SENSORDEVICES 2022
The Thirteenth International Conference on Sensor Device Technologies and Applications

Development of Sensor Devices for Structural Health Monitoring of Buildings and Civil Infrastructures

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Narito KURATA
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- Background
  - Architectural & Structural Engineering
  - Earthquake Engineering
- Research & Development
  - Structural Control Systems for Earthquake Hazard Mitigation
  - Structural Health Monitoring
    - Earthquake Monitoring and Structural Health Monitoring by Sensor Networks
    - Risk Information Delivery System
    - Energy Monitoring
    - Environmental Monitoring
  - Application of Sensor Networks to Smart Buildings and Civil Infrastructures

Recent Research Topics
－Technologies towards Smart Architecture and City

Design


3Dスキャンデータ処理


VRによる建築設計


BIMとセンシング連携

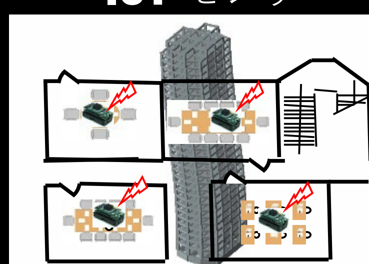
Measure

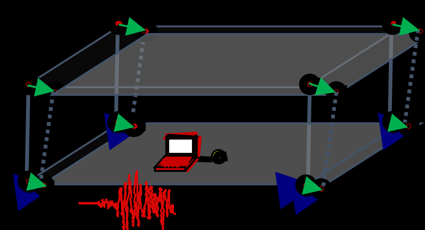

IoT センサ

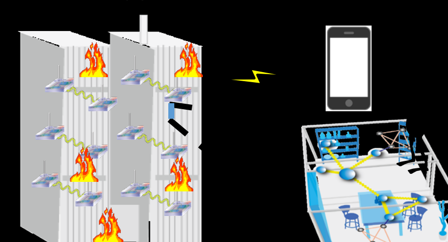

映像センサ


自律型電源システム

Communicate


無線センサネットワーク

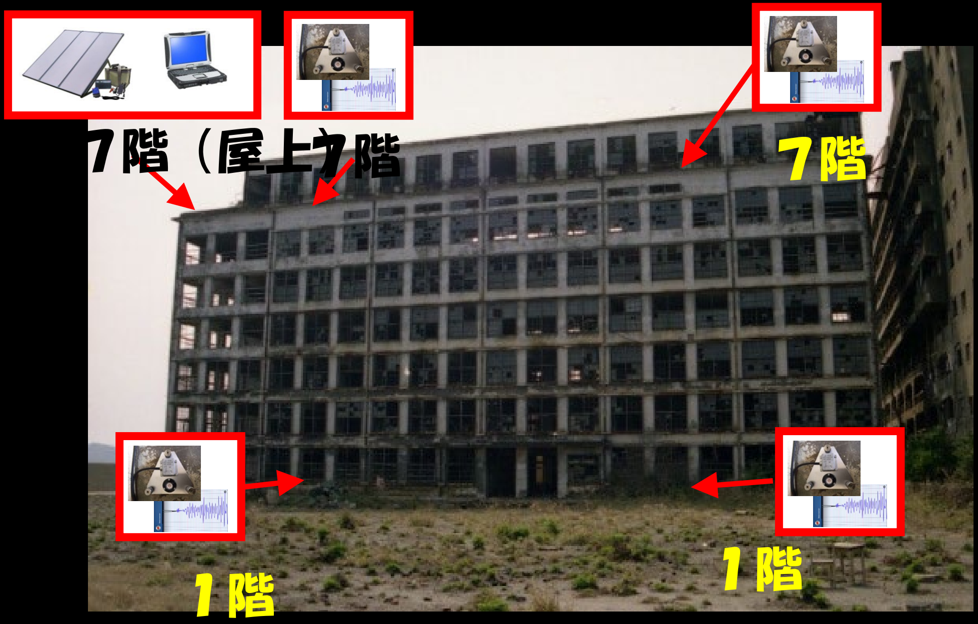

地震時損傷の自動通知


リアルタイム災害情報伝達

Recent Research Topics

－Maintenance of World Heritage Structures

－Battleship Island and Angkor Wat



World Heritage

- World Heritage is defined by the UNESCO World Heritage Convention as a “Convention Concerning the Protection of the World Cultural and Natural Heritage.
- The purpose of the World Heritage Convention is to establish an effective framework of international cooperation and support in order to protect Cultural and Natural Heritage sites that hold remarkable universal value from the threat of damage or destruction and preserve them, as they are the legacy of the world and all mankind.
- As the main regulation, the Contracting Parties are primarily obligated to protect the heritage sites existing in their own countries and pass them on to the future generations.

World Heritage

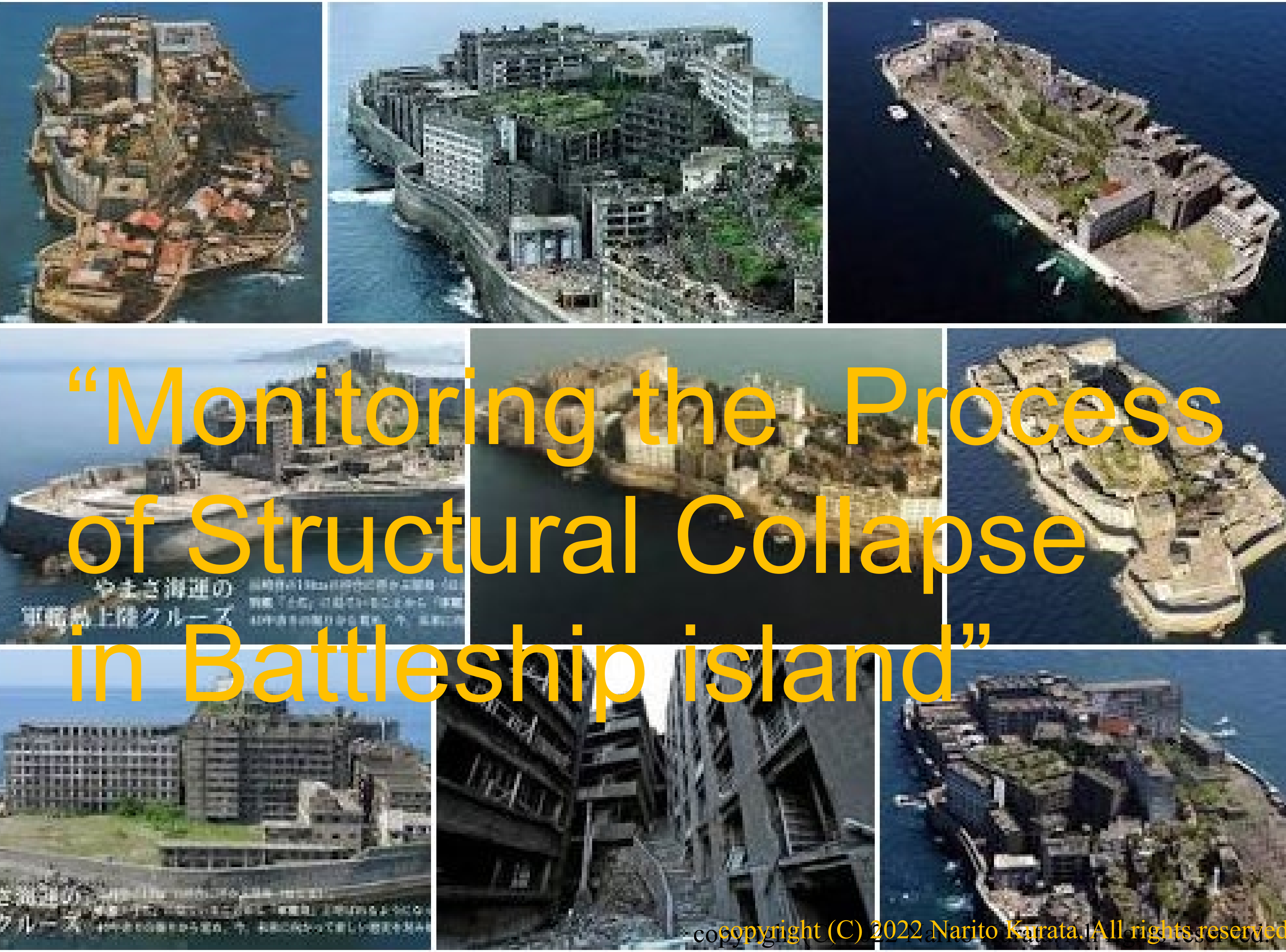
- The structures registered as heritage sites are expected to be maintained and managed for centuries.
- However, heritage sites are subject to serious crises that damage these universal values, including armed conflict, natural disasters, large-scale construction, urban development, tourism development, and commercial poaching.
- To maintain and manage World Heritage Structures, an understanding of the condition should be obtained by monitoring heritage sites. Monitoring should be performed in accordance with the environmental needs and circumstances of each site.

World Cultural Heritage sites in Japan






“Monitoring the Process of Structural Collapse in Battleship island”



Battleship Island

Location of Battleship Island

Battleship Island

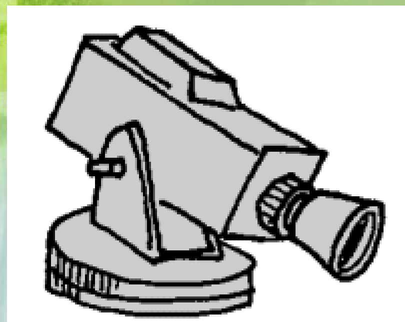
We can go anywhere under special permission

Building with the foundations exposed

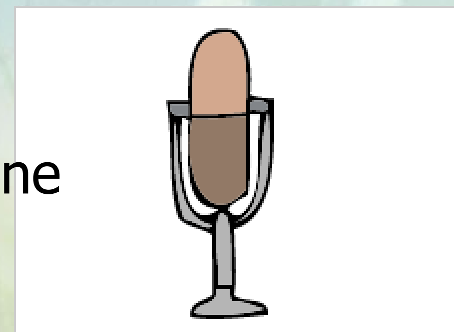
First Multi-family Housing Building of Reinforced Concrete, Built 100 Years Ago

Monitoring the Collapse Process of Buildings

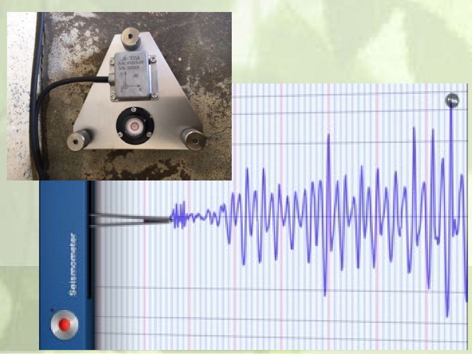
Camera



Microphone



Vibration Sensor

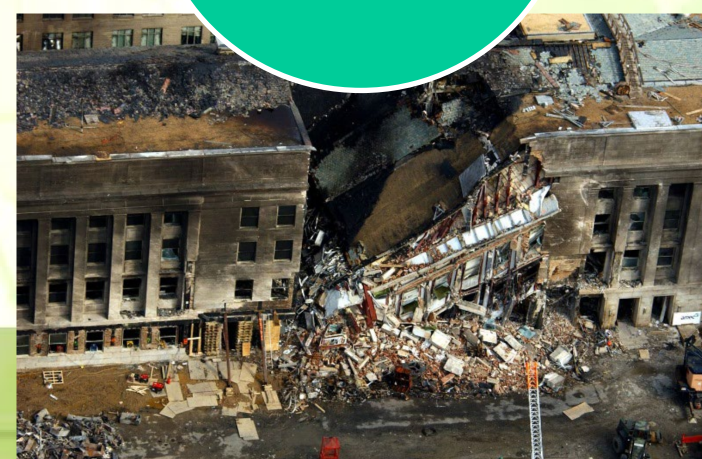


video

sounds

vibtation

collapse process

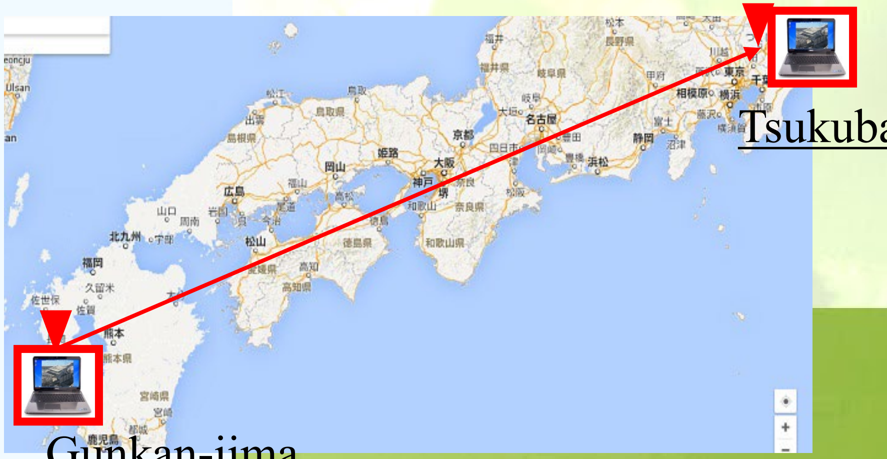


Sensor Network and Data Transmission

No Power Supply in Battleship Island

Data can be collected by wireless communication over the ocean

Station in Main Land

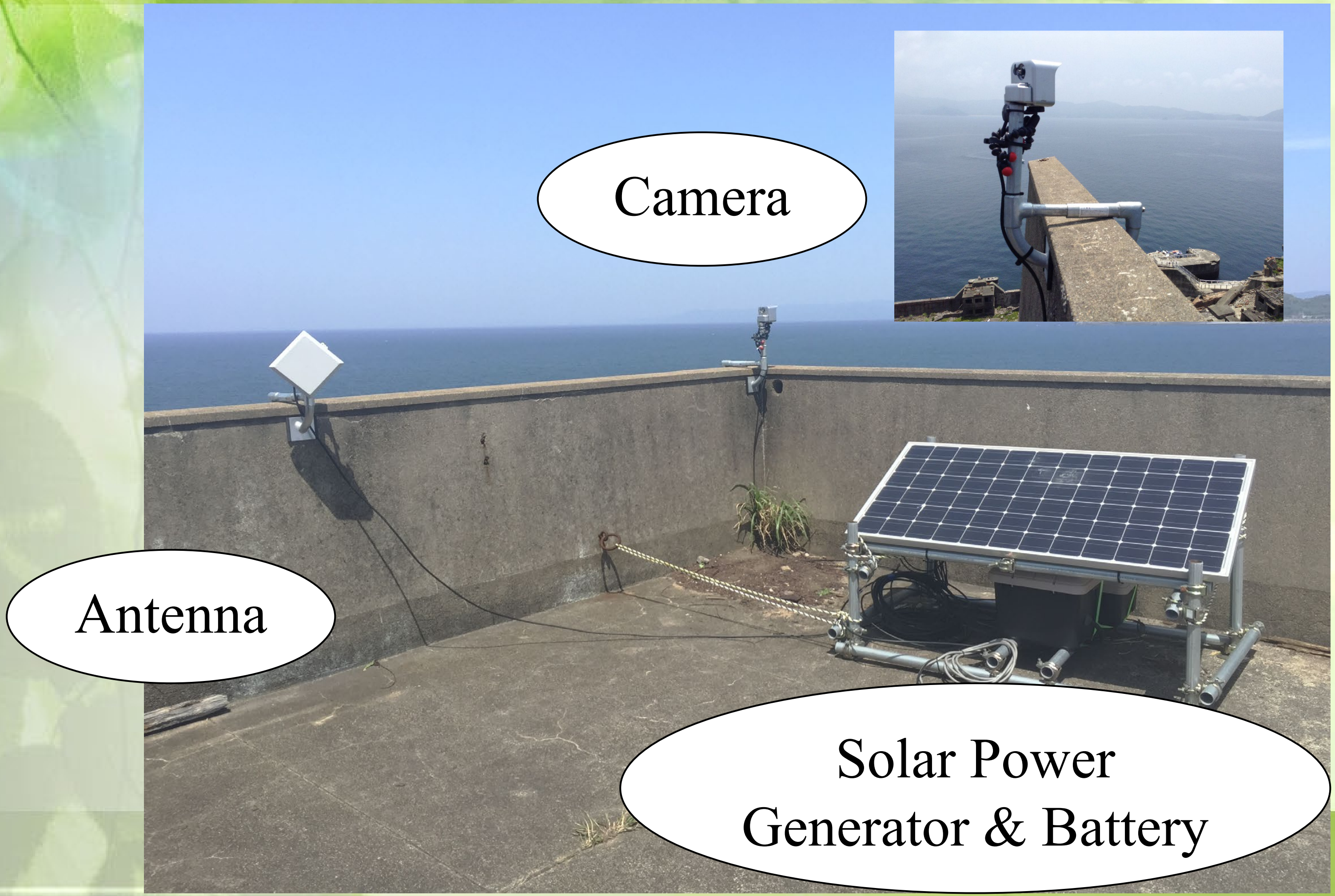


Tsukuba

Gunkan-jima

Residence for Executives

Solar Power Generator, Battery, Antenna, and Camera installed on the Rooftop



Antenna Installed on Building in the Main Land

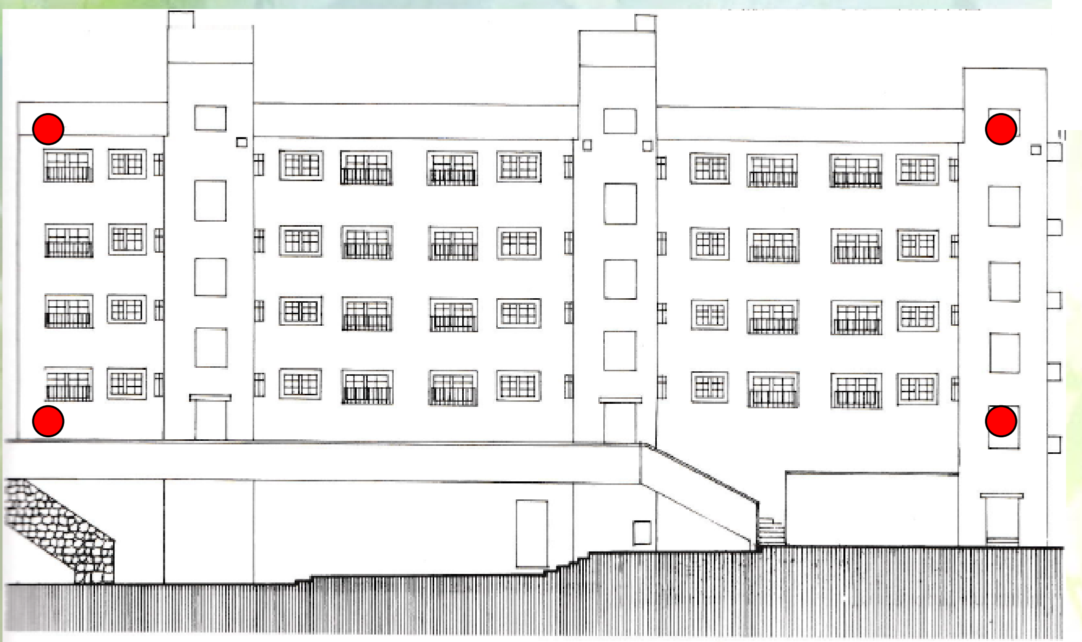
Battleship-island

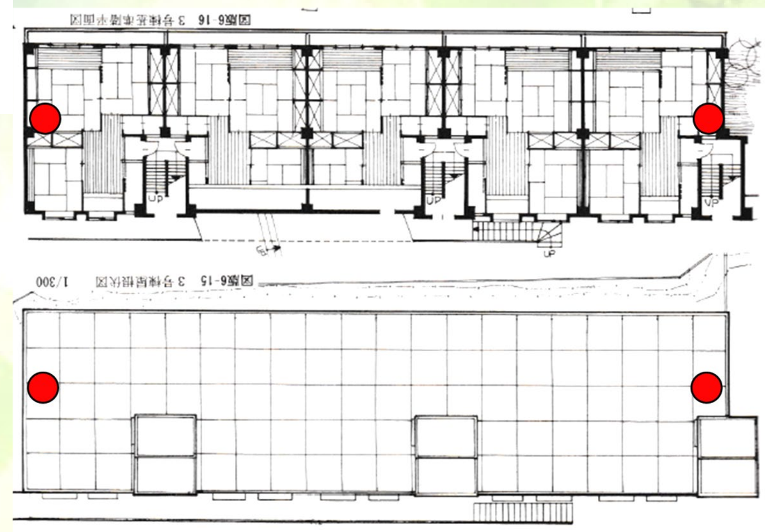
Acceleration Sensor System

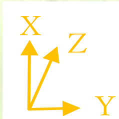
Acceleration Sensor System for No.3 Building (First Stage)

North side

South side



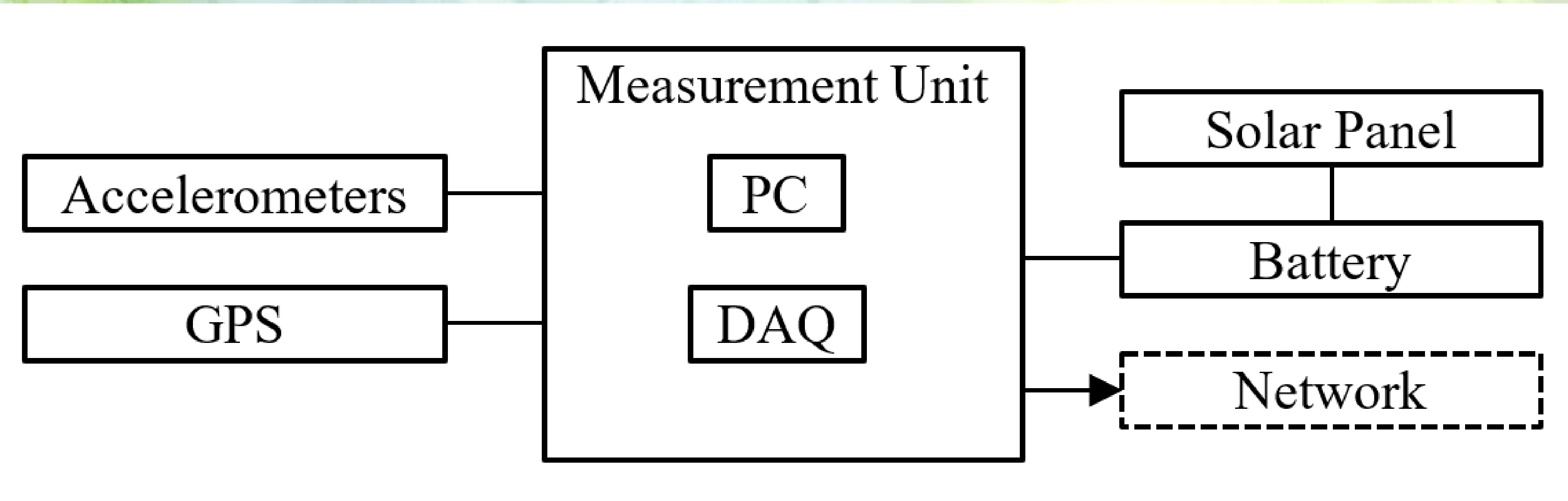




3-axis Acceleration Sensor

– 4 acceleration sensors

Vibration Measurement System

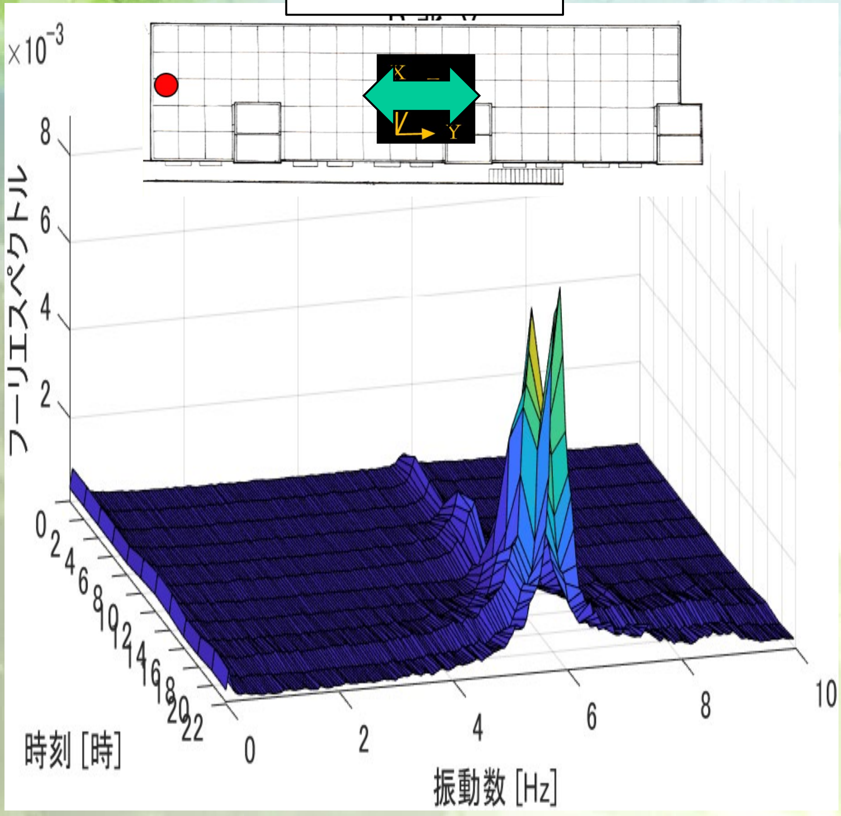


Specifications of Accelerometer

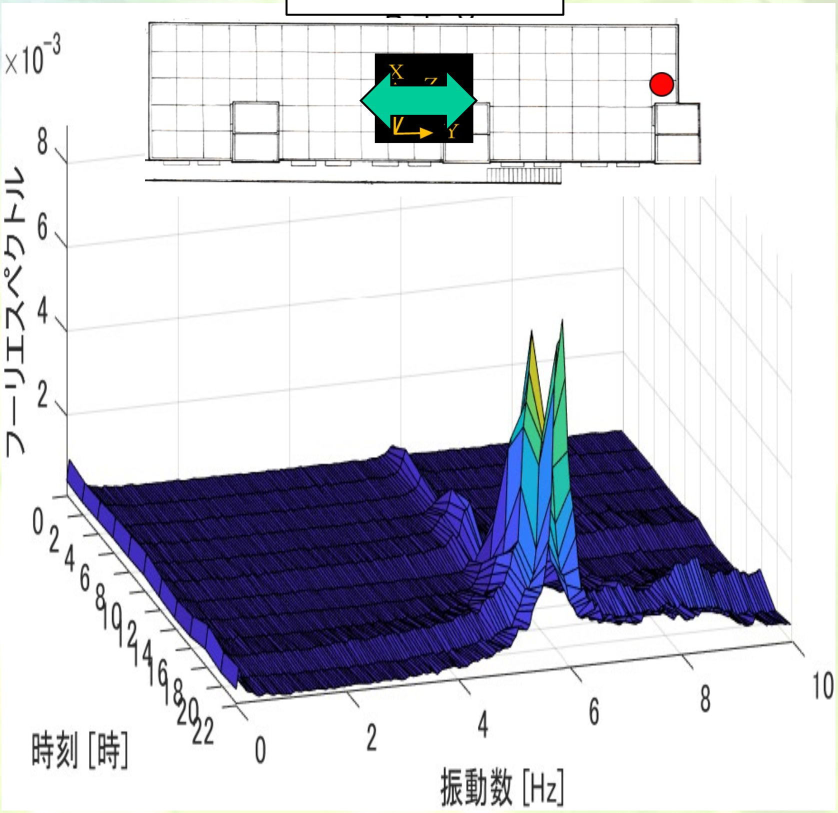
Item	Units	JA-70SA
Measurement range	±m/s^2 [±G]	X,Y axes: ±19.6 or higher [±2] Z axis: -9.8 - +29.4 [-1~+3]
Voltage sensitivity (Note 1)	V/(m/s^2) [V/G]	0.2039±5% [2.000±5%]
Zero point imbalance (Note 2)	m/s^2 [mG]	X,Y axes: within ±0.98 [±100] Z axis: 9.81±0.98 [-1000±100]
Case alignment	mrad	within ±20
Linearity	%FS	within ±2
Self-noise (@1~30Hz)	(m/s^2) rms/√Hz [Grms/√Hz]	9.8×10^{-6} [1×10^{-6}]
Frequency response	Hz(±3dB)	≥200
Voltage sensitivity:temperature coefficient	ppm/° C	within ±200
Zero point imbalance: temperature coefficient	μ(m/s^2)/° C [μG/° C]	±1961[±200]

