PGA are over determined. It may be caused by the site effect.

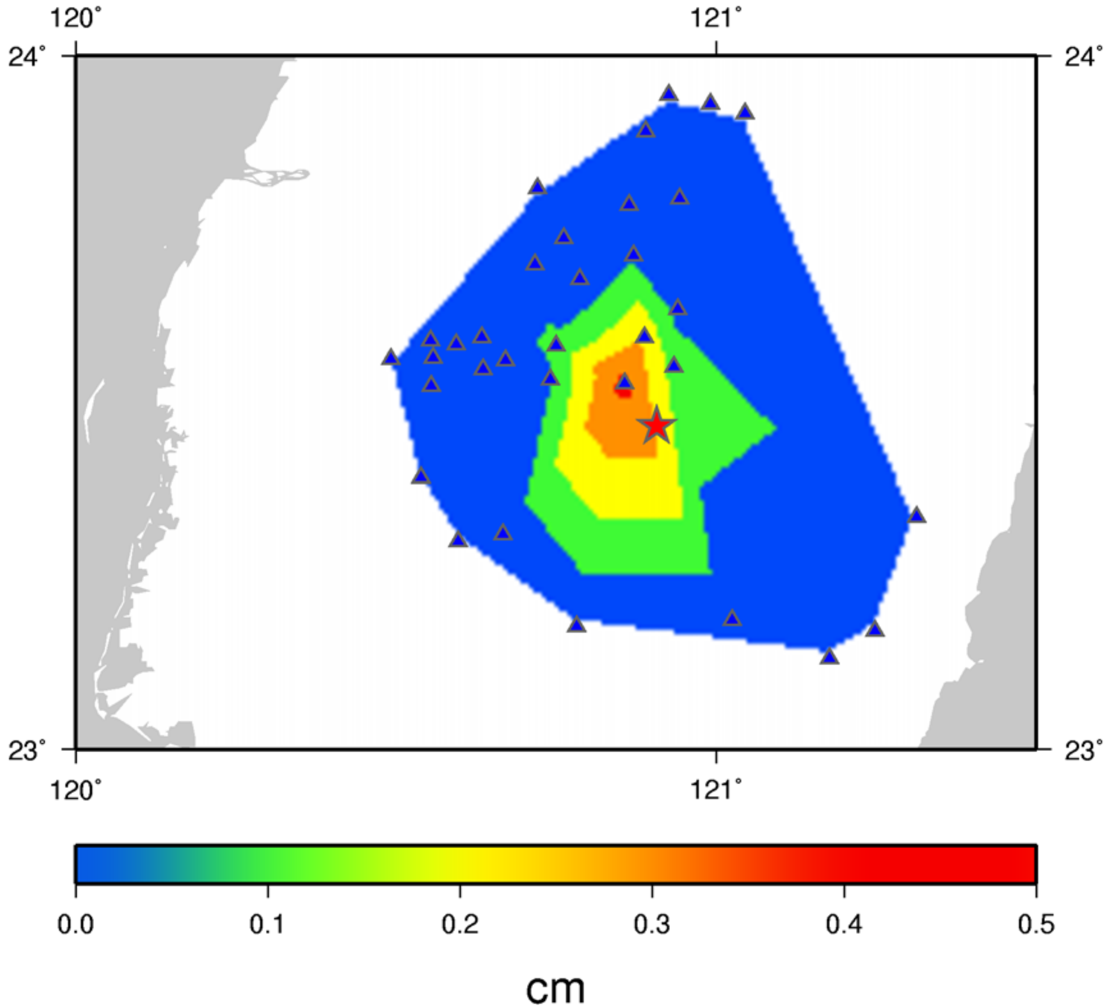
Thanks for your attention.

Discussion

How soon can it be issued a warning by on-site EEW ?

An average Pd of 0.1 cm obtained from the 5 nearest recording
Stations is used as the threshold value to confirm an occurrence
Of earthquakes in the current EEW system of CWB in Taiwan.
(Hsiao et al., 2009)

Pd After Origin Time 10 sec



Distance of the nearest station is 27 km.

Rex Allen algorithm (Allen, 1978)

1. **define a (positive) characteristic function of the signal that can be computed at each new sample;**

2. **recursively compute, at each new sample, a Long Term Average (LTA) of the characteristic function; this LTA is a synthetic description of the background noise in one unique number (or a reduced set of numbers);**

3. **recursively compute, at each new sample, a Short Term Average (STA) of the characteristic function; this STA is supposed to be very similar to the LTA when the signal is only due to the background noise; but STA is supposed to very quickly become very different from LTA when the seismic signal begins.**

4. **The ratio STA/LTA is close to 1 when the signal is in the background noise. A “pick” is declared when the STA/LTA ratio goes over a predefined threshold.**

Validate Each Picks in the Earthworm Pick_ew module

Waveform Filtering Parameters

1. CharFuncFilt
2. StaFilt and LtaFilt
3. RawDataFilt
4. ClipCount

Event Termination/Evaluation Criteria (checking for noise)

1. MinPeakSize
2. MaxMint
3. i9 (MinCodaLen in the program)
4. Itr1, MinSmallZC and MinBigZC

Coda Termination Parameters

1. Erefs
2. CodaTerm, AltCoda and PreEvent

Validate Each Picks in the Earthworm Pick_ew module

Waveform Filtering Parameters

1. CharFuncFilt
2. StaFilt and LtaFilt
3. RawDataFilt
4. ClipCount

Signal to noise ratio of each pick is also considered.

