The Eleventh International Conference on Sensor Device Technologies and Applications

SENSORDEVICES 2020

November 21, 2020 to November 25, 2020 - Valencia, Spain

Performance Evaluation of High-Accuracy Time Synchronization Sensor Device Using Indoor GNSS Time Information Delivery System for Structural Health Monitoring of Buildings and Civil Infrastructures

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and

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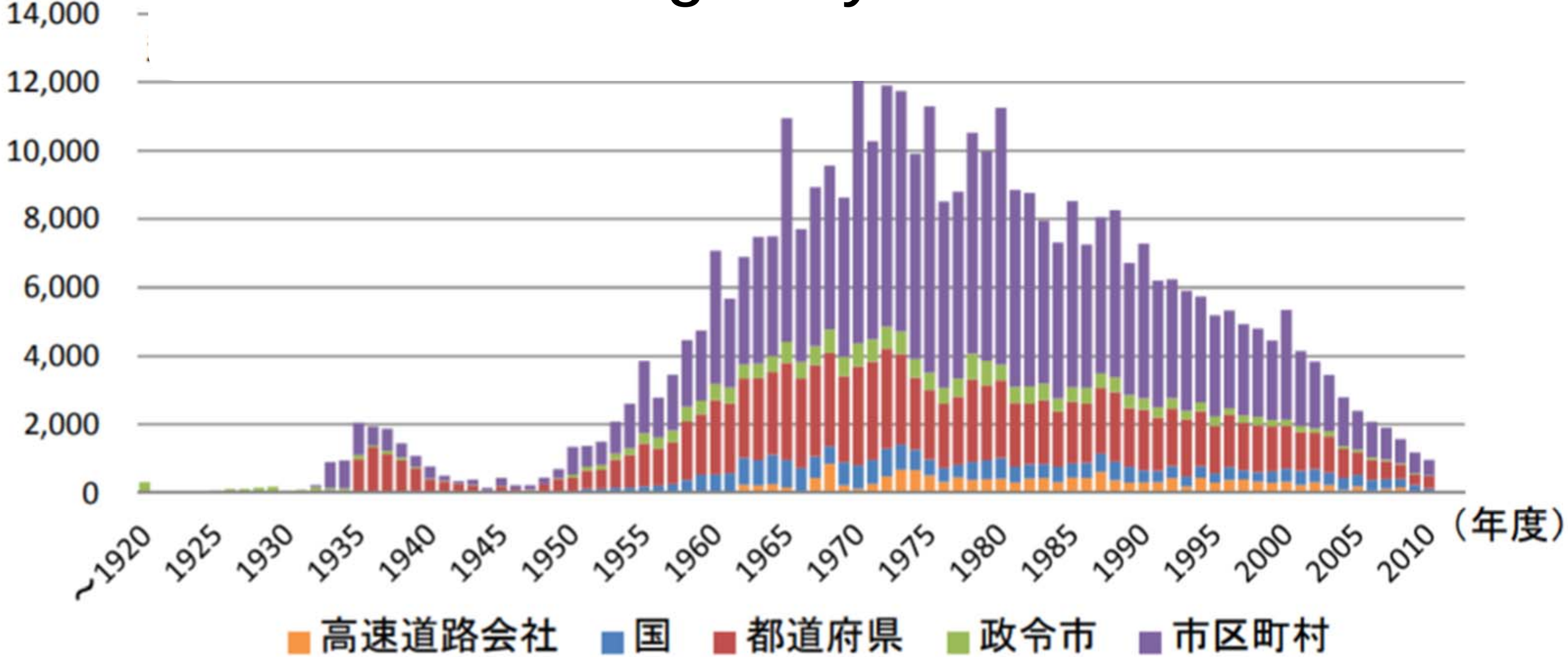
- Background
  - Architectural & Structural Engineering
  - Earthquake Engineering
- Research & Development
  - Structural Control Systems for Earthquake Hazard Mitigation
  - Structural Health Monitoring
    - Earthquake Monitoring and Structural Health Monitoring by Sensor Networks
    - Risk Information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

Necessity of smarter inspection and maintenance of civil infrastructure

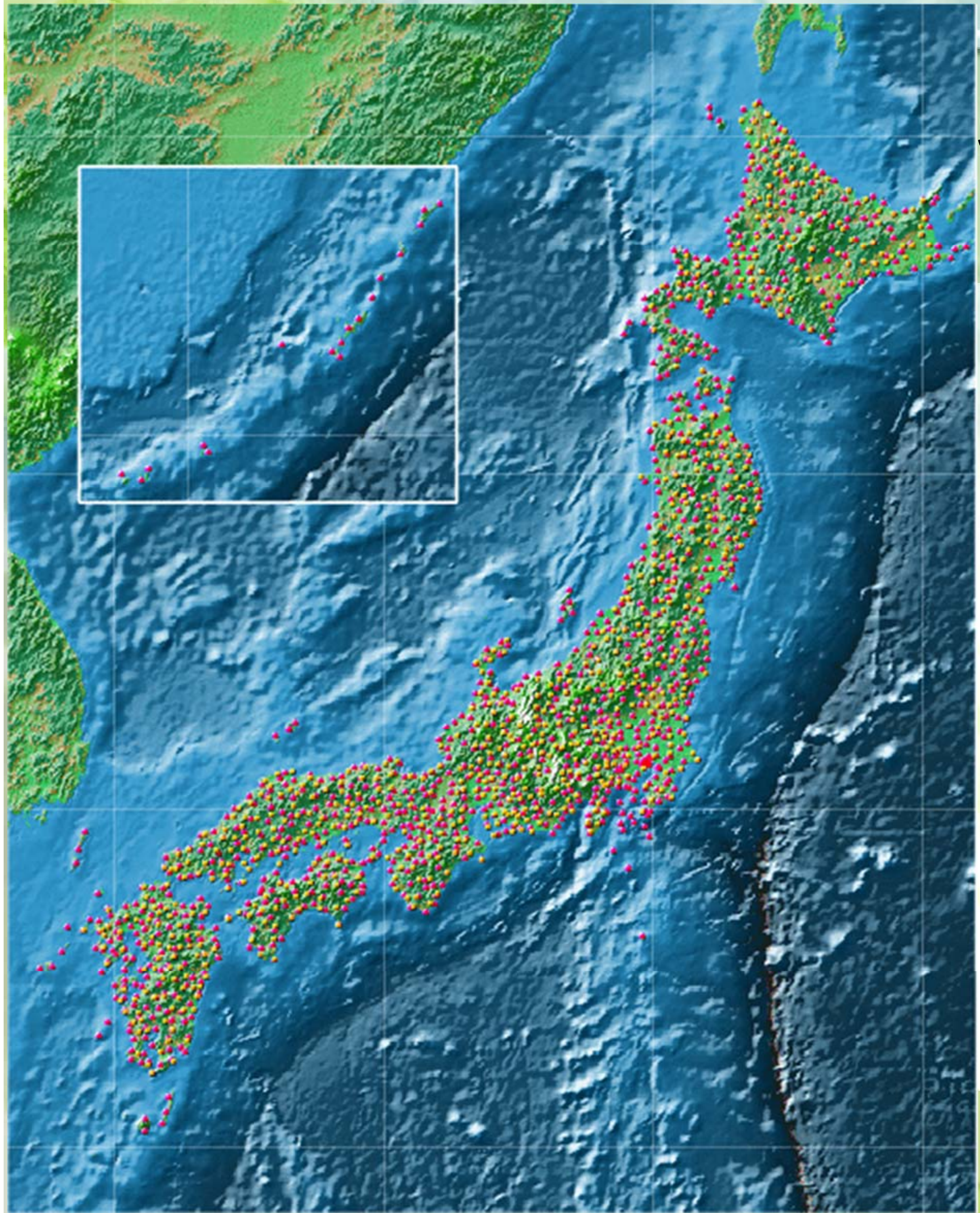
Number of Bridges by Construction Year



https://www.mlit.go.jp/road/road_e/03key_challenges/1-2-2.pdf

Great Hanshin-Awaji Earthquake (Kobe Earthquake) , 1995.1.17

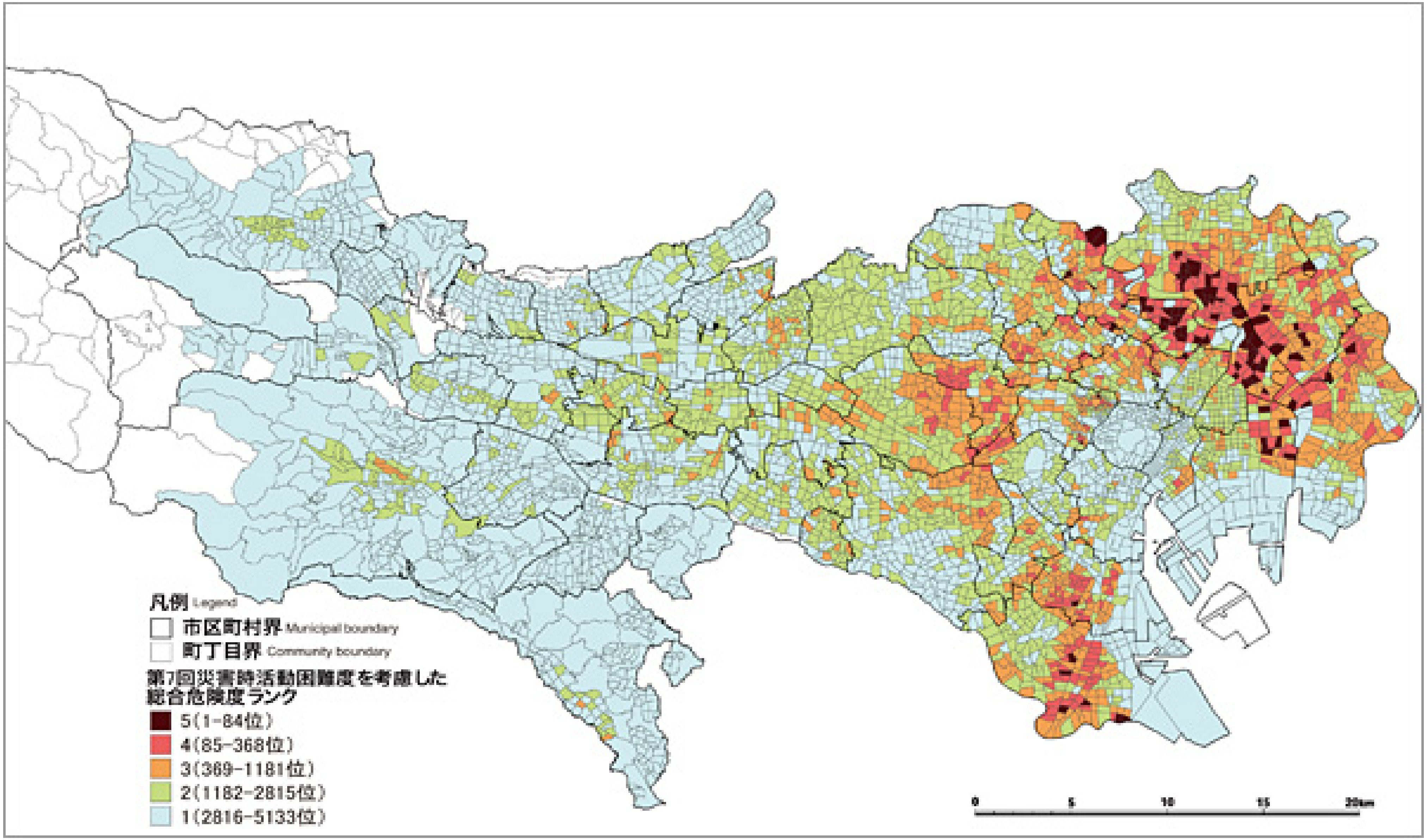
Japanese Earthquake Observation Network



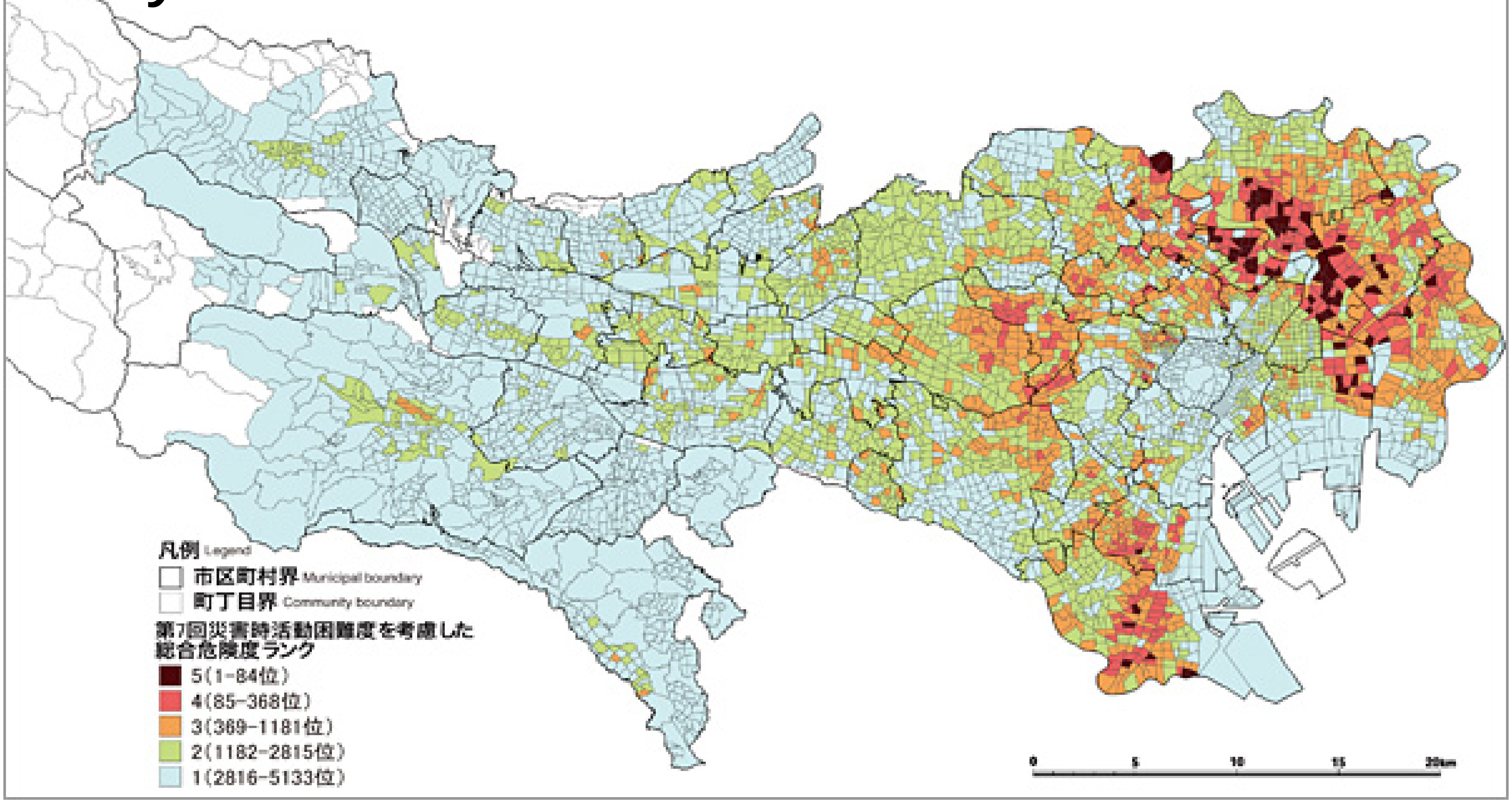
- Earthquake data is obtained from 1,742 observatories deployed all over Japan
- The average station to station distance is about 25km
- However, it is not enough for installation for all cities

