

Operational Procedures of Agencies Contributing to the ISC

Seismic Network and Routine Data
Processing
- Japan Meteorological Agency -

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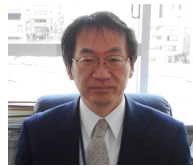
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Operational Procedures of Contributing Agencies

5.1 Seismic Network and Routine Data Processing -Japan Meteorological Agency-

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5.1.1 Overview

Japan and its vicinity is one of the most seismically active regions in the world, and the Japanese people have long suffered from damage by strong ground motions caused by earthquakes as well as from tsunamis. They experienced damaging earthquakes such as the Nobi earthquake in 1891, the Meiji-Sanriku earthquake in 1896, the Kanto earthquake in 1923, the Kobe earthquake in 1995¹ and the Tohoku earthquake in 2011², each of which caused more than 5,000 casualties, and many lives and properties have been lost in other events.

In order to study the earthquakes and mitigate disasters caused by them, contemporary seismic observations began late in the 19th century. It was also understood that a prompt warning/information system for earthquakes and tsunamis would be an important tool to reduce casualties. In this regard, Japan Meteorological Agency (JMA), as one of the responsible governmental organizations, has developed seismic observation networks that are designed for the prompt issuance of earthquake and tsunami warnings to notify as early as possible the regions likely to be affected by strong motions and tsunamis causing damage. JMA additionally plays an important role in providing countries in the northwest Pacific region with detailed forecast information on tsunamis in the area, acting as the Northwest Pacific Tsunami Advisory Center.

JMA also has the responsibility for maintaining a national earthquake catalogue covering the Japanese islands and their vicinity down to 700 km in depth (Figure 5.1). The data archive contains information on earthquake locations as well as phase arrival-time data and focal mechanisms. There are several other seismic networks in Japan developed by other institutions, including research universities for academic purposes and local governments for disaster mitigation purposes. JMA retrieves and uses all the available data from these other networks for a better understanding of the seismicity.

The seismic network of JMA is described here, along with JMA data processing and analysis.

¹JMA officially named the Kobe earthquake as "the 1995 Southern Hyogo Prefecture Earthquake."

²JMA officially named the Tohoku earthquake as "the 2011 off the Pacific Coast of Tohoku Earthquake."