Fourier Spectrum for Acceleration Data at Roof Floor in Y direction

North side

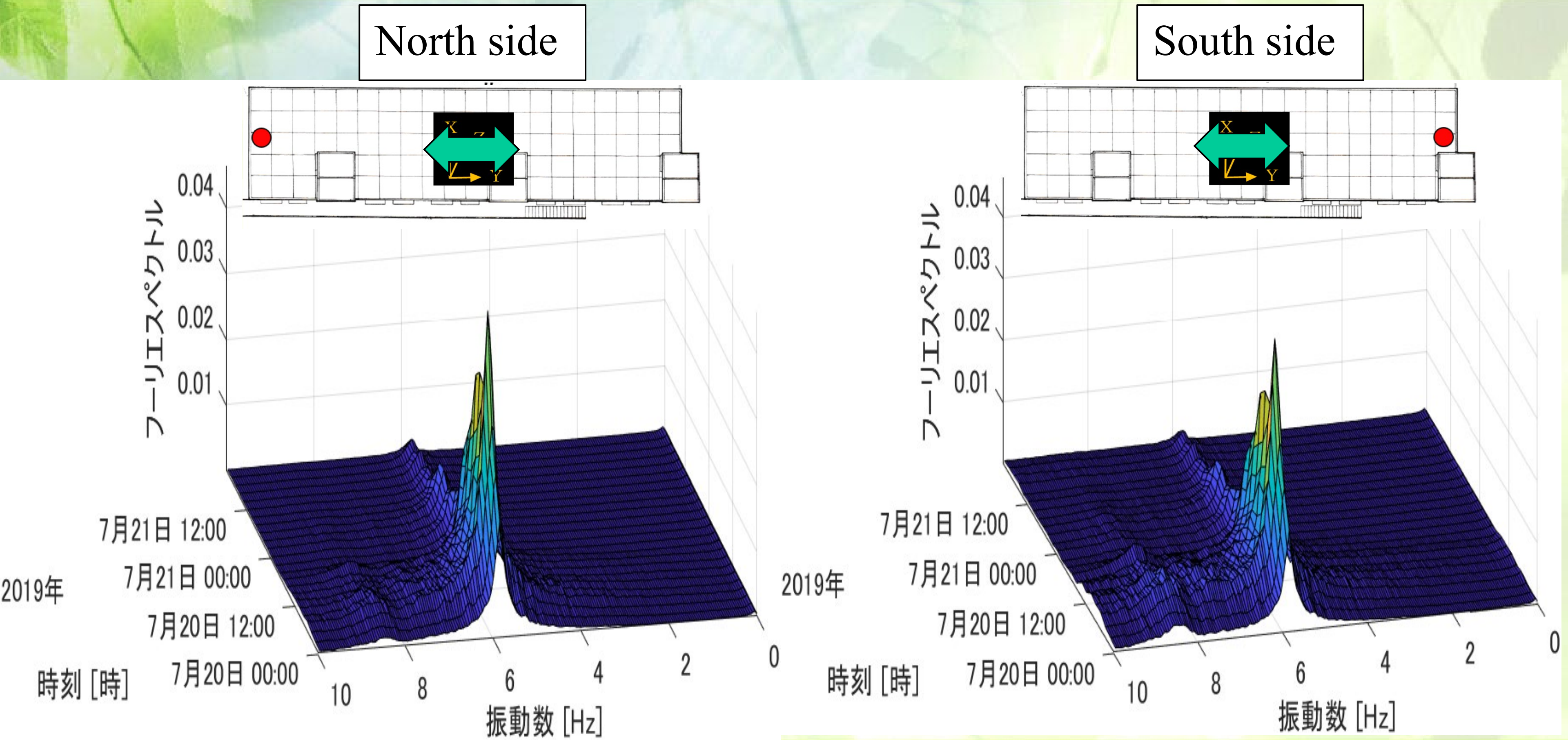


South side



June 29th, No wind and moderate wind

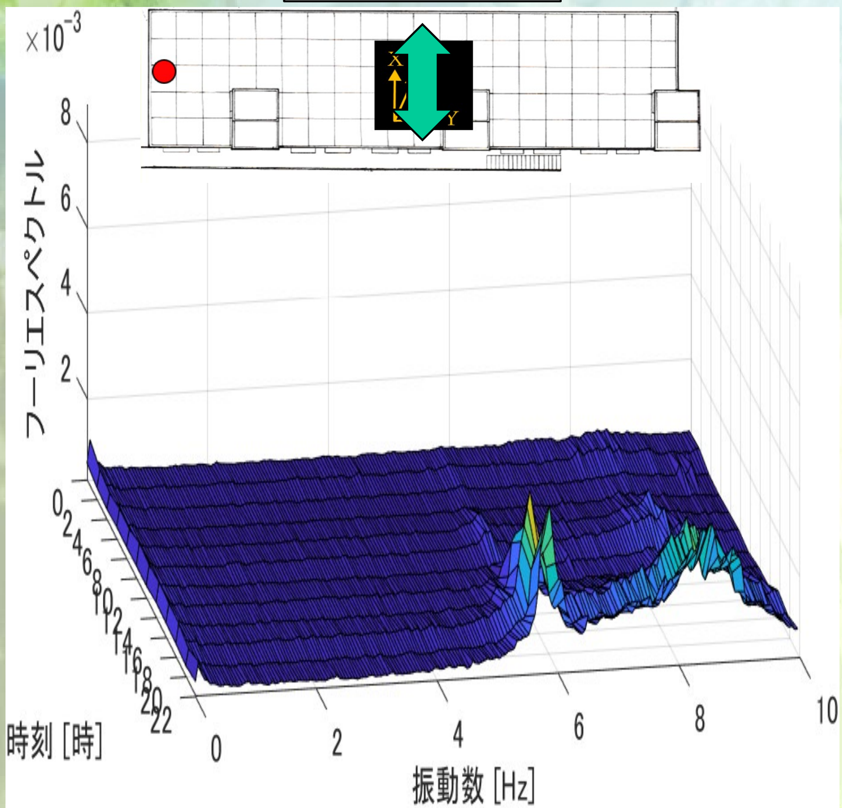
Fourier Spectrum for Acceleration Data at Roof Floor in Y direction



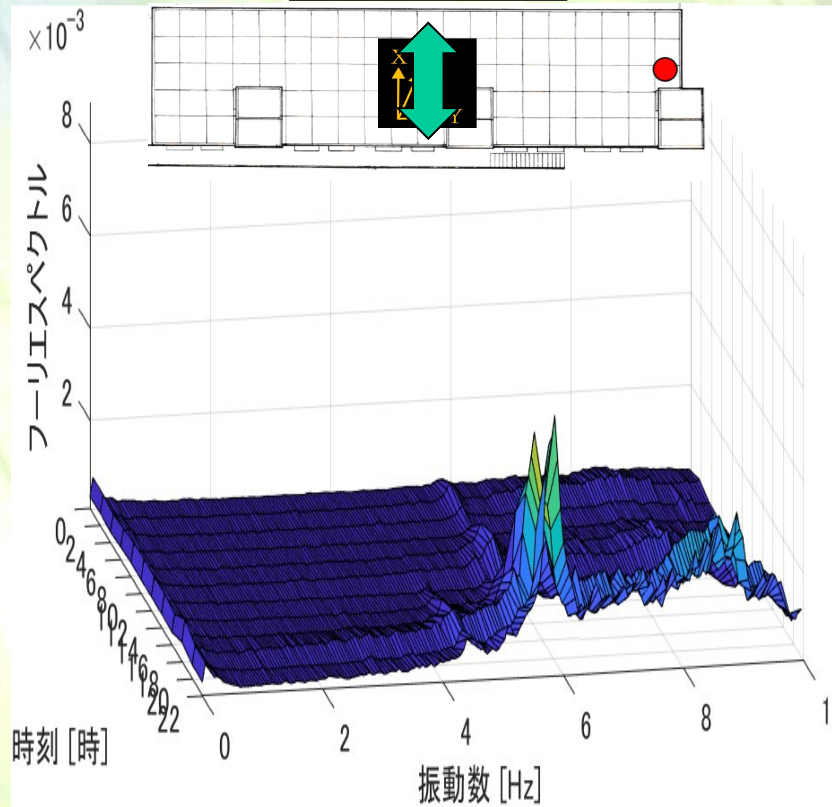
July 20th, Strong wind

Fourier Spectrum for Acceleration Data at Roof Floor in X direction

North side

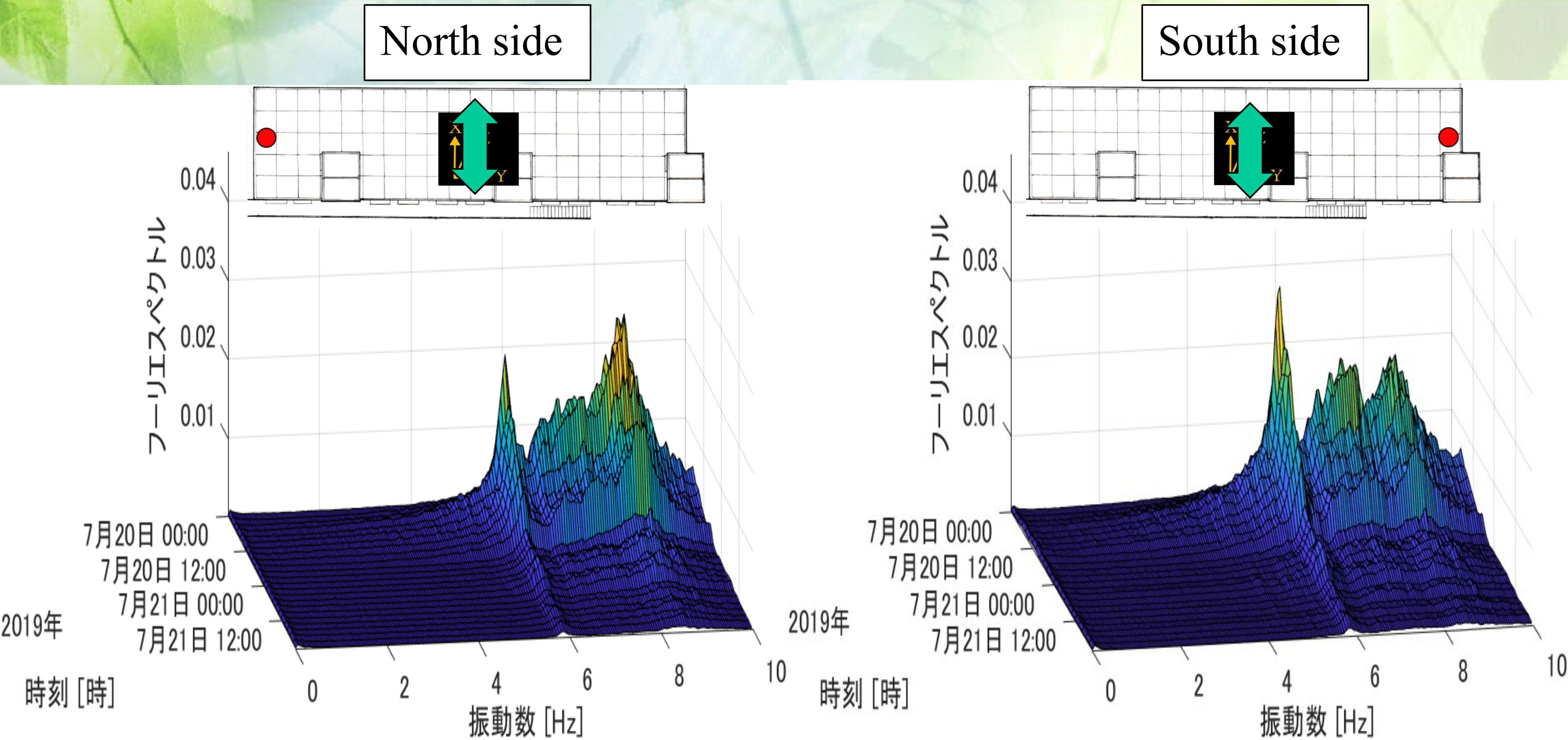


South side



June 29th, No wind and moderate wind

Fourier Spectrum for Acceleration Data at Roof Floor in X direction

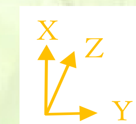


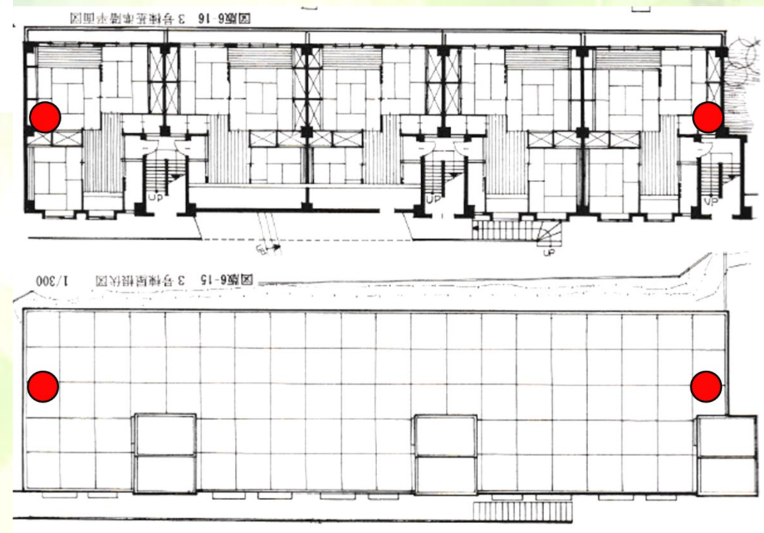
July 20th, Strong wind

Acceleration Sensor System for No.3 Building (Second Stage)

North side

South side

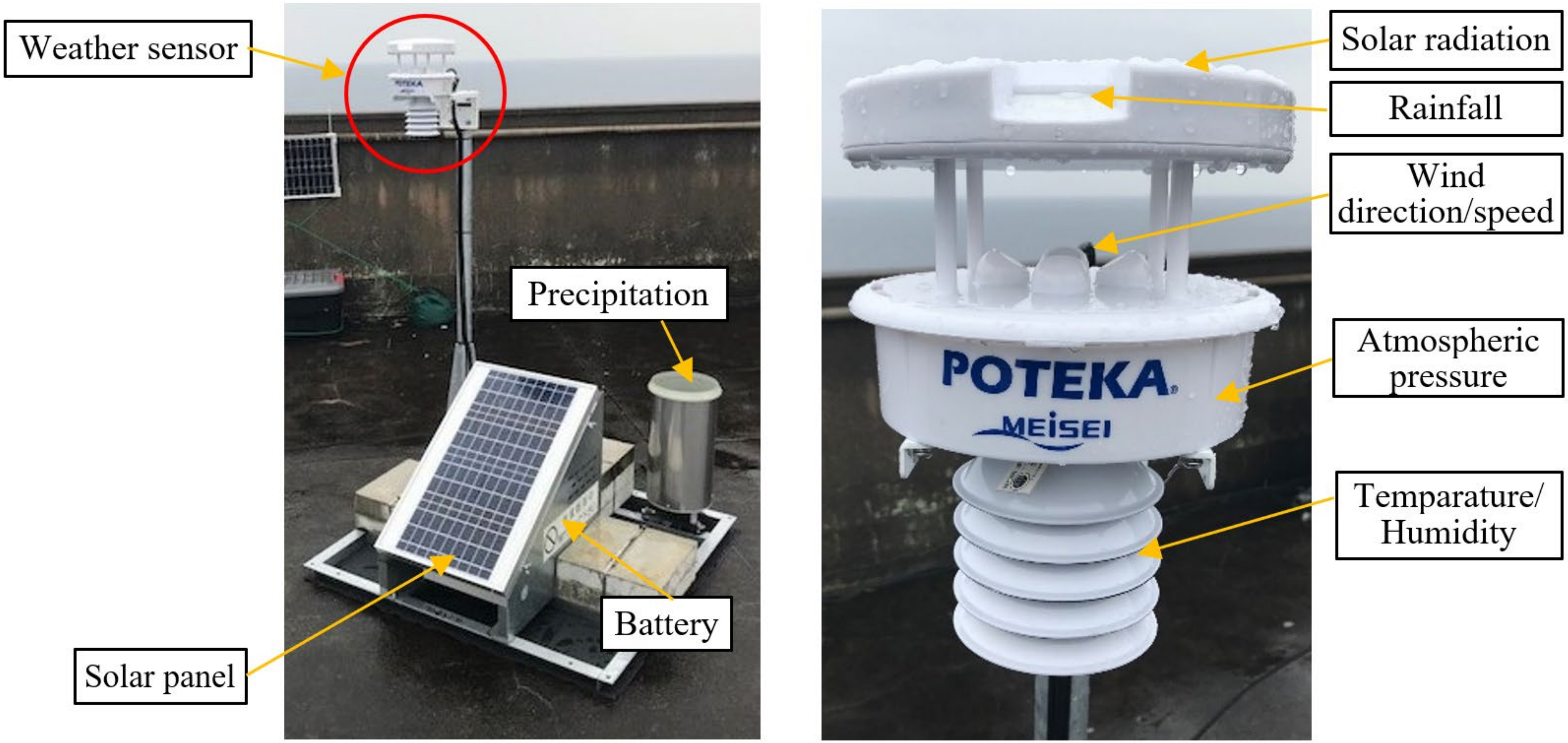




● 3-axis Acceleration Sensor

– 10 acceleration sensors

Meteorological Observation System



(a) System View (b) Weather Sensor

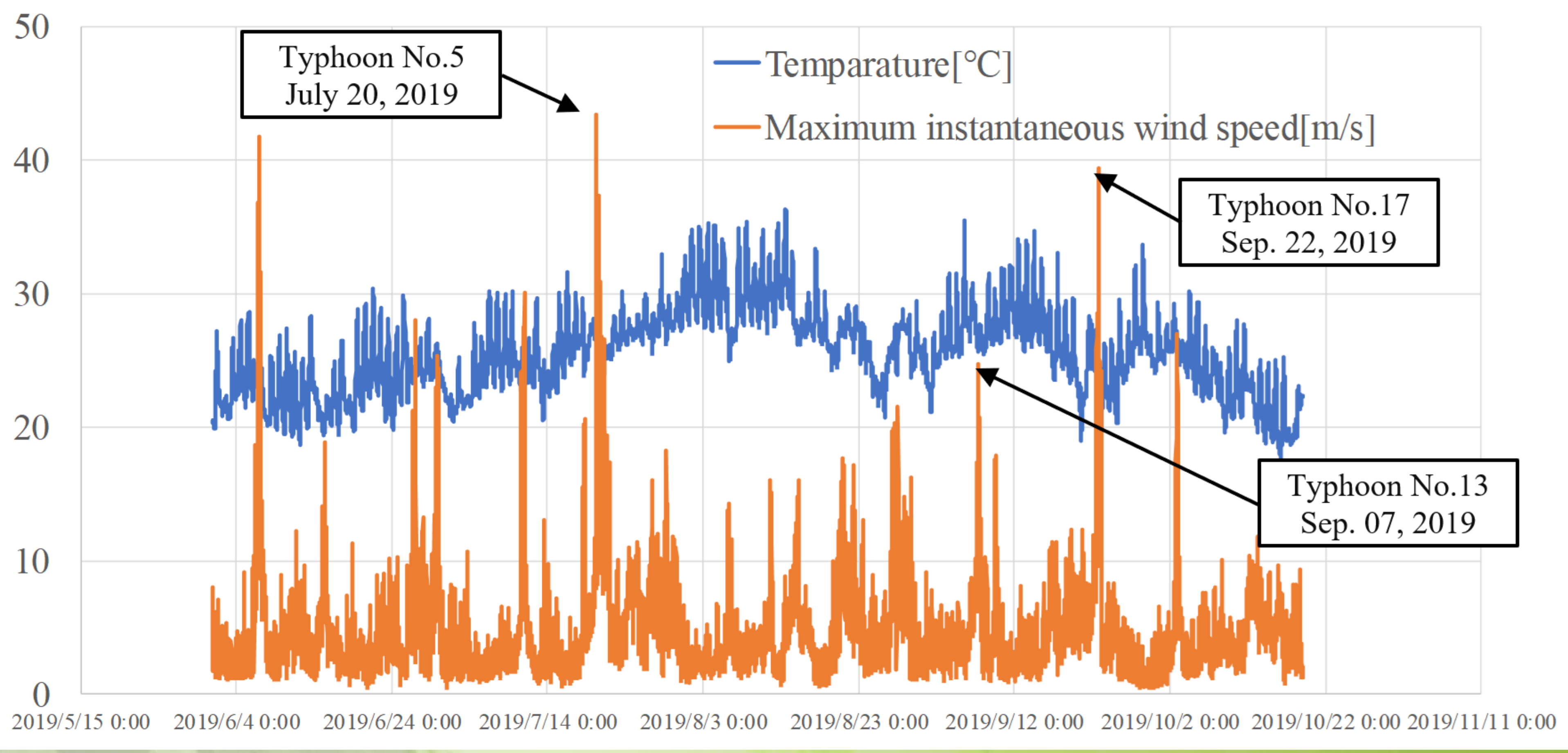
Specifications of Meteorological Observation System

Observation element of weather sensor	Air temperature, atmospheric pressure, humidity, solar radiation, wind direction, wind speed, rainfall, precipitation
Sampling period	1 second
Statistical interval (output values)	1 min average
Communication interval	60 sec (variable from 10~999 sec)
Data storage	14 days
Solar battery capacity	30 W
Storage cell capacity	18 Ah
Built-in cell	Nickel-hydrogen cell 700mAh
Power interruption backup time	More than 6 hrs.
Operating temperature range	-10° C~+60° C
Wind speed resistance	Average wind speed 60m/s
Communications circuit	3G circuit

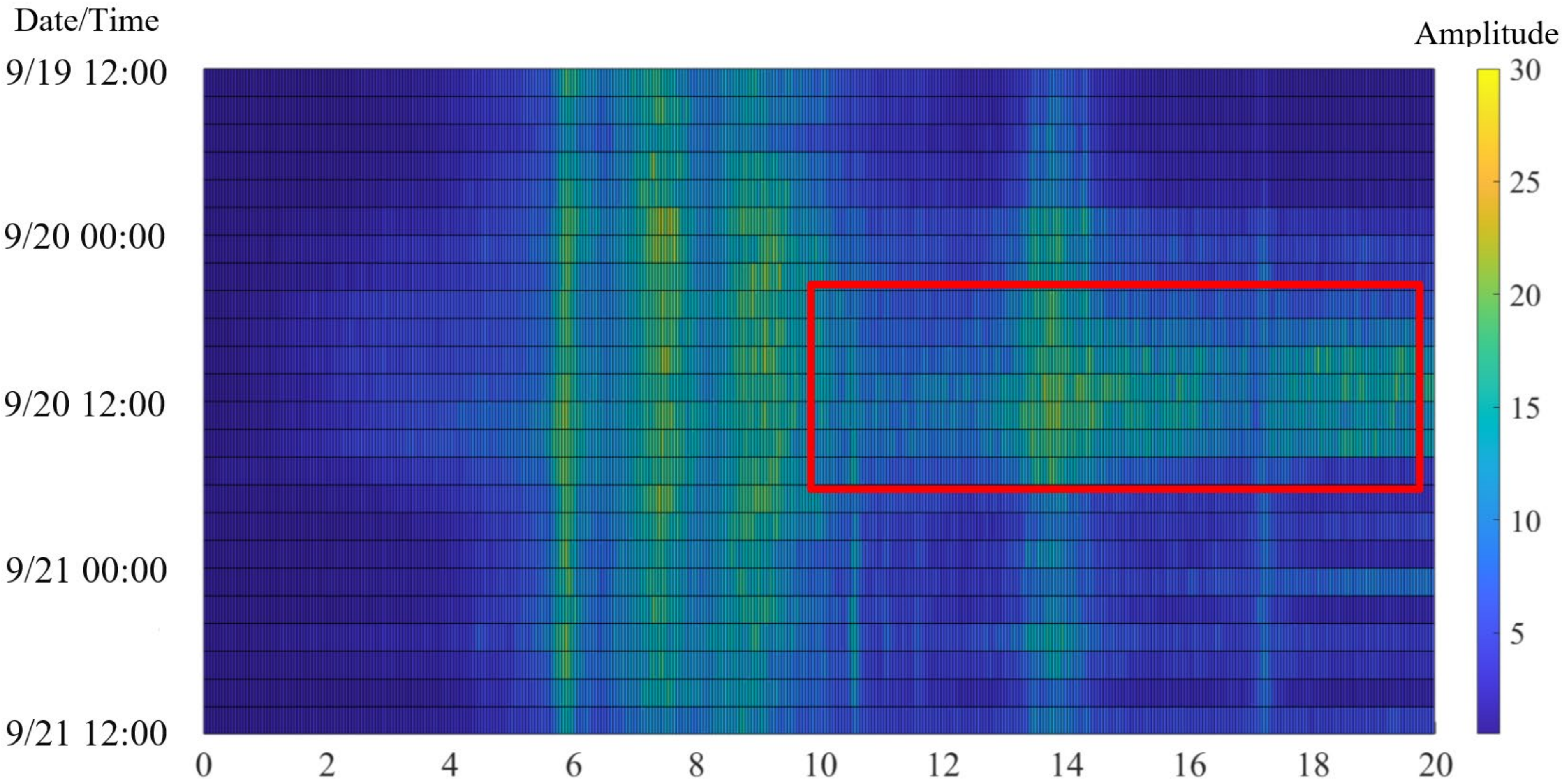
Specifications of Weather Sensor

Element	Measurement method	Observation range	Precision
Air temperature	Platinum resistor	-50.0~+50.0° C	±0.3° C
Humidity	Capacitive type	0.0~100.0%RH	±5%
Atmospheric pressure	Capacitive type	870.0~1050.0hPa	±0.7hPa
Wind direction	Ultrasonic	0~360°	±10°
Wind speed	Ultrasonic	0.0~30.0m/s	±0.3m/s (0~10m/s) ±5% (10~30m/s)
Solar radiation	Photodiode	0~1400W/m^2	±10%
Rainfall	Capacitive type	0/1	-
Precipitation	Tipping bucket type	Below 200mm/h	±0.5mm (below 20mm) ±3% (above 20mm)

Average Air Temperature and Maximum Instantaneous Wind Speed



Fourier Amplitude Spectrum Ratios of Acceleration Data (Short-side component)



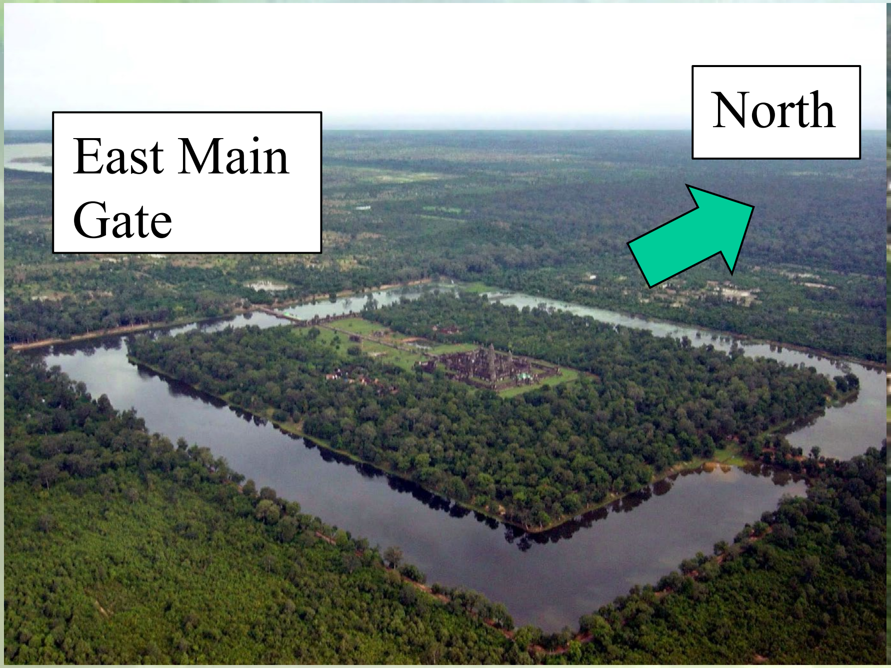
Angkor Wat

The World Heritage Site of Angkor Wat is part of the Angkor Ruins located in the northwestern part of Cambodia. The structure is a Hindu temple, and is regarded as a masterpiece of Khmer architecture.

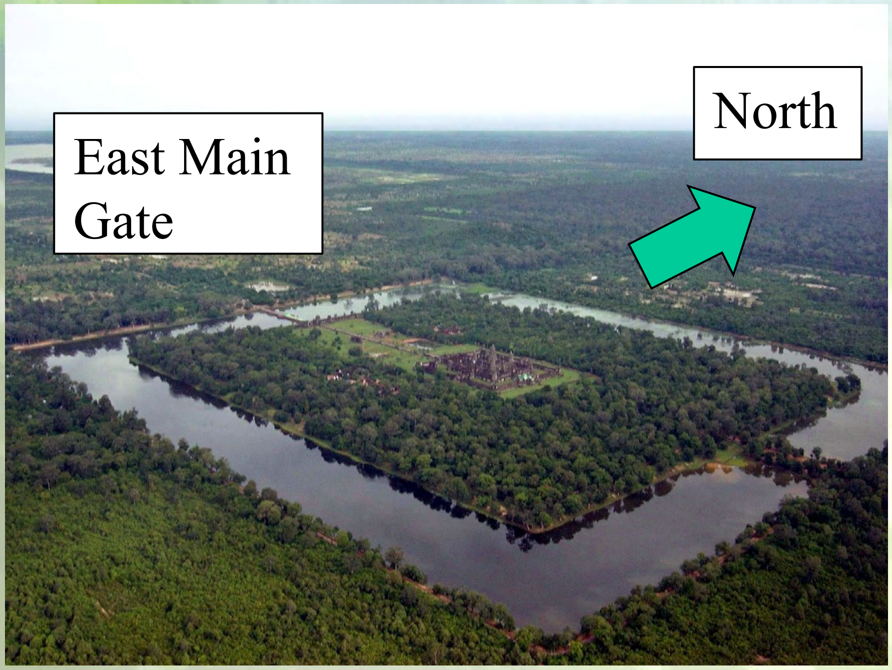
An image of the structure is displayed in the center of the Cambodian flag.

Monitoring of Angkor Wat site in Cambodia

Angkor Wat



Angkor Wat



Structures of Angkor Wat

- The Structures of Angkor Wat were mainly constructed from sandstone and laterite, and the temple was built by utilizing steelmaking technology in a nearby area.