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

Total Risk Ranking of Each Town in Tokyo



Real-time monitoring of each town in Tokyo is desirable

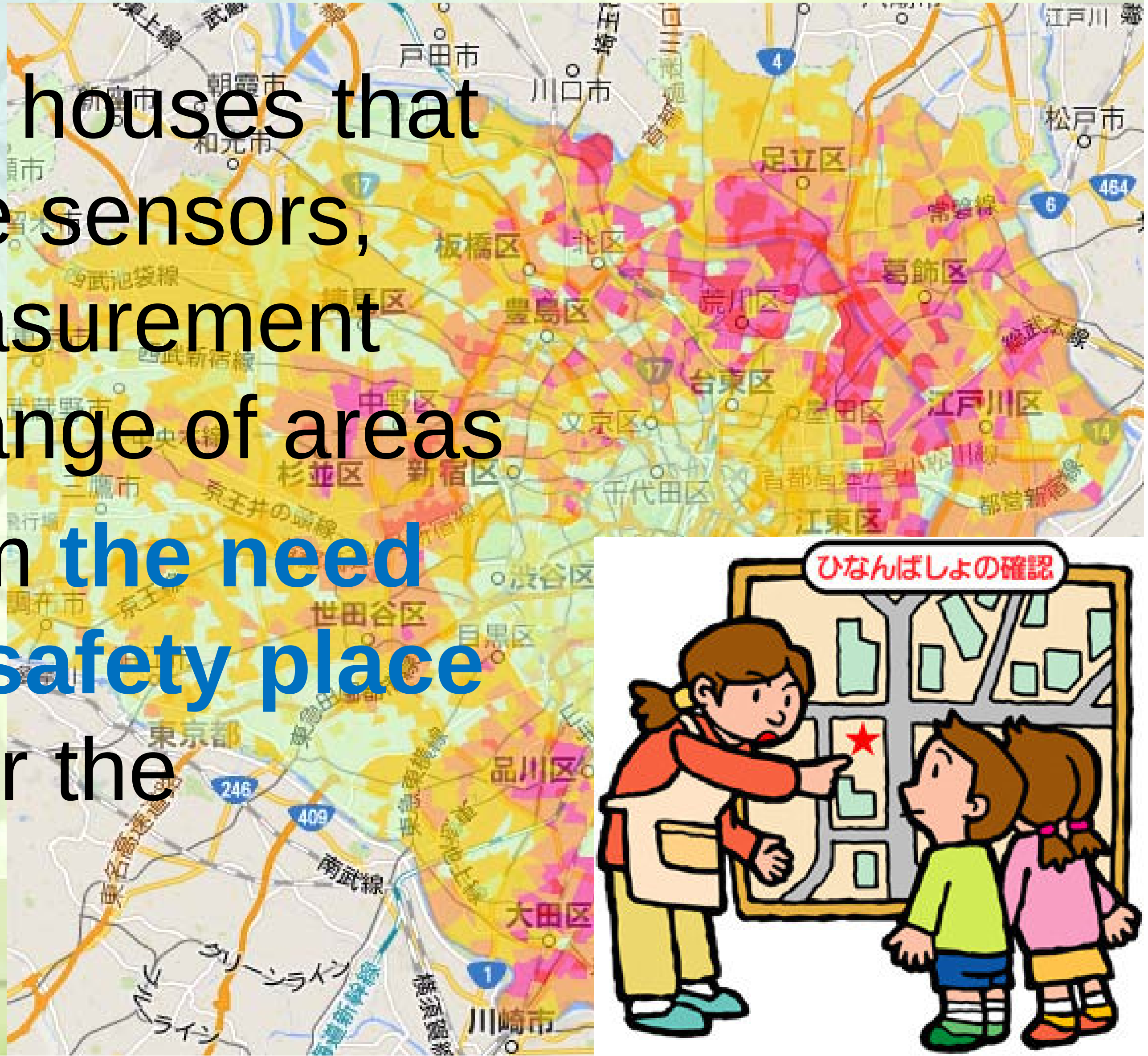


Benefits of installing earthquake sensors to all the houses and buildings

- 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 and buildings

- 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

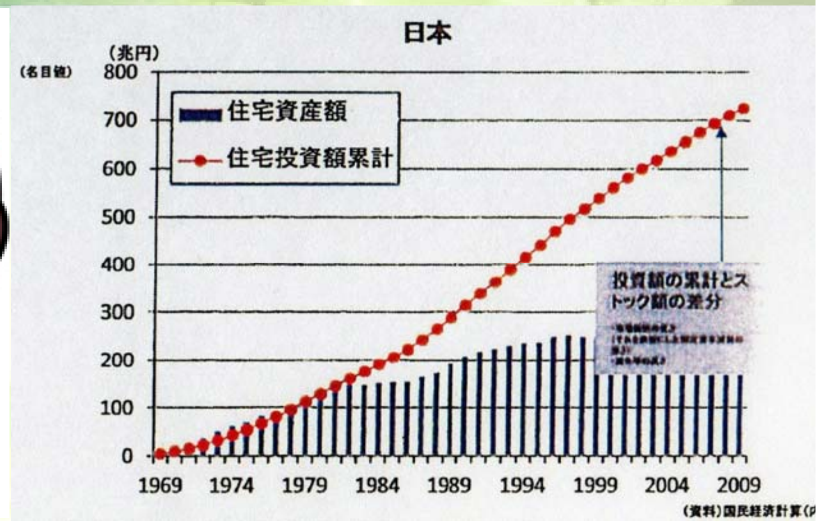


Benefits of installing earthquake sensors to all the houses and buildings



- 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

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	21,001	2020
Lawson	14,444	2020
Familymart	16,656	2020
McDonalds	2,914	2020
Mini Stop	1,999	2020
Doutor Coffee	1,301	2020
Starbacks	1,600	2020

The need for accurate time information

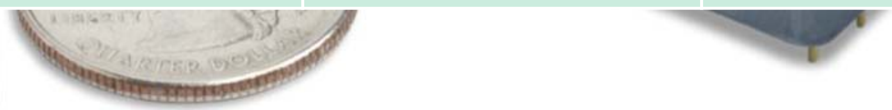
- Accurate time information as well as location information are necessary to analyze the data for structural health monitoring of buildings and civil infrastructures
- Time synchronization between the sensors in a wide area is not easy
  - GNSS signal cannot be used in the houses and buildings
  - The wire and wireless communication is limited
- It is desirable that the sensor itself has autonomously accurate time information

Development of a Sensor Device Capable of Autonomously Keeping Accurate Time Information Equipped with a Chip Scale Atomic Clock

Chip Scale Atomic Clock (CSAC) is available

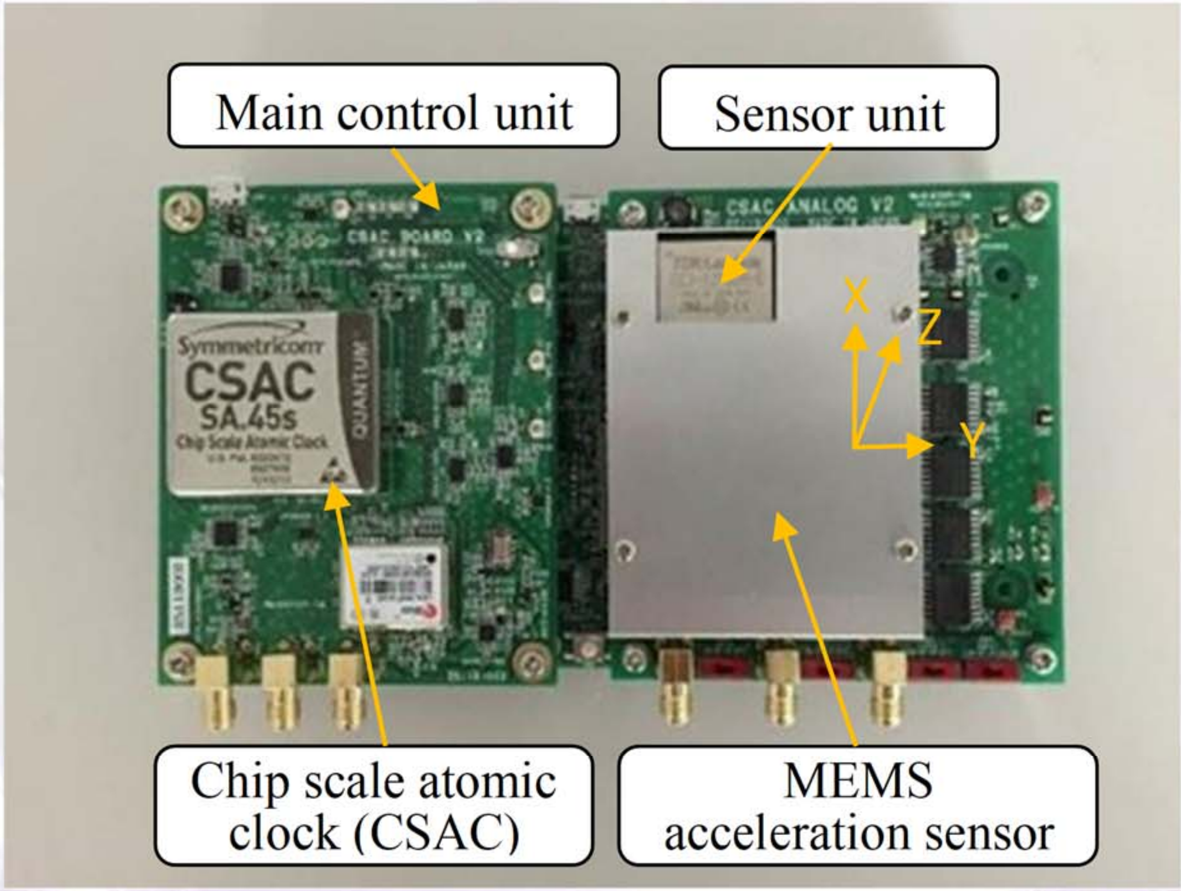
- Comparison among various atomic clocks and oscillator