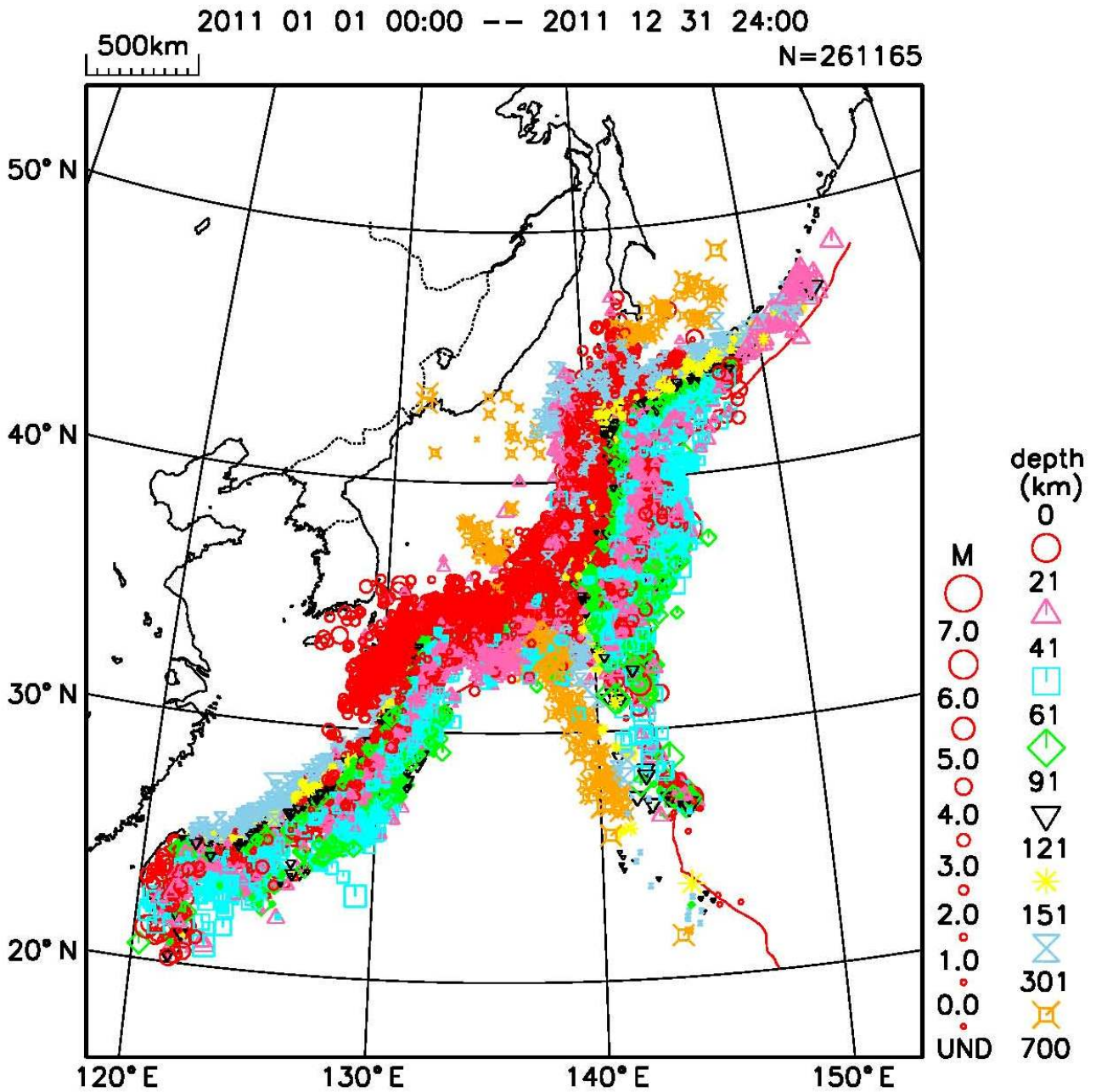


Figure 5.1: Earthquake distribution in 2011. The map shows the JMA coverage area for monitoring seismicity.

5.1.2 Types of networks

JMA operates several sub-networks, with combinations of accelerometers, velocity meters and broadband seismometers, for various purposes as described in the following.

i) The seismic network for Earthquake and Tsunami Early Warnings

One of the most important missions for JMA is to monitor earthquake activity so as to provide earthquake and tsunami early warnings in a timely manner to notify those who are likely to be affected by strong motions and tsunamis to take appropriate action and avoid danger. JMA operates a seismic network, consisting of accelerometers, velocity meters and ocean-bottom seismometers, designed for the prompt issuance of earthquake and tsunami early warnings.

Accelerometers - Multi-function seismic stations

There are about 280 accelerometers installed (Figure 5.2), each equipped with an on-site processor that is capable of determining automatically the seismic phase arrival-times and amplitudes, as well as estimates for the azimuth of the earthquake epicenter and the focal distance: these results are used as input data for the Earthquake Early Warning process (Kamigaichi *et al.*, 2009; Doi, 2011). They are also capable of estimating seismic intensity (see below). This type of station is referred to as a “multi-function seismic station” because it provides not only waveform data with 100 Hz sampling but also the several other types of analyzed outputs mentioned. The data and estimates are transmitted on a real-time basis through dedicated terrestrial telephone lines to the JMA Headquarters in Tokyo and to the Osaka Regional Headquarters. JMA has upgraded these stations by installing satellite-link communication equipment as a backup for the case of landline network interruption, by setting up emergency battery power supplies to cover a period of up to 72 hours in the event of a long-term electricity blackout.

Velocity meters

About 240 of the multi-function seismic stations also have velocity meters to detect small earthquakes. Waveform data with 100 Hz sampling from these velocity meters are transmitted on a real-time basis through dedicated terrestrial telephone lines to the JMA Headquarters in Tokyo and to the Osaka Regional Headquarters.

Ocean-bottom seismometers

JMA operates three sets of wired ocean-bottom seismometers, each of which has three-to-five velocity meters. One of the sets has five accelerometers in the same cells as the velocity meters. They are included in the accelerometer network for earthquake and tsunami early warning operation. Waveform data with 100 Hz sampling are transmitted on a real-time basis through dedicated terrestrial telephone lines to the JMA Headquarters in Tokyo and to the Osaka Regional Headquarters.