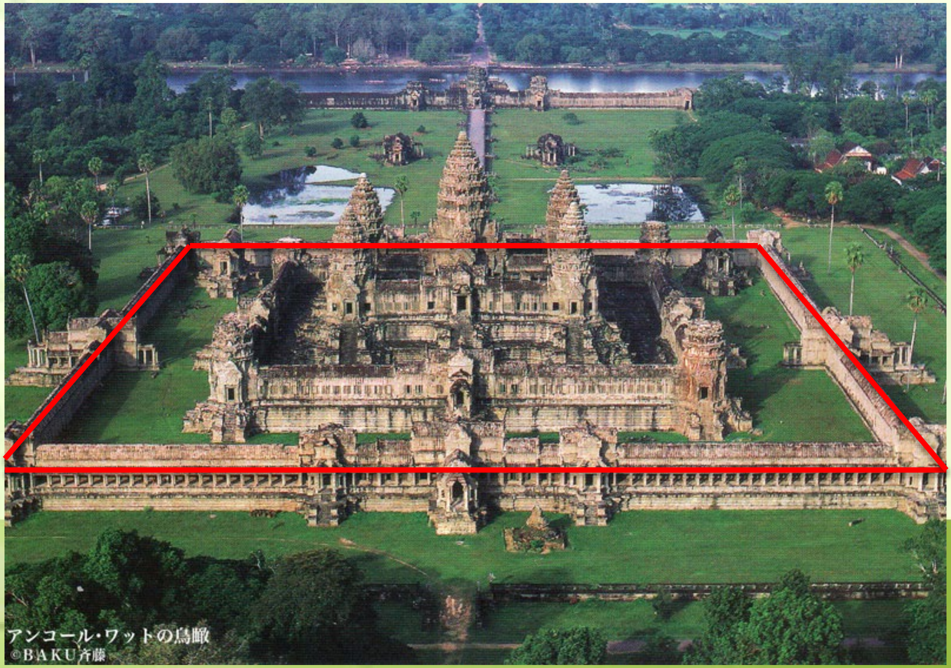
Sandstone

Laterite

Structures of Angkor Wat

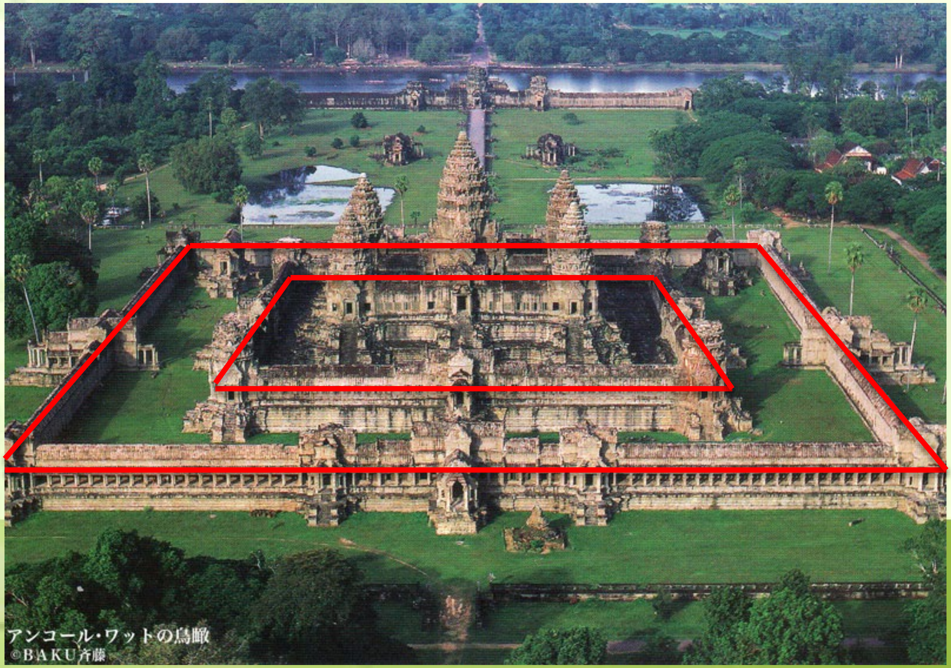
- The structures are surrounded by a three-storied corridor.

- The first story corridor is 200 meters in length from east to west, and 180 meters in length from north to south.



Structures of Angkor Wat

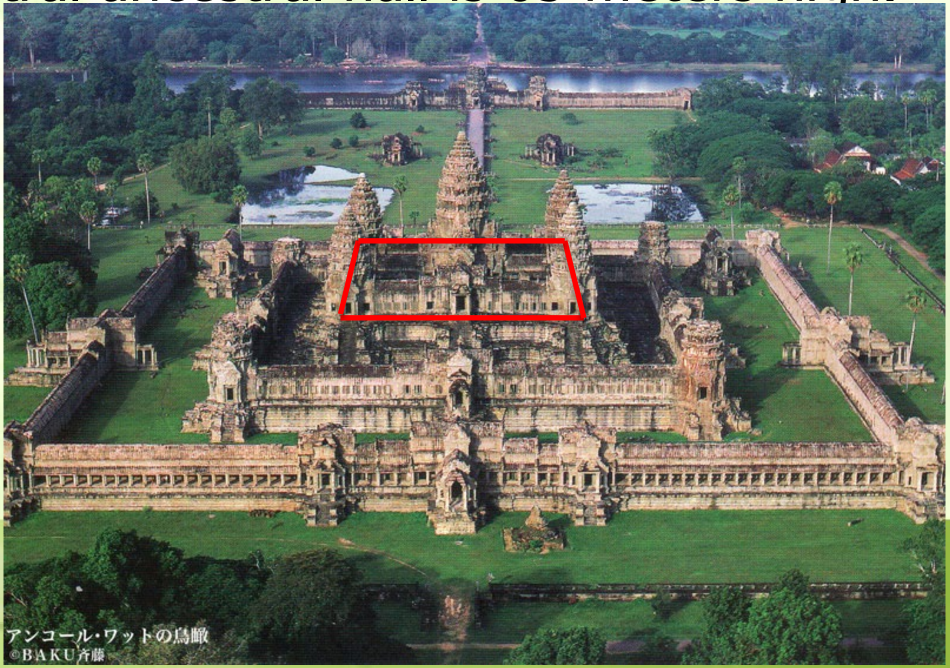
- The second story corridor is 115 meters in length from east to west, and 100 meters in length from north to south.



Structures of Angkor Wat

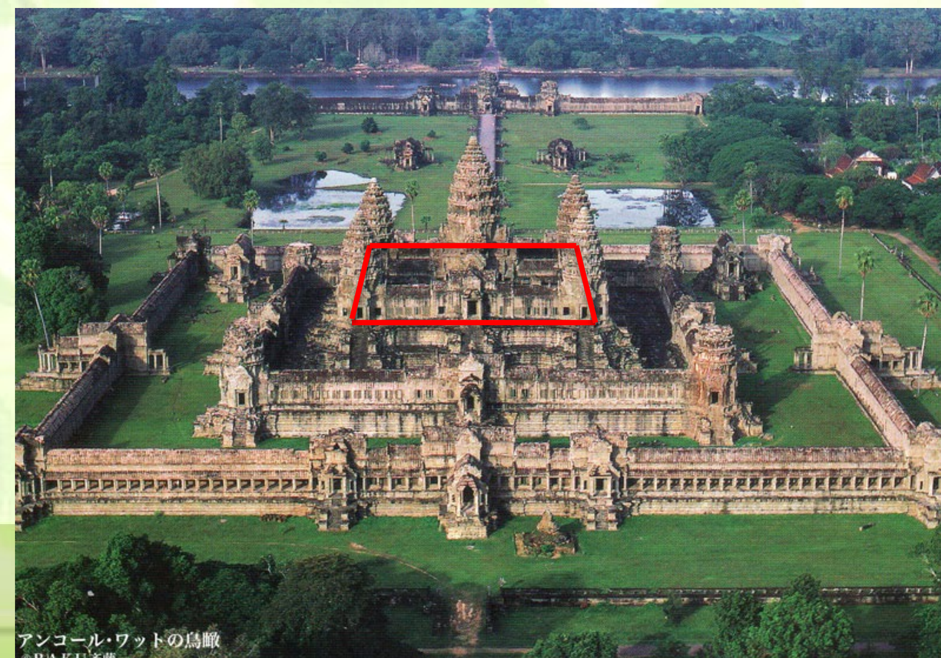
- The third story corridor is 60 meters long on each side, and 13 meters higher than the second story corridor.

- In this corridor, five ancestral halls are located in each of the four corners and in the center; the central ancestral hall is 65 meters high.



Structures of Angkor Wat

- To enter the third story corridor, it is necessary to climb a steep set on stone steps.



Acceleration Sensor for Vibration Measurement of Buildings and Structures

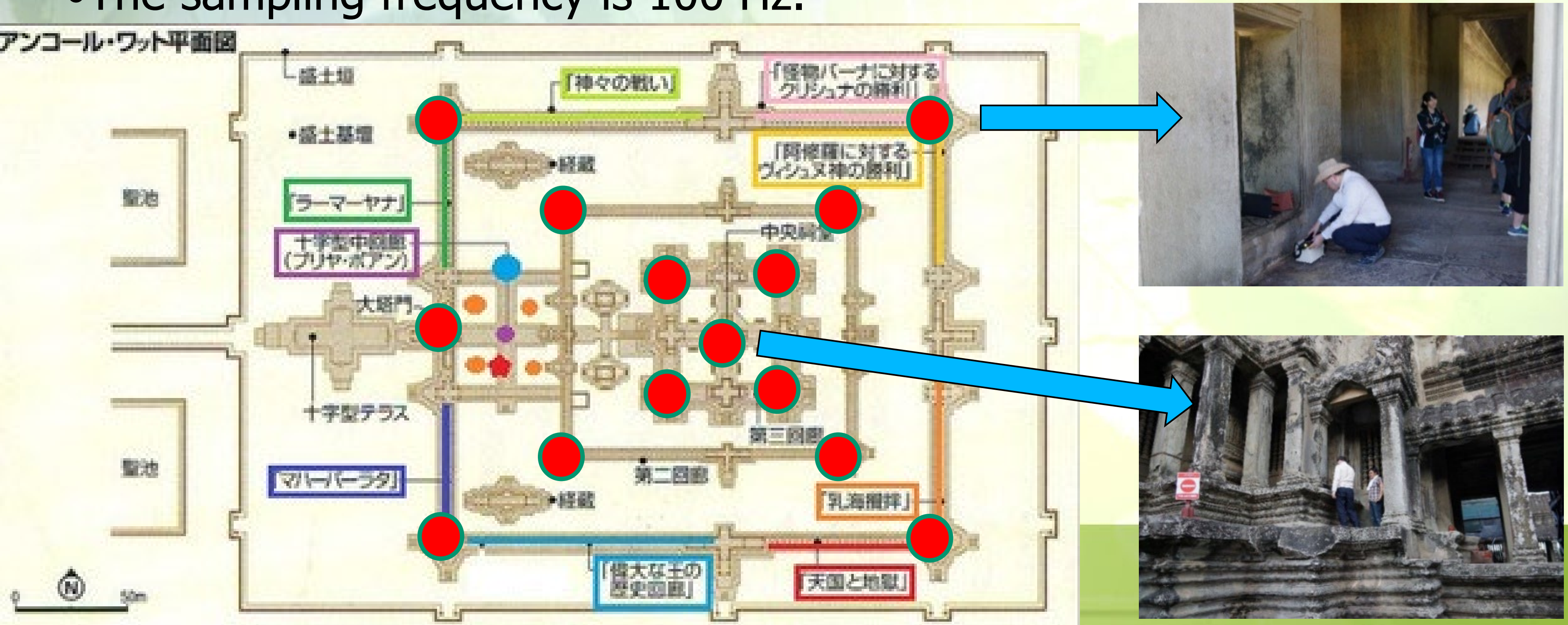
- High performance 3-axis acceleration sensor
- 24 bit A/D
- Built-in data logger
- Accurate Time Information by GPS

Specification of Acceleration Sensor

Model	JA-40GA04 (Japan Aviation Electronics Industry)
Measurement component	Up and down × 1, horizontal × 2
Max. measurement range	± 4 G
Voltage sensitivity	2.000 V/G ± 3%
Self-noise (1 to 30 Hz)	0.7×10^{-6} G/√Hz
Frequency characteristic	DC to 200 Hz
Battery	Lithium ion secondary battery
Continuous utility time	10 hours
Input range	±10 V, ±1 V
Sampling	200 Hz, 100 Hz, 40 Hz, 1 Hz
Resolution	24 bit (⊿Σ model AD)
Dimension / Weight	172×245×160 mm, about 4,500 g

Plan of Angkor Wat and Measurement Points ●

- A constant tremor was measured by single portable sensor every 10 minutes at each location point (●) of the first, second, and third corridors of Angkor Wat.
- The sampling frequency is 100 Hz.



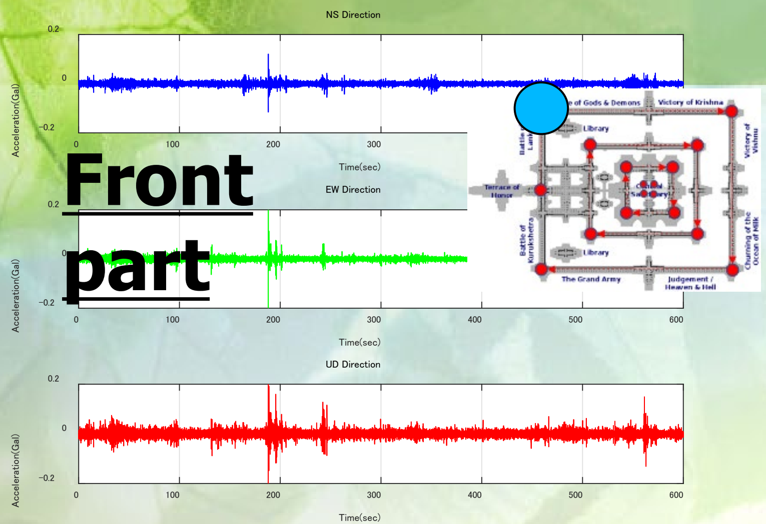
Influence of frequent walking by travelers

There is a heavy impact from the vibrations created by tourist traffic in Angkor Wat.

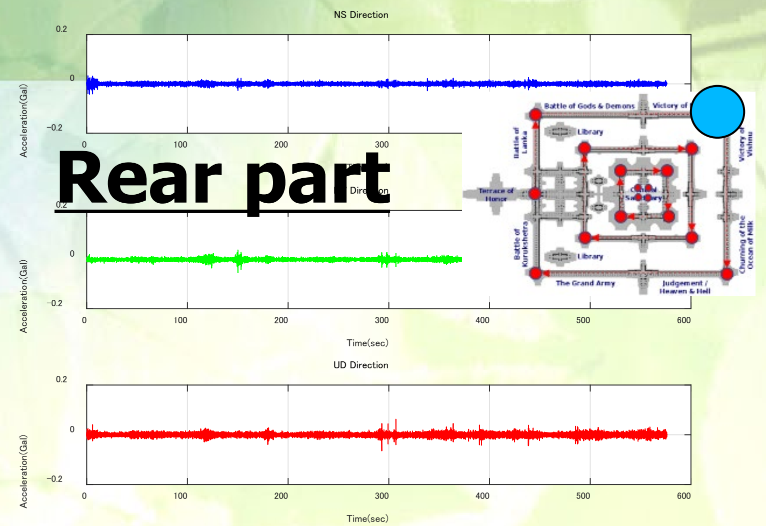
As a common tour route, tourists enter Angkor Wat from the west side entrance. They then proceed up to the second and third story corridor.

Measured acceleration data at the first story corridor

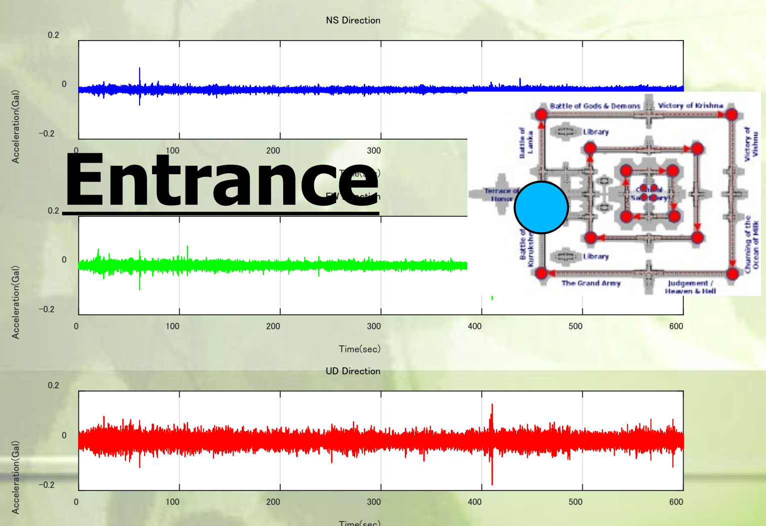
Front part



Rear part



Entrance

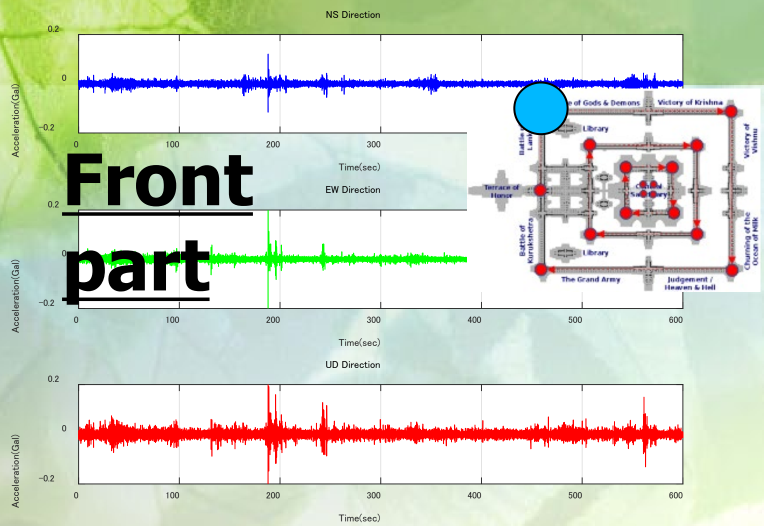


Comparing the up-down vertical acceleration, the amplitude of acceleration becomes smaller when moving from the entrance to the front and rear section.

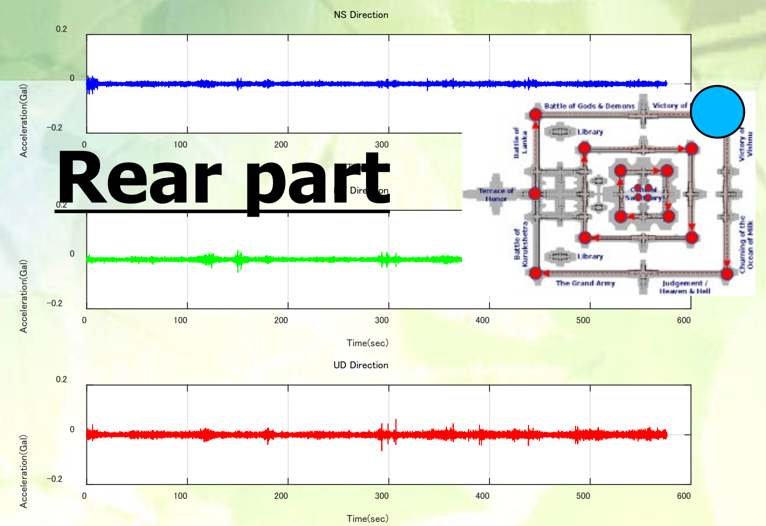
It is in accordance with the flow of tourist traffic.

Measured acceleration data at the first story corridor

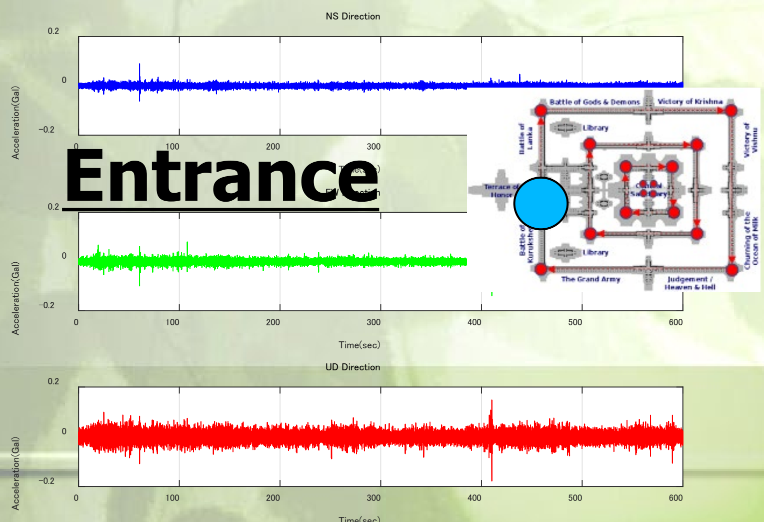
Front part



Rear part



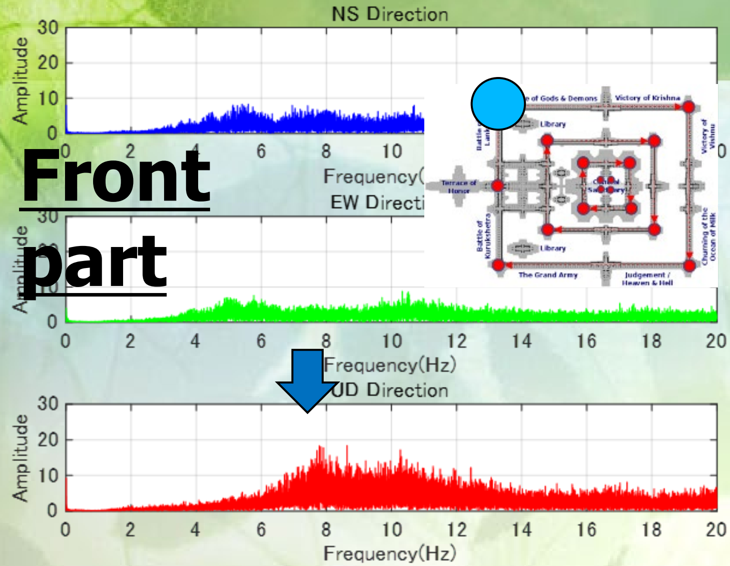
Entrance

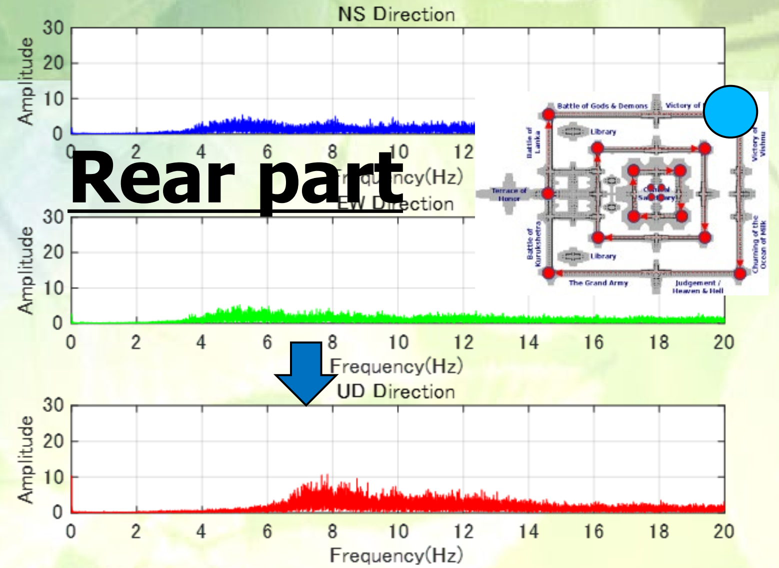


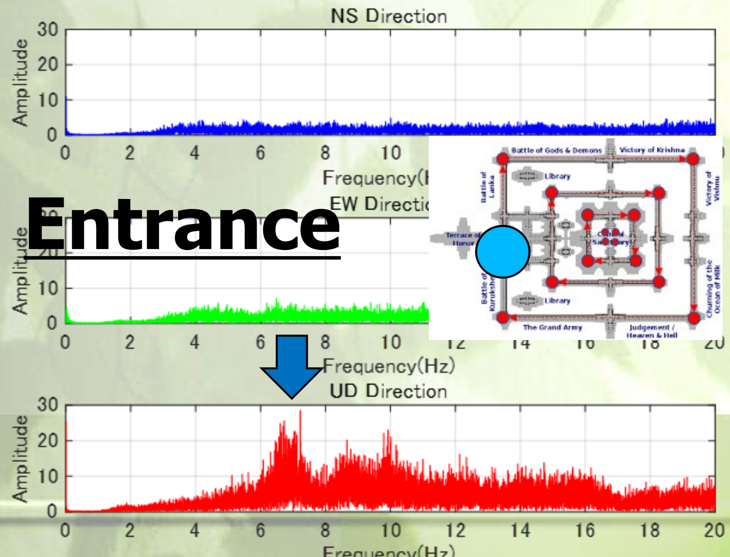
The burden of traffic is largest on the entrance, where a large number of tourists visit and walk.

Therefore, early maintenance is required.

Fourier spectrum of acceleration data at the first story corridor





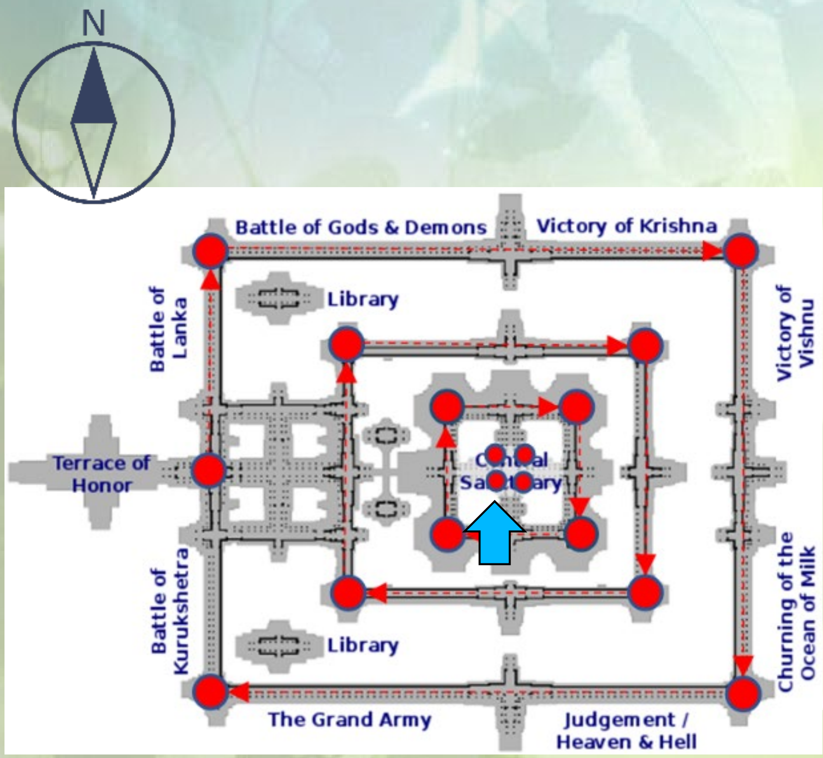


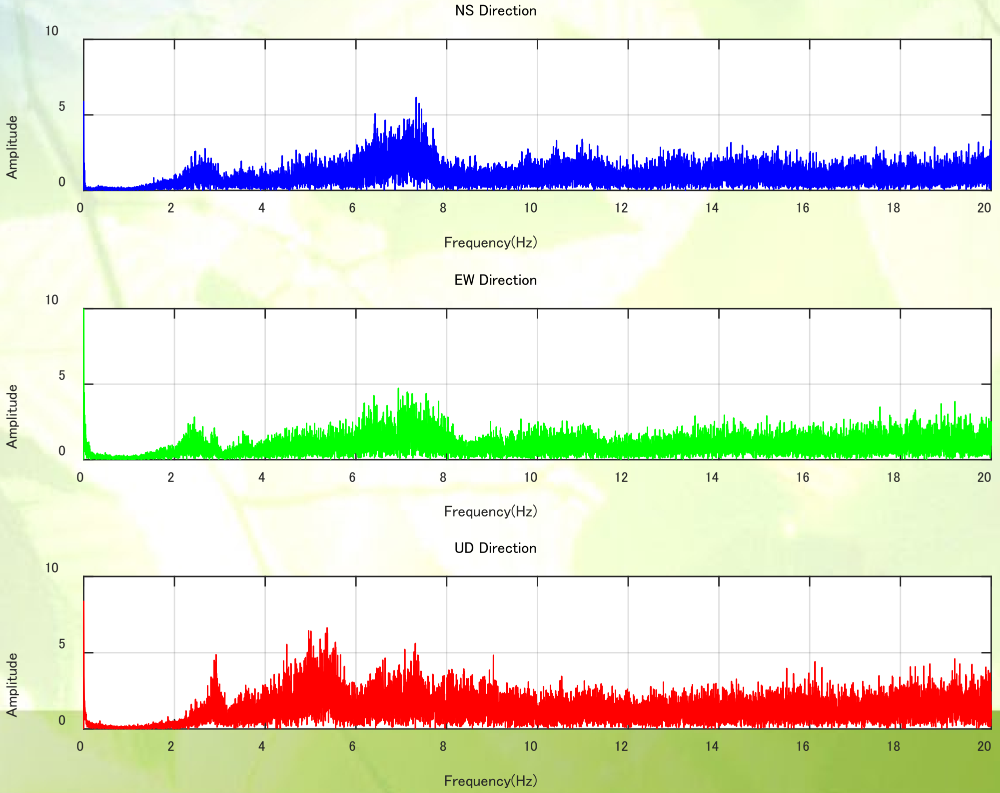
Frequency peaks are indicated by blue arrow marks.

Vibrations of 6-8 Hz are considered to be caused by tourist traffic and local vibrations.

Measurement at the third story corridor

•Fourier spectrum of the acceleration data as measured in the southwestern part of the central tower in the third story corrido.