	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



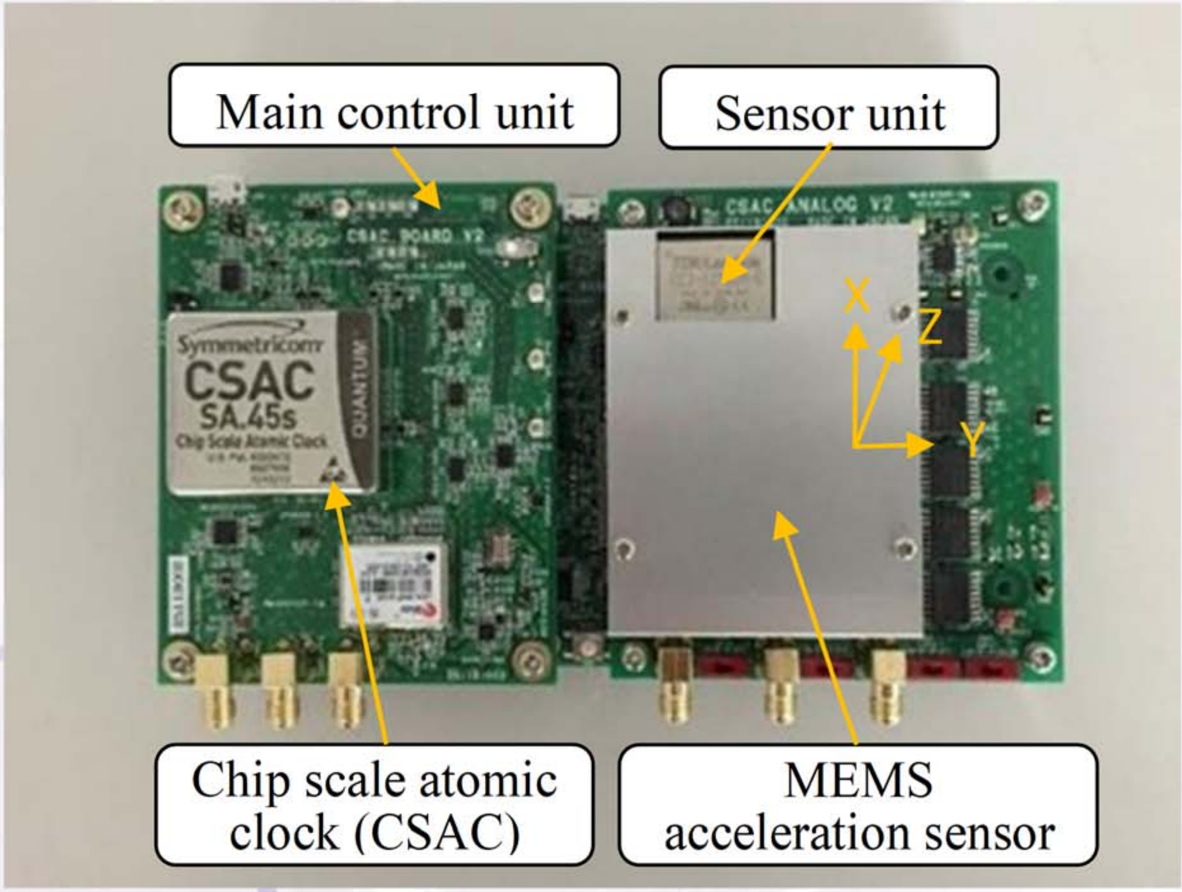
Development of sensor device with CSAC

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

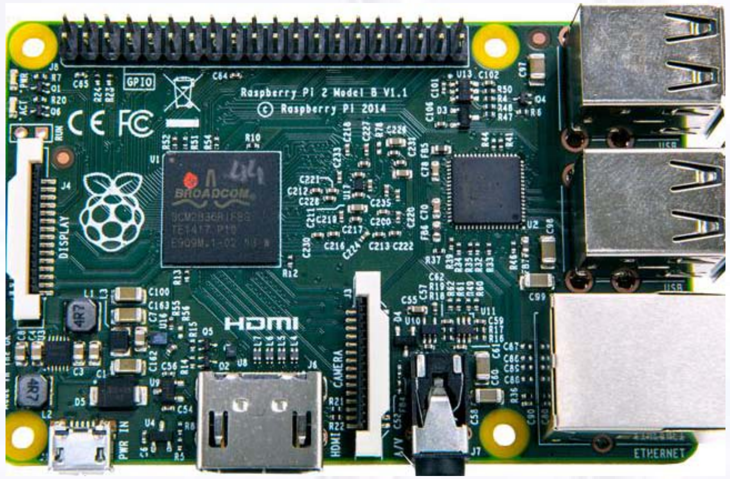


Development of sensor device with CSAC

- Wireless communication unit has been built using a Raspberry Pi



Main control unit and sensor unit

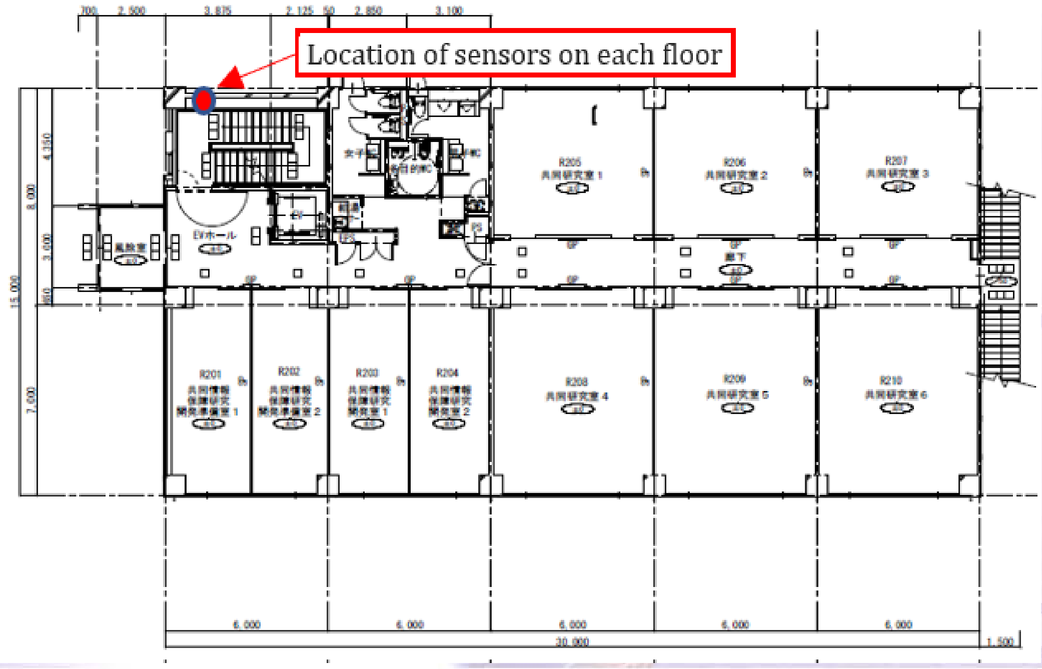


Raspberry Pi 2 Model B:

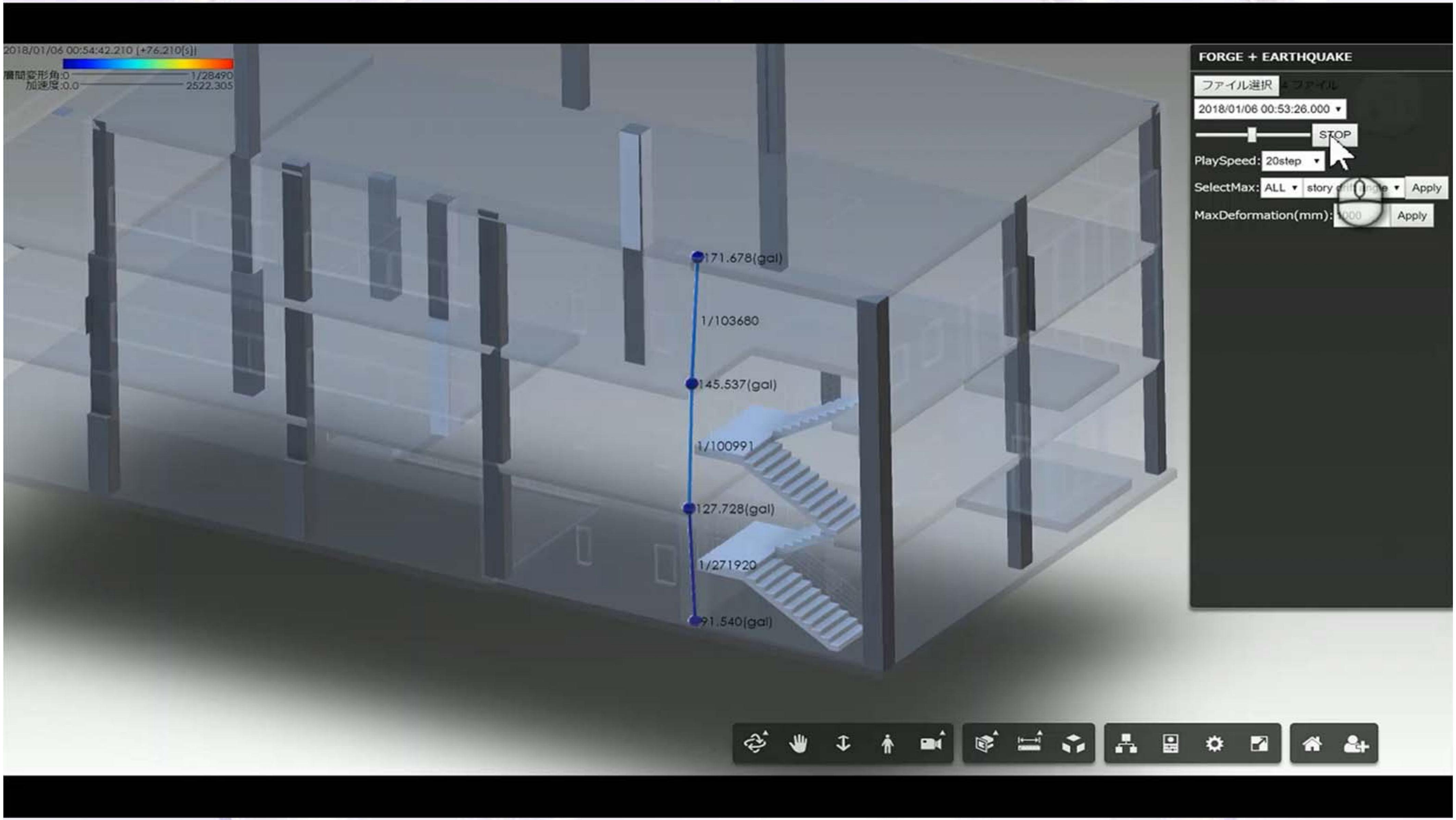
Ethernet, 3G and Wi-Fi are available

Application to Actual Building and Bridges

- The developed new 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.



Visualization of structural health evaluation by sensor devices with CSAC



Problem

- The use of autonomous high-precision time-synchronization sensor devices with CSAC solves the problem of time synchronization between a large number of installed sensors in buildings and civil infrastructures.
- However, mass supply and price reduction of CSAC have not yet been realized.

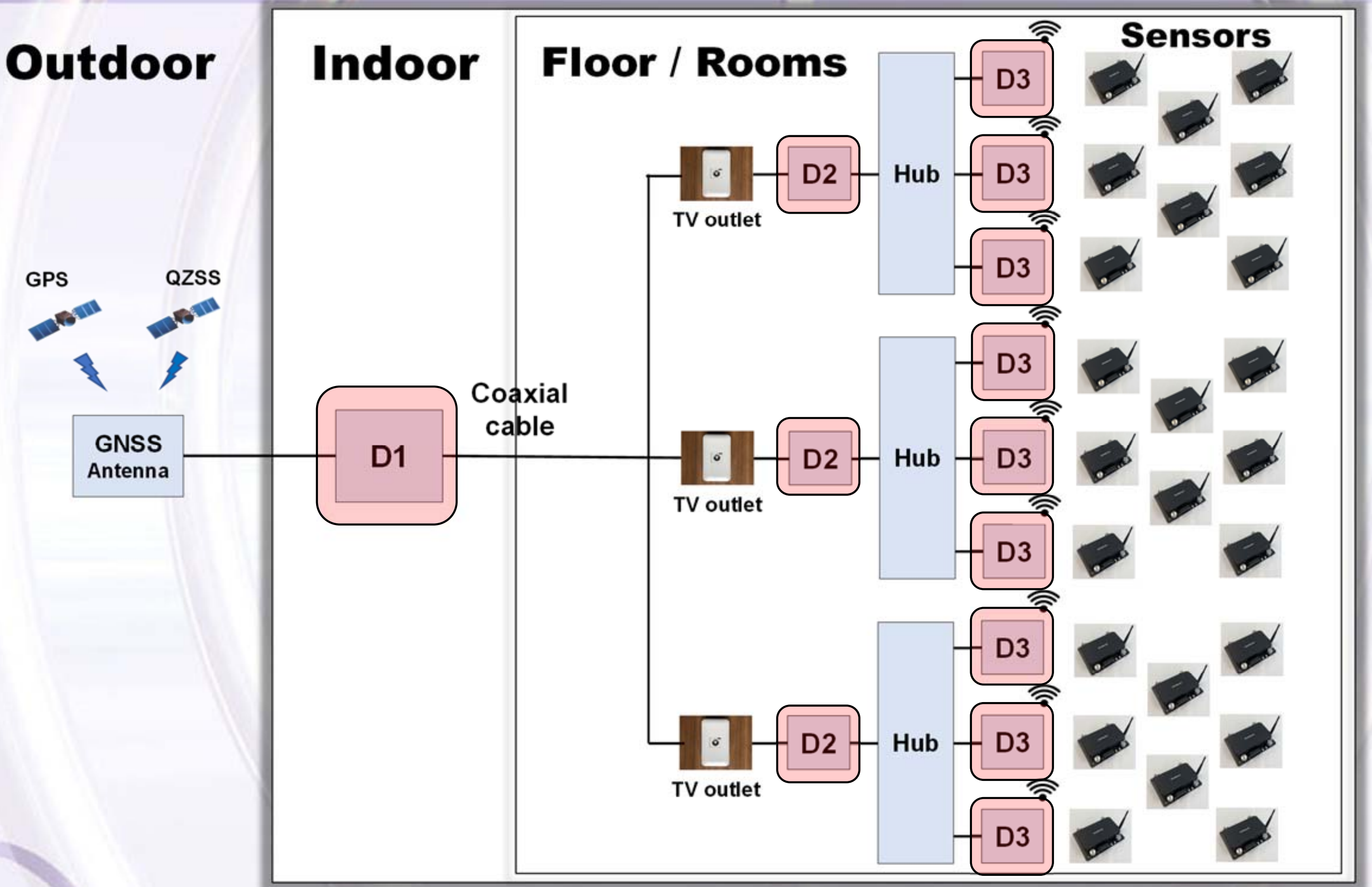
Development

- Although Global Navigation Satellite System (GNSS) time information is generally only available outdoors, we designed a system capable of using GNSS time information indoors.
- We further developed a sensor device able to receive indoor GNSS time information and to add high-accuracy time information to measured data.

Indoor GNSS time information delivery system

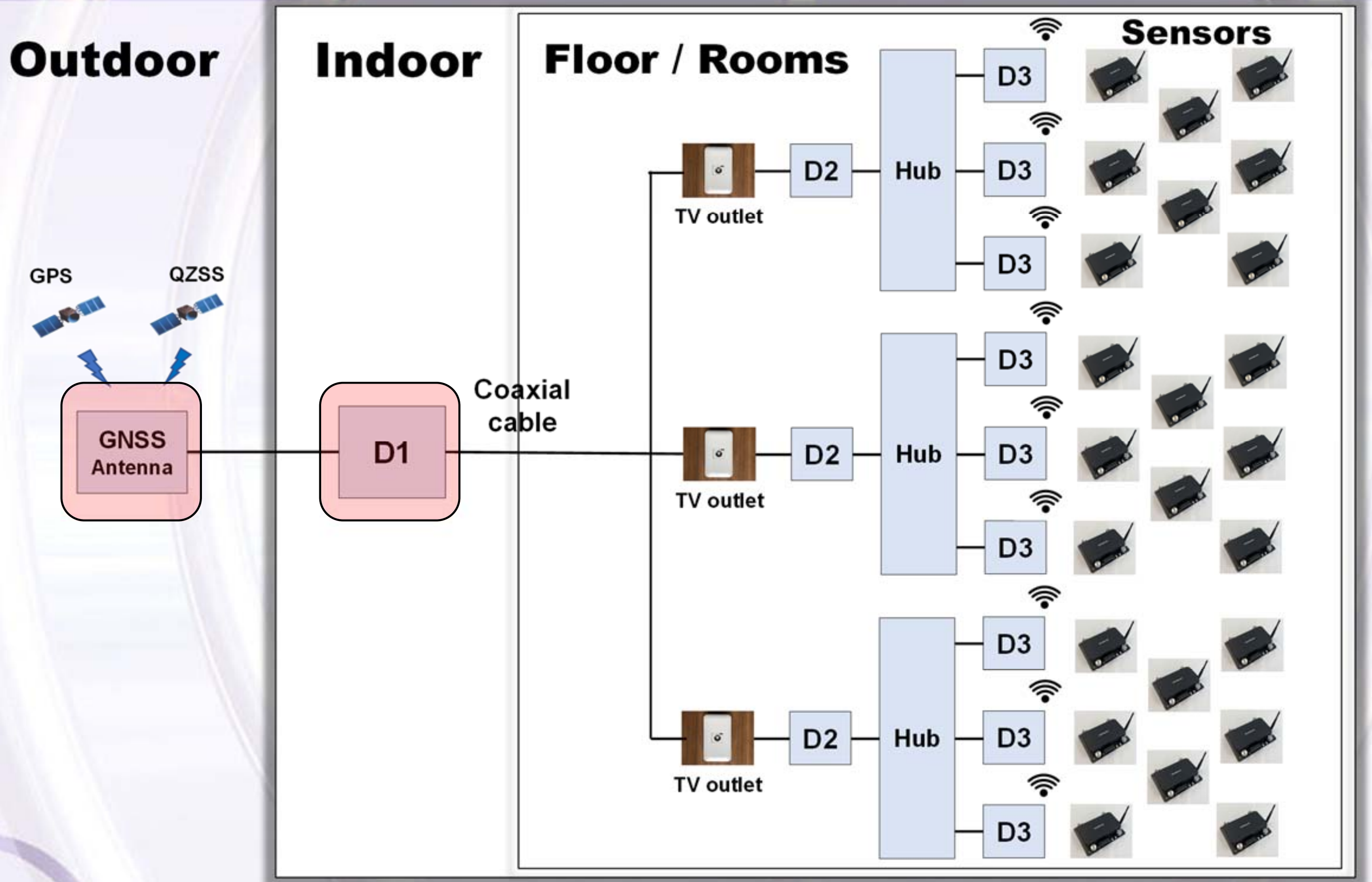
- GNSS signals are received on the roof of a building, and delivered as broadcasting into the building by using the transmission path of an existing system, such as a common antenna TV system or cable TV system.
- A transmitter is installed at any location from which the delivery of GNSS signals into the building is desired, and the signals are sent.
- By mounting a GNSS receiver on each sensor device and implementing a mechanism to add high-accuracy time stamps to measured data, it becomes possible to collect data sets whose high-accuracy time synchronization is ensured from indoors