ii) The network of broadband stations

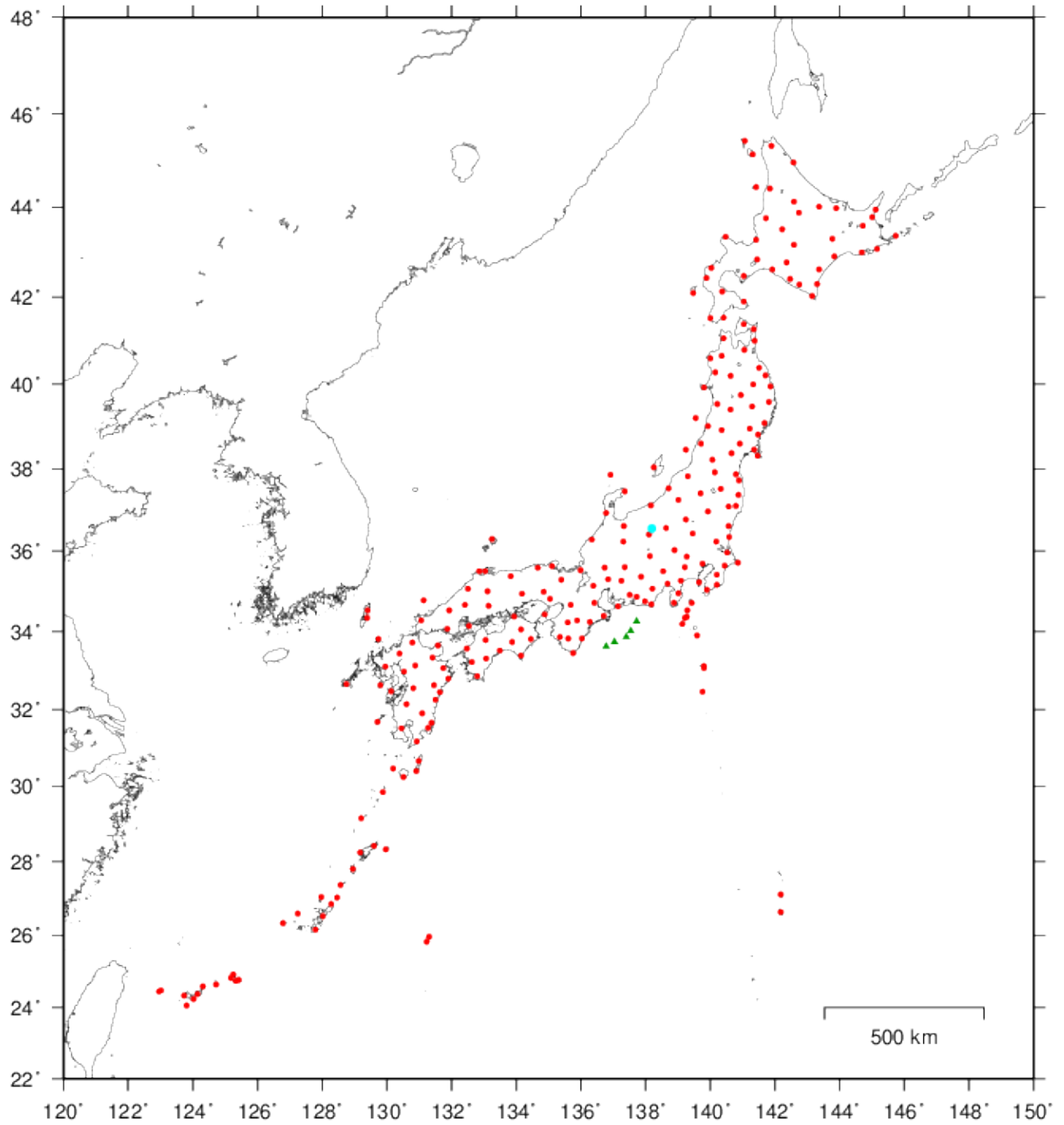


Figure 5.2: The JMA seismic network of accelerometers.

JMA operates 20 broadband stations with STS-2 seismometers (Figure 5.3). Waveform data with 20 Hz sampling are transmitted on a real-time basis through dedicated phone lines to the JMA Headquarters in Tokyo and to the Osaka Regional Headquarters. The broadband data are used not only for centroid moment tensor (CMT) solutions for earthquakes but also for evaluating the moment magnitude as an update for the earlier magnitude estimation of an earthquake in the tsunami forecast operation.