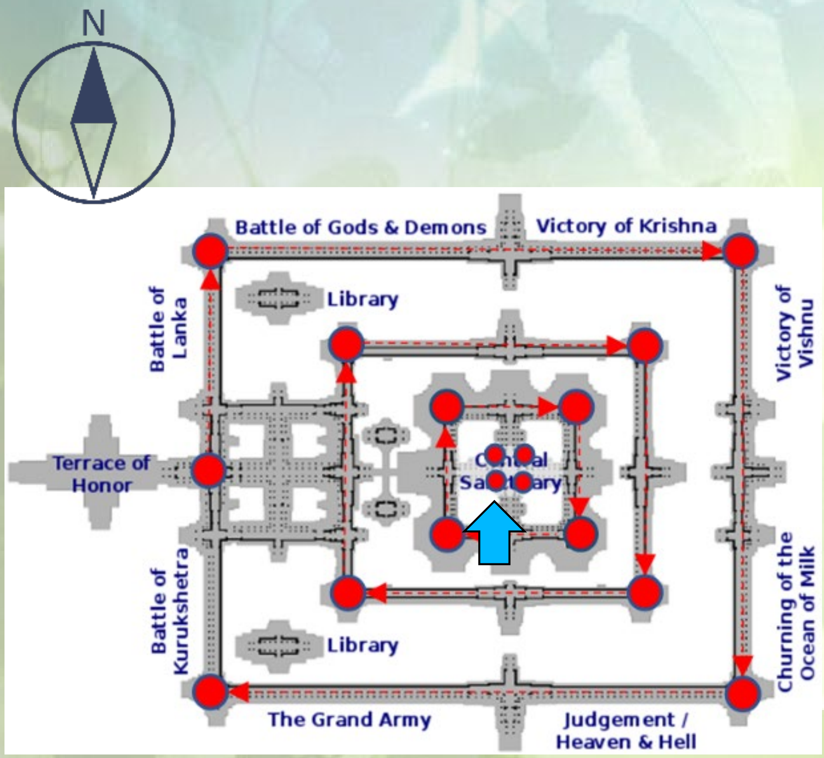


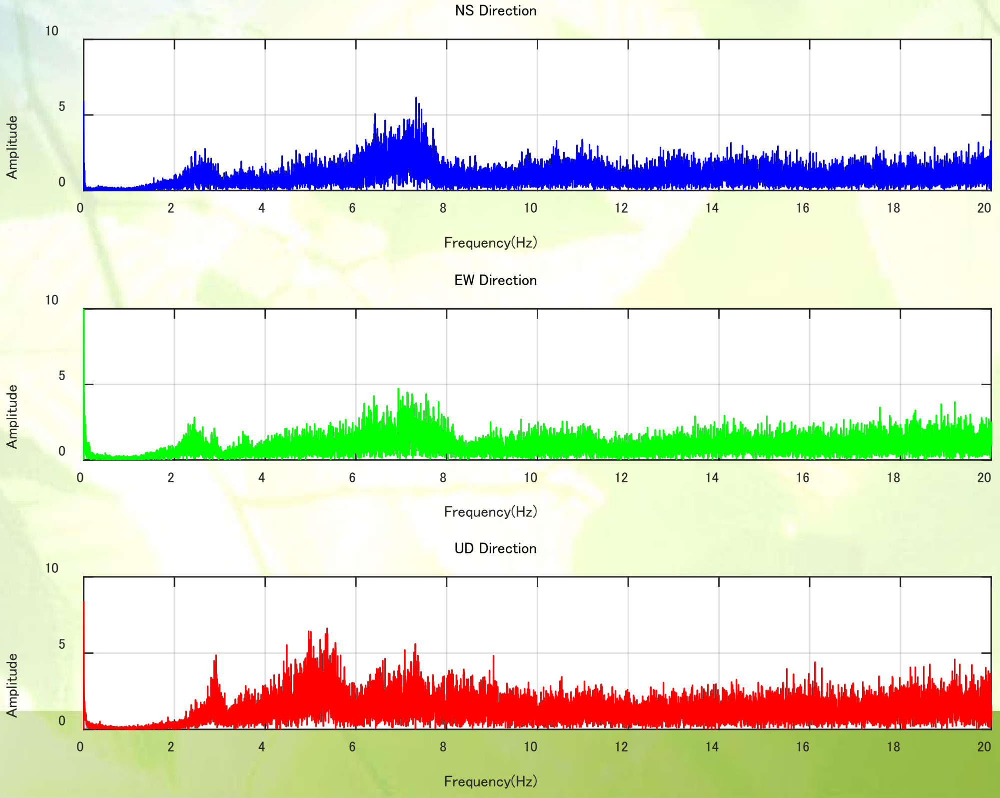


Fourier spectrum of acceleration data

Measurement at the third story corridor

•Each Figure is comprised of north-south(NS), east-west(EW), and up-down vertical direction(UD) components.

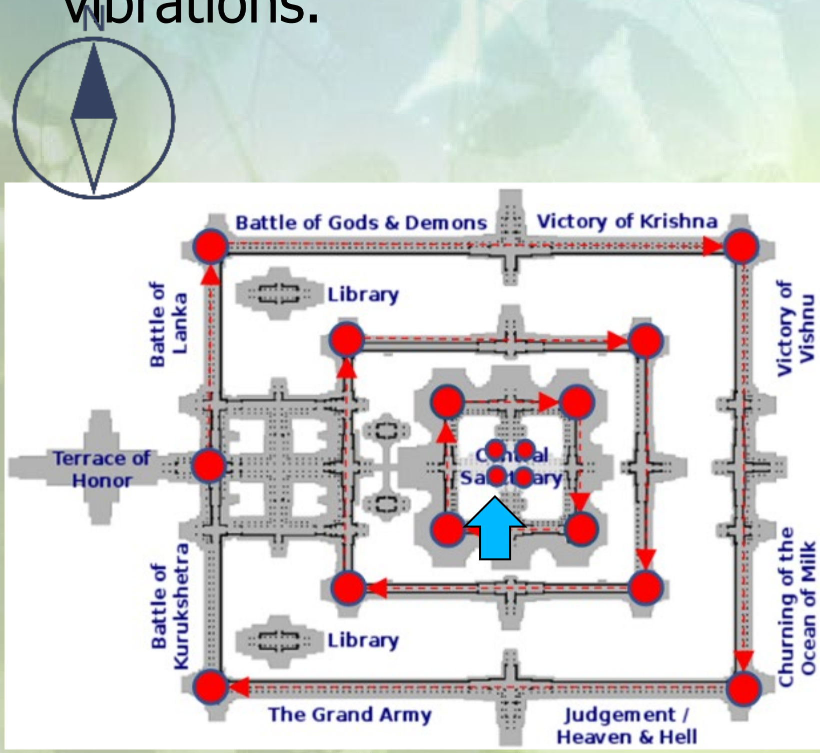


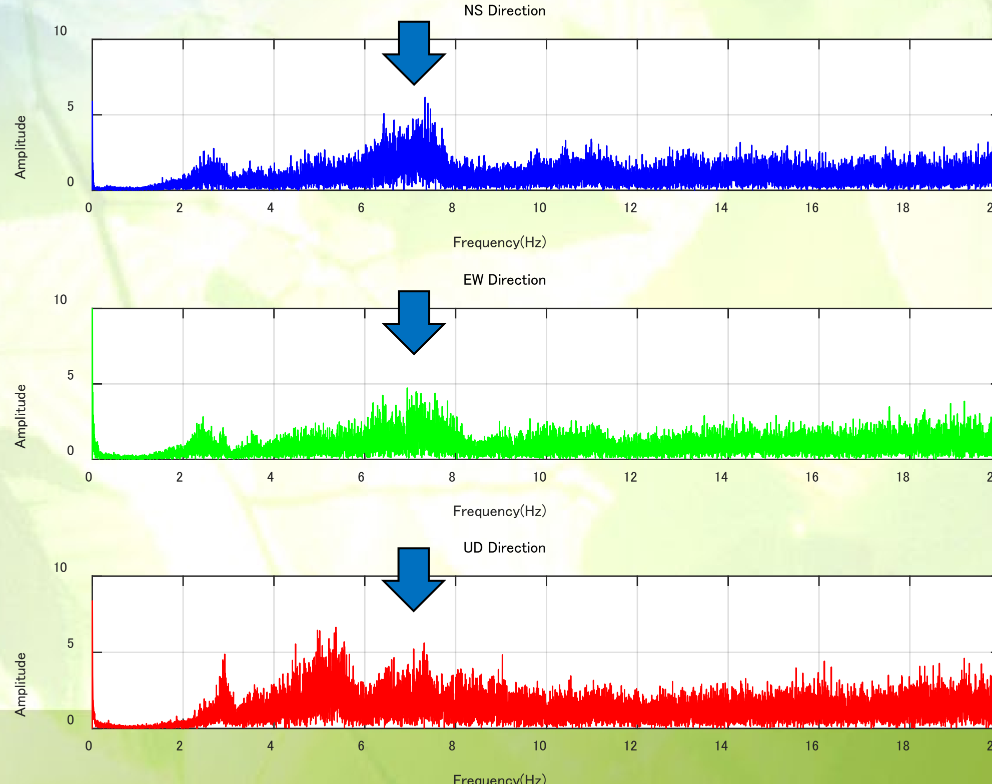


Fourier spectrum of acceleration data

Measurement at the third story corridor

•Vibrations of 6-8 Hz are considered to be caused by tourist traffic on the stairs externally attached to the third story corridor, and local vibrations.

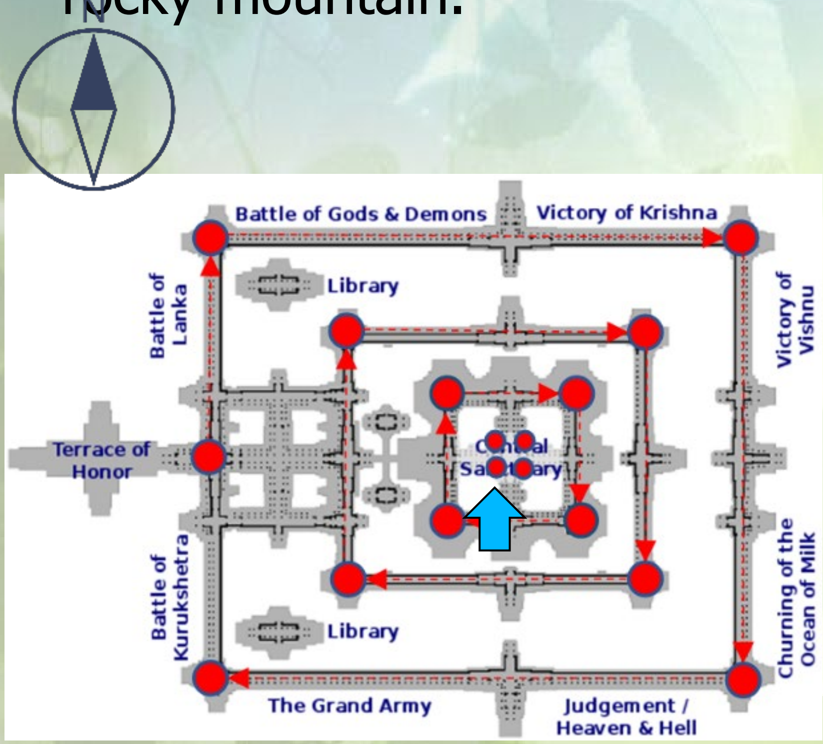


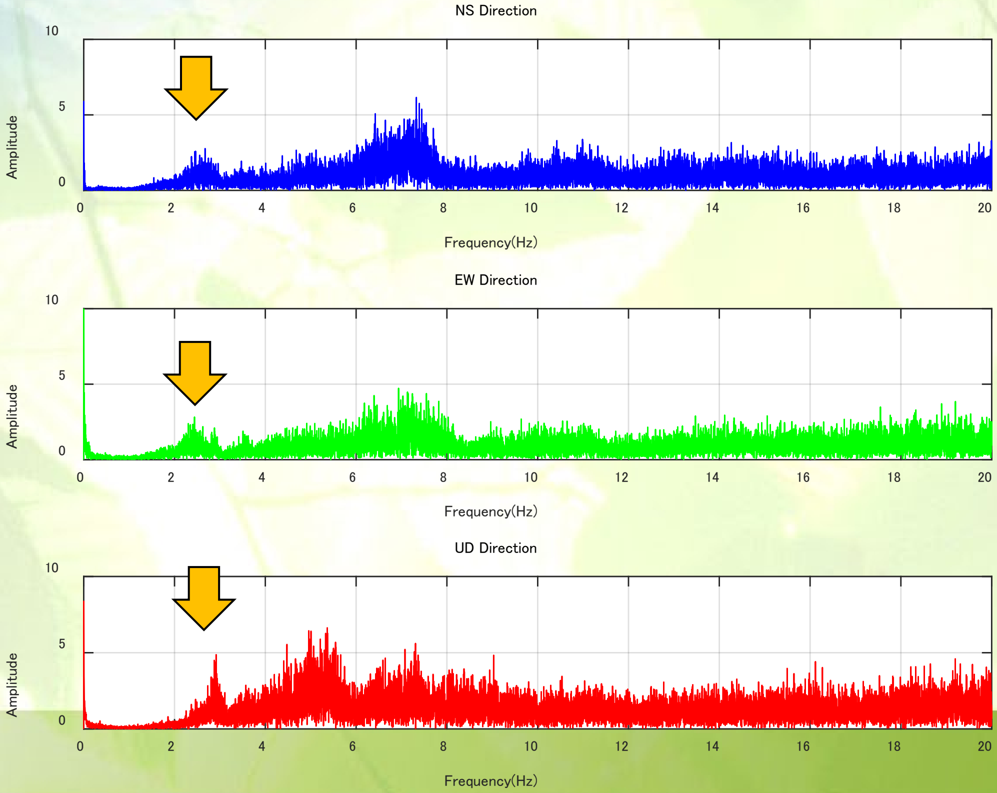


Fourier spectrum of acceleration data

Measurement at the third story corridor

•The structure of Angkor Wat at the third story corridor have a natural frequency of around 3 Hz. The structures resembles a rigid rocky mountain.

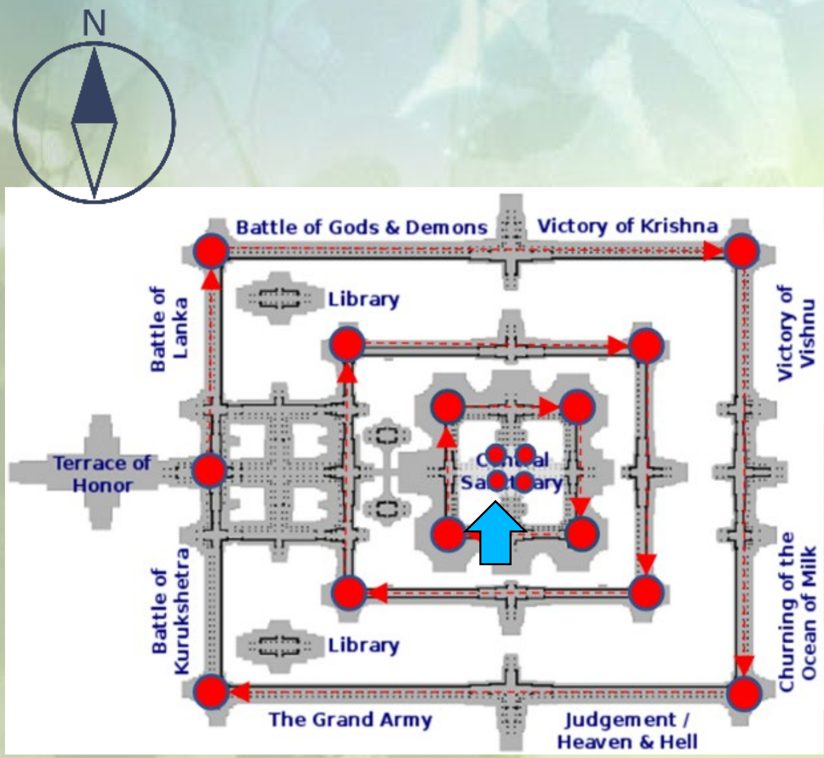


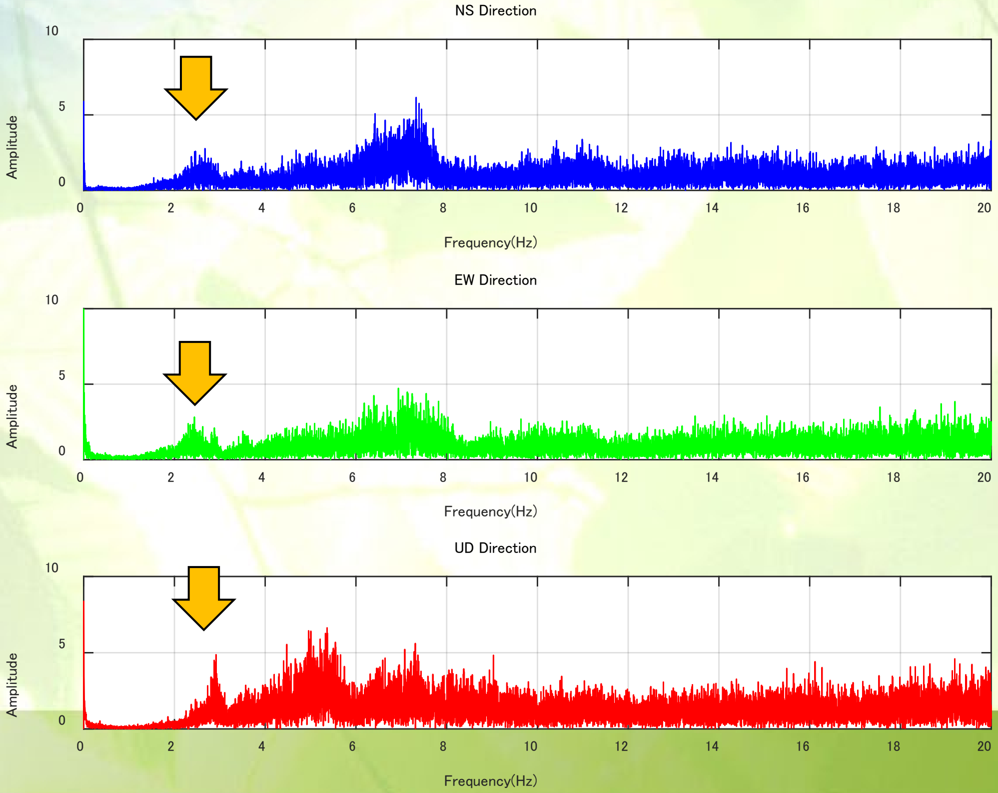


Fourier spectrum of acceleration data

Measurement at the third story corridor

•If the natural frequency moves to the lower side, stiffness will be lost, and structural deterioration and damage can be evaluated.

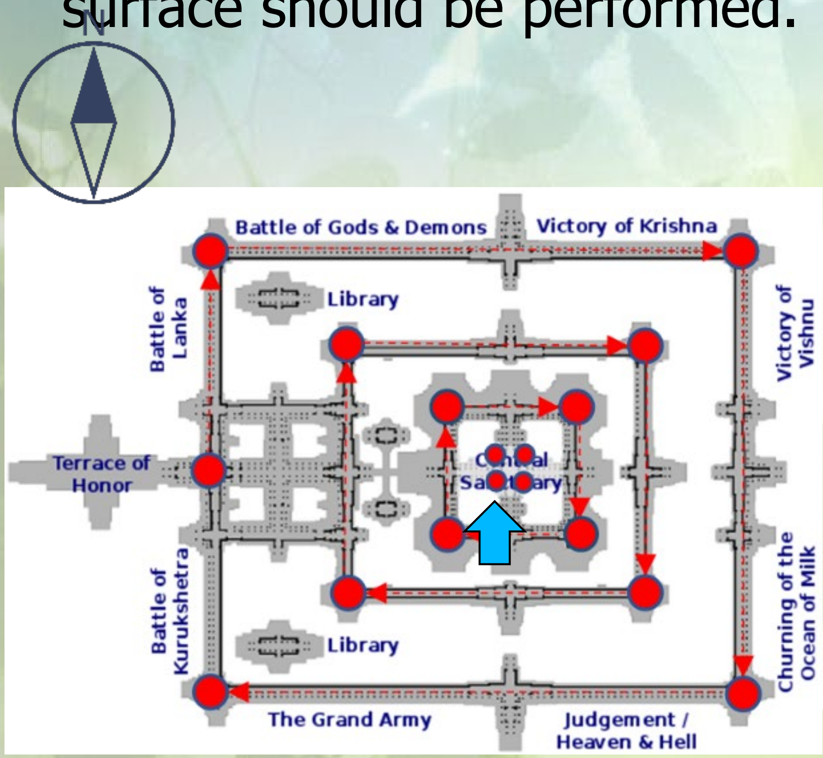


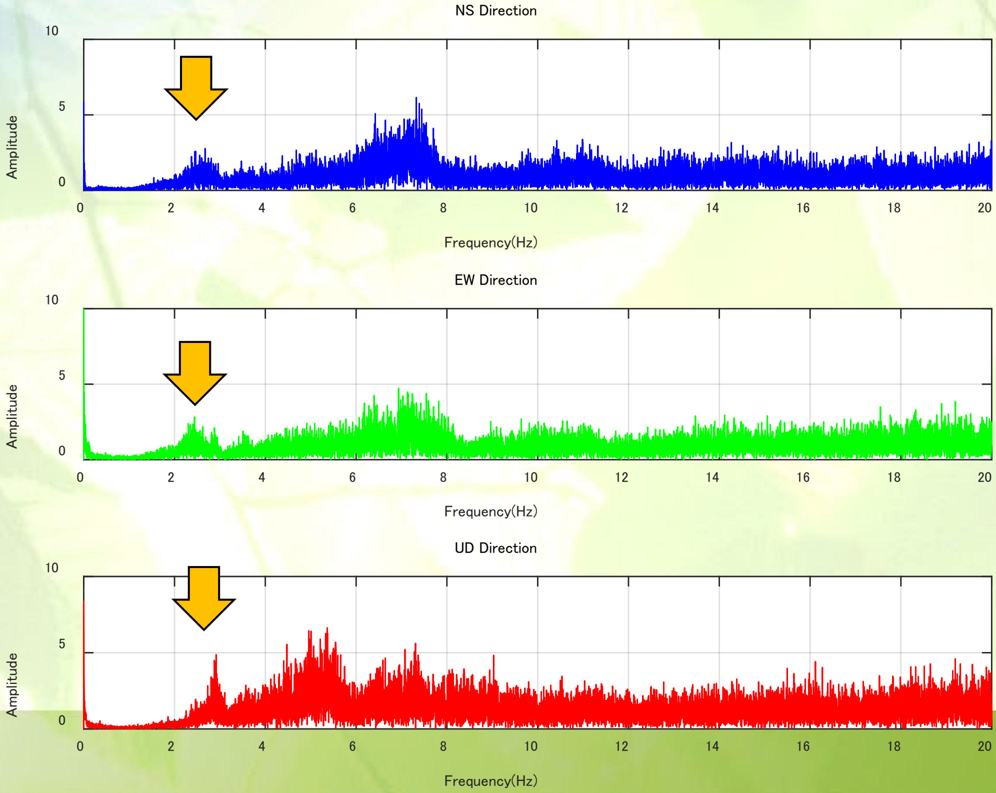


Fourier spectrum of acceleration data

Measurement at the third story corridor

•In order to accurately evaluate this kind of natural frequency, a time synchronous measurement between the structure and the ground surface should be performed.

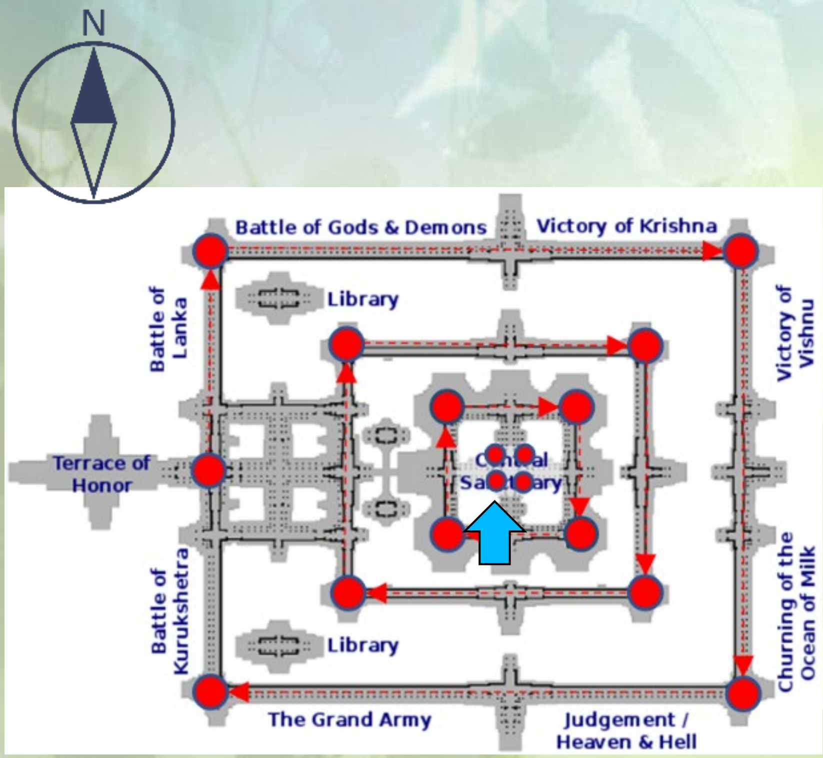


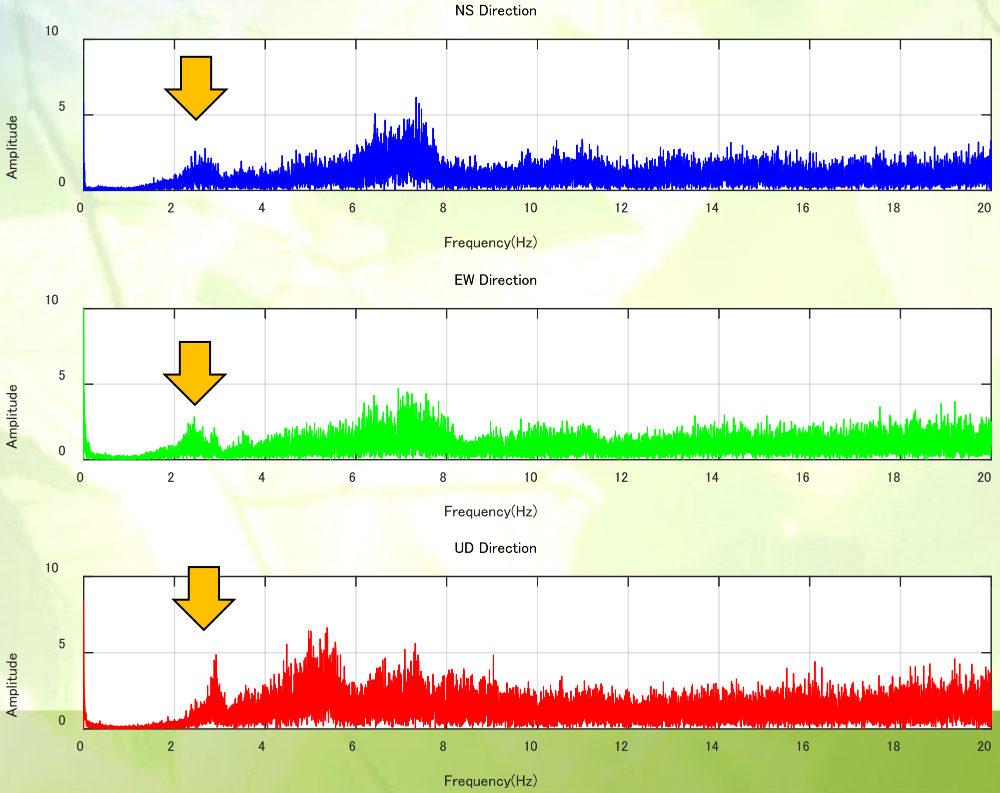


Fourier spectrum of acceleration data

Measurement at the third story corridor

•Measurements should also be taken at the tops of the five ancestral halls (at each of the four corners and the center of the corridor).