Event Termination/Evaluation Criteria (checking for noise)

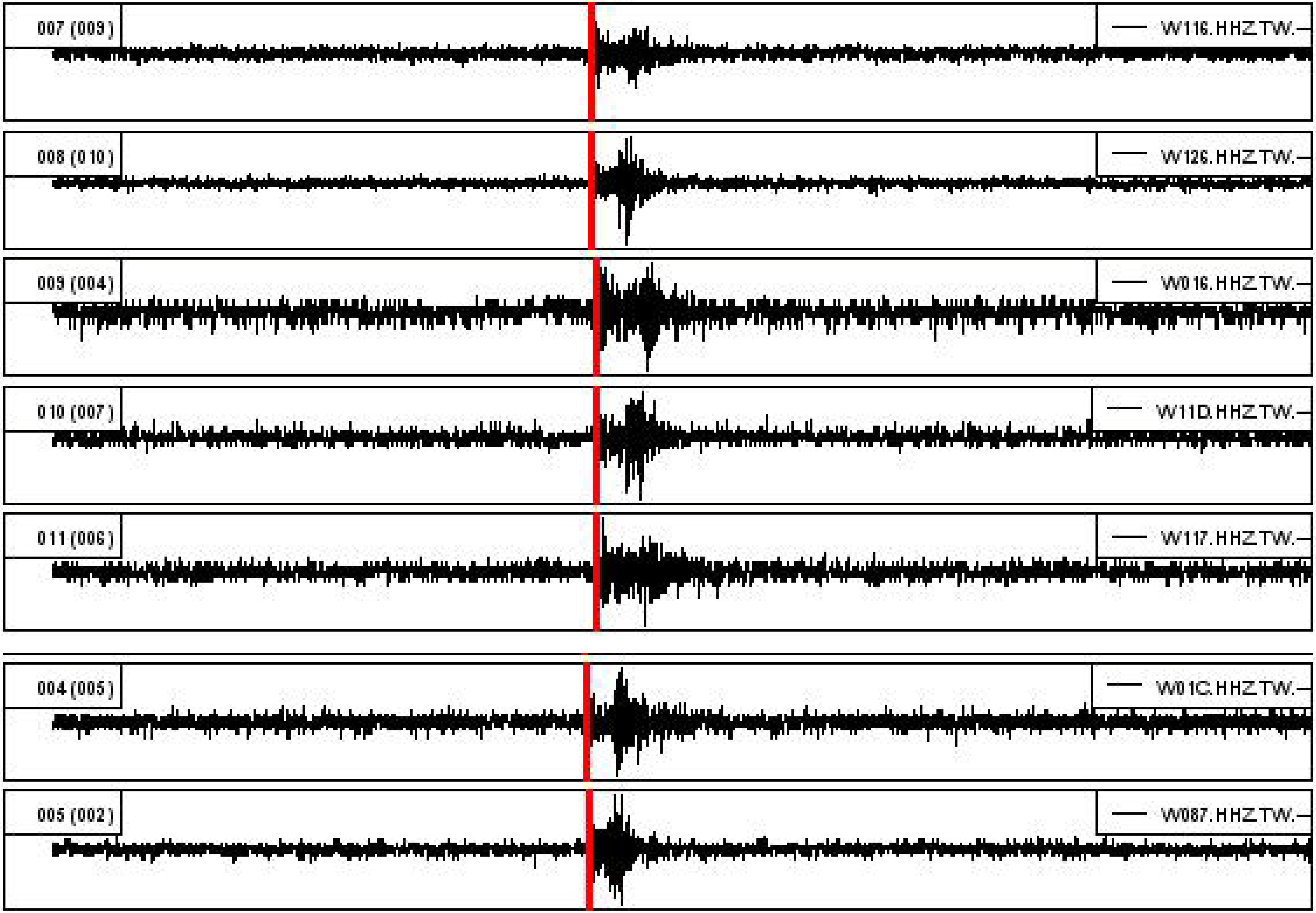
1. MinPeakSize
2. MaxMint
3. i9 (MinCodaLen in the program)
4. Itr1, MinSmallZC and MinBigZC

Coda Termination Parameters

1. Erefs
2. CodaTerm, AltCoda and PreEvent

For EEW purpose We do not check the coda term.

Auto-Picking



Rex Allen algorithm (Allen, 1978)

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3. **recursively compute, at each new sample, a Short Term Average (STA) of the characteristic function; this STA is supposed to be very similar to the LTA when the signal is only due to the background noise; but STA is supposed to very quickly become very different from LTA when the seismic signal begins.**

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Validate Each Picks in the Earthworm Pick_ew module

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2. StaFilt and LtaFilt
3. RawDataFilt
4. ClipCount

Event Termination/Evaluation Criteria (checking for noise)

1. MinPeakSize
2. MaxMint
3. i9 (MinCodaLen in the program)
4. Itr1, MinSmallZC and MinBigZC

Coda Termination Parameters

1. Erefs
2. CodaTerm, AltCoda and PreEvent

Validate Each Picks in the Earthworm Pick_ew module

Waveform Filtering Parameters

1. CharFuncFilt
2. StaFilt and LtaFilt
3. RawDataFilt
4. ClipCount

Signal to noise ratio of each pick is also considered.