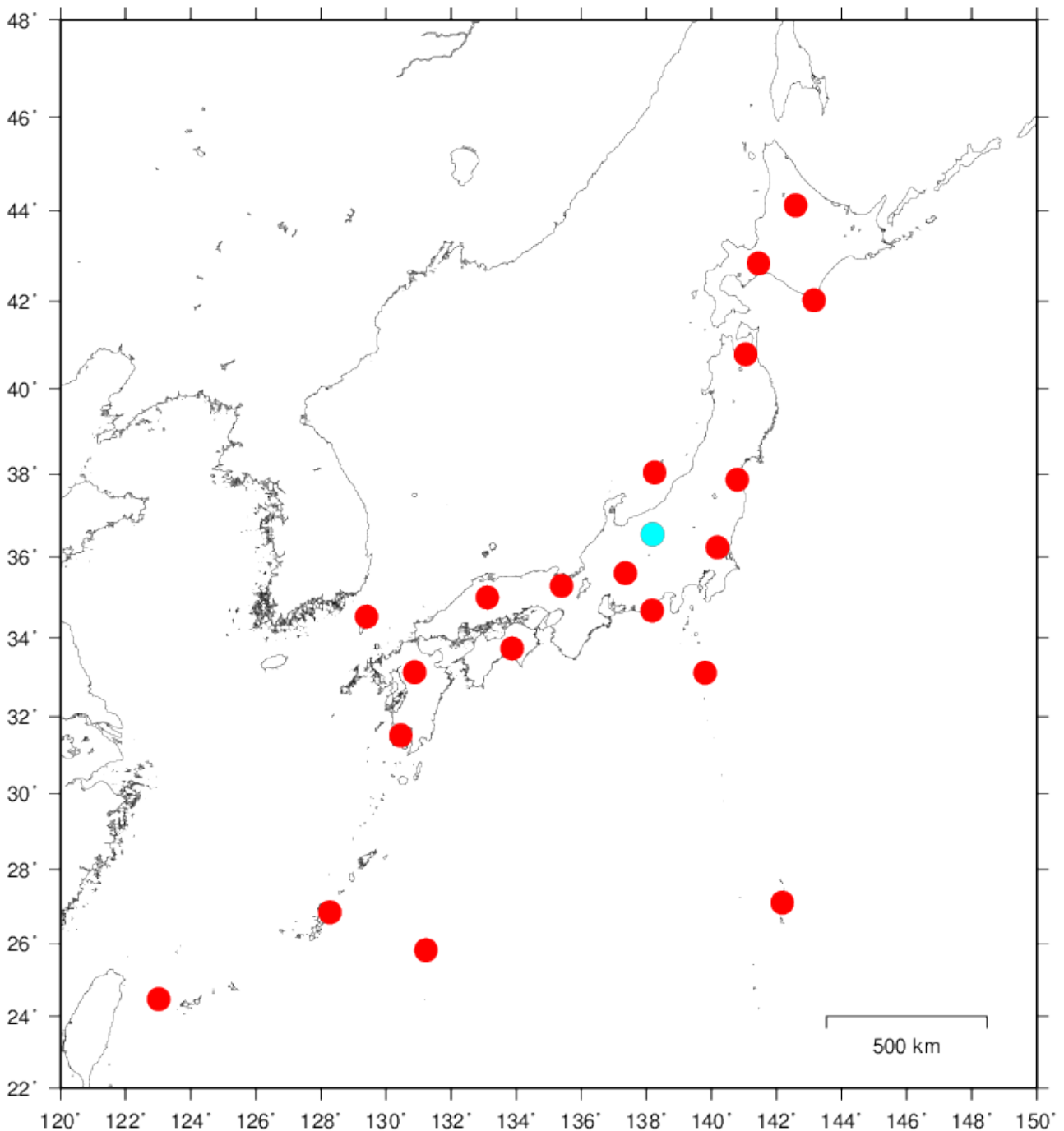


Figure 5.3: Distribution of JMA broadband stations (STS-2). The blue circle shows a location of Matsushiro Observatory.

iii) Matsushiro Seismic Array System (MSAS)

The MSAS consists of eight seismic stations arranged in a circle, the diameter of which is about 10 km, and the data processing units at Matsushiro Observatory (Figure 5.3). The advantage of seismic array observation is such that:

- (1) It is possible to reduce the signal degradation from background noise, using the beam-forming technique in which individual channels are delayed and summed appropriately to enhance a signal and cancel the noise.
- (2) The arrival direction and apparent velocity of the seismic signals can be determined from arrival-time differences at array elements used in forming the array beam to observe the best signal.

The system is mainly used for teleseismic event analysis and for locating small seismic swarms in the vicinity of the array.

iv) The network for seismic intensity measurement

Seismic intensity is key information in Japan, not only for emergency operation organizations but also for residents and visitors, for knowing how severe the strong ground-motion occurrence is and how wide-spread the damaging area is. The responsible agencies can then judge the necessity, urgency, and priority of search and rescue operations from the seismic intensity distribution following an earthquake occurrence.

JMA has developed an instrumental seismic intensity meter that is capable of measuring seismic intensity automatically from measurements of accelerations of ground motions, taking into account the amplitudes and frequencies (see Appendix 5.1.9). These seismic intensity values better represent human perceptions of the motions and the behaviours of furniture or buildings than single measures of PGA (peak ground acceleration) or PGV (peak ground velocity). It is thus possible to know, within a few minutes after the earthquake occurrence, the distribution of strong motions and the likely regions suffering damage.

JMA operates about 660 seismic intensity measurement stations nationwide (Figure 5.4), monitoring the damaging impact for densely populated cities and towns. Multi-function seismic stations also form part of the seismic intensity station network. Seismic intensity values are transmitted on a real-time basis through dedicated phone lines to the JMA Headquarters in Tokyo and to the Osaka Regional Headquarters. For backup resilience, half of the stations are equipped with a satellite communication capability using the geostationary meteorological satellite operated by JMA.