Fourier spectrum of acceleration data

Maintenance and Management of World Heritage Structures

- Accumulate and analyze data by monitoring

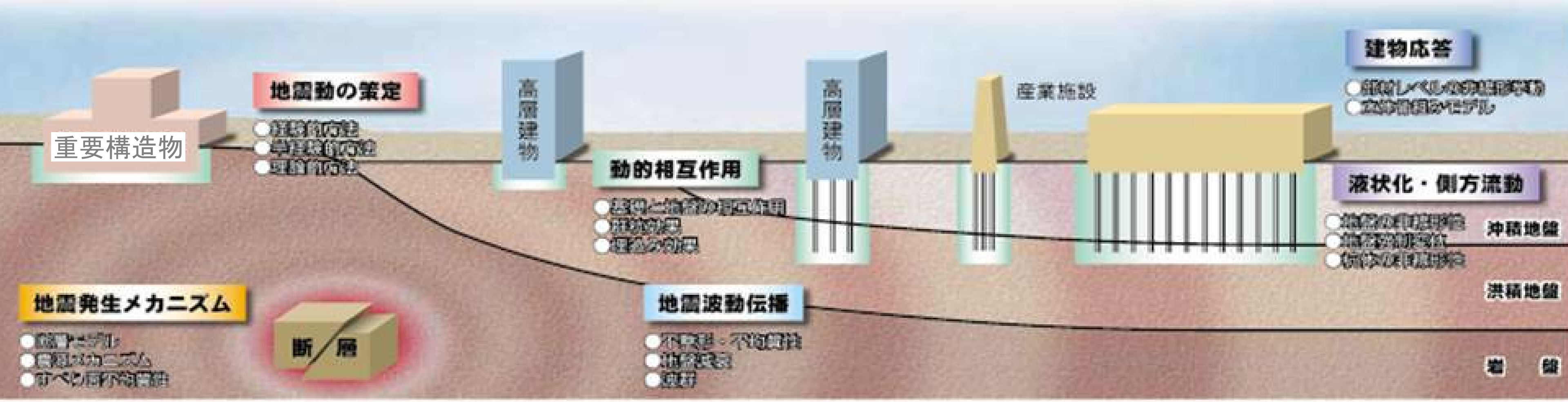
Desirable Sensor Technology for Battleship Island

- Aged deterioration of the building structure is progressing
- Autonomous energy supply system and sensor network system with low power consumption

Desirable Sensor Technology for Angkor Wat Site

- Typical sightseeing spot
- Wireless IoT sensor device with battery, and MEMS sensor with low power consumption and high accuracy

Cyber Physical Systems for Earthquake Hazard Mitigation

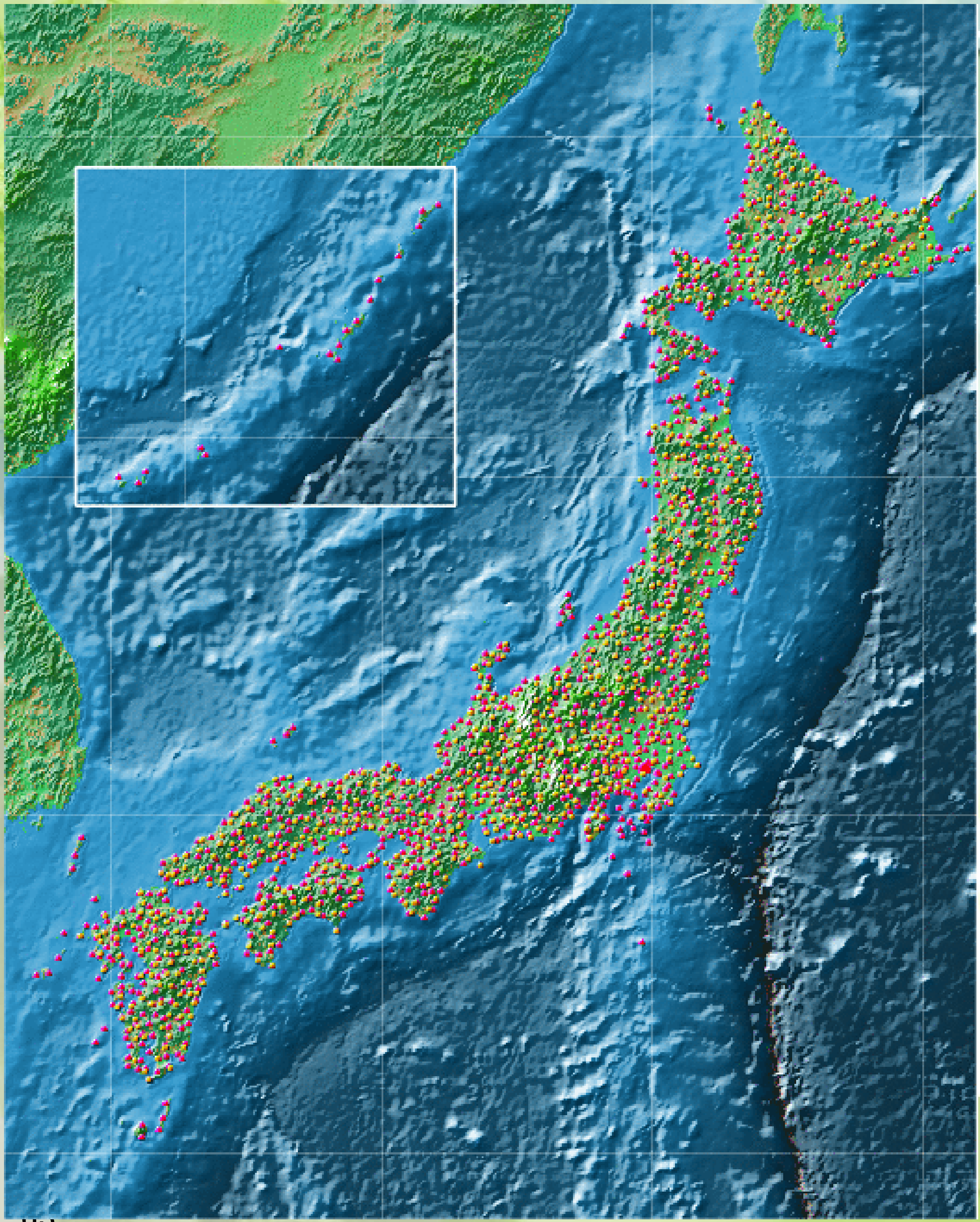


Japanese Earthquake and Tsunami

- the Great Hanshin-Awaji Earthquake in 1995
- the Great East Japan Earthquake in 2011

Great Hanshin-Awaji Earthquake (Kobe Earthquake) , 1995.1.17

- 6,434 people were killed

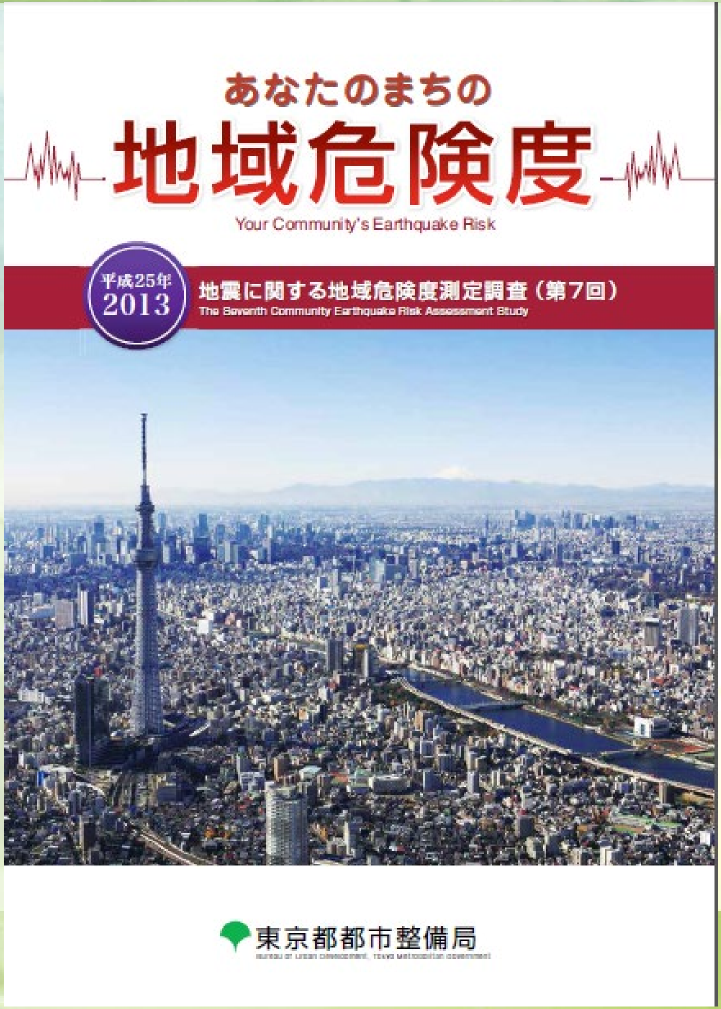


Japanese Earthquake Observation

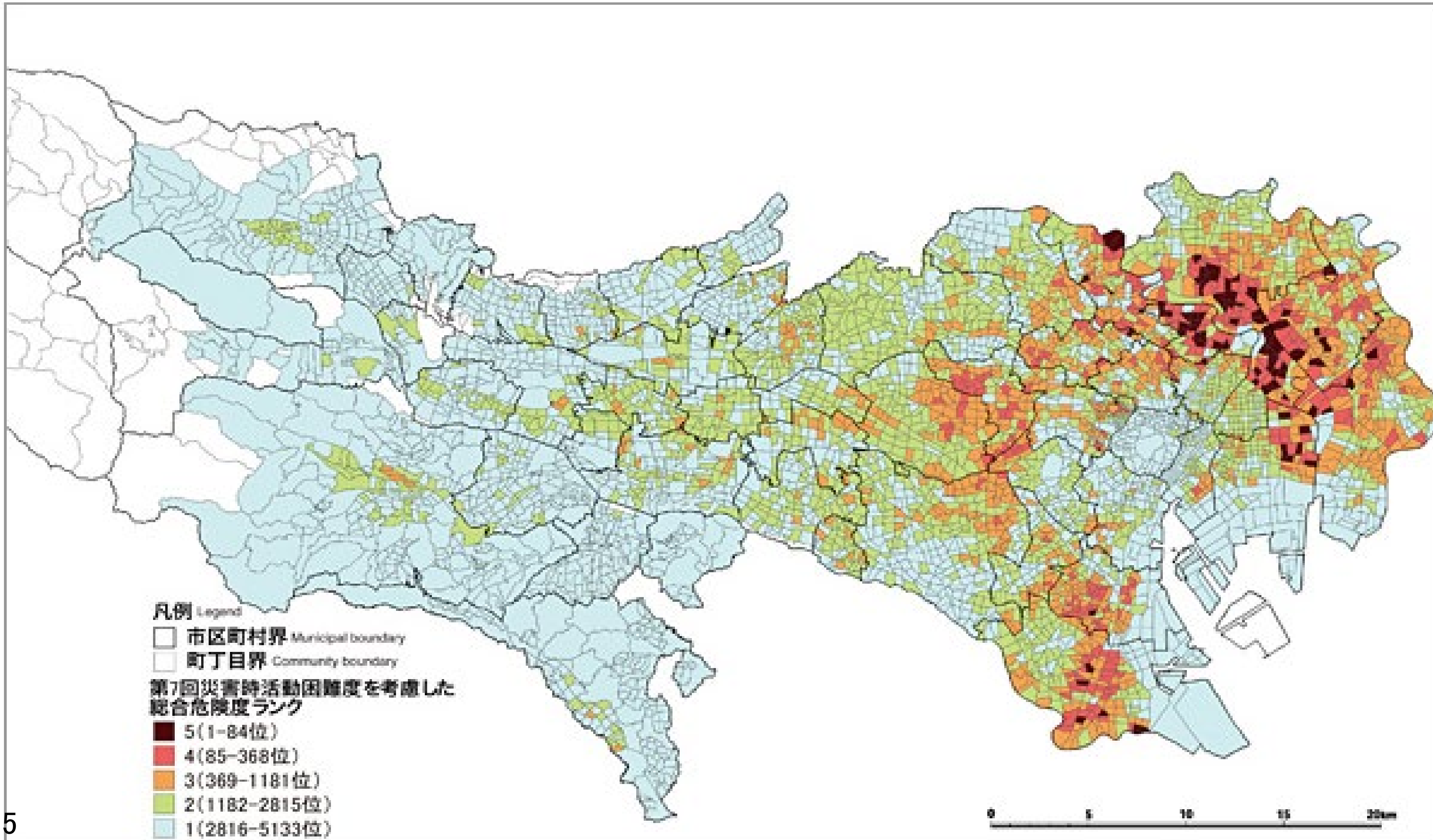
- Earthquake data is obtained from 1,742 observatories deployed all over Japan
- The average station to station distance is about 25km
- However, it is not enough for installation for all cities

http://www.bosai.go.jp/

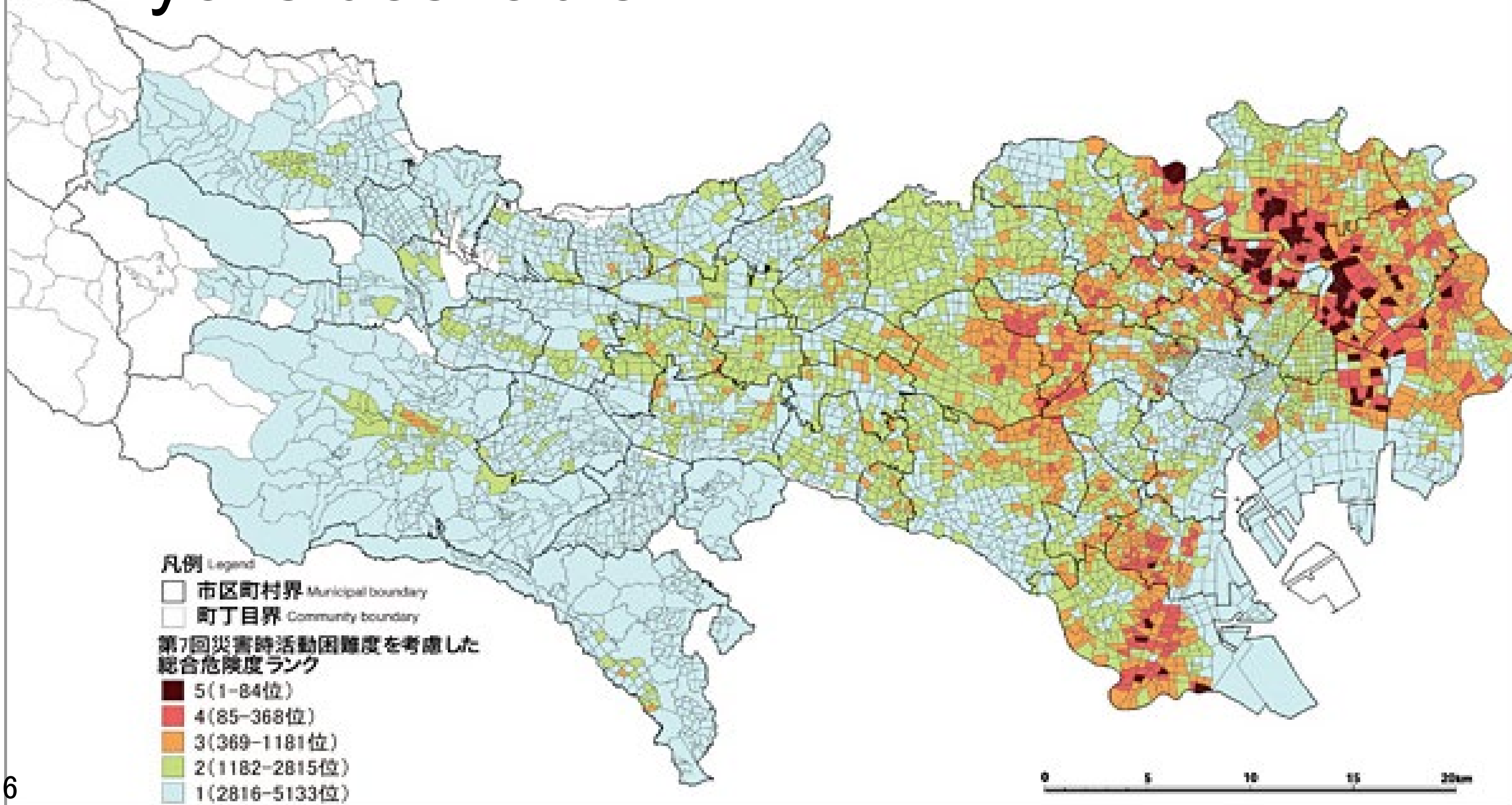
Report of Regional Hazard Measurement of Each Town in Tokyo



Total Risk Ranking of Each Town in Tokyo



Real-time risk monitoring of each town in Tokyo is desirable

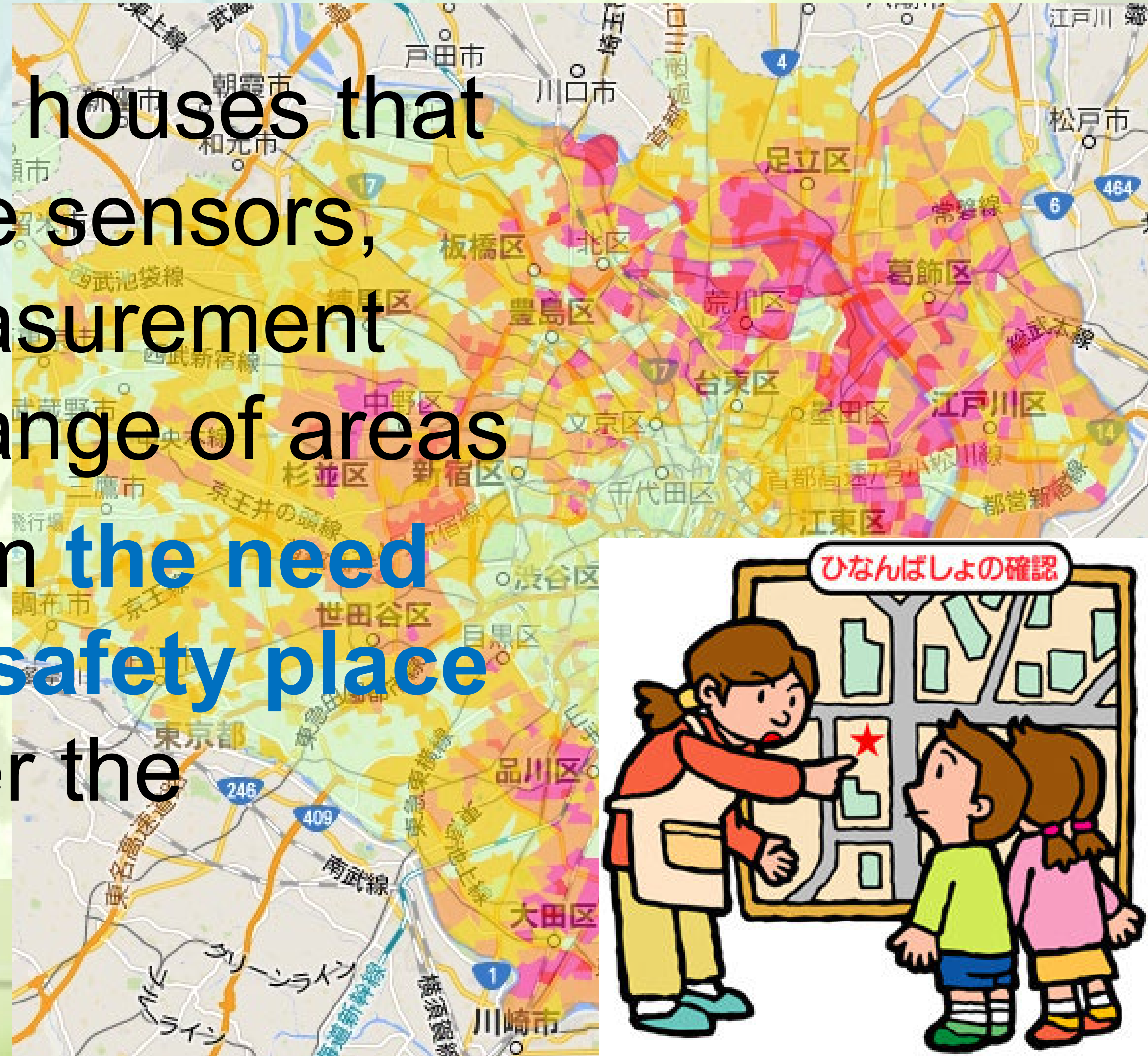


Benefits of installing earthquake sensors to all the houses

- Situation just after the earthquake can be grasped in a single house by the local government
- The data can be used in decision-making of crisis management

Benefits of installing earthquake sensors to all the houses

- Residents of the houses that have earthquake sensors, can see the measurement data of a wide range of areas
- They can confirm **the need for refuge and safety place** immediately after the earthquake

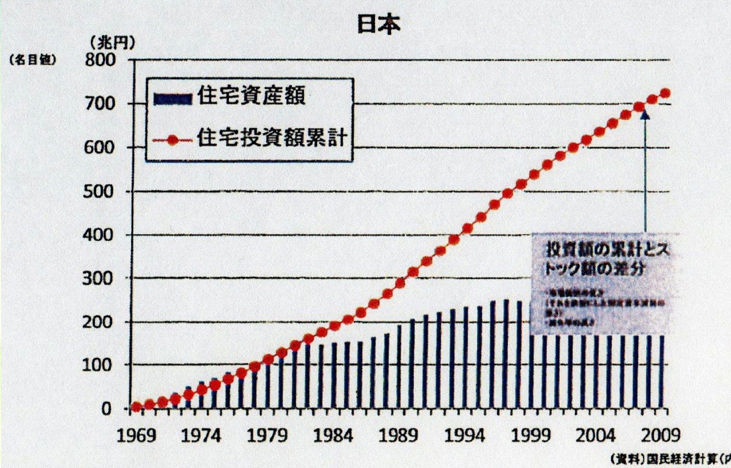


Benefits of installing earthquake sensors to all the houses



- From sensors installed on the ground (first) floor, liquefaction of the ground can be detected
- The data has a significant effect on the real estate price

Benefits of installing earthquake sensors to all the houses and buildings



- From sensors installed on the roof, earthquake data over a lifetime of house can be stored
- This data affects the price of used houses

Benefits of installing earthquake sensors to all the houses and buildings

- We can also take advantage to traffic vibration pollution caused by large trucks to pass through the road in front of the house
- This is also a serious problem to be solved

Earthquake Sensors in all Wi-Fi Hotspot in Japan

- For wide-spread deployment of sensors , collaboration with the nation-wide chain stores that offers a Wi-Fi hotspot is effective
- Just placing a sensor that can be connected to Wi-Fi, it is possible to collect earthquake data easily

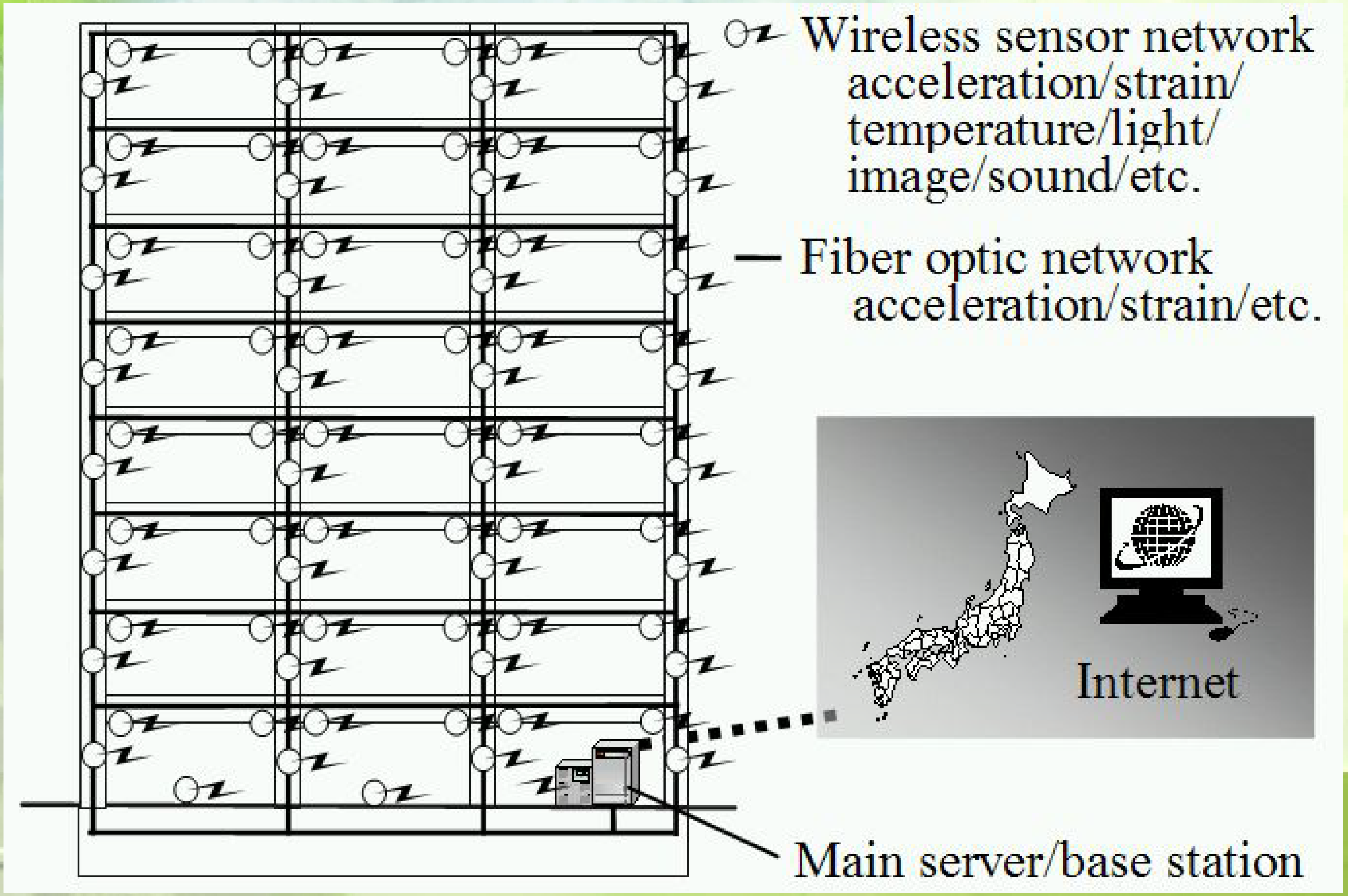
Number of Nation-Wide Chain Stores

Store Name	Number of Stores	Reference Timeframe
Seven Eleven	17,569	2017
Lawson	12,276	2017
Familymart	11,399	2017
Circle K Sunkus	6,330	2017
McDonalds	3,065	2014
Mini Stop	2,162	2017
Doutor Coffee	1,025	2017
Starbacks	1,096	2014

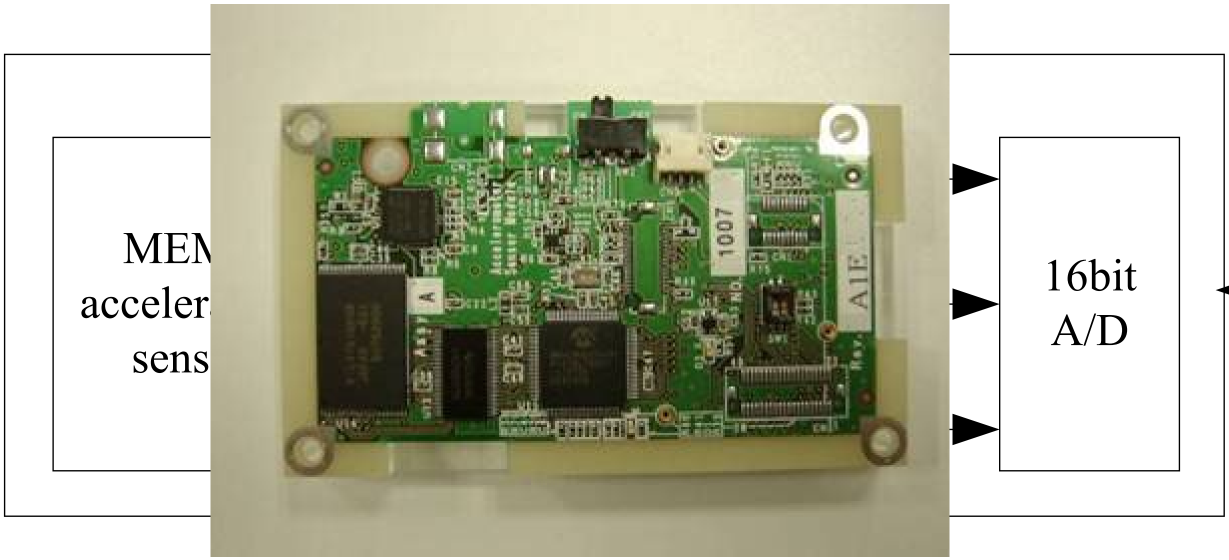
The need for accurate time information

- Accurate time information as well as location information are necessary to develop the Disaster Big Data Infrastructure and analyze the data
- Time synchronization between the sensors in a wide area is not easy
  - GPS cannot be used in the houses and buildings
  - The wire and wireless communication is limited

Sensor Networks in the Future Smart Building



Development of Wireless Sensor Network Module for Ubiquitous Structural Monitoring

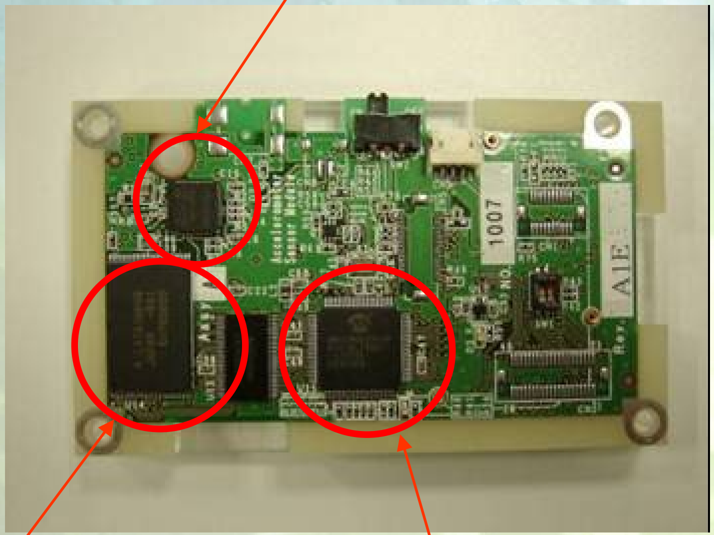


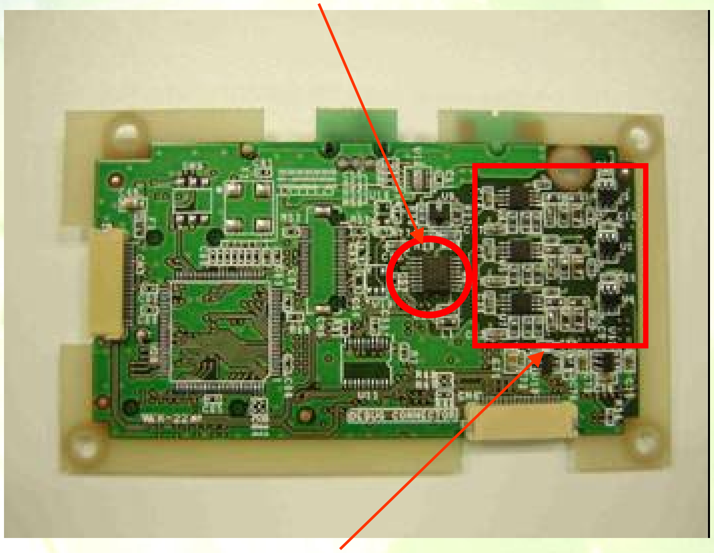
Acceleration Sensor Board

Wireless Network Module

Kurata N, Suzuki M, Saruwatari S, Morikawa H. Application of Ubiquitous Structural Monitoring System by Wireless Sensor Networks to Actual High-rise Building. Proc. of 5th World Conference on Structural Control and Monitoring. 2010