System configuration



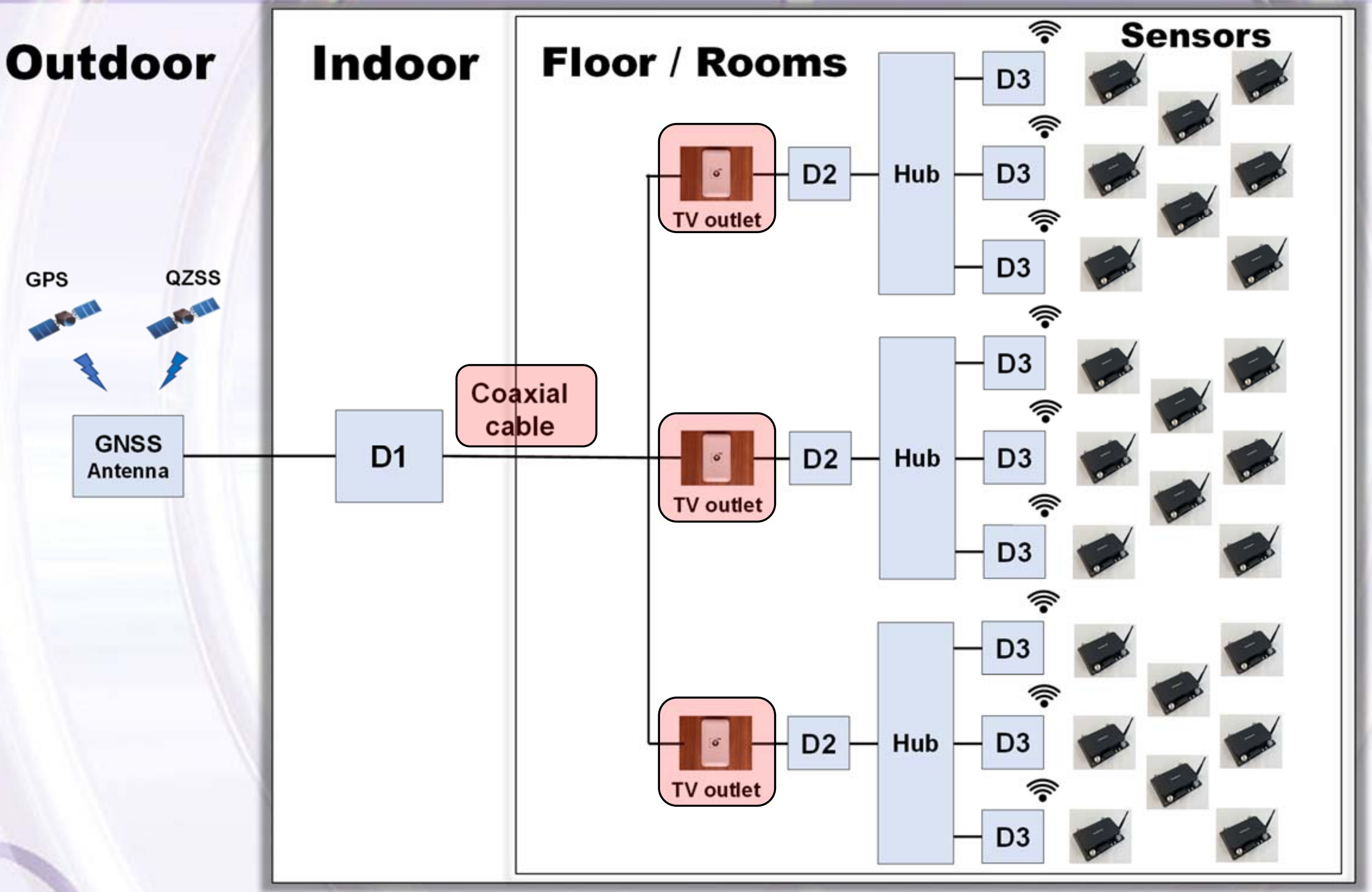
- An indoor GNSS time information delivery system consists of D1 on the roof, D2 inside the building, and D3 at the terminal (a transmitter for delivering GNSS time information indoors).

System configuration



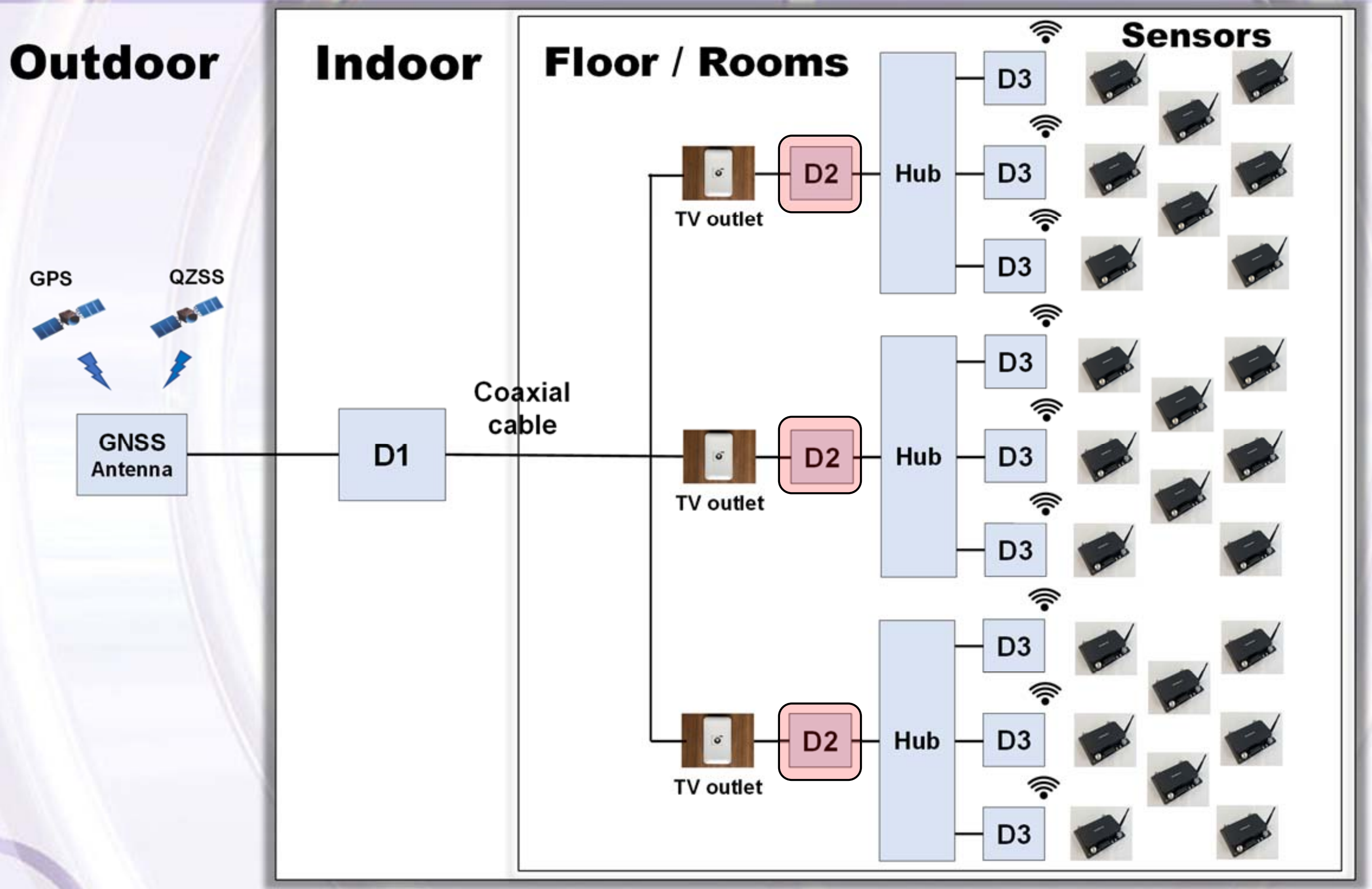
- D1 receives a signal from the GNSS satellite, frequency-converts the synchronized time signal, and transmits it into the building.

System configuration



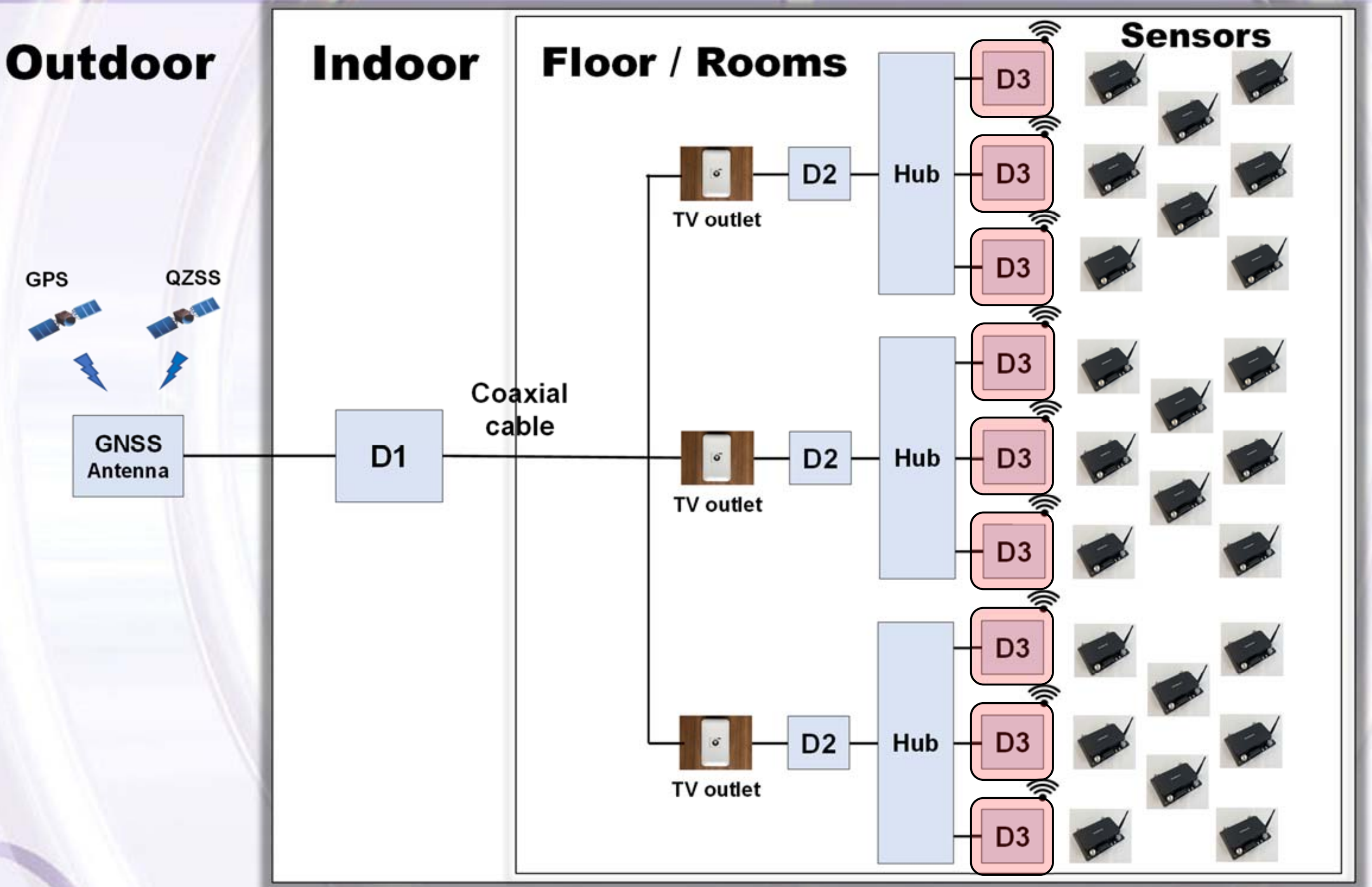
- The transmission path of a CATV system or cable TV system in a building is used to deliver indoors high-accuracy times synchronized with GNSS satellites.