5.1.3 Data sharing with other organizations

There are other seismic networks in Japan that are maintained by universities and research institutes for their academic purposes. Several universities in Japan have co-operated and developed a regional seismic network, consisting of around 300 velocity-type seismometers and several accelerometers. The National Institute for Earth Science and Disaster Prevention (NIED) has also developed their nationwide network called “Hi-net” to monitor small earthquakes since 1997 and a broadband station network called

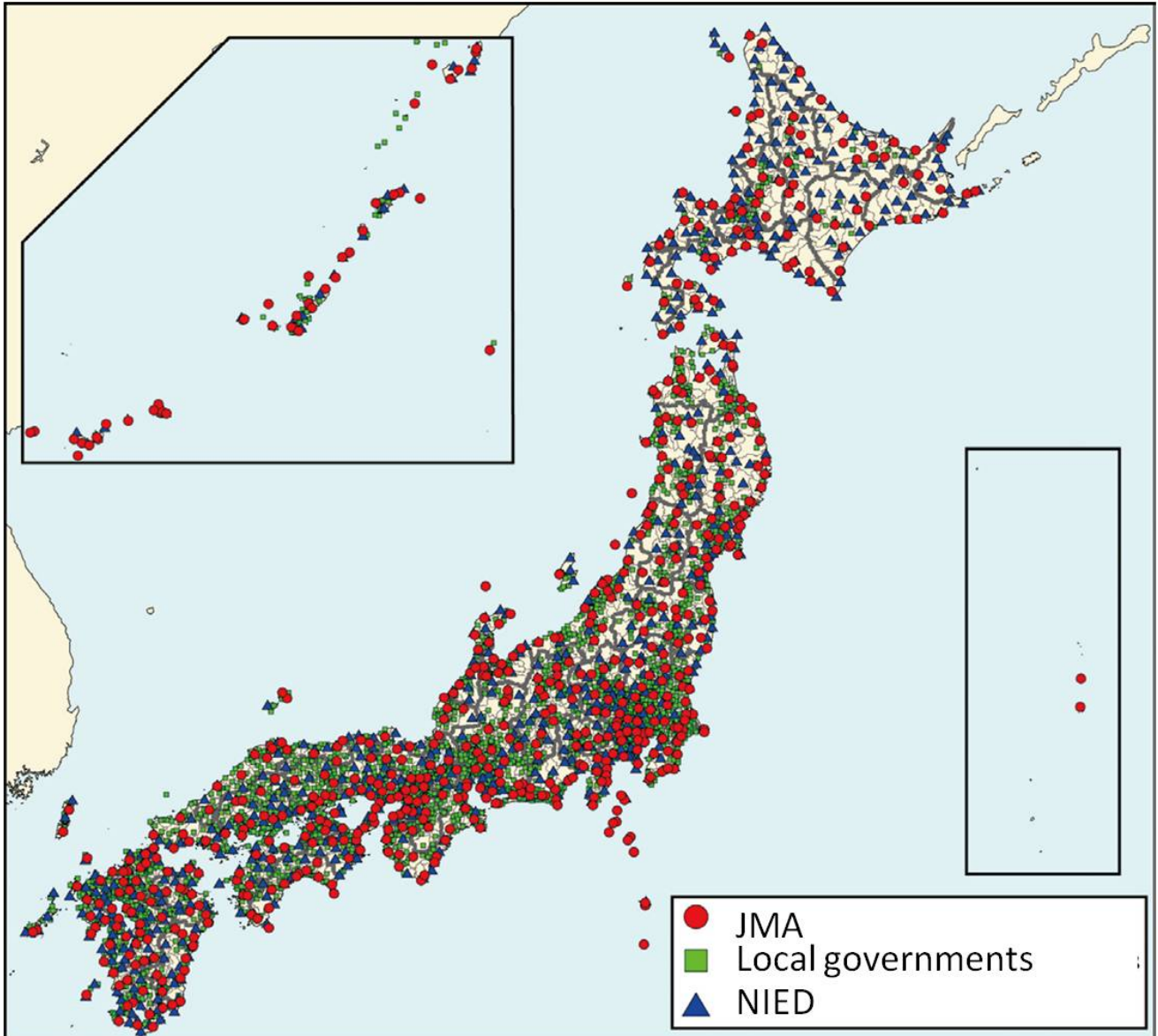


Figure 5.4: Distribution of seismic intensity measurement stations.

“F-net” since 1994. There are also some additional regional seismic stations maintained by other research institutes and local government authorities. Data from these stations (Figure 5.5) are shared among the network owners, and JMA uses all of the available data to improve the estimations of earthquake locations. The results are archived in the earthquake catalogue and are useful for evaluating seismic hazard.

NIED and local government authorities also operate as many as 3,700 seismic intensity measurement stations (Figure 5.4). The intensity values processed at each of these stations are disseminated to JMA on a real-time basis, and are then merged into JMA’s own compilation for a prompt issuance of seismic intensity information. No waveform data from these stations are retrieved in real time.