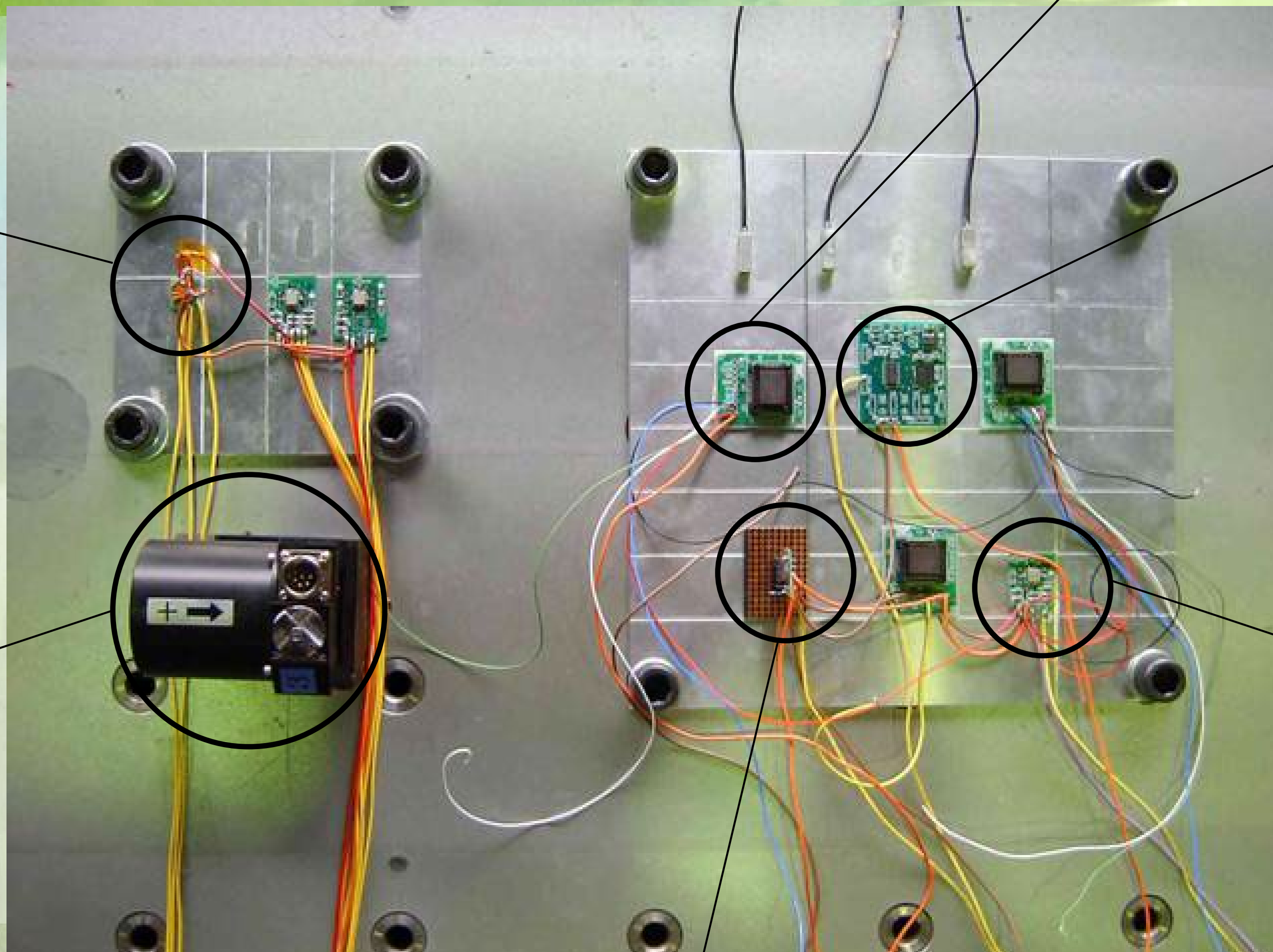
Development of Sensor Board



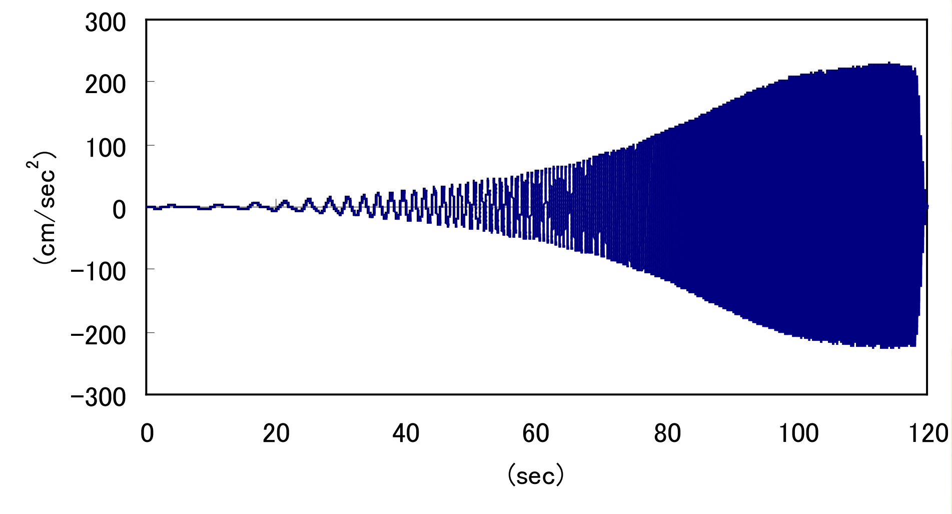


Kurata N, Suzuki M, Saruwatari S, Morikawa H. Application of Ubiquitous Structural Monitoring System by Wireless Sensor Networks to Actual High-rise Building. Proc. of 5th World Conference on Structural Control and Monitoring. 2010

Benchmark Test for MEMS Sensor chips



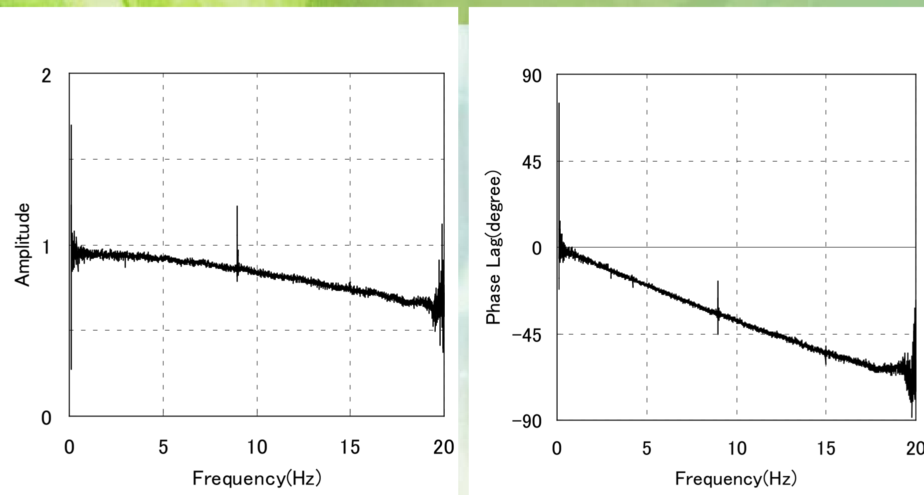
Input wave: Swept sine with 0.1 to 20Hz



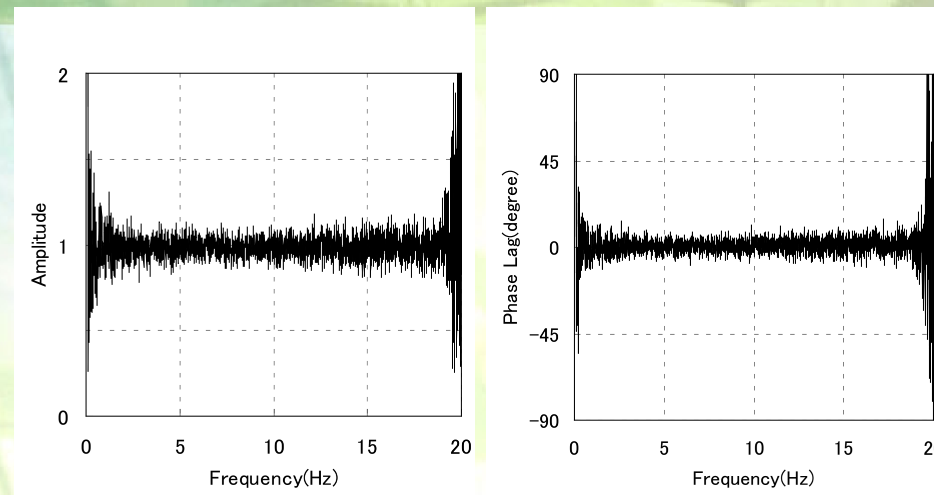
<u>The sampling was 100 Hz and the 16 bit A/D converter was used in the test</u>

Performance of MEMS Sensors

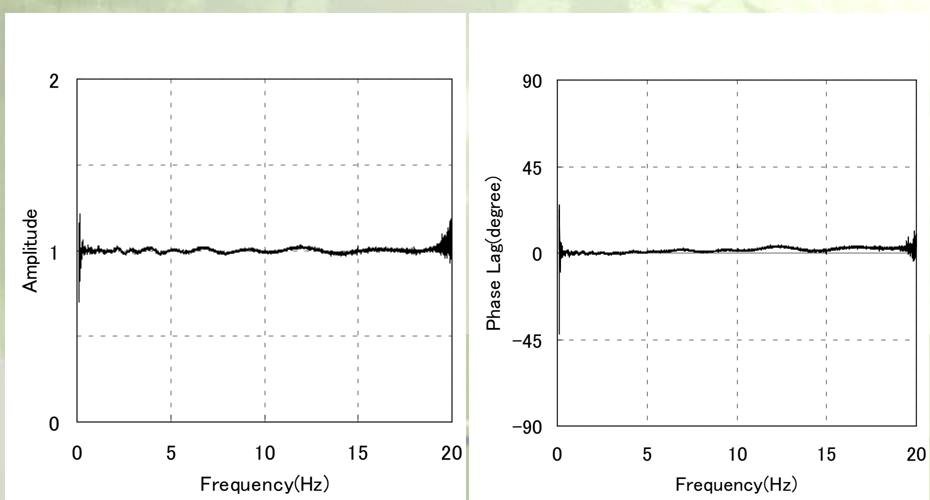
Sensor #1



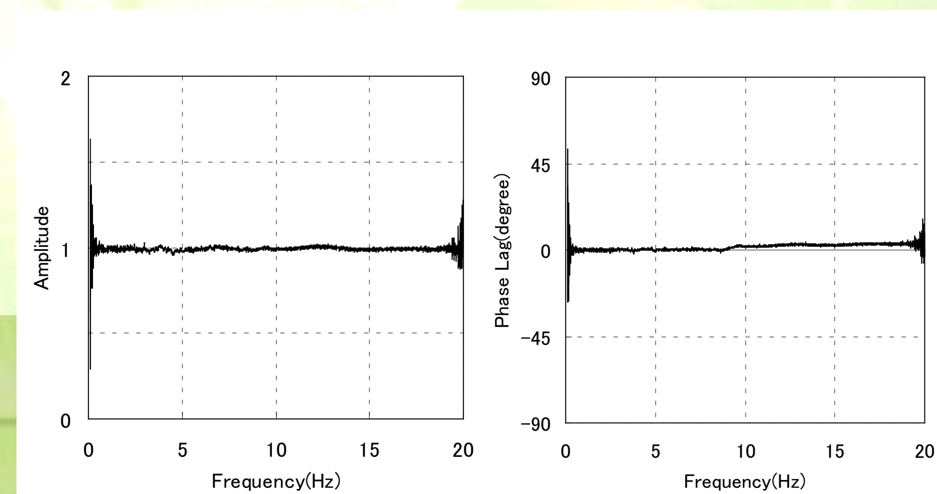
Sensor #2



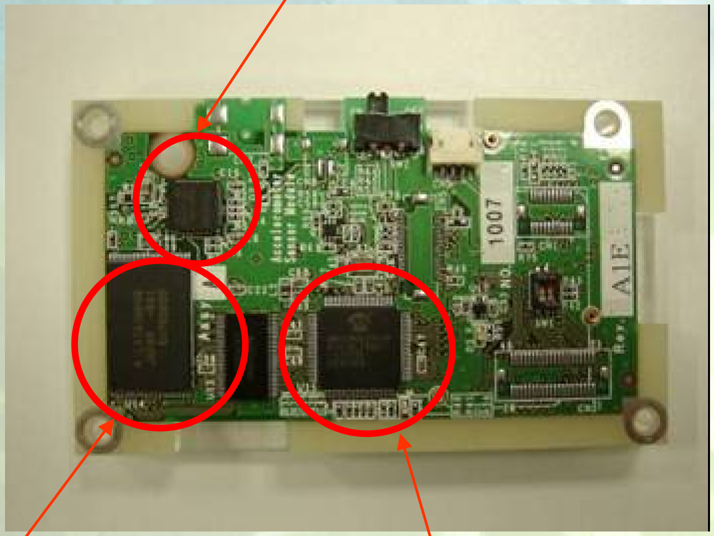
Sensor #3

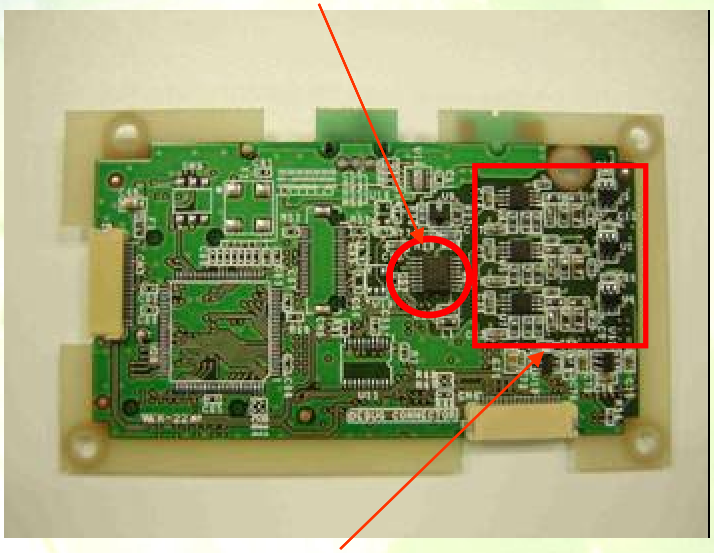


Sensor #4



Development of Sensor Board



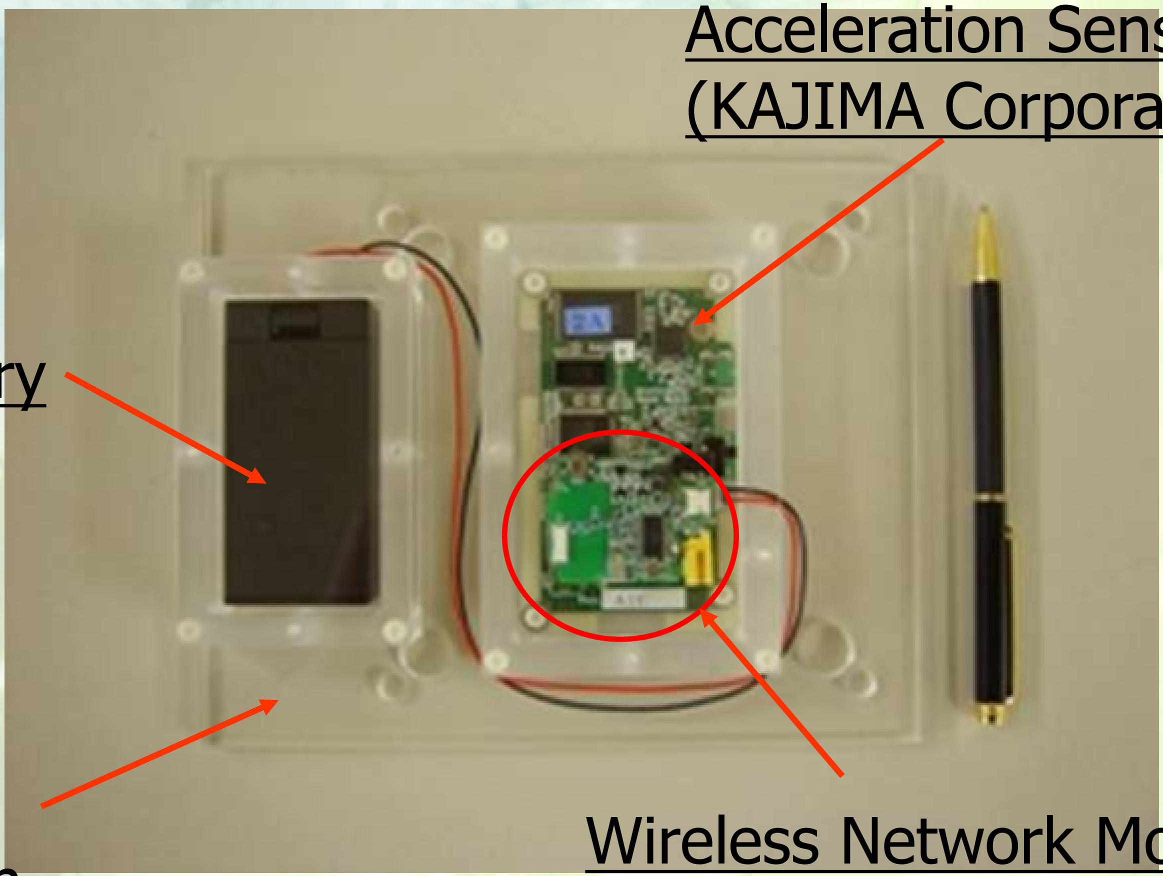


Kurata N, Suzuki M, Saruwatari S, Morikawa H. Application of Ubiquitous Structural Monitoring System by Wireless Sensor Networks to Actual High-rise Building. Proc. of 5th World Conference on Structural Control and Monitoring. 2010

Package of Wireless Sensor Network Module for Ubiquitous Structural Monitoring

Acceleration Sensor Board
(KAJIMA Corporation)

Battery

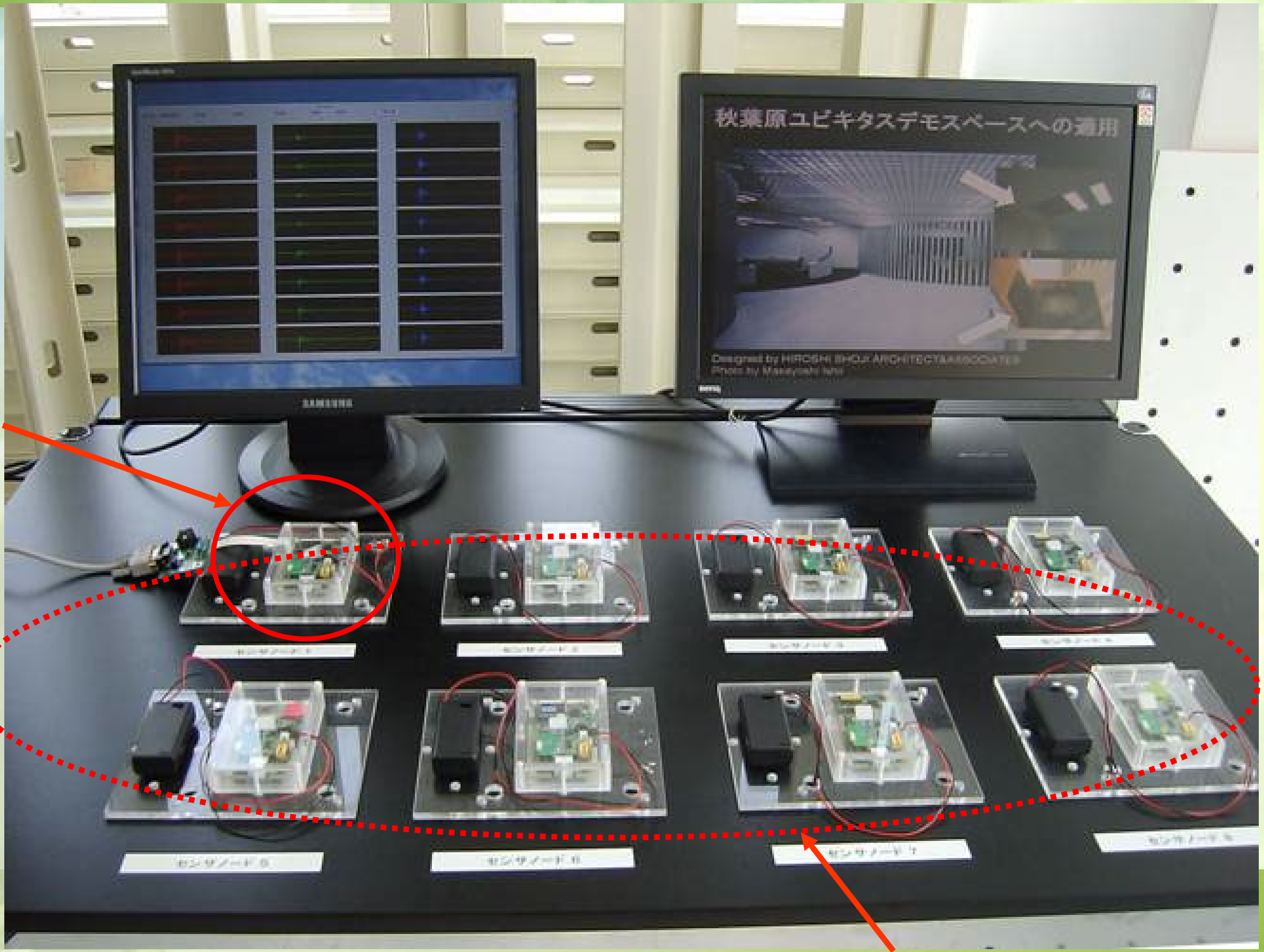


Casing for
Installation

Wireless Network Module

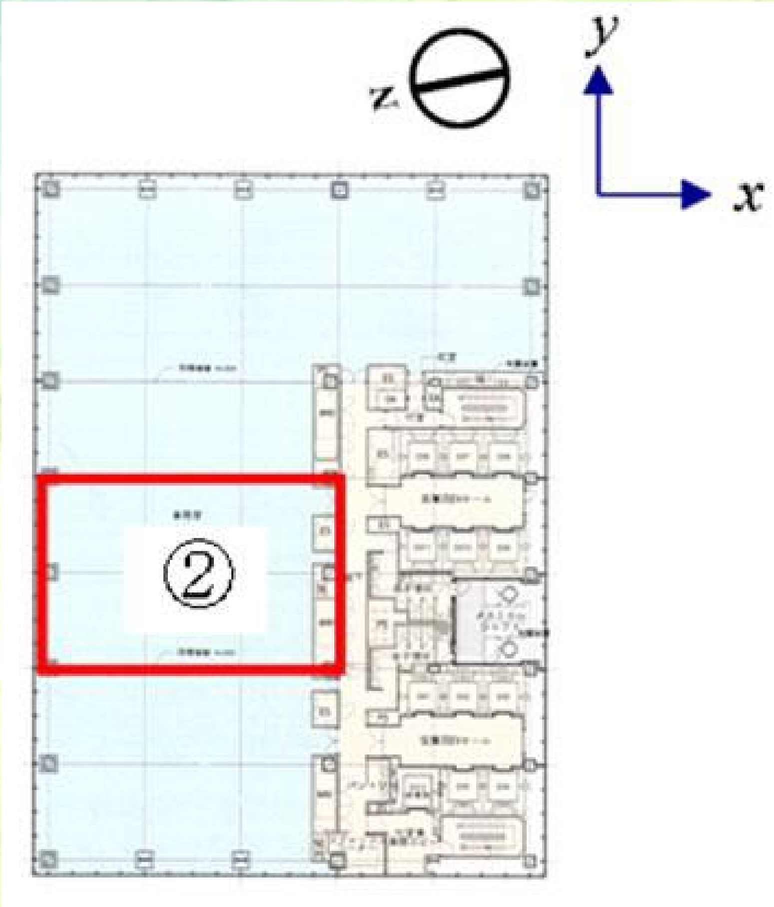
Ubiquitous Structural Monitoring System

Sink node



Sensor nodes

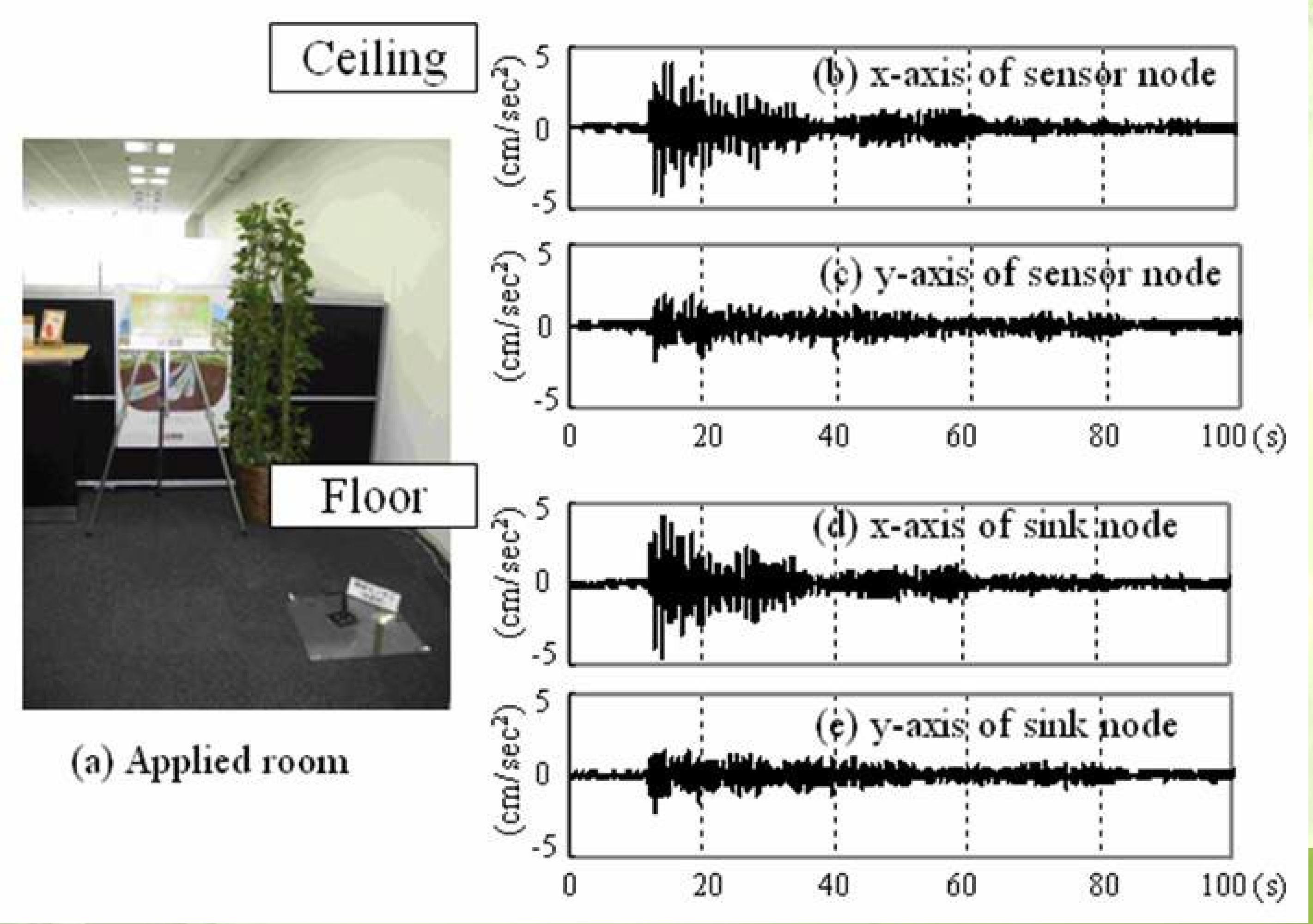
Applied to High-rise Building in Akihabara, Tokyo



Installation

Kurata N, Suzuki M, Saruwatari S, Morikawa H. Application of Ubiquitous Structural Monitoring System by Wireless Sensor Networks to Actual High-rise Building. Proc. of 5th World Conference on Structural Control and Monitoring. 2010