Event Termination/Evaluation Criteria (checking for noise)

1. MinPeakSize
2. MaxMint
3. i9 (MinCodaLen in the program)
4. Itr1, MinSmallZC and MinBigZC

Coda Termination Parameters

1. Erefs
2. CodaTerm, AltCoda and PreEvent

For EEW purpose We do not check the coda term.

Itr1, MinSmallZC and MinBigZC

Sta->isml —— S

grows with the velocity of the counter of zero-crossings *Sta->m*

Sta->itrm —— L

grows with the velocity of the counter of *Sta->m / Itr1*

When S reaches L, the event is over

itrm = Parm->Itr1 + (Sta->m / Parm->Itr1);

When S reaches L the event is declared over. If this happens in a time shorter than *MiCodaLen*, the trigger is refused

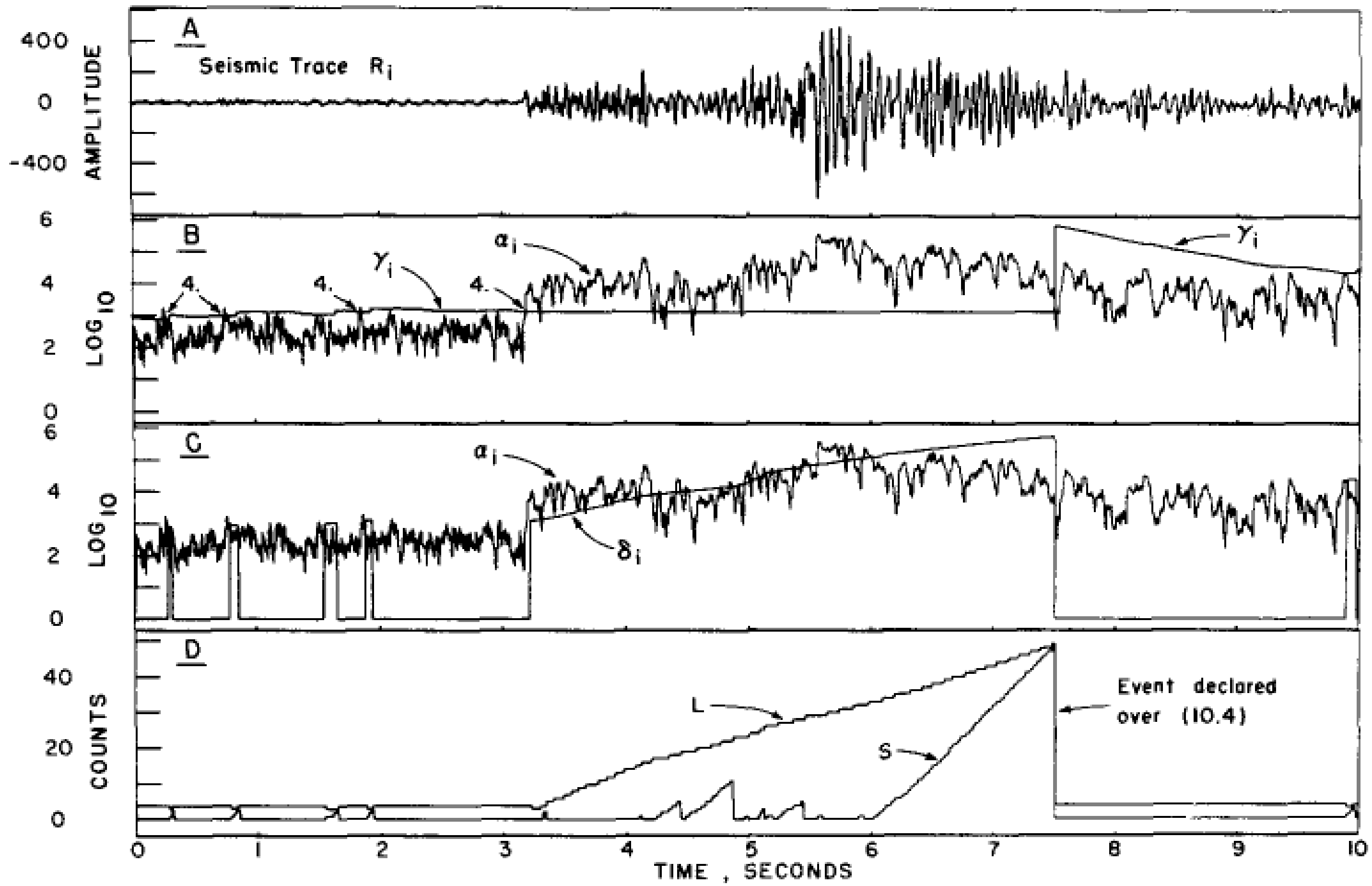


FIG. 4. Operating parameters during an event. (a) Seismic trace. (b) Short-term average α_i, of characteristic function and reference level, γ_i. Points indicated as "4" refer to statement 4 in program flow charts. Note false onsets before arrival of real event. Amplitude scale is logarithmic. (c) Short-term average α_i, and the criteria level δ, carried during observation of an event. Logarithmic amplitude scale. (d) Quantities L and S, which determine point at which event is declared over.