5.1.4 Data processing

- i) Emergency operation - Automatic processing of earthquake early warnings and fast

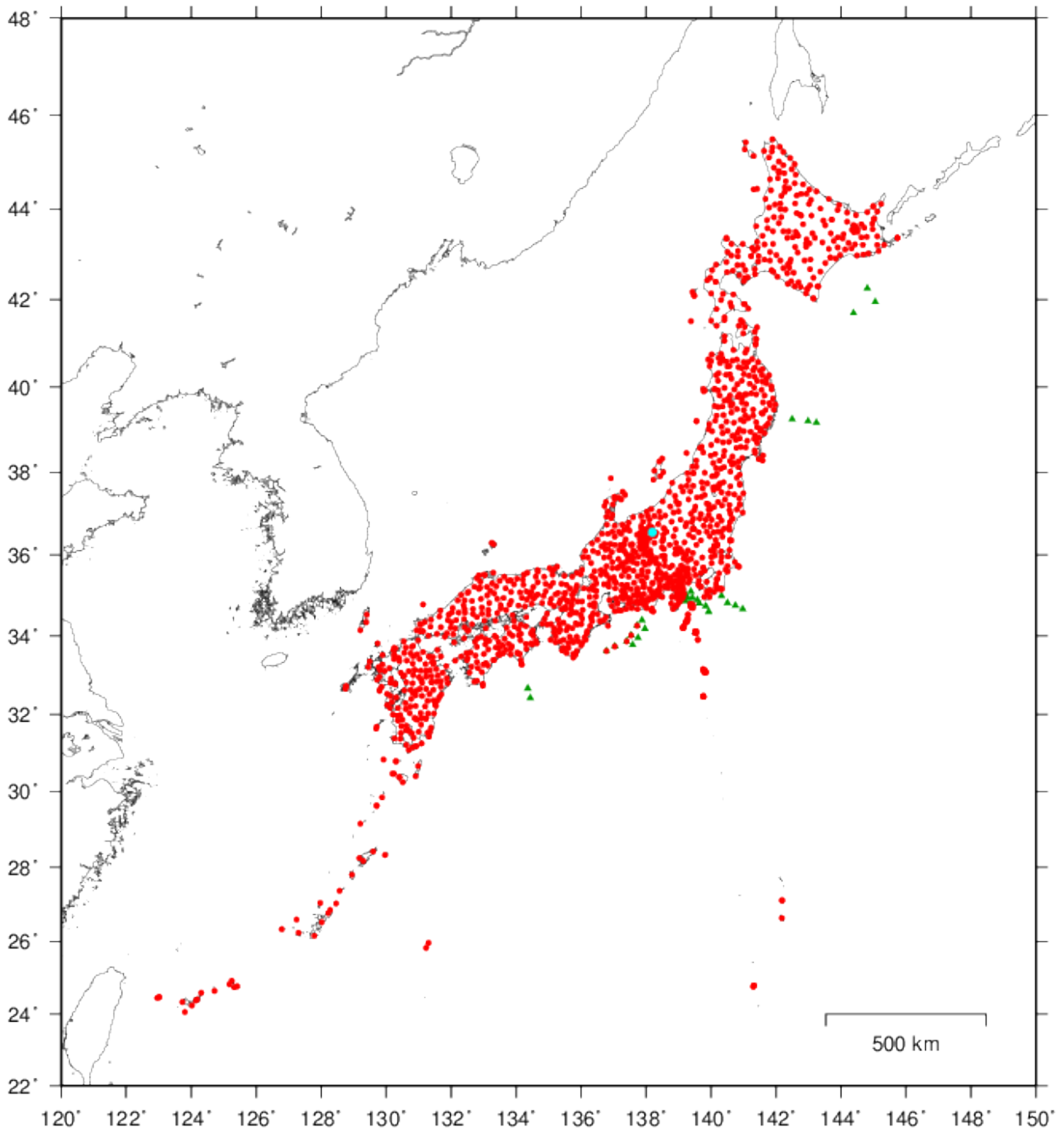


Figure 5.5: Distribution of seismic stations contributing data shared among JMA, universities and other institutions.

determinations of location and magnitude for tsunami warnings

Data processing for earthquake early warning occurs first during the sequence of the seismic data analysis when an earthquake is detected, and it is a thoroughly automated operation carried out simultaneously at the JMA Headquarters and at the Osaka Regional Headquarters to estimate a hypocenter and a magnitude based on outputs from multi-function seismic stations for moderate to severe strong motions generated by an earthquake (Kamigaichi *et al.*, 2009).

Waveform data are also processed simultaneously at the JMA Headquarters and at the Osaka Regional Headquarters to identify tsunami-genic earthquakes. Locations and magnitudes calculated on the basis of automatic readings of phase arrival-times and maximum amplitudes from multi-function seismic stations, as well as from seismic stations of other institutions, are presented to analysts on duty. The duty analysts review the results and decide whether to issue a tsunami warning, where appropriate, together with several other kinds of seismic information, including estimates of earthquake location, depth, magnitude and observed seismic intensities.

An initial tsunami warning should be issued within two-to-three minutes after the detection of seismic waves, and the other seismic information should follow not more than 15 minutes later. The duty analysts will also refer to the centroid moment tensor solution, which is automatically computed within 10-30 minutes after the earthquake occurrence using broadband station data, to re-evaluate from the focal mechanism and depth estimates the likelihood that a tsunami was generated. This further review is used to update the information provided by the observations that were required within two-to-three minutes for the initial tsunami warning.