Example of Actual Earthquake Record



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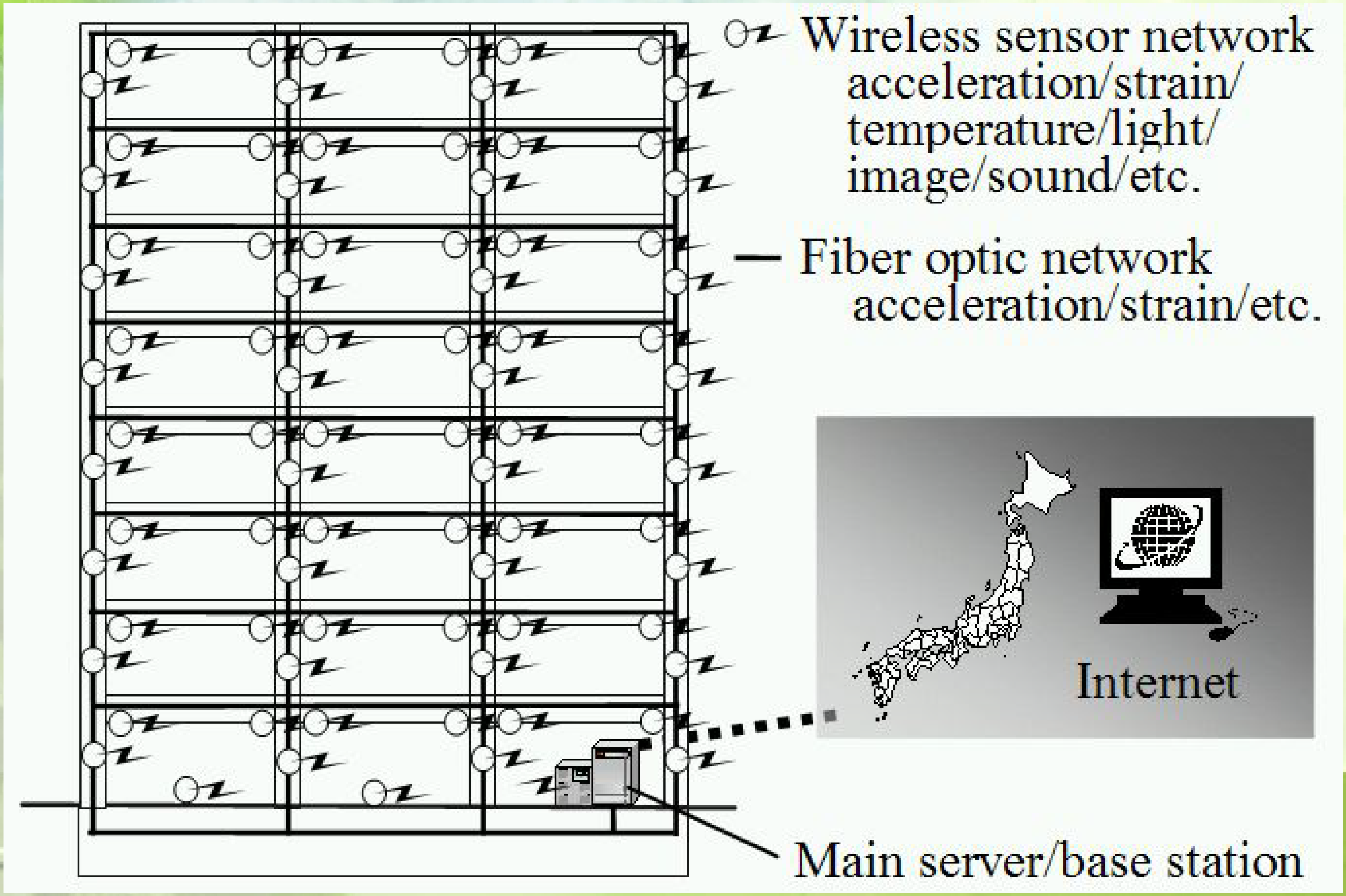
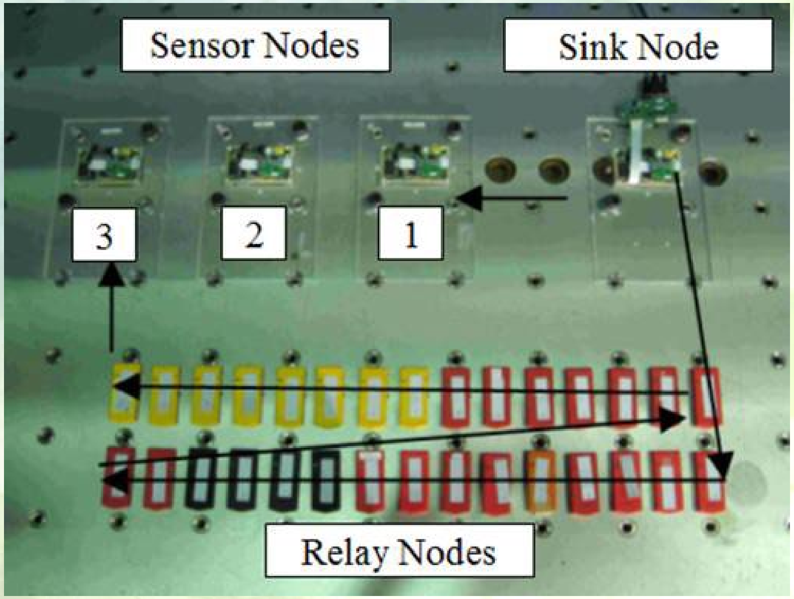
Sensor Networks in the Future Smart Building

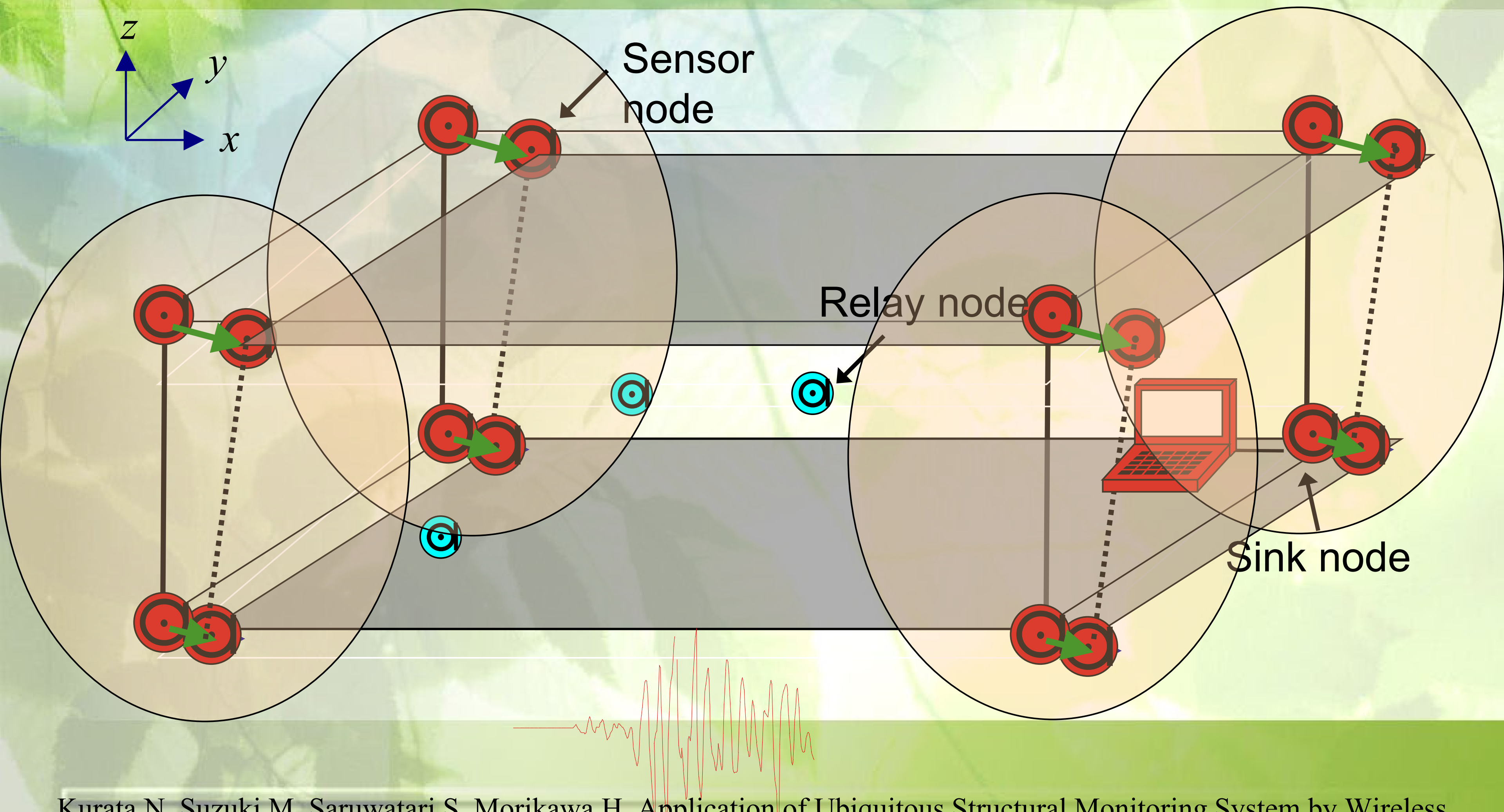


Verification of Ad-hoc Multi-hop Communication by Shaking Table



- Swept sine wave with 0.2 to 20 Hz was input to the shaking table
- Sensor node 1 received synchronization packets from sink node by single hop
- Sensor node 3 received them by multi-hop through thirty relay nodes

Experiment of Ad Hoc Network and Multi-hop Communication Function



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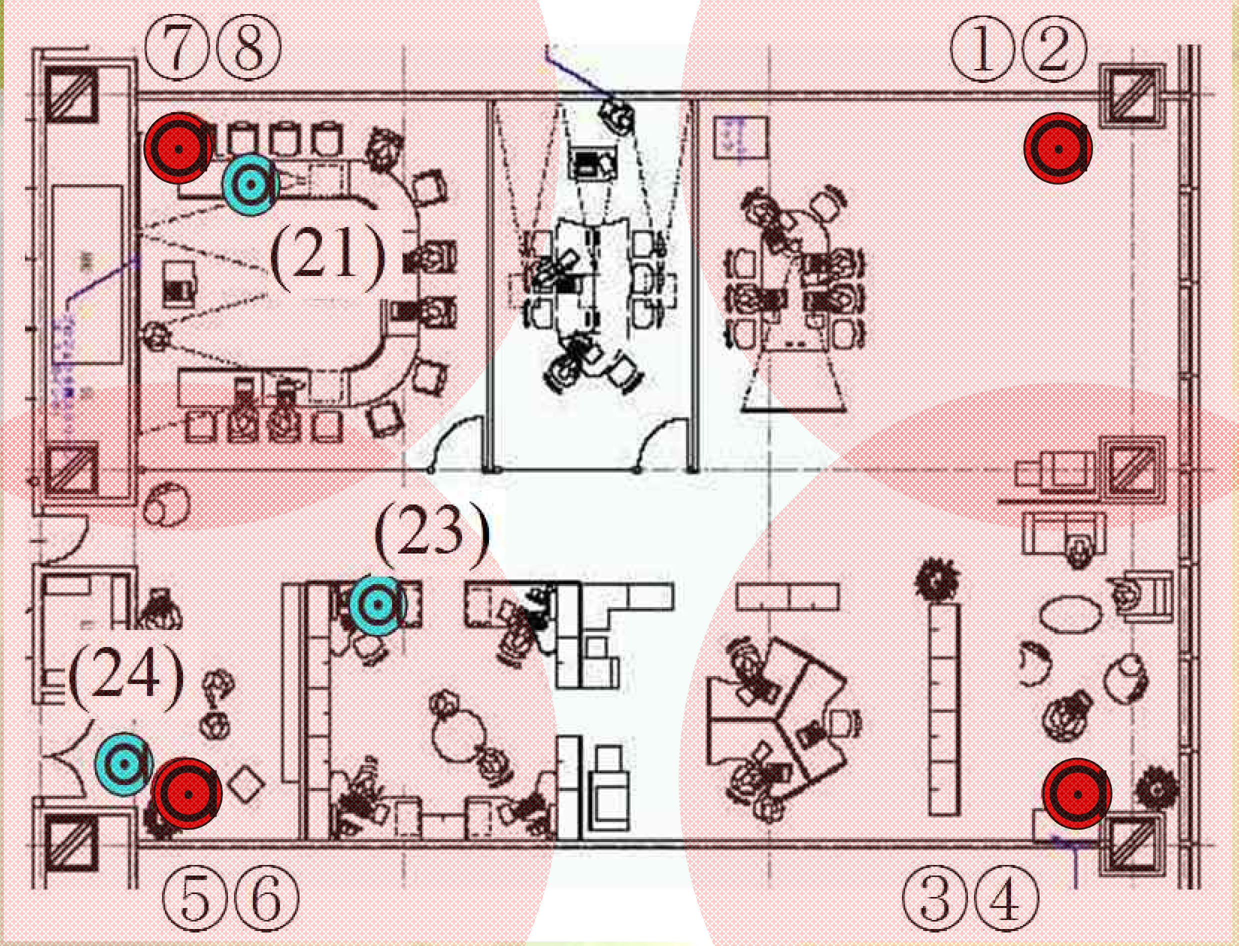

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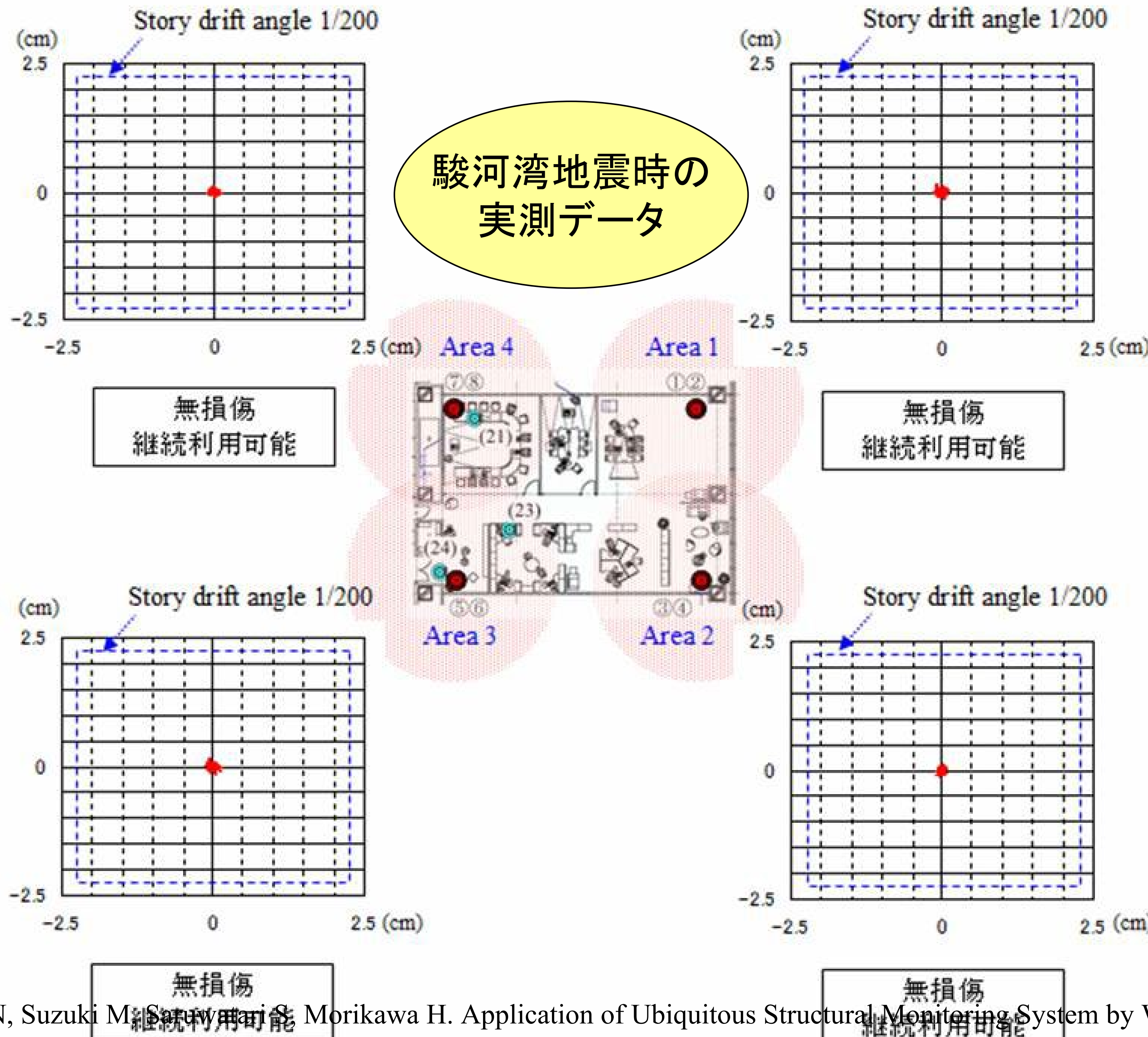


Kurata N, Suzuki M, Saruwatari S, Morikawa H. Application of Ubiquitous Structural Monitoring System by Wireless Sensor Networks to Actual High-rise Building. Proc. of 5th World Conference on Structural Control and Monitoring. 2010

The need for accurate time information

- Accurate time information as well as location information are necessary to develop the Disaster Big Data Infrastructure and analyze the data
- Time synchronization between the sensors in a wide area is not easy
  - GPS cannot be used in the houses and buildings
  - The wire and wireless communication is limited
- It is desirable that the sensor itself has autonomously accurate time information

Development of a Sensor Module Equipped with an Atomic Clock

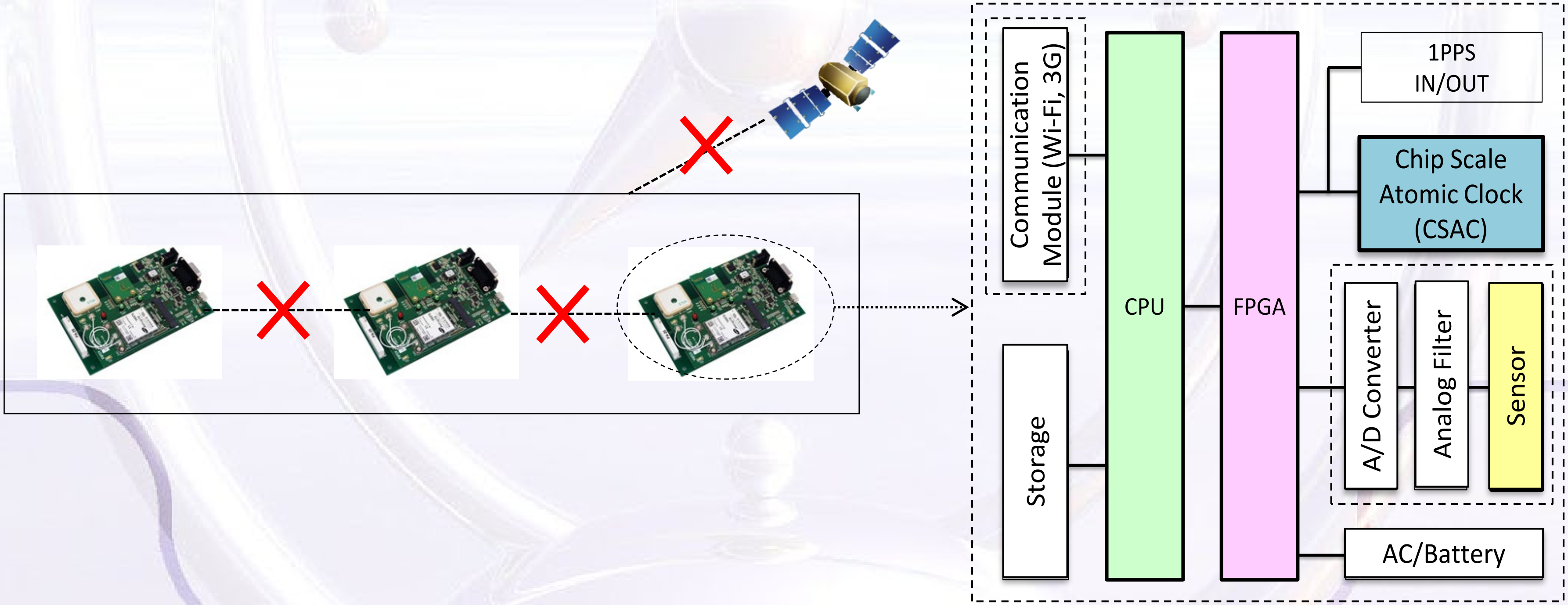
Chip Scale Atomic Clock (CSAC) is available

- Comparison among various atomic clocks and oscillator

	Cesium atomic clock	Rubidium atomic clock	CSAC	Crystal oscillator
Time for 1-sec. delay	50,000 years	1000 years	1000 years	One day
Size	0.1 m^3	1000 cm^3	17 cm^3	10 mm^3
Power consumption	50 W	Several 10 W	120 mW	10 μW

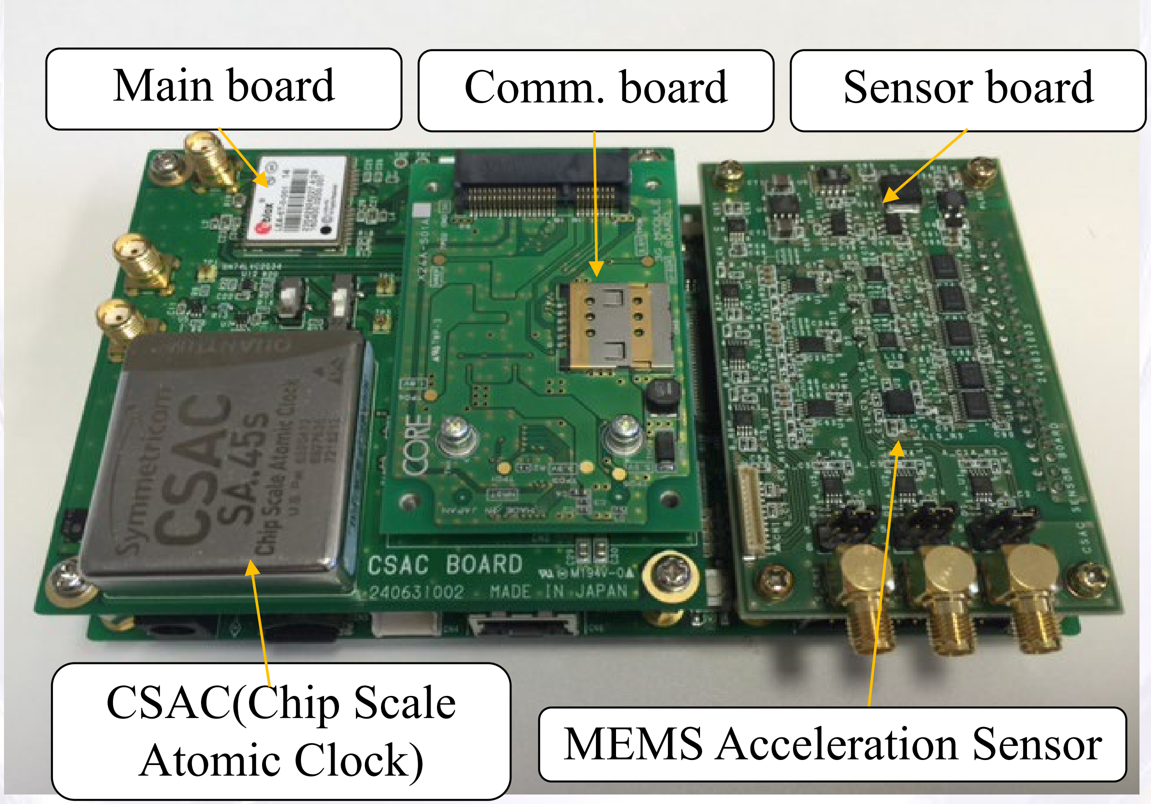
Autonomous Time Synchronization Sensing Technology Applying the CSAC

- Sensor module architecture that realizes a high precision time index
- Applied to a wide variety of sensors



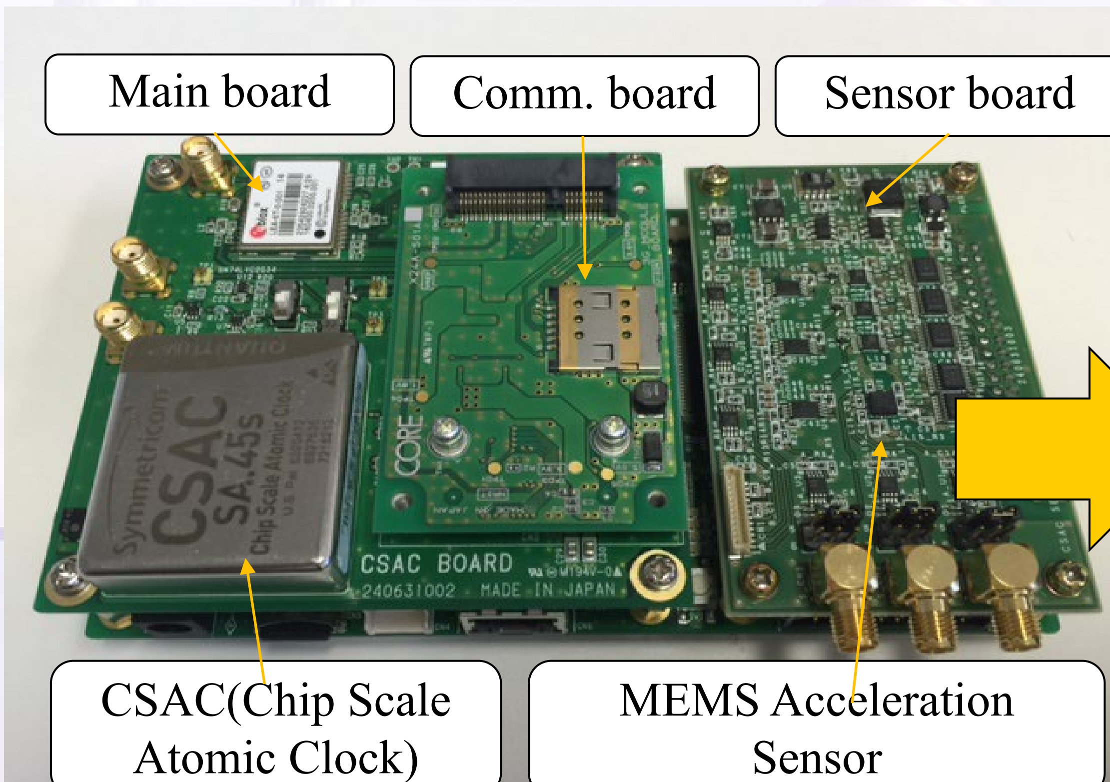
Development of Prototype Sensor Module with CSAC

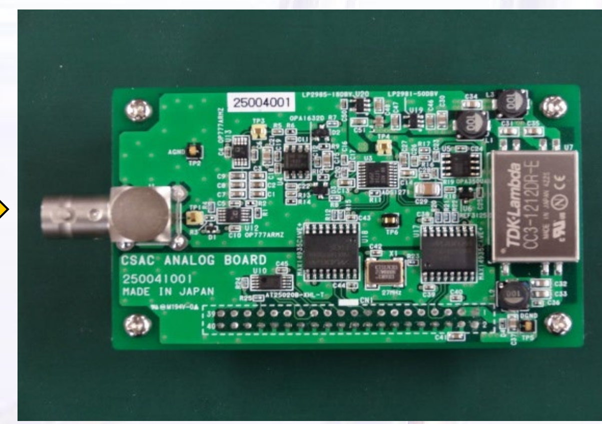
- It consists of Main board with CSAC, Communication board with Wi-Fi, 3G, Ethernet, and Sensor board with MEMS acceleration sensor



CSAC Module can be used as a data logger

- Sensor board with MEMS acceleration sensor can be exchanged with external input board
- Any analog sensors can be connected



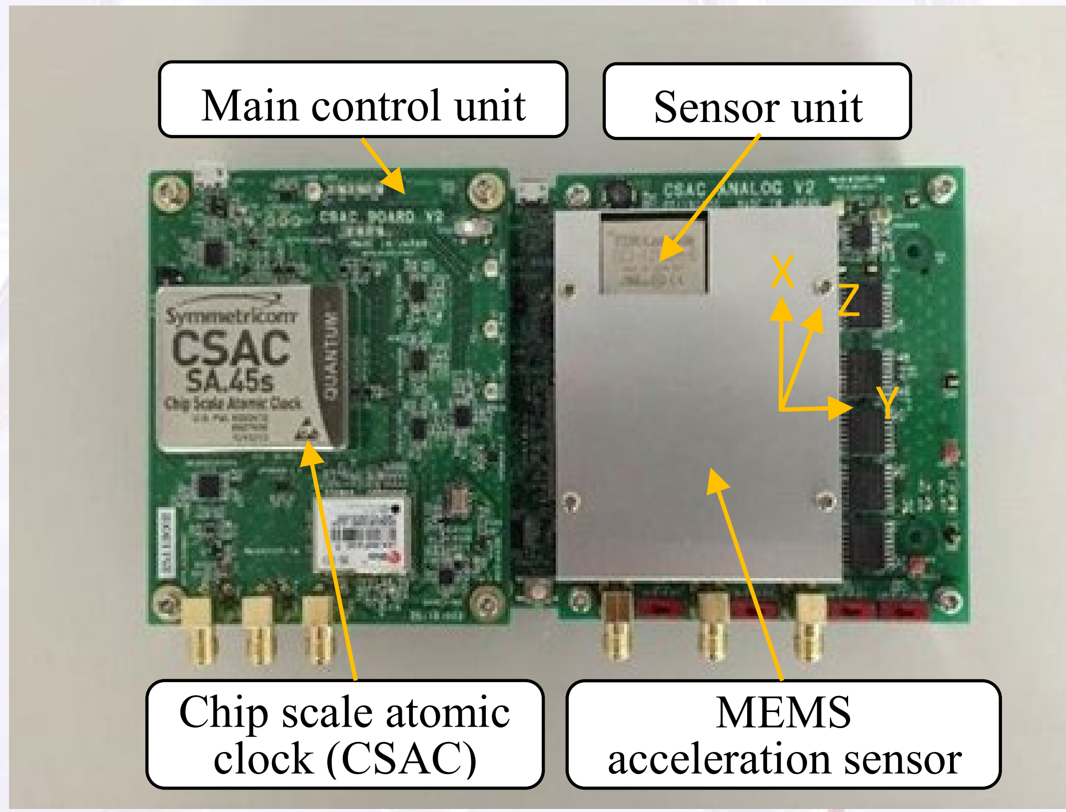


External Input Board

Development of Sensor Module with CSAC

- After the development of prototype module, improved module has developed

Prototype module



Improved module

Improvements from prototype module

(1) The external analog sensor input interface has been improved to include three channels.