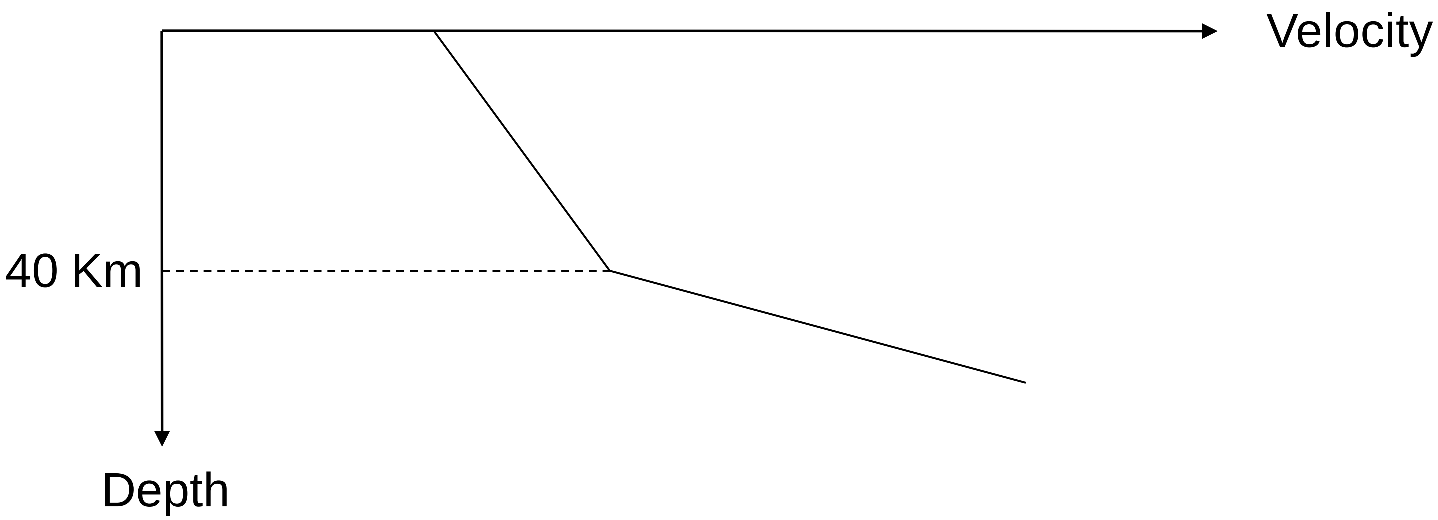
(ALLEN, 1978)

Determination of earthquake location

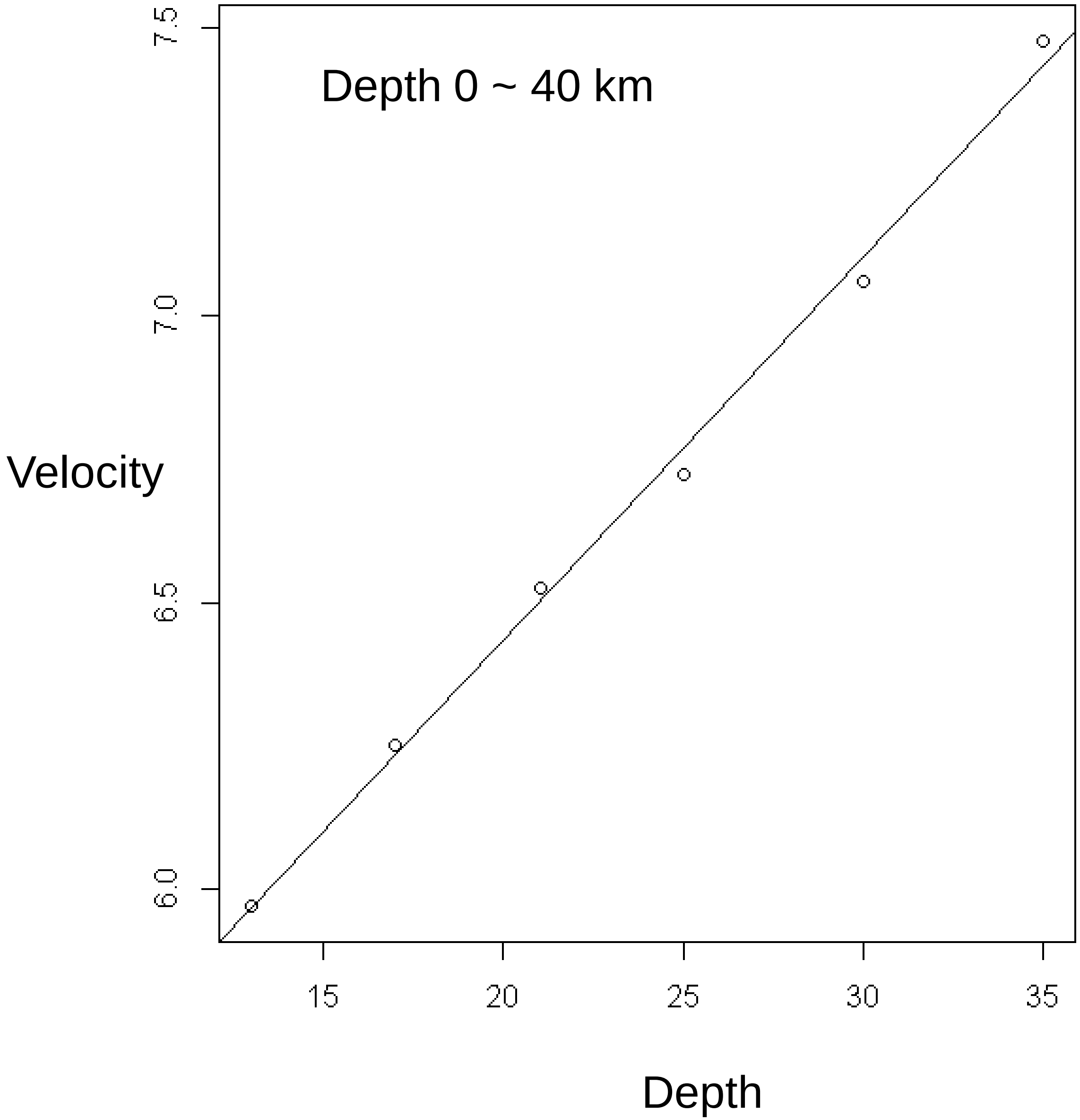
Determination of Continuous Velocity Model