System configuration



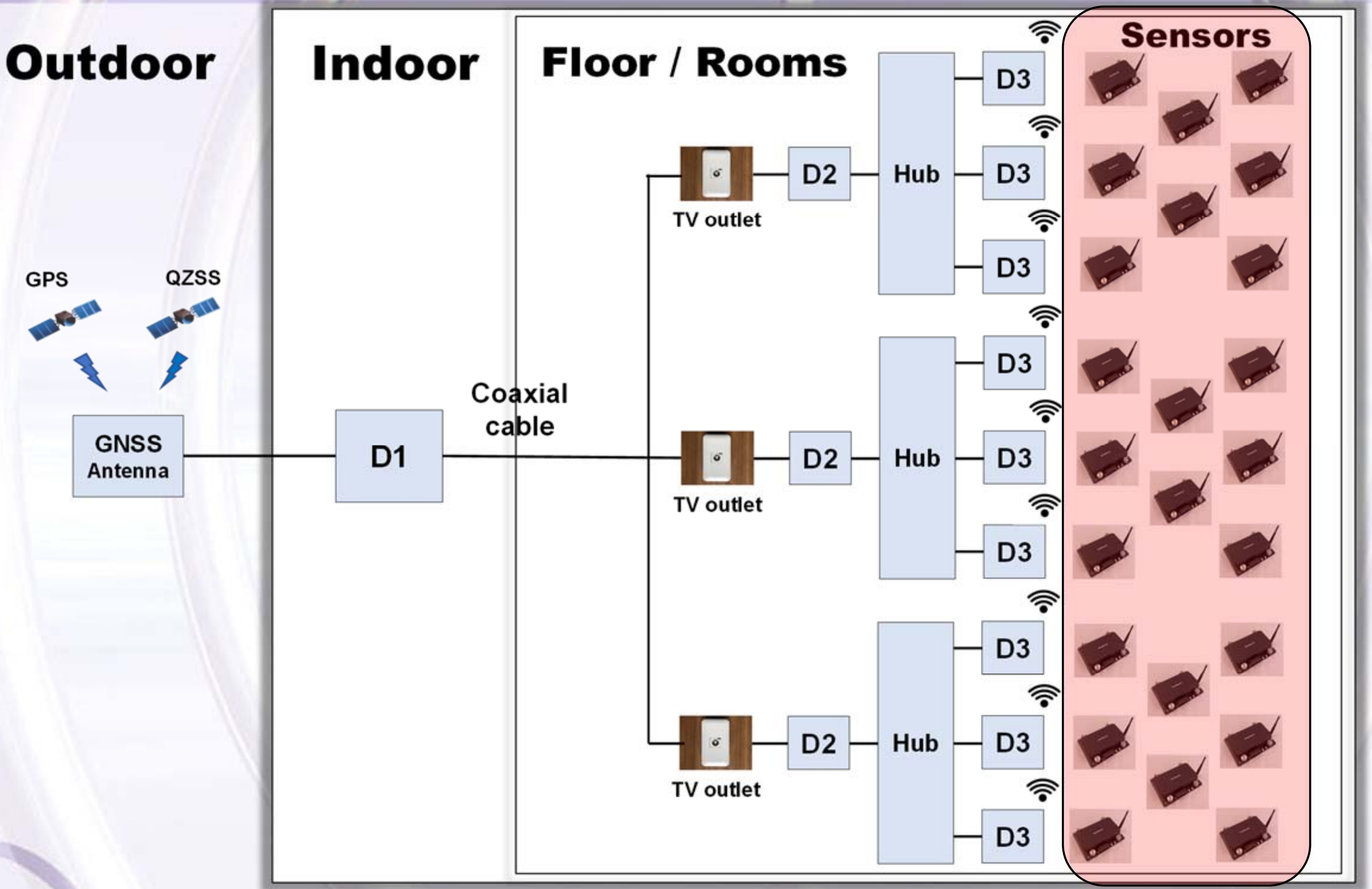
- D2 receives time signals from D1 and demodulates them into high-accuracy time synchronization signals (PPS signals).

System configuration



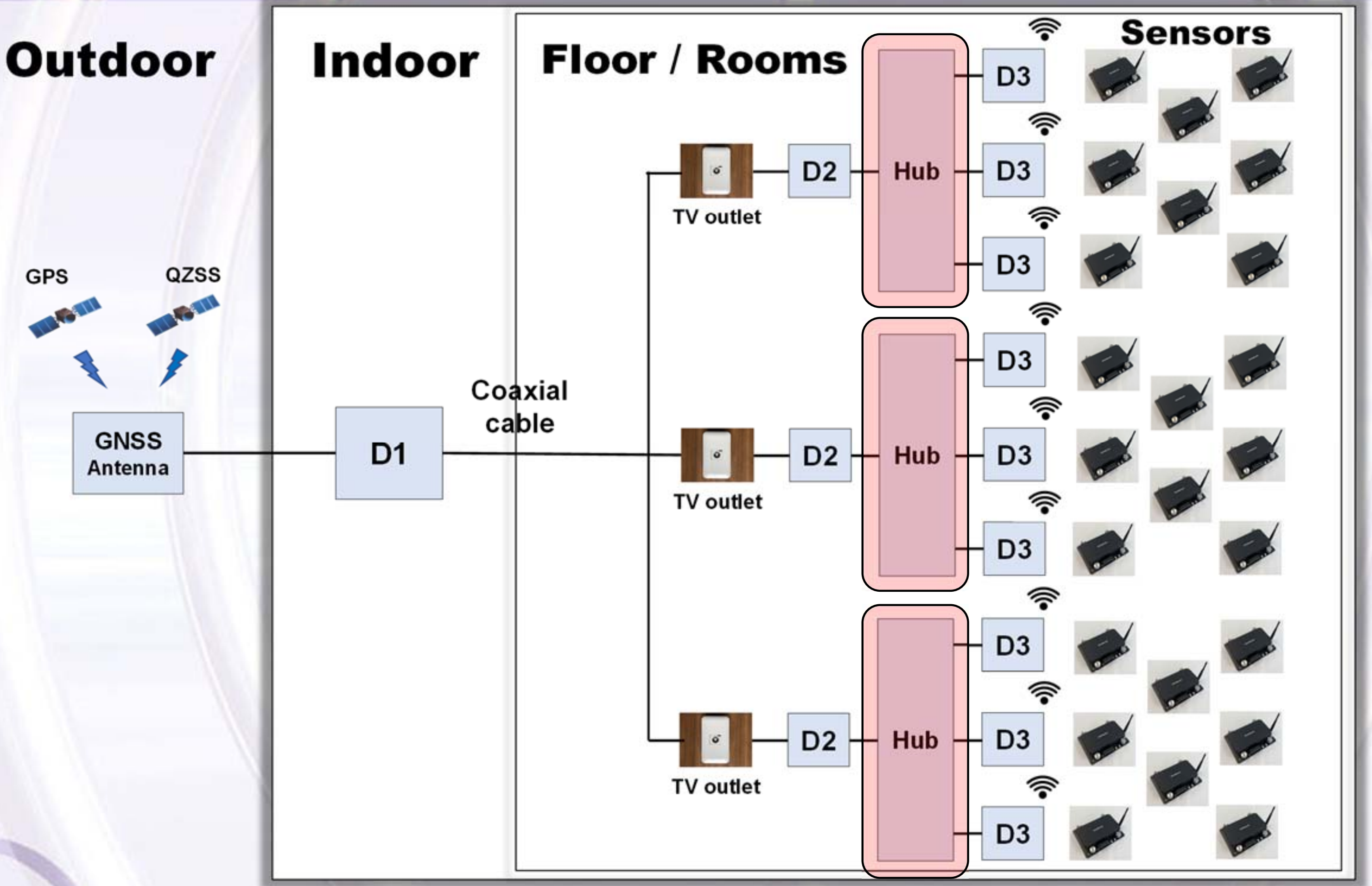
- D3 receives data from D2, adjusts the timing, and sends time information to a sensor device.

System configuration



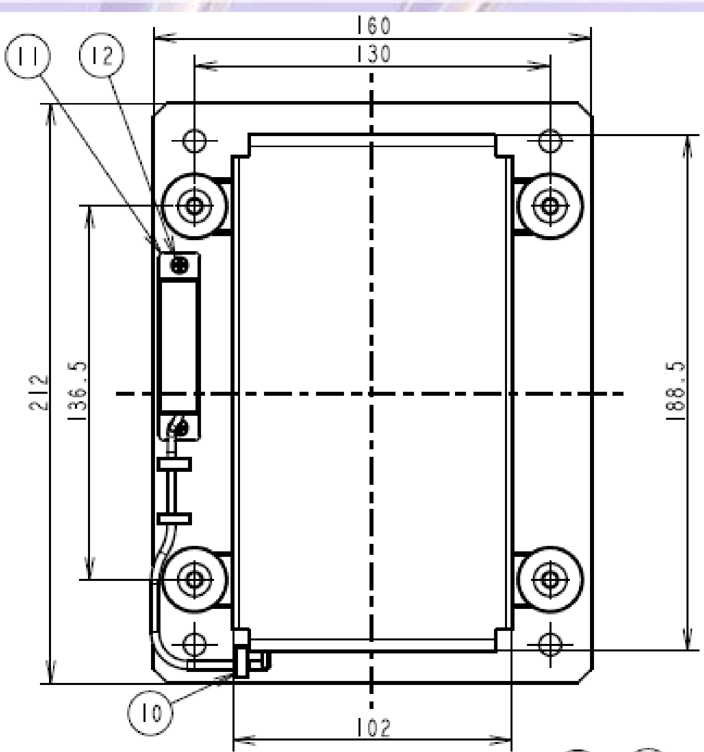
- Time information sent from D3 is received by a sensor device to add high-accuracy time information to measured data.

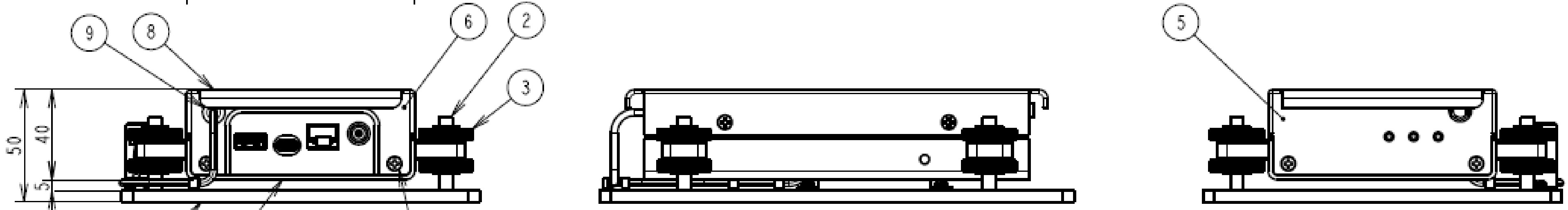
System configuration



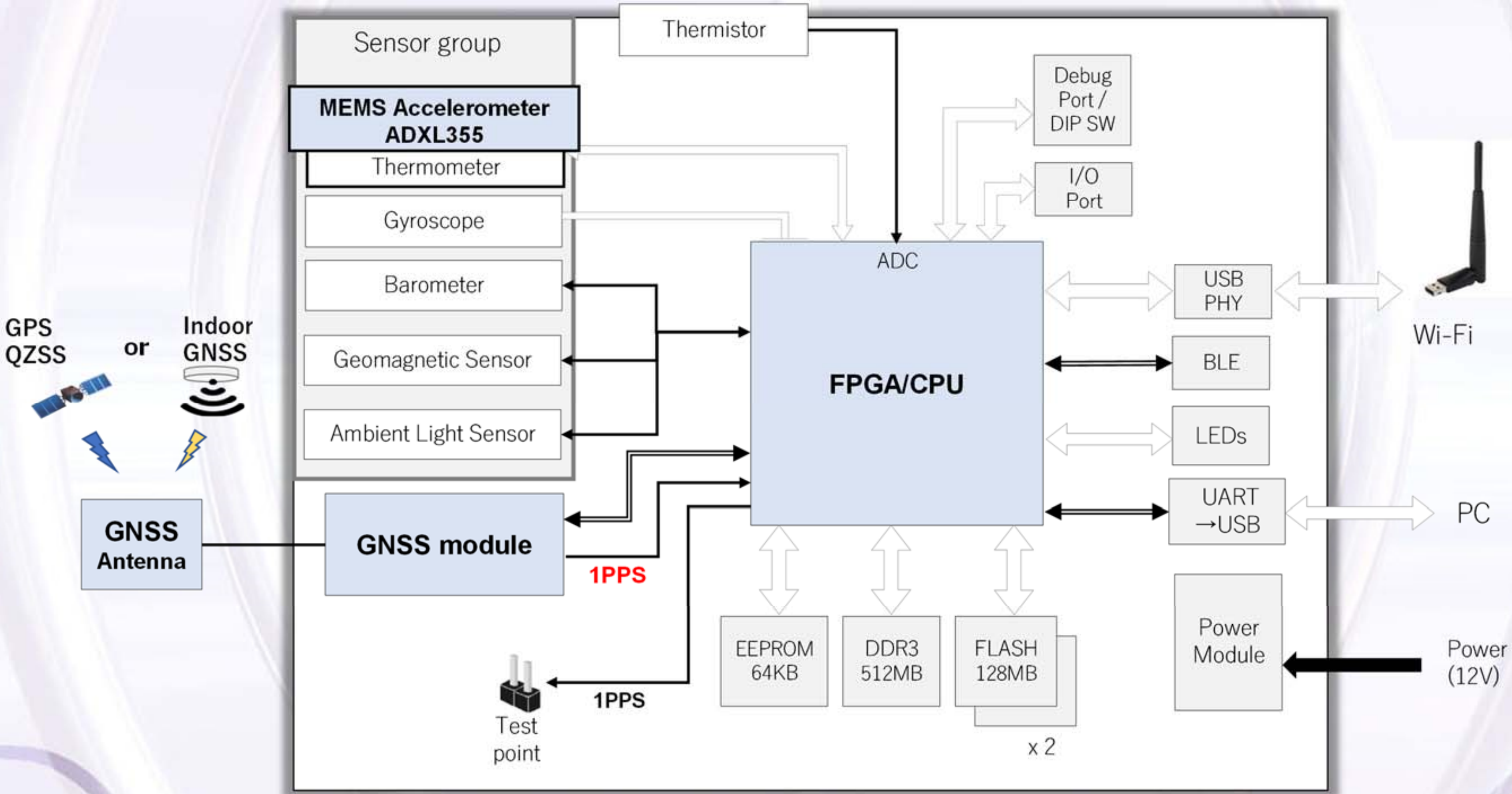
- By using a hub, it is possible to connect multiple D3s under D2.