(2) The A/D converter has been improved to feature 24-bit resolution.

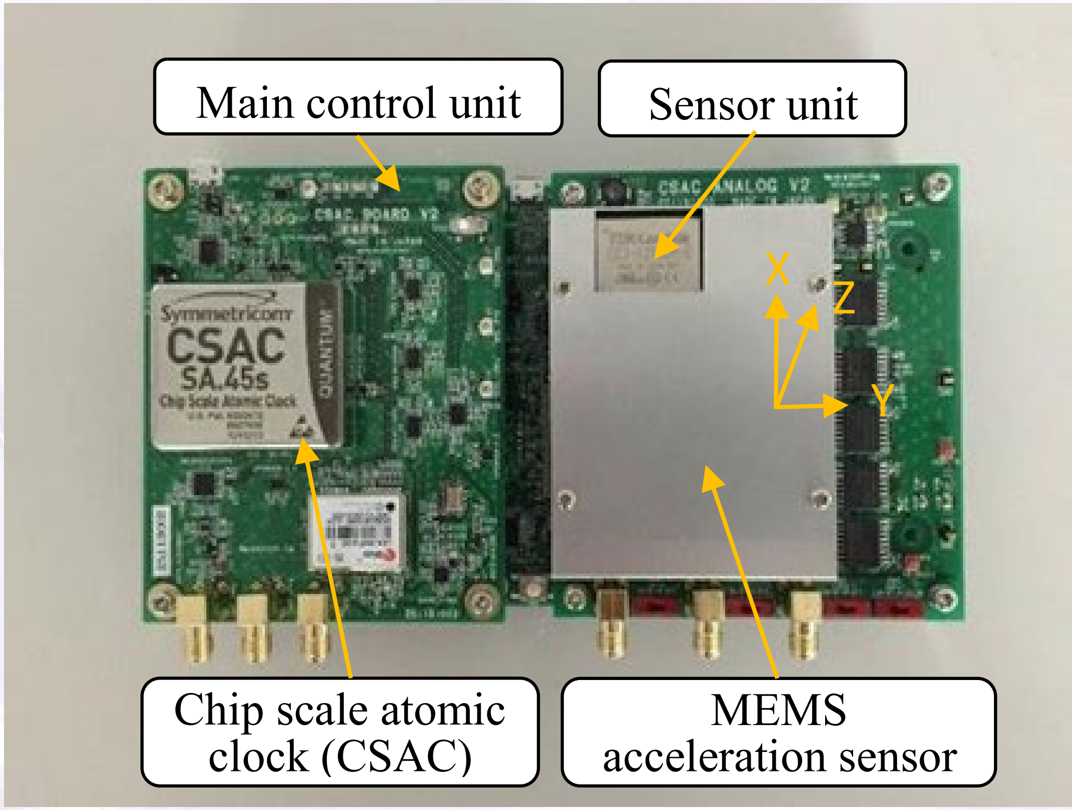
(3) The FPGA has been reinforced for the above items (1) and (2).

(4) The wireless communication unit has been separated, and it has been built using a Raspberry Pi 2 Model B, which is commercially available.

(5) Time synchronization using IEEE 1588 has been implemented.

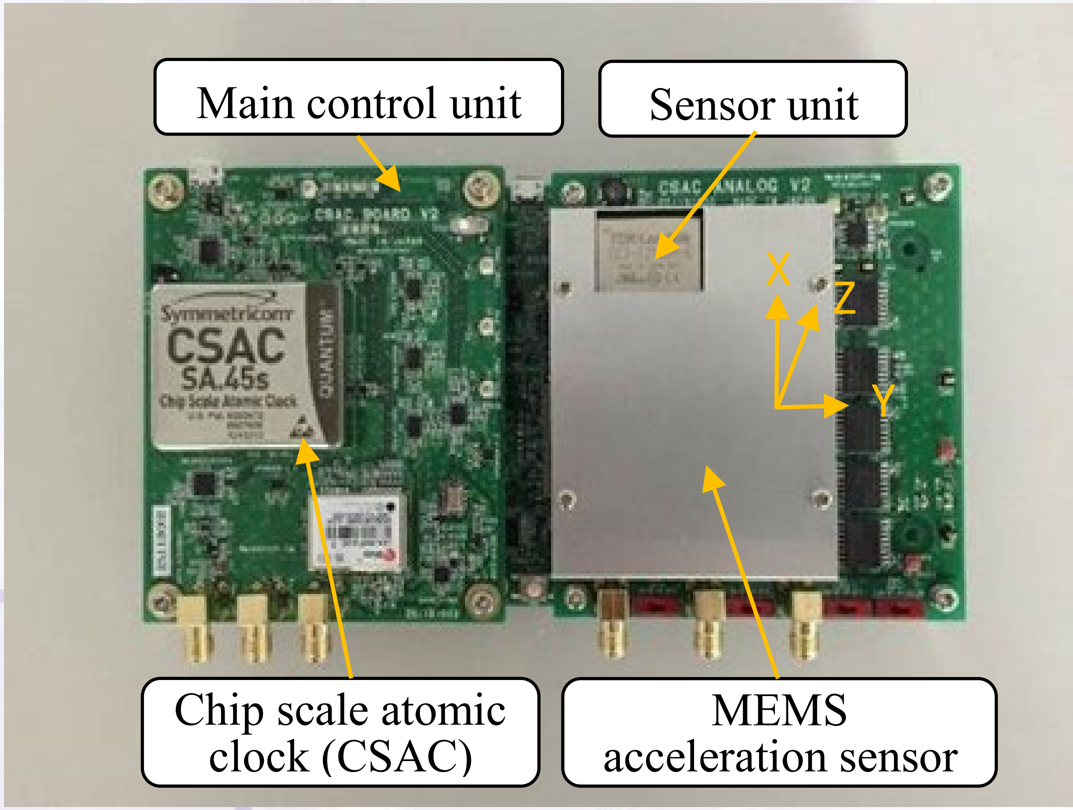
Improved Sensor Module with CSAC

- It consists of Main control unit with CSAC and Sensor unit with three axis MEMS acceleration sensor and three external analog sensor input interface

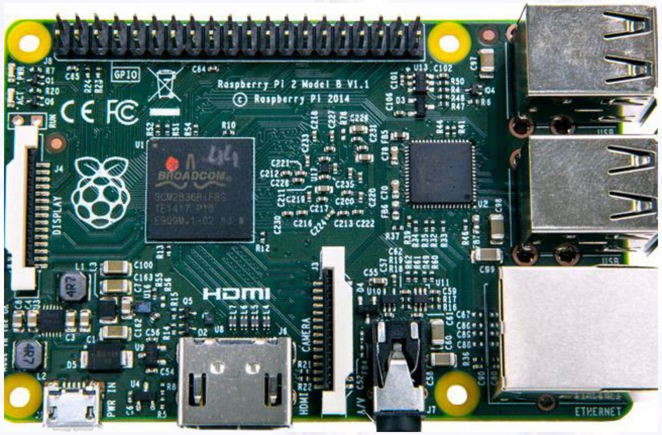


Development of Sensor Module with CSAC

- The wireless communication unit has been built using a Raspberry Pi 2 Model B



Main control unit and sensor unit

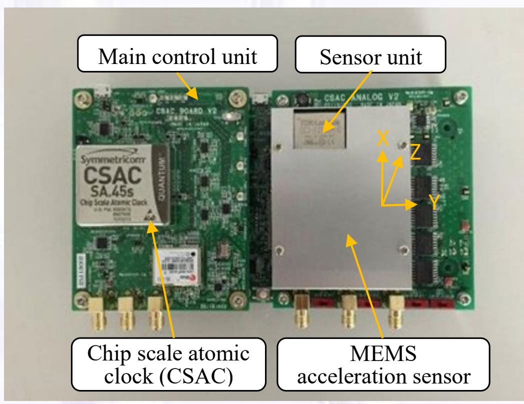


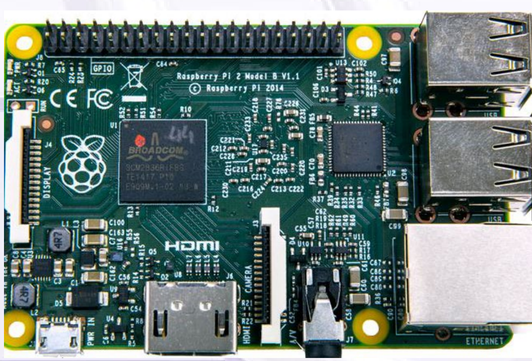
Raspberry Pi 2 Model B:

Ethernet, 3G and Wi-Fi are available

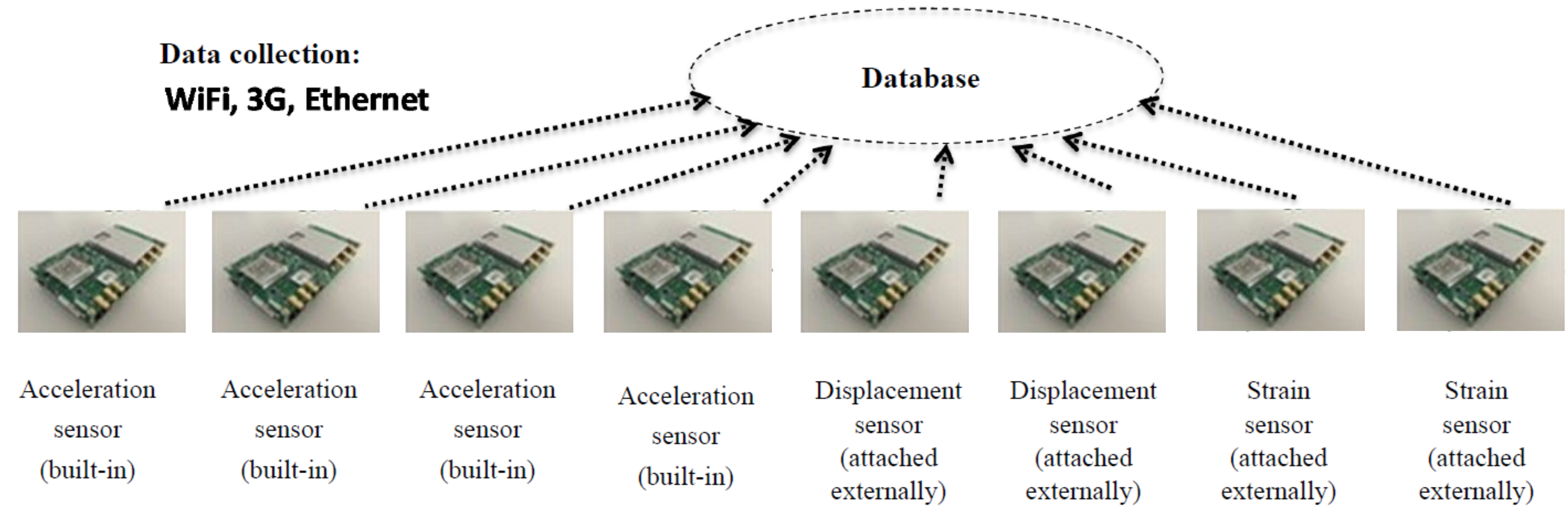
Development of Sensor Module with CSAC

- The case for units has developed
- All units and Raspberry Pi are integrated in the case





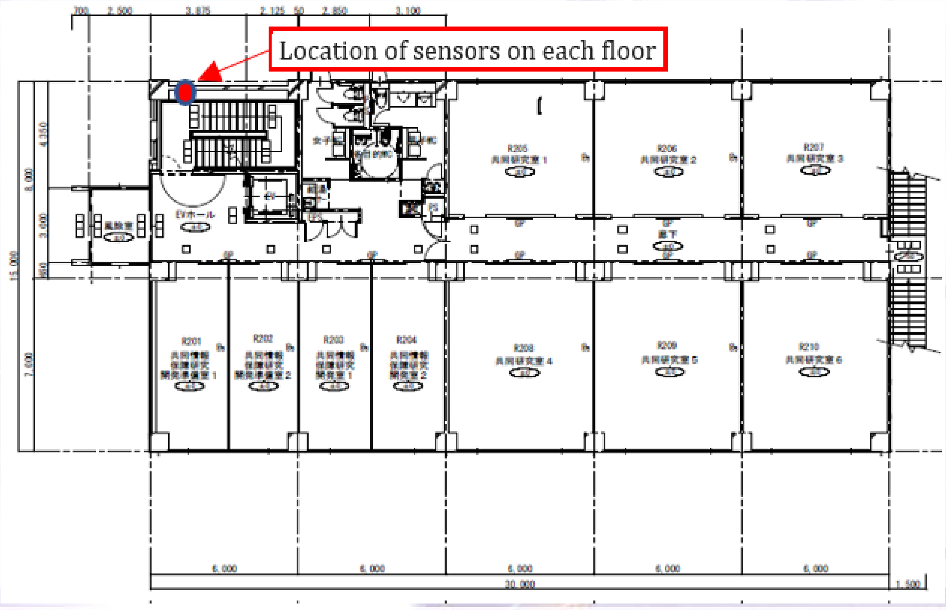
Construction of autonomous time synchronization sensor system



- Through use of the CSAC module equipped with a sensor unit incorporating a MEMS acceleration sensor or an external analog sensor, it allows for intermixed use of many kinds of sensors for the Disaster Big Data

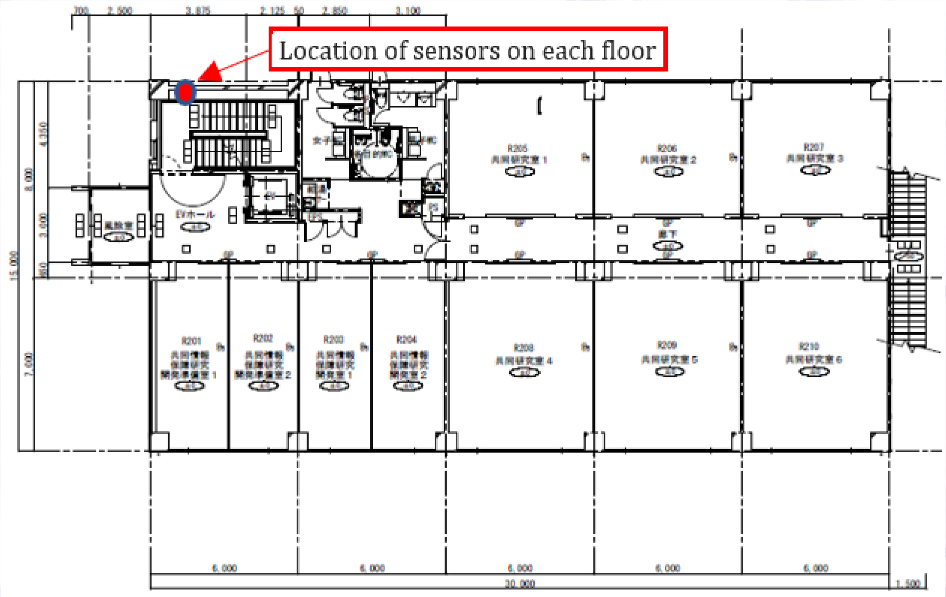
Application to Actual Building

- The developed practical devices were installed in an actual building and seismic observation started in October 2017.
- The building is a three-story reinforced concrete building built in Tsukuba, Ibaraki, Japan.



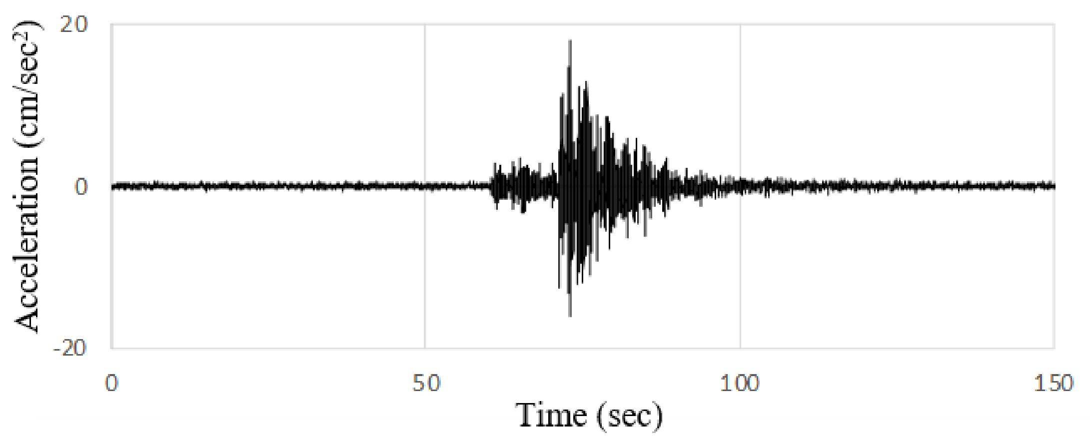
Application to Actual Building

- In each floor, one practical device was installed.
- Figure shows the plan of 2nd floor of the building and locations of the practical devices installed.

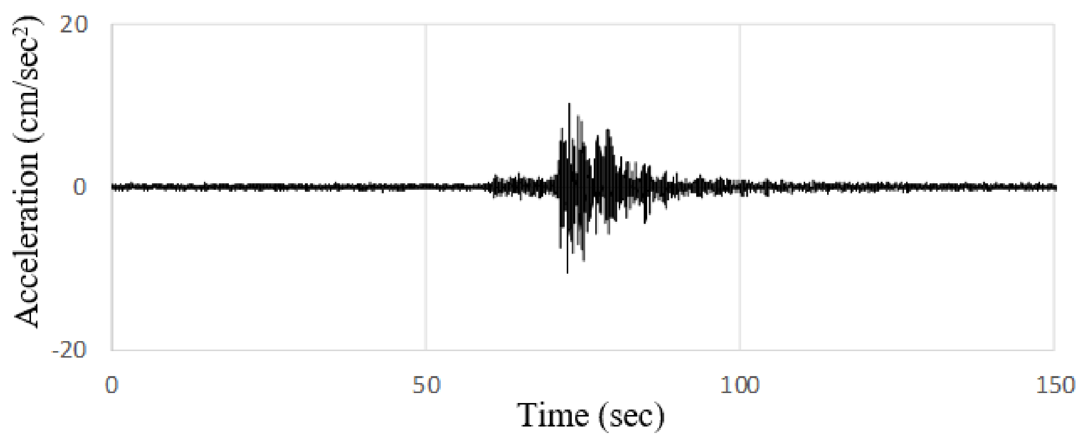


Observed Earthquake Records

No	Date	Time	Name of	Magnitude /	Local/Max. Intensity



(a) Roof top floor (3rd ceiling)

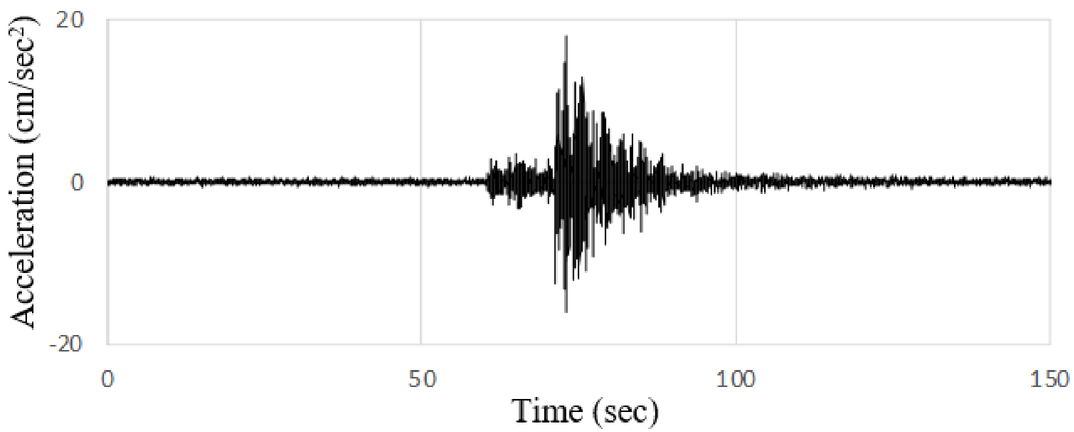


(b) 1st floor

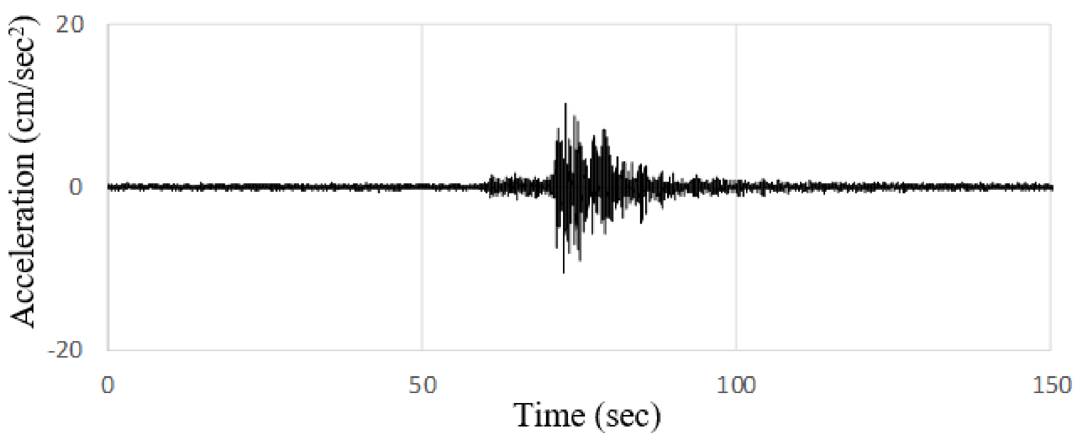
An example of measured acceleration of the largest earthquake in the building

Observed Earthquake Records

No	Date	Time	Name of	Magnitude /	Local/Max. Intensity



(a) Roof top floor (3rd ceiling)

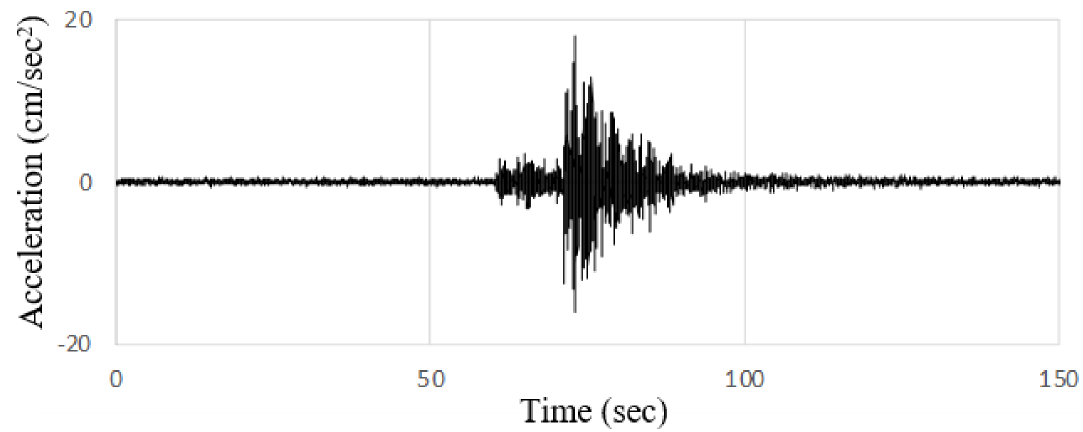


(b) 1st floor

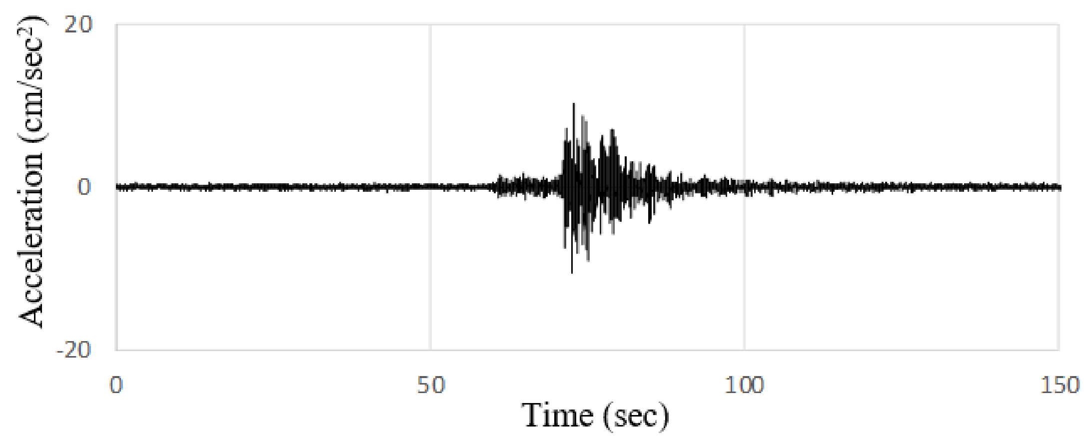
Measured results of the 1st floor and the 3rd ceiling (floor of the rooftop) in a horizontal direction

Observed Earthquake Records

No	Date	Time	Name of	Magnitude /	Local/Max. Intensity



(a) Roof top floor (3rd ceiling)



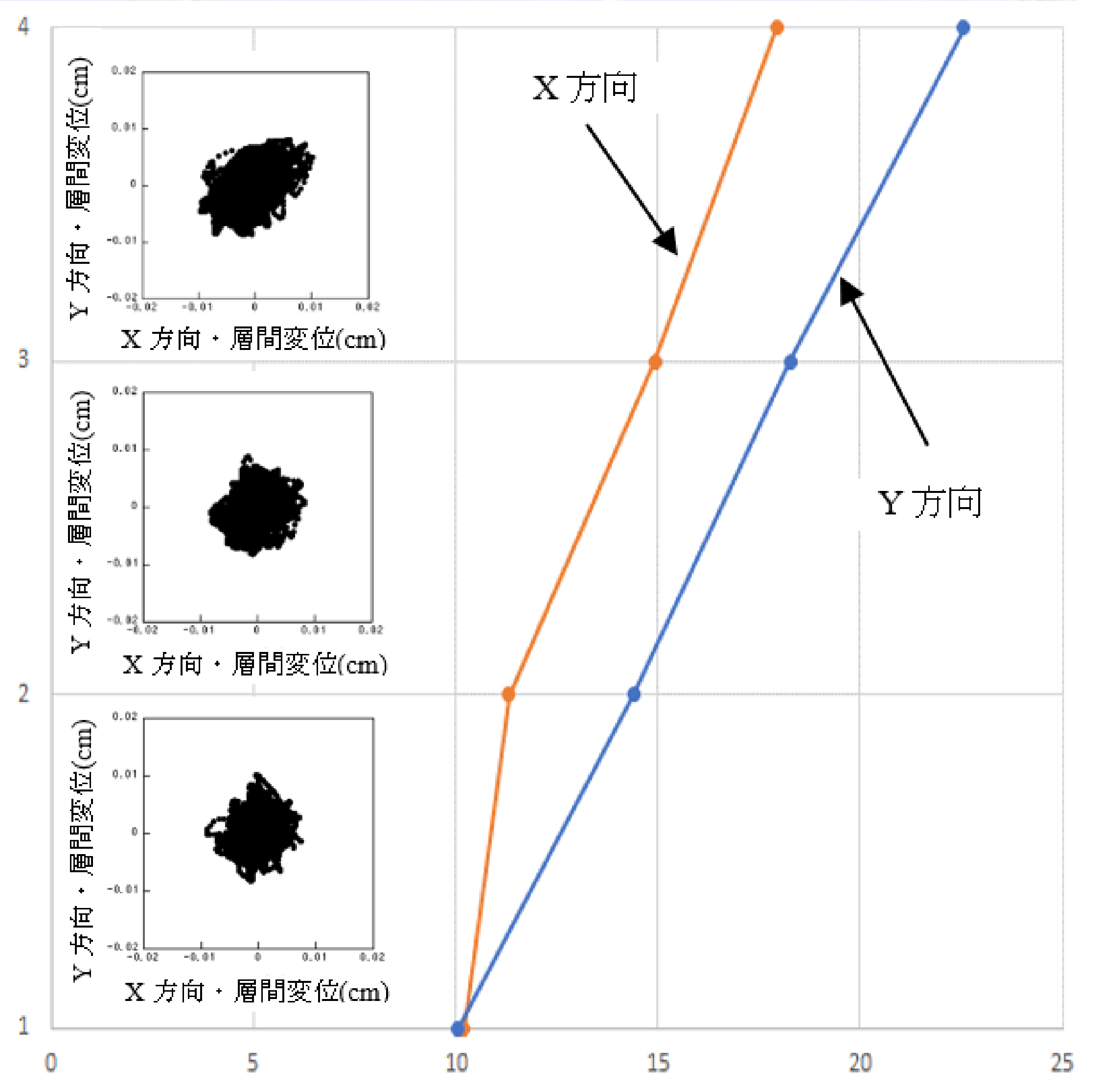
(b) 1st floor

For the 1st floor, an acceleration of 10.2 cm/sec2 at the maximum is observed.

For the rooftop, the vibration of the earthquake is amplified and the maximum value of the acceleration is greater.

Function and usability of the improved practical device, which was installed onto an actual building, were verified by the case of seismic observation.

Maximum Acceleration and Inter-story Drift



Summary

- Application
  - maintenance and management of World Heritage Structures
  - earthquake hazard mitigation
  - maintenance and management of building and civil infrastructures
- Sensor Device Technology
  - Wireless sensor network
  - Autonomous time synchronization sensing with CSAC

Conclusion

- Results of vibration measurement and data analysis of the structures at Battleship Island and Angkor Wat were reported
- Structures registered as World Heritage Sites are expected to require maintenance and management for centuries
- To maintain and manage a World Heritage structure, it is necessary to obtain knowledge of its status by suitably monitoring the environment in accordance with the structure’s circumstances

Conclusion

- Future direction on World Heritage monitoring and the need for the development of sensor device were discussed
- Research and development relating to a sensor device that autonomously retains highly accurate time information by applying a CSAC was reported

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Thank you for your attention