$$V(D) = V_o + G * D$$

V: Velocity at different depth
Vo: Initial velocity
G: constant
D: Depth

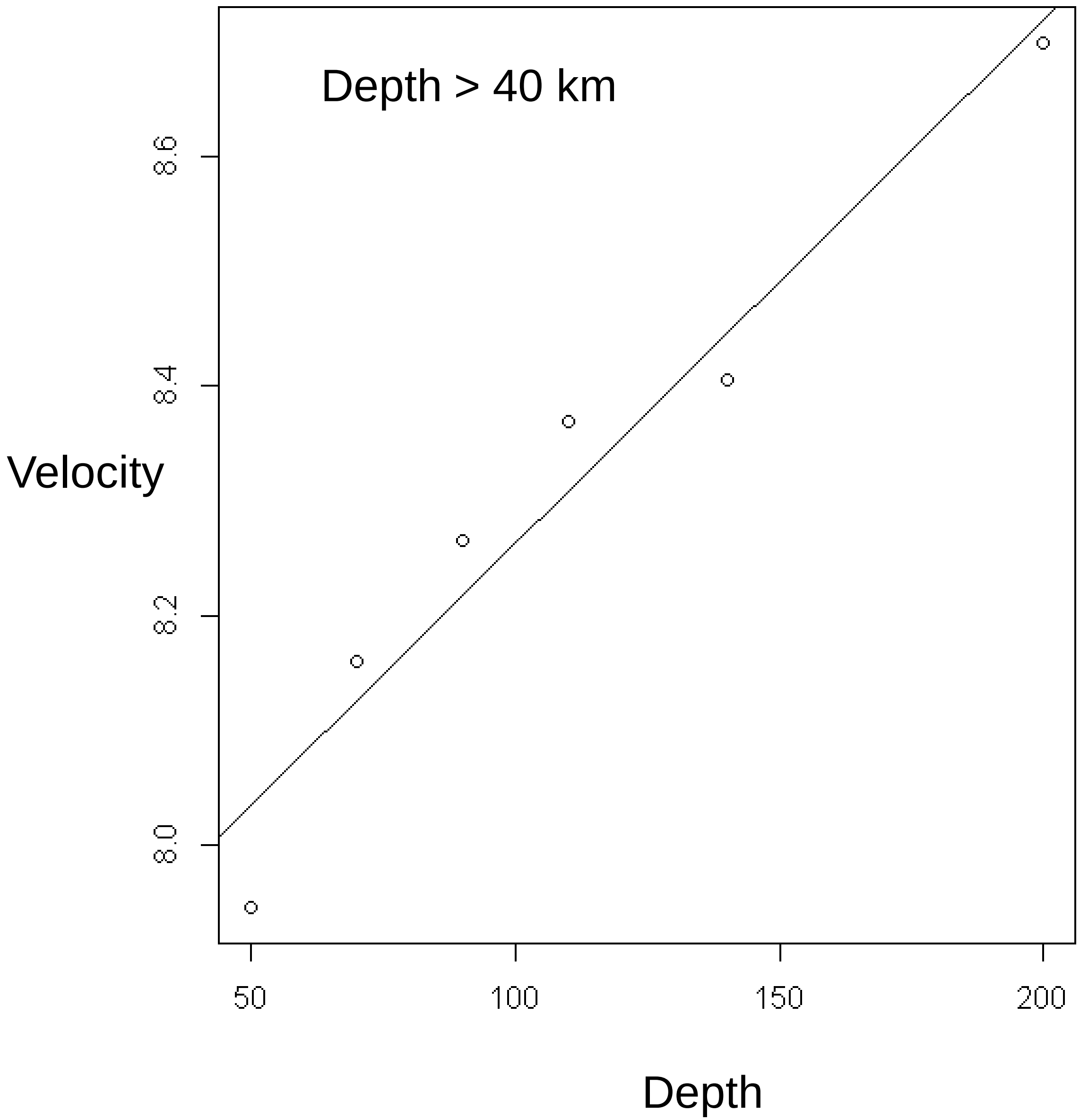


Velocity = 5.10298 + 0.06659 * Depth



Make an average of
3D-Velocity model
(Wu et al., 2009)

Velocity = 7.804799 + 0.004573 * Depth



Make an average of
3D-Velocity model
(Wu et al., 2009)

Features of Earthworm