The early warning system continues to be updated in the light of experience gained from recent events such as the 2011 off the Pacific Coast of Tohoku Earthquake (Japan Meteorological Agency, 2013).

- ii) Precise analysis - Routine daily review and quality control for the national earthquake catalogue

Seismic events from 0-24 hours in local time are reviewed daily by analysts at six regional operation centers of JMA, each monitoring an area almost 1000 km by 1000 km. The independent analyses are done using different processes from those used for the earthquake and tsunami early warnings.

- a) Automatic process

Continuous waveform data, telemetered from seismic stations digitally on a real-time basis, are processed to identify automatically individual seismic events. Phase data at certain groupings of stations are used to locate each earthquake and to estimate the origin time and magnitude. The results are then checked for seismological consistency, such as comparing the differences between observed and computed P-phase and S-phase arrival-times or the consistency of apparent velocity across the grouping of stations. Some identified events remain without hypocenter or magnitude estimations.

b) Review by personnel

Analysts review the results produced by the automatic calculations so as to

- delete false events (noise or artifacts),
- check for consistency with previous seismicity,
- check if the trend in residuals of phase arrival-times shows bias,
- check the azimuth gap of stations included, and so on.

Analysts will re-measure phase arrival-times and maximum amplitudes if necessary.

Reviewed data are relayed to the JMA Headquarters on the afternoon of the next day. Analysts there merge all the reports, checking for duplication of events, and the preliminary results are published on the JMA web-site. After another review, the final determinations are archived and published as the monthly bulletin for Japan a few months later.

iii) Methodology

a) Determination of hypocenters:

Hypocenters are calculated using the arrival-times of P-waves and S-waves, and magnitudes are calculated using the maximum seismic-wave amplitudes. An iterative method (Hamada *et al.*, 1983), an extension of Geiger's method (Geiger, 1910), is used to calculate hypocenters.

The data weight is given by the following formula, where R denotes the hypocentral distance (Ueno *et al.*, 2002):

$$\text{For P-waves } (W_p) : W_p = R_{min}^2 / R^2$$

$$\text{For S-waves } (W_s) : W_s = W_p / 3$$

R_{min} : Hypocentral distance of the station nearest to the hypocenter (km)

(if $R_{min} \leq 50$, then $R_{min} = 50$: if $W_p > 1$, then $W_p = 1$)

The data of any station with large travel-time residuals are not used for the calculations. The depth of focus is calculated first with no restrictions. If the solution is unstable, then the best solution is searched by changing the depth in 1 km steps. In the case that the focus is located in a region where focal depths are considered to be not well determined, such as in the Kurile Islands region, the focal depth is fixed at 30 km.

The JMA2001 travel-time tables (Ueno *et al.*, 2002) are used for the theoretical travel-times. For earthquakes located near the Kurile Islands, the travel-time tables given by Ichikawa (1978) are used. The Jeffreys-Bullen travel-time tables (Jeffreys and Bullen, 1958) are used for earthquakes having an epicentral distance of 2000 km or more from the JMA seismic network.

In principle, the calculation is done only when more than five P or S-wave arrivals have been observed at three or more stations (a criterion used since January 1983). If the number of stations with observations exceeds 40, the nearest 40 stations from the focus are used in the calculation (a criterion used since October 1997). Procedures for the selection of stations are as follows:

A characteristic distance (Δ_{lim}) is defined in terms of the following empirical equation:

$$\Delta_{lim} = \Delta_3^2/100 \text{ (km)} + H \text{ (km)} + 100 \text{ (km)}$$

Here Δ_3 denotes the epicentral distance of the third nearest station from the trial hypocenter; H is focal depth: the unit is kilometre.

The 16 stations nearest to the trial hypocenter are selected without regard to station quality. An additional 24 stations within Δ_{lim} are then selected based on the epicentral distance and station quality, where the station quality is given as an attribute constant derived from seven classes regarding the S/N ratio, data-sending capability and average travel-time residual etc. If the number of selected stations is still not enough for robust estimation in the case of an offshore earthquake or a deep earthquake, for example, additional stations outside Δ_{lim} may be selected until the number of stations becomes sufficient.

b) Determination method for magnitudes:

i. Magnitude M_J at the Local Meteorological Observatories

This is calculated only for large and shallow ($H \leq 60$ km) earthquakes using acceleration data from the multi-function seismometers installed at the Local Meteorological Offices. M_J is given by the average of observations of

$$M_J^{OBS} = \log\sqrt{(A_N^2 + A_E^2)} + 1.73\log\Delta - 0.83$$

using the maximum displacement amplitudes at the stations (Tsuboi, 1954). Here the acceleration data are integrated twice to obtain the displacement data, to which a high-pass (6 s) filter is applied to simulate the mechanical strong-motion seismographs. This method will be provisionally used until JMA can confirm the independence of C_D in the next relation (below) for the magnitude of large earthquakes, especially of M7 class or above.