Development of sensor device able to receive indoor GNSS signals



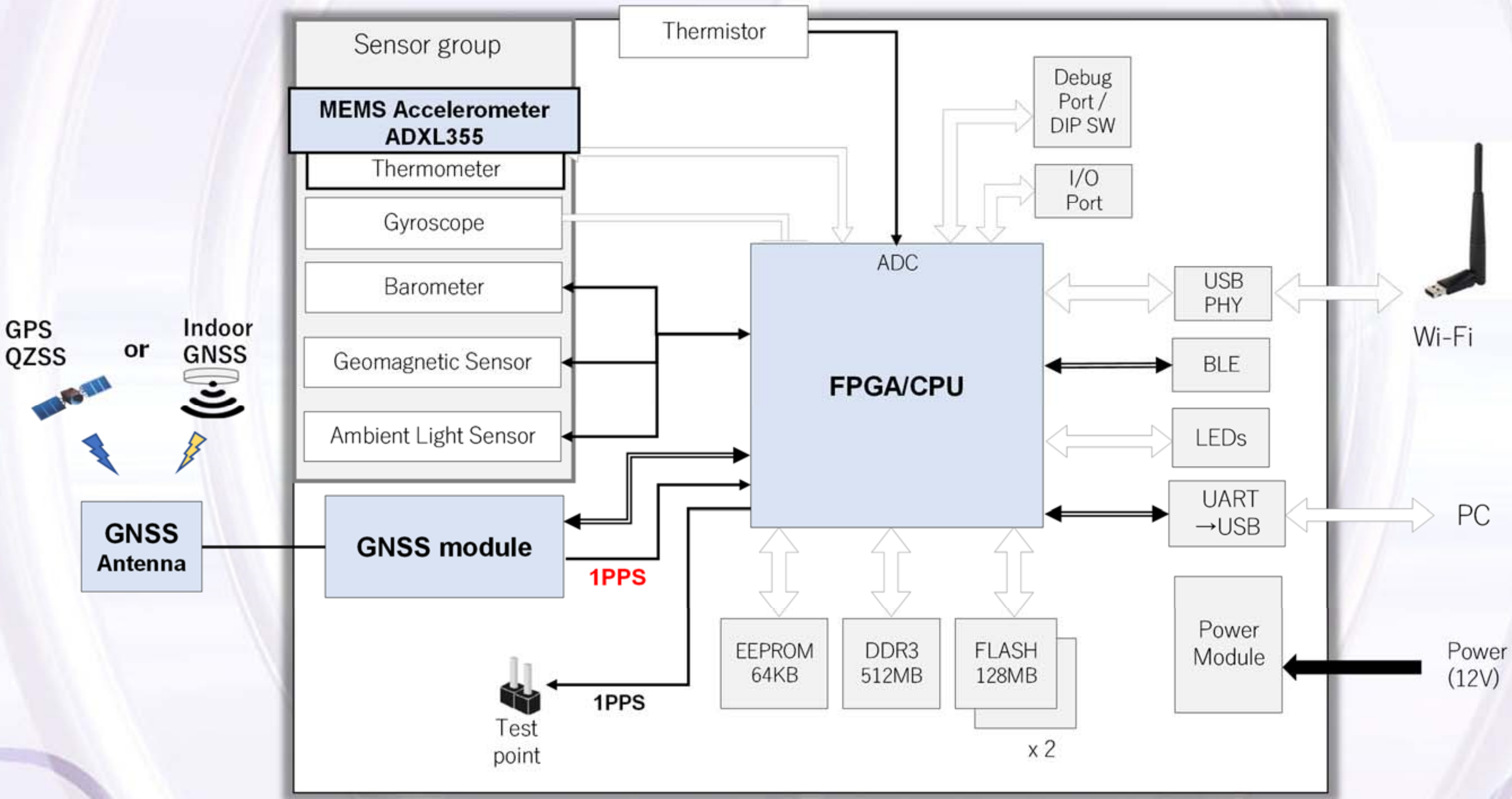


System configuration



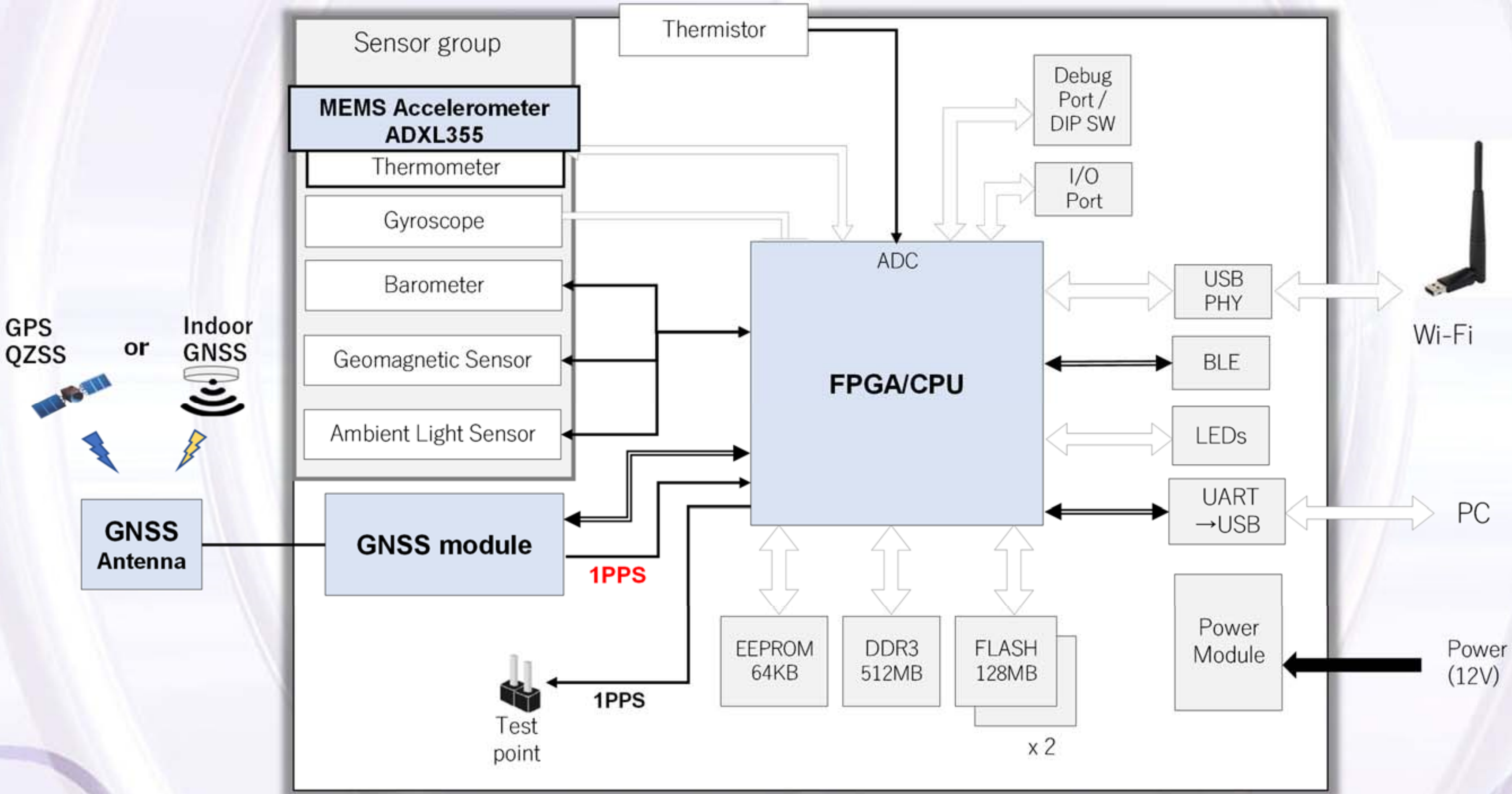
- The sensor device consists of such components as a GNSS receiver, FPGA, CPU, memory, local storage, and network interface.

System configuration



- The FPGA controls the sensor's measurement while generating time stamps using GNSS signal-based ultra-high accuracy time information.

System configuration



- Measured data is stored in the memory, then sent to the network via Ethernet or wireless communication.
- Data can be collected using a wired or wireless method.

Specifications of sensor device

GNSS module	FURUNO/GF-8801
Frequency	1555.983-1610.202 MHz
Center frequency	1597.926 MHz
FPGA/CPU	Zynq2 (CPU Dual-core ARM Cortex-A9)
RAM	SDRAM 512Mbyte
ROM	Serial-FLASH 128Mbyte× 2
Power supply	14 W (Typ.)
Size	102（W）× 172.5（D）× 40（H）
Weight	1.65 kg

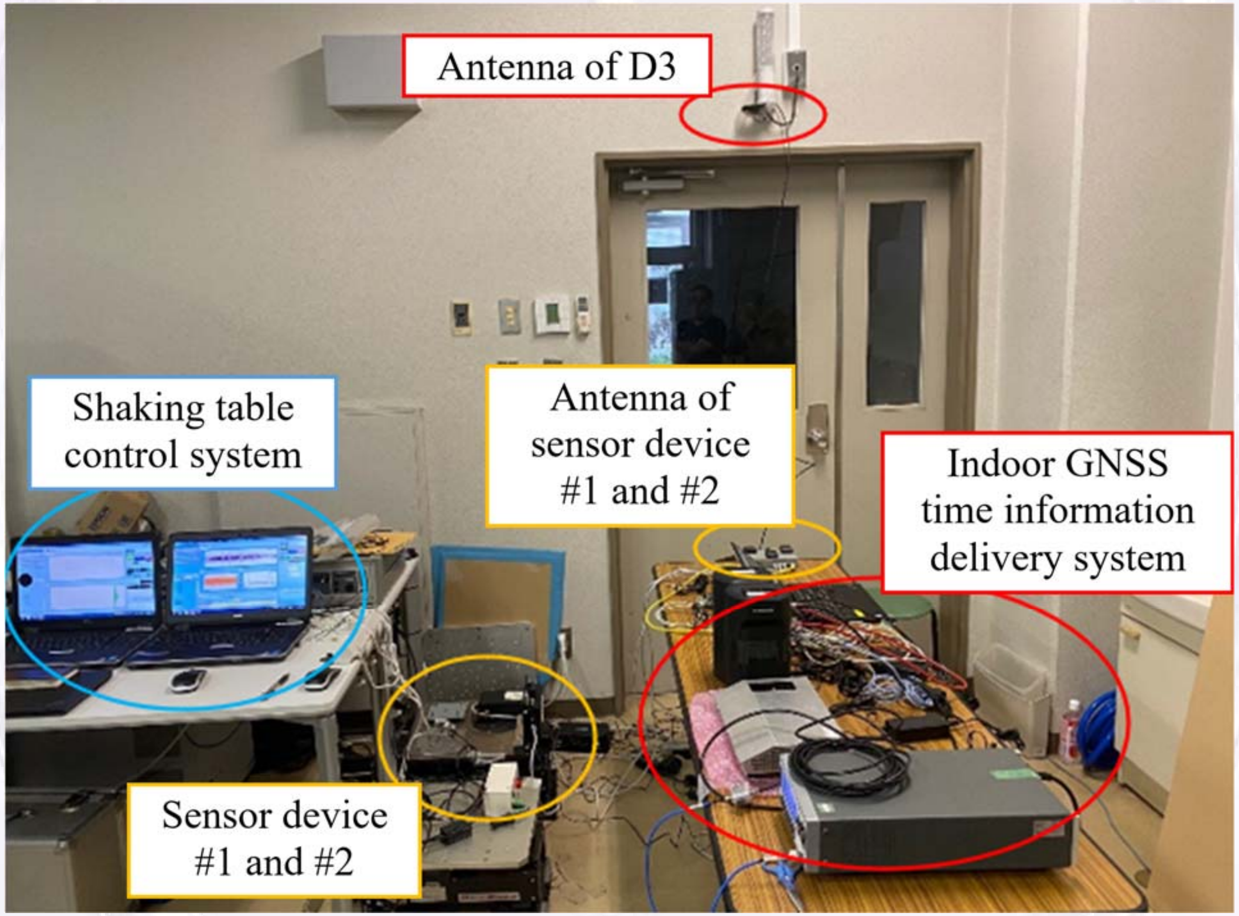
Development of sensor device able to receive indoor GNSS signals

- A sensor device normally consists of components, such as a CPU that controls measurement, an analog sensor, analog filter, A/D converter, memory, and network interface.
- In this development, to reduce the risk that noise will enter during measurement, a sensor device was developed with a digital sensor mounted on it instead of an analog sensor.

Specifications MEMS digital acceleration sensor

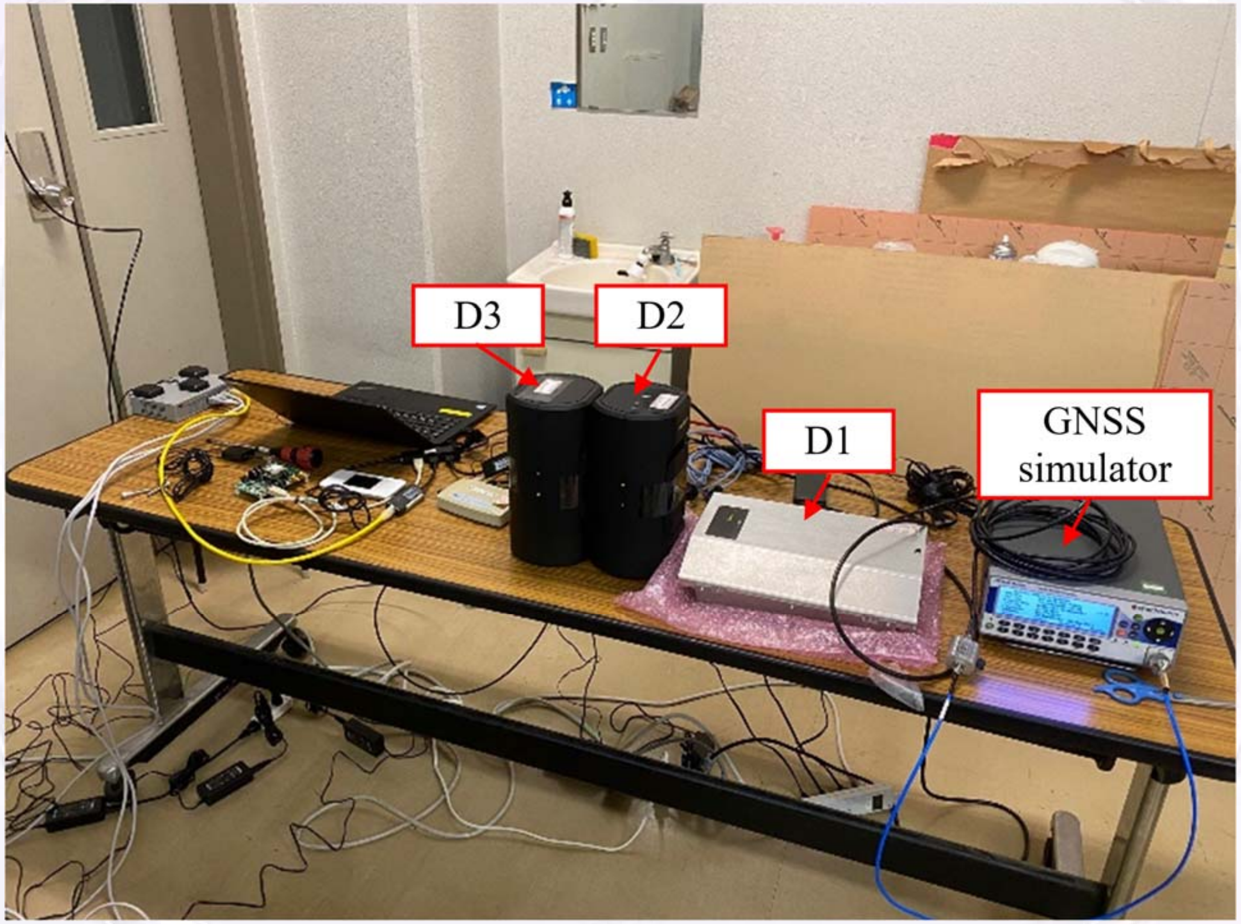
Model	ADXL355
Measurement direction	3
Maximum acceleration (± G)	2
Outside dimensions (mm)	6 × 6 × 2.1
Consumption current (µA)	200
Stand-by power consumption (µA)	21
Sensitivity	256,000 LSB/G ± 8%
Noise characteristics	22.5 µG/√Hz
ADC Resolution	20 Bits
Operating temperature Range (° C)	-40 - +125