Data Input

1. Instrument
2. Time Series

Data processing

1. Filter
2. picking
3. Locating

Data Exchange

ther Institutes

Data Archive

1. Continuous
2. Events

Waveform Display

1. Waveform
2. Spectrum

Programming

1. Data Input
2. EEW
3. Format

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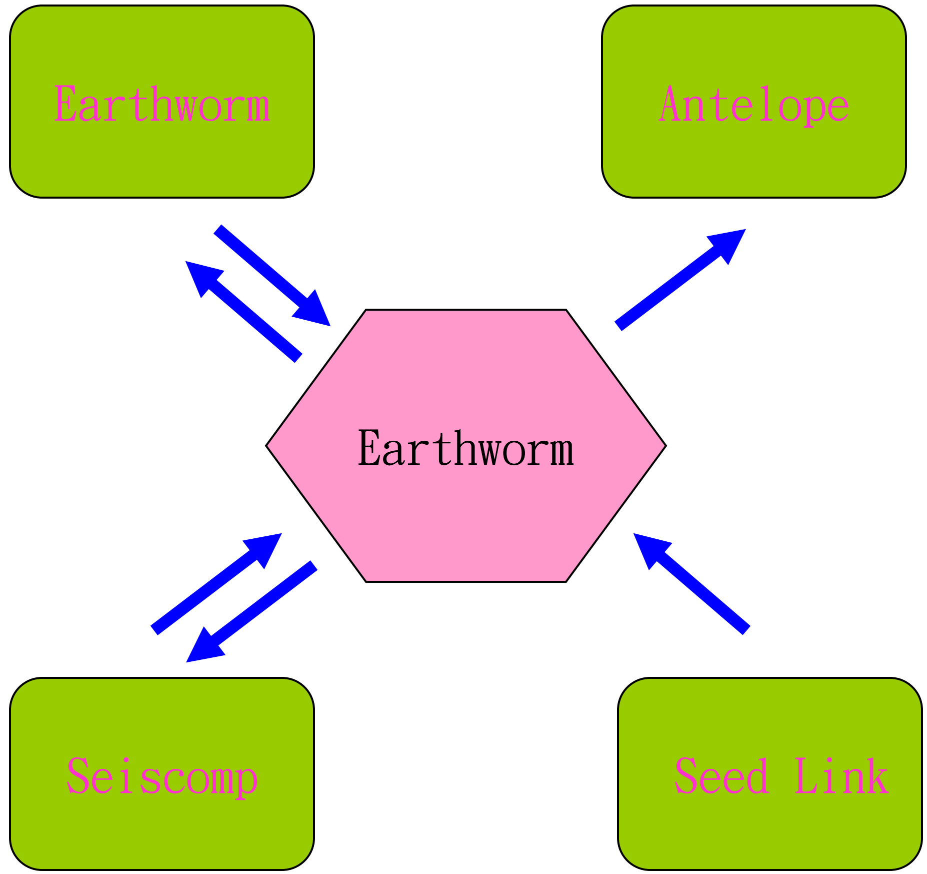