Overall view of experimental system



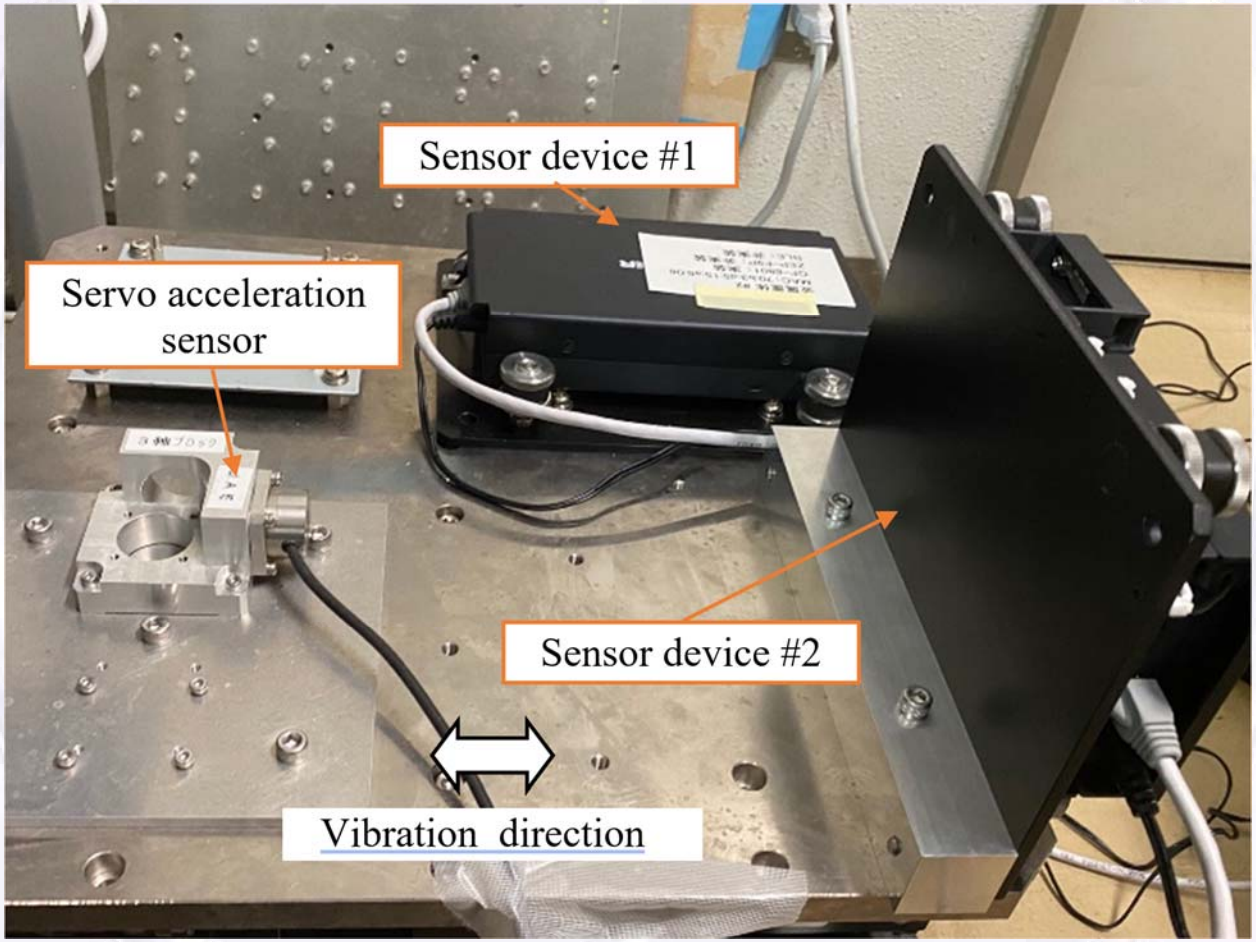
- Red circle: indoor GNSS time information delivery system
- Yellow circle: sensor device and shaking table
- Blue circle: shaking table control system

Indoor GNSS time information delivery system



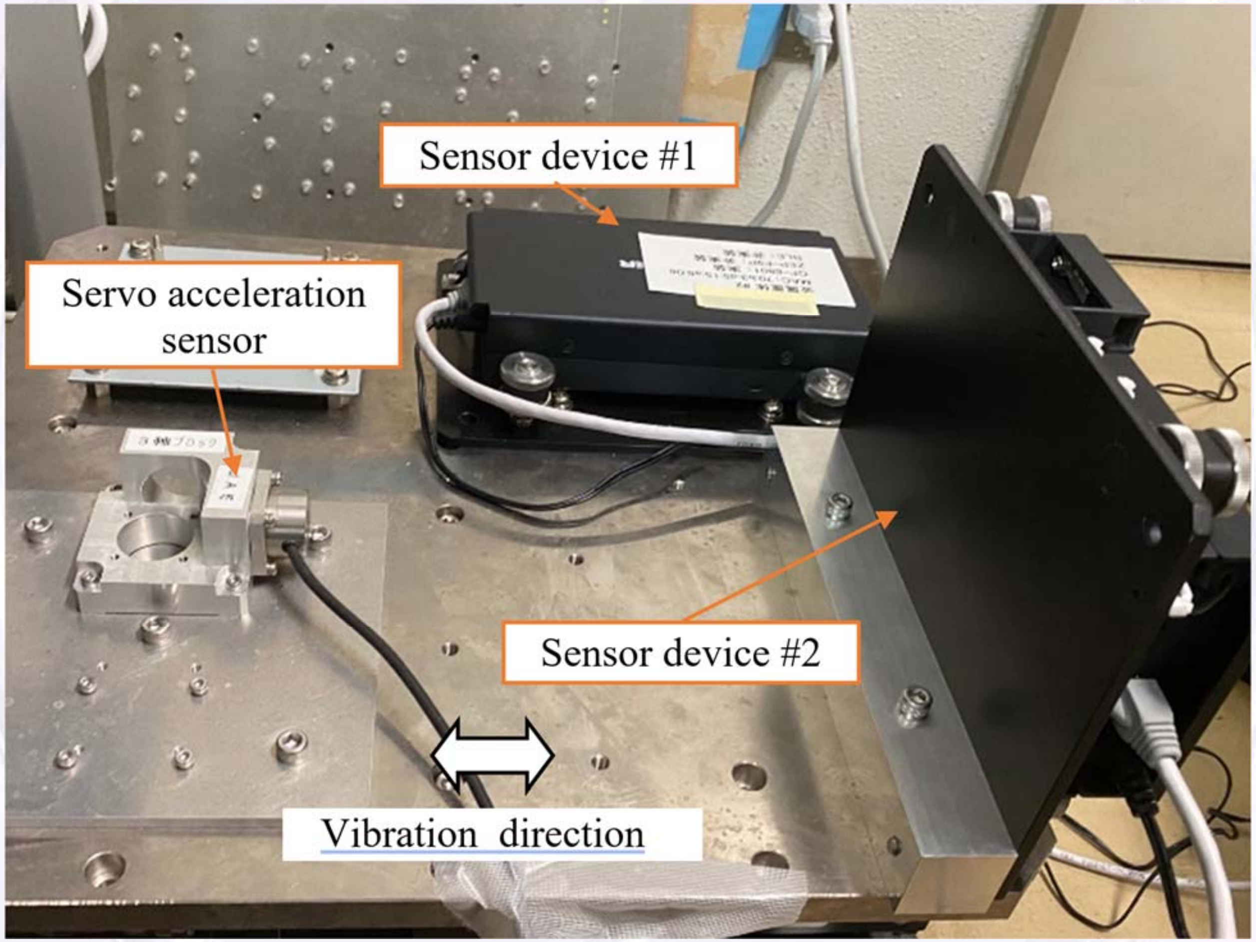
- Indoor GNSS time information delivery system consists of D1, D2, and D3. The time signal was generated by the GNSS simulator and input to D1.

Sensor device and shaking table



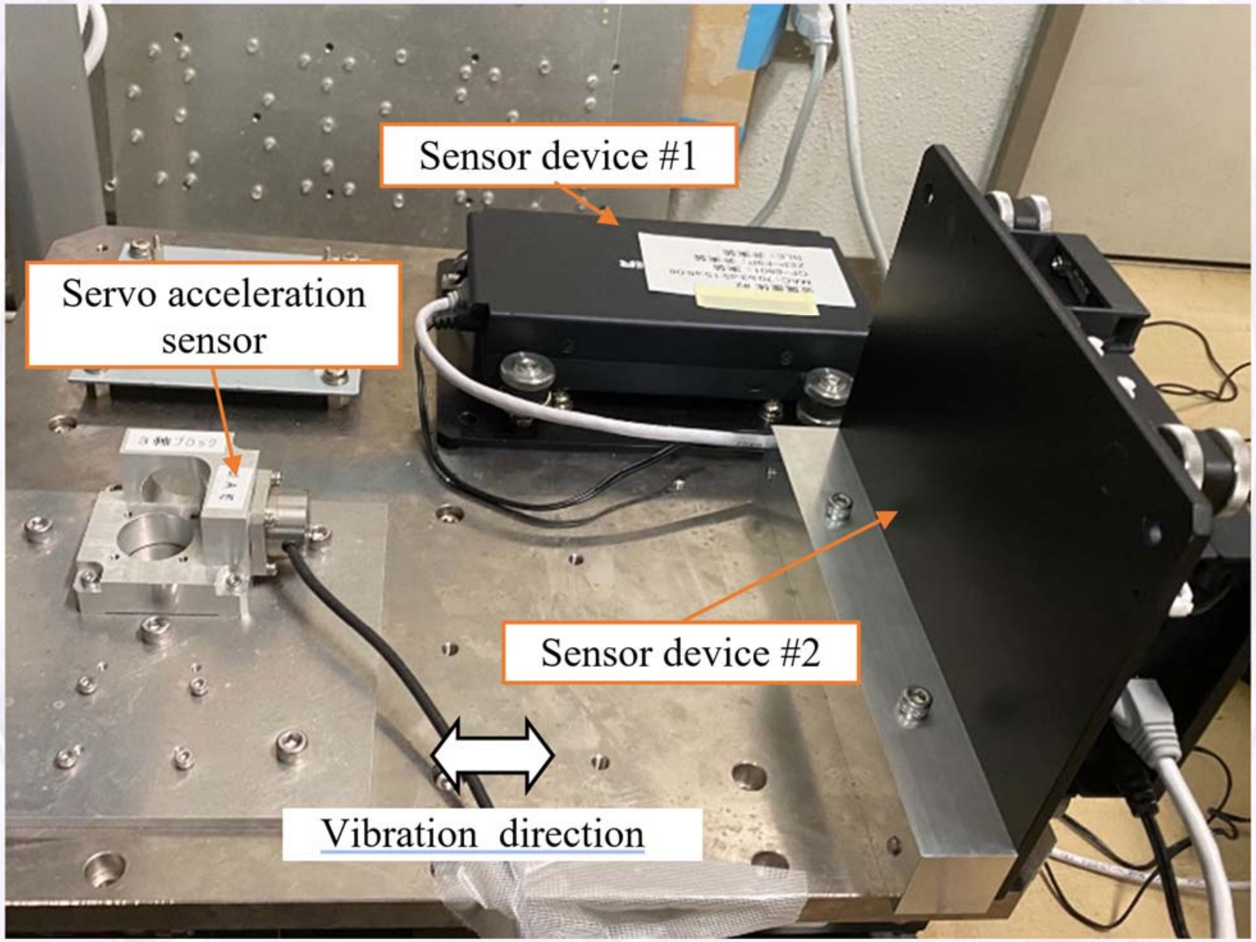
- Sensor device receives time information sent from D3 and adds high-accuracy time information to measured data.

Sensor device and shaking table



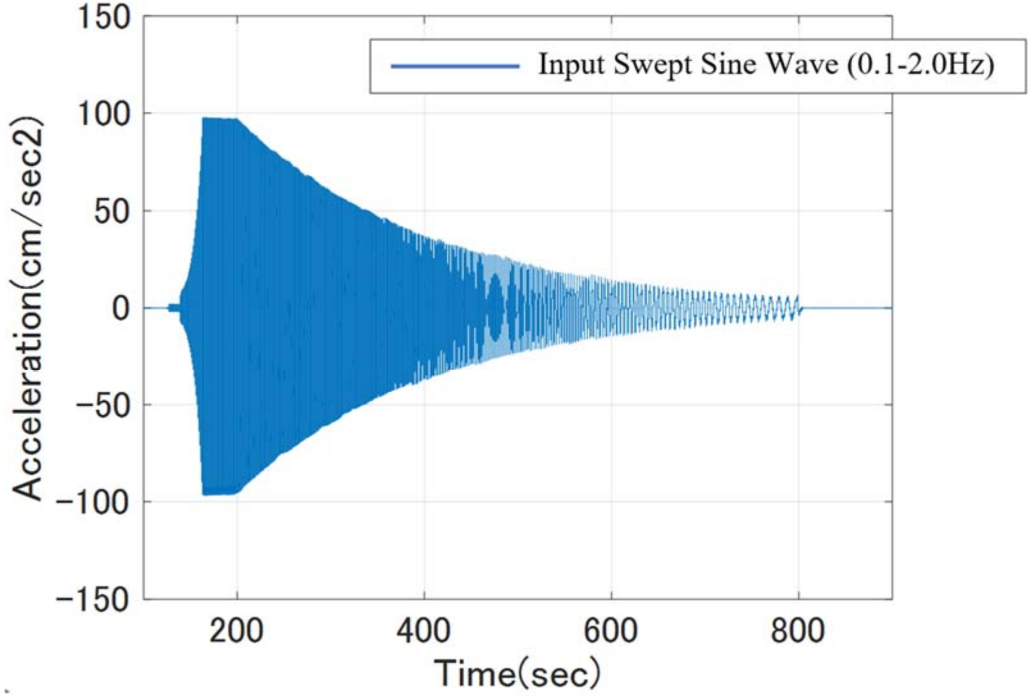
- Two sensor devices and a servo acceleration sensor for comparison were fixed to the shaking table, and the same vibration was applied to compare the results of measurement.

Sensor device and shaking table

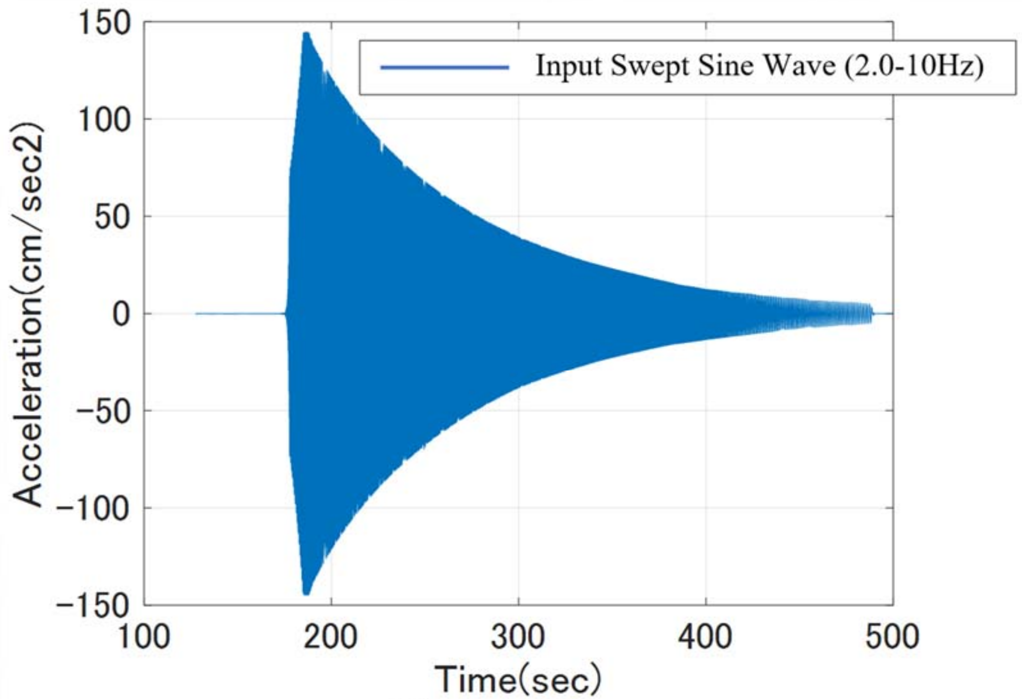


- Vibrations were applied to the horizontal direction of sensor device # 1 and the vertical direction of sensor device # 2.

Input swept sine waves



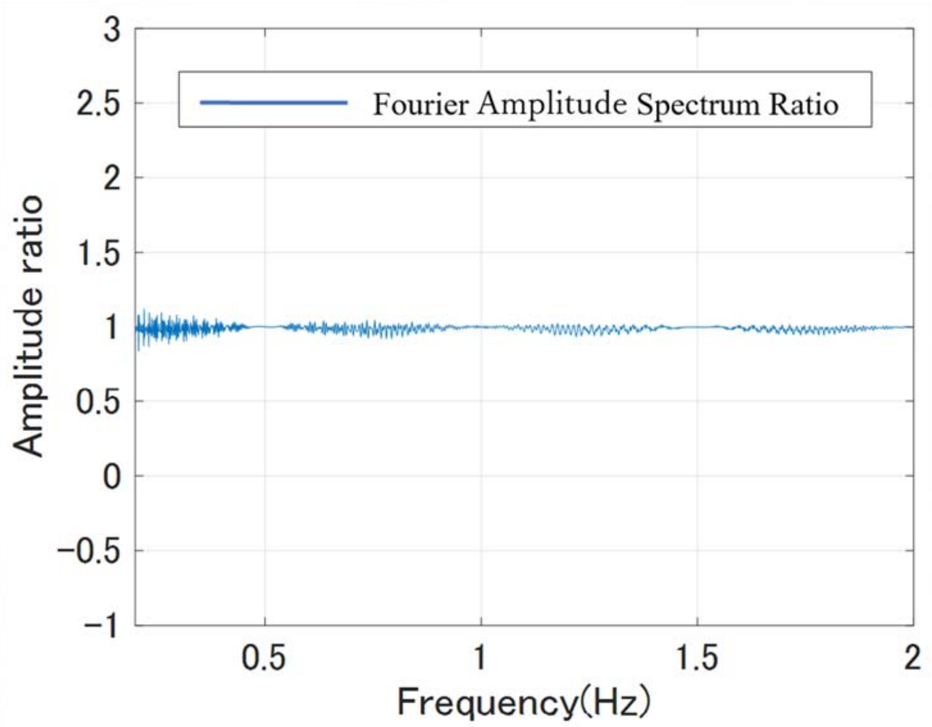
(a) 0.1-2.0 Hz



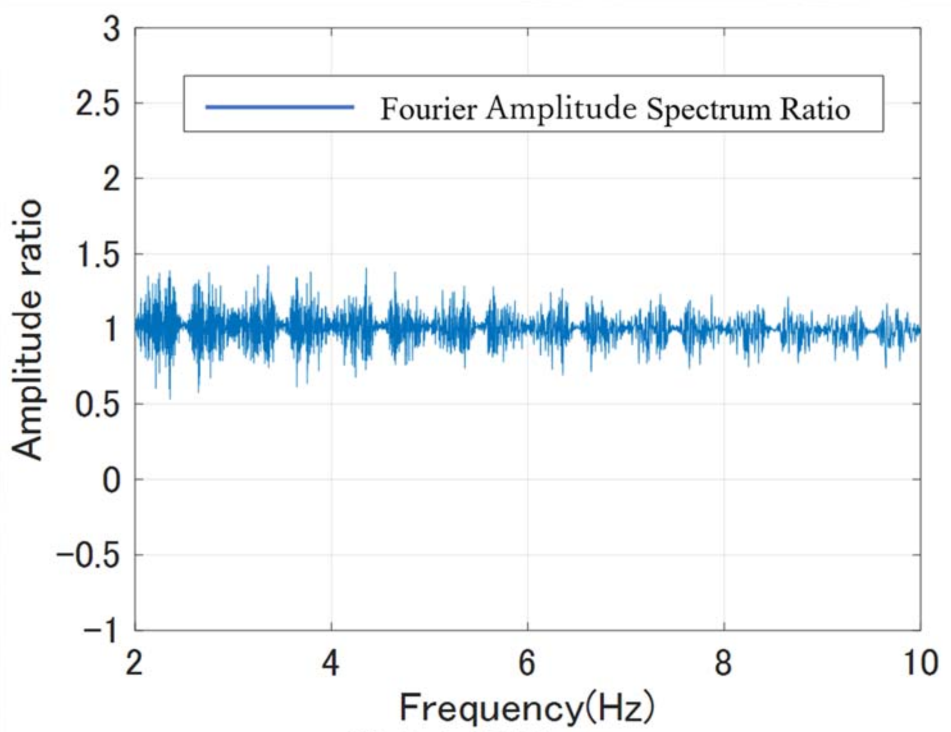
(b) 2.0-10Hz

- Input waves: 0.1–2.0 Hz and 2–10 Hz swept sine waves
- Sampling frequency for each sensor device: 100 Hz

Fourier amplitude spectrum ratios of sensor device #1 compared to servo acceleration sensor



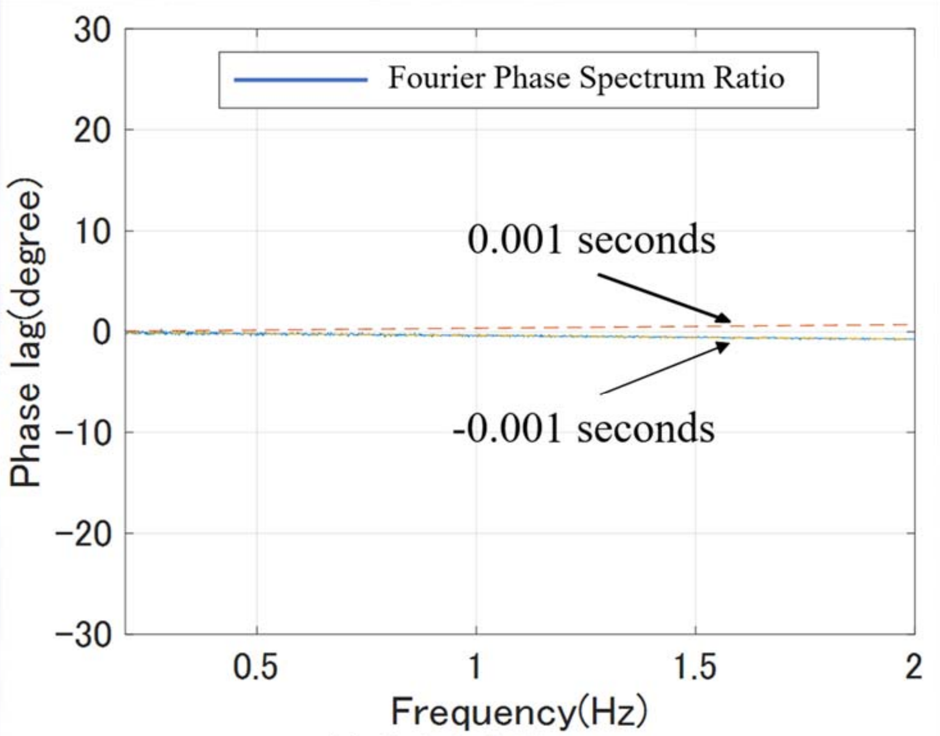
(a) 0.1-2.0 Hz sweep



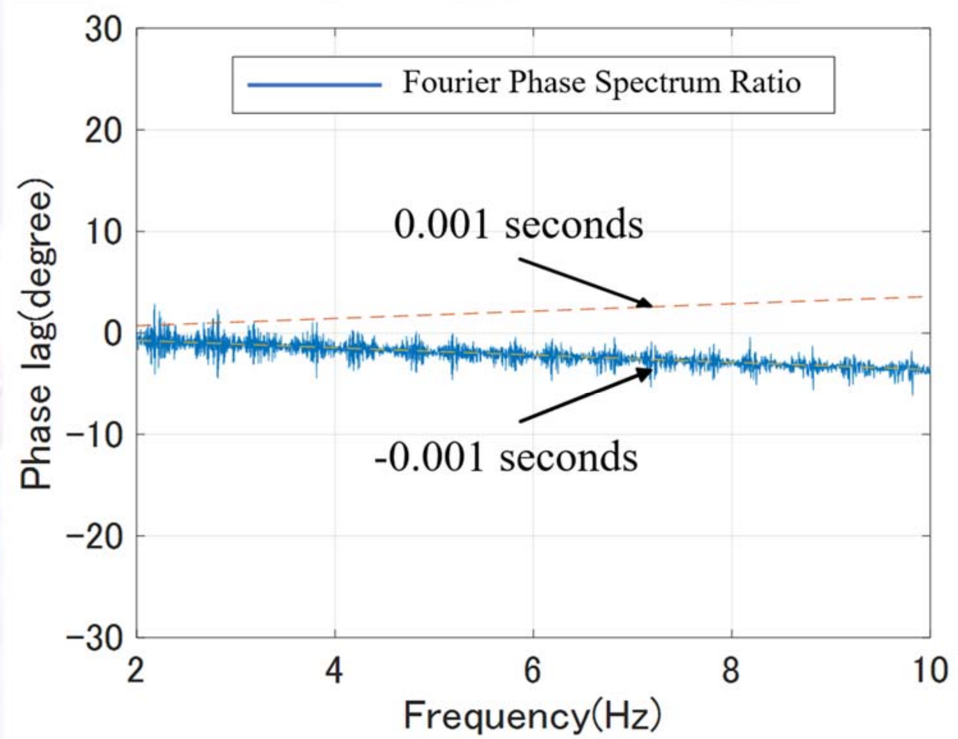
(b) 2.0-10Hz sweep

- Compared to the servo acceleration sensor, the amplitude of the sensor device #1 was flat in the 0.1–2.0 Hz and 2–10 Hz bands, showing that the MEMS digital acceleration sensor mounted in the sensor module has good performance in terms of components in the horizontal direction.

Fourier phase spectrum ratios of sensor device #2 against sensor device #1



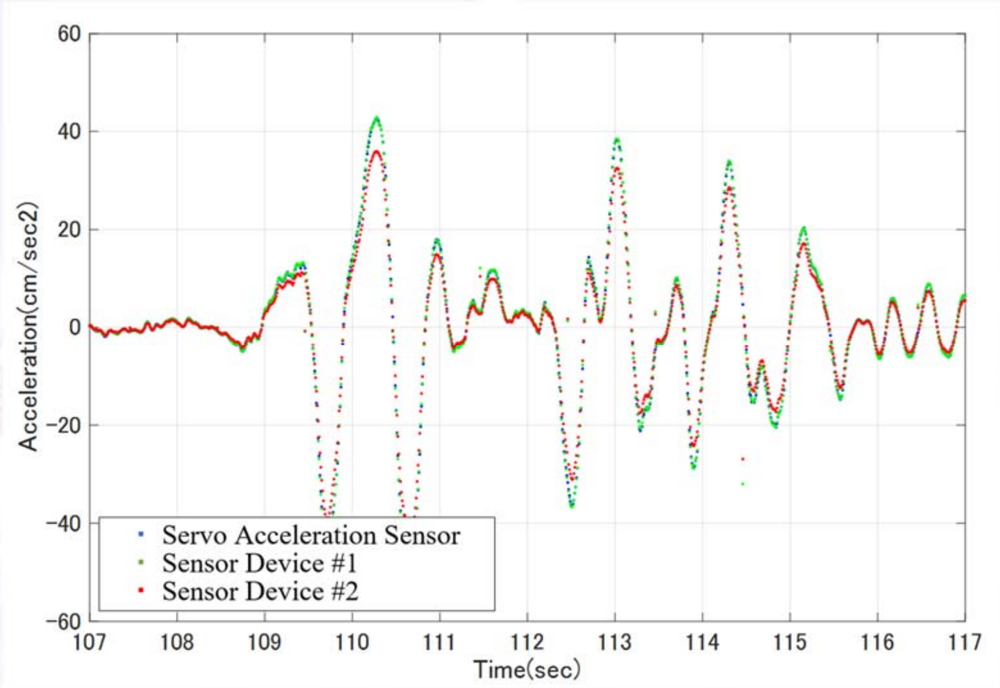
(a) 0.1-2.0 Hz sweep



(b) 2.0-10Hz sweep

- Phase delays within 0.001 seconds are plotted in dotted lines. Time synchronization within 0.001 seconds could be realized between the sensor modules.

Seismic wave input experiment



- The results in the three cases matched, confirming that the developed sensor device has a good measurement performance, equivalent to that of the servo acceleration sensor.

Conclusion

- For the purpose of application to the structural health monitoring of buildings and civil infrastructures, or to earthquake observations, development of a sensor device that adds high-accuracy time information to measured data by using a system to deliver indoor Global Navigation Satellite System (GNSS) time information was reported.

Conclusion

- A system for delivering GNSS time information indoors was demonstrated.
- Development of a sensor device with a mechanism for receiving GNSS signal-based time information was explained in detail.
- Results of a shaking table experiment conducted to evaluate the basic performance of the sensor device were presented.

Conclusion

- Measurement performance and time synchronization function of the developed sensor device were verified.
- Developed sensor device could be applied to such automatic operations as structural health monitoring of buildings and civil infrastructures and earthquake observations.
- Verification using an actual building is now scheduled to be carried out.

Acknowledgement

This research was partially supported by JSPS KAKENHI Grant Number JP16K01283 and JP19K04963