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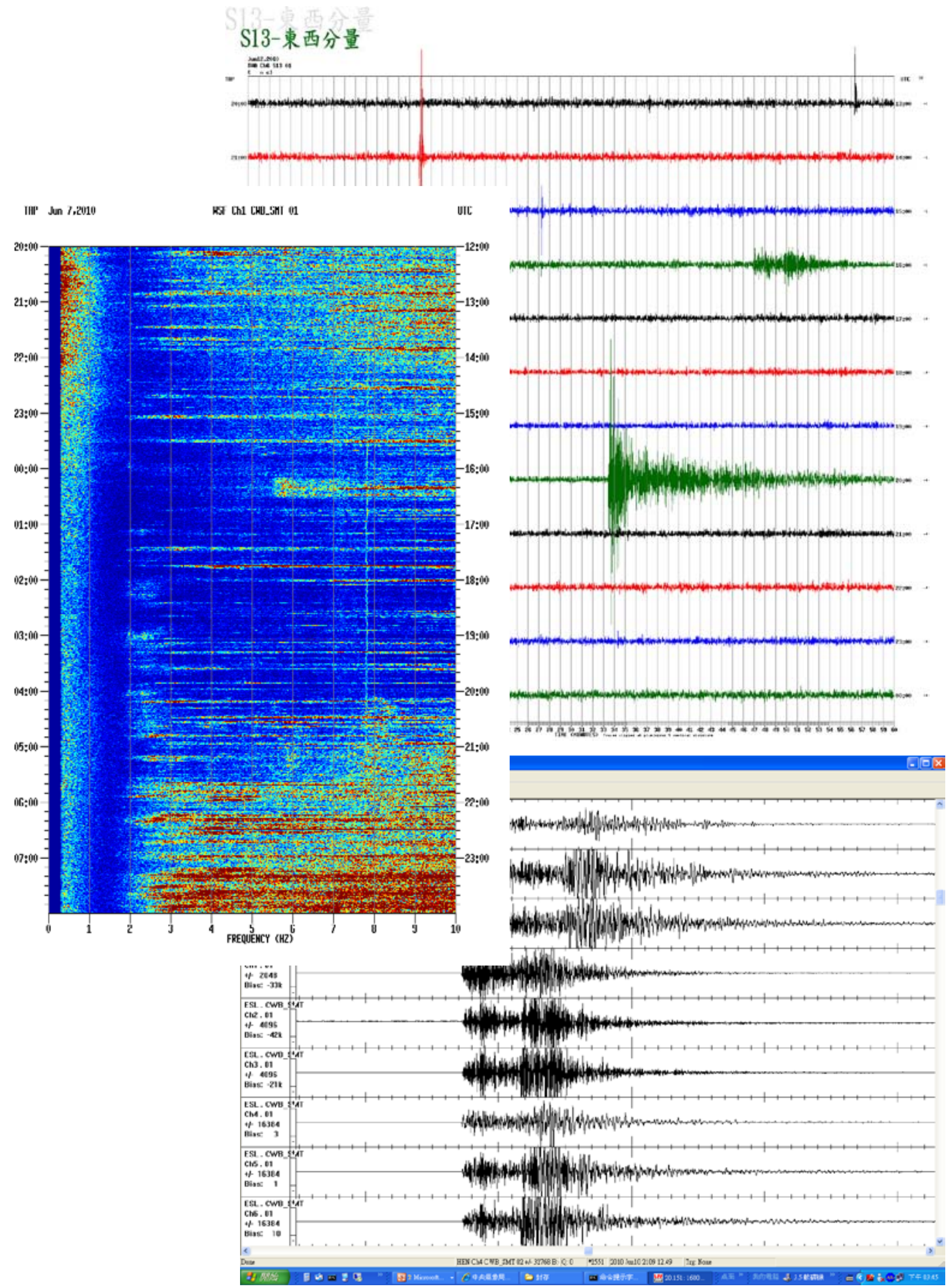

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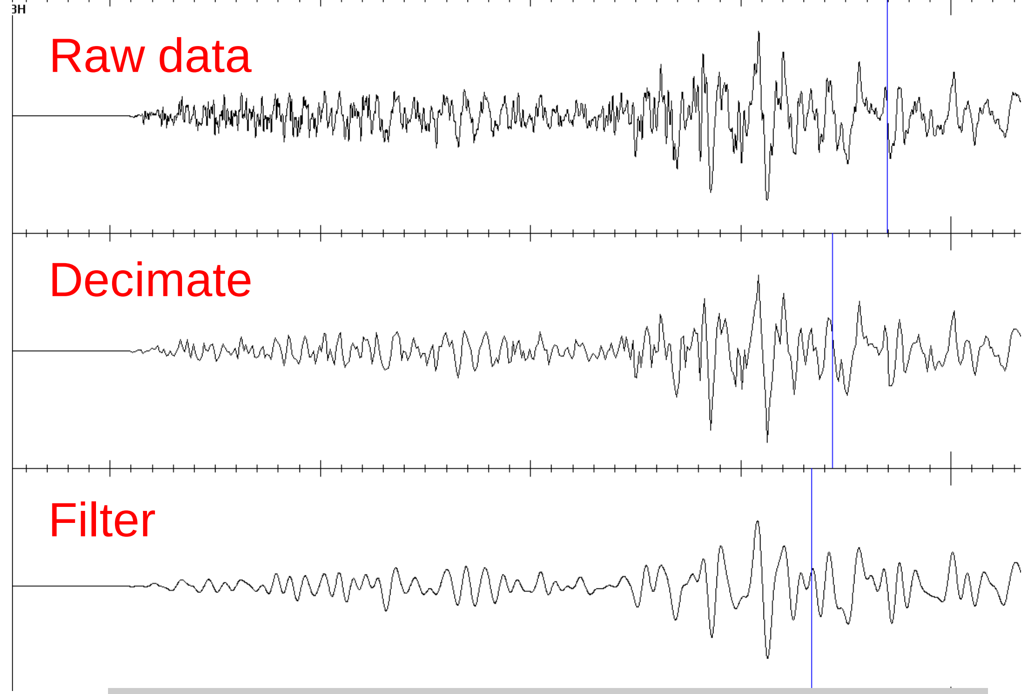

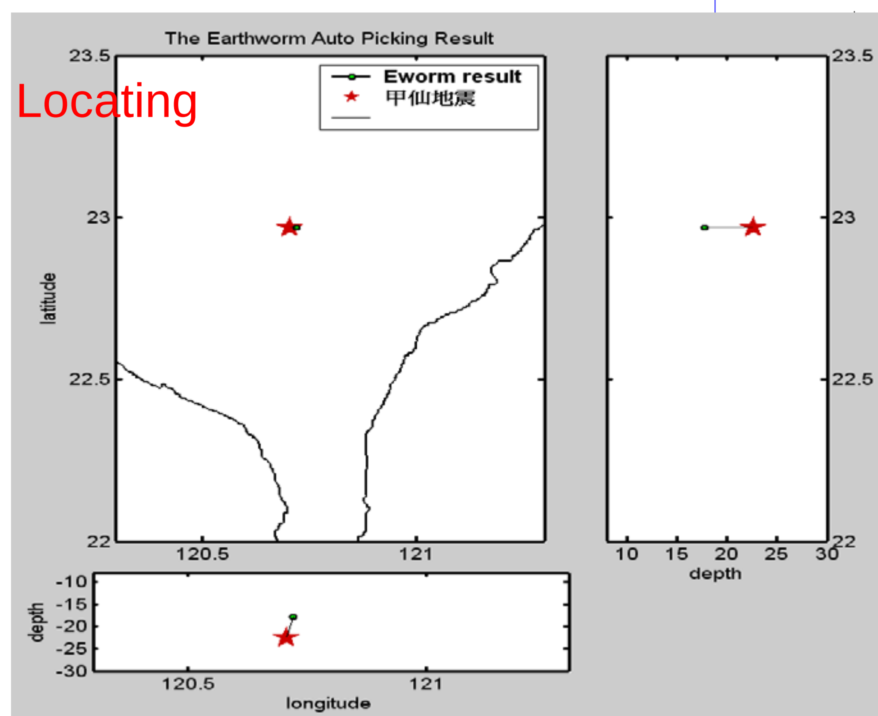

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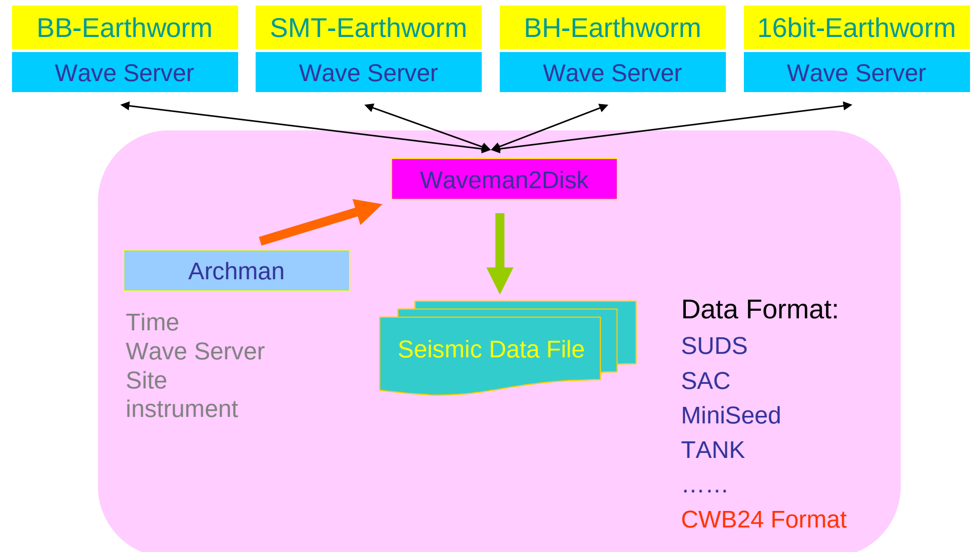

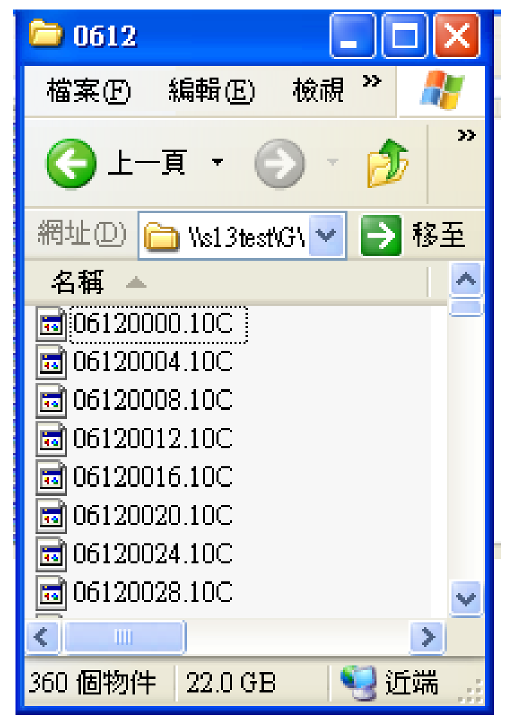

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