ii. Displacement magnitude M_D

This is calculated as the average of observations of

$$M_D^{ST} = \log\sqrt{(A_N^2 + A_E^2)} + \beta_D(\Delta, H) + C_D$$

over stations in the ranges $R \geq 30$ km and $\Delta \leq 700$ km for maximum amplitudes of displacement in the horizontal components (Katsumata, 2004). If the number of stations involved in the average is less than three, Δ is extended out to 2000 km. If the number of the stations used to obtain M_D is two, it is denoted as M_d .

iii. Velocity magnitude M_V

This is calculated as the average of observations of

$$M_V^{ST} = \alpha \log A_Z + \beta_V(\Delta, H) + C_V$$

over stations in range $5 \text{ km} \leq R \leq 400 \text{ km}$ for maximum amplitude of velocity in the vertical component (Funasaki *et al.*, 2004). If the number of stations involved in the average is less than four, Δ is extended out to 1000 km. If the number of the stations used to obtain M_V is two or three, it is denoted as M_v .

iv. Moment magnitude M_w

A moment magnitude M_w is given as a result of the centroid moment tensor (CMT) solution.

The averaging procedure for *i*, *ii* and *iii* in the above is as follows. First, an initial mean of magnitudes at all the stations is calculated. Then a mean and standard deviation of magnitudes for the stations is calculated, discarding those values deviating more than 0.5 from the initial mean. This mean value is adopted as the magnitude only if the standard deviation is less than 0.35.

The calculated value is adopted as the JMA magnitude according to the priority order $M_J > M_D > M_V > M_d > M_v$, and this is then given as the primary magnitude estimate. The moment magnitude is generally given as the secondary magnitude estimate when CMT solutions are determined; otherwise a secondary magnitude estimate is given according to the priority order.

For reference, the meanings of the symbols used in the above formulas are as follows:

| | |
|--------------------|---|
| H | Focal depth (km) |
| Δ | Epicentral distance (km) |
| R | Hypocentral distance (km) |
| α | Constant $1/0.85 = 1.176$ |
| β_D, β_V | Terms showing dependence on Δ and H (see Figures 5.6 and 5.7) |
| C_D | Correction value (= 0.2) used for accelerometers |
| C_V | Correction value depending on types of seismometers (see Table 5.1) |
| A_N, A_E | Maximum displacement amplitude in the horizontal component of accelerometers. The unit is micrometres (10^{-6} m). |
| A_Z | Maximum velocity amplitude in the vertical component of velocity meters. The unit is 10^{-5} m/s. |

Table 5.1: Correction value estimated for each type of seismometer (C_V)

| Type of seismometer | Value |
|---|-------|
| Velocity meters | 0.00 |
| JMA OBS (velocity) | 0.47 |
| JMA velocity type installed in volcanic region | 1.13 |
| Other organization, bore-hole installation (velocity) | 0.48 |

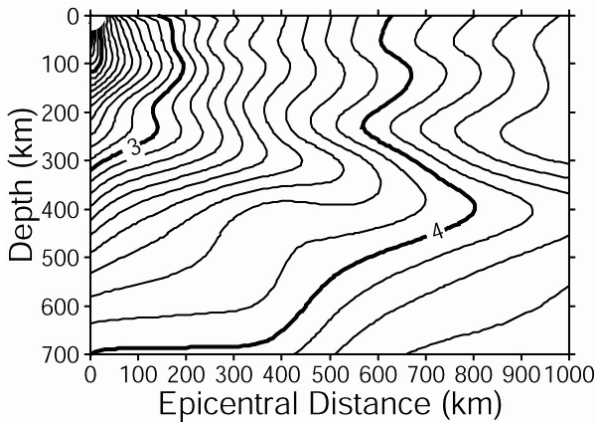


Figure 5.6: Contour representation of β_D .

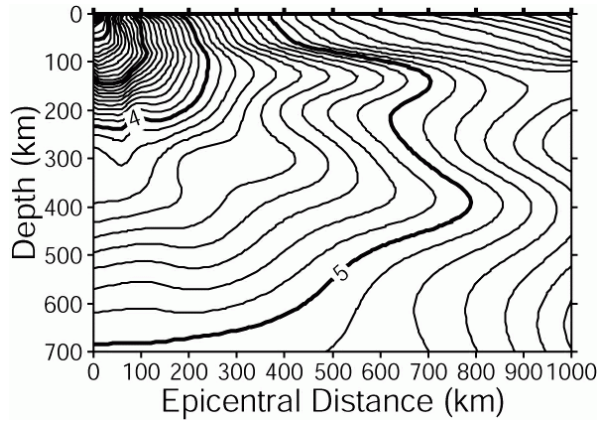


Figure 5.7: Contour representation of β_V .

5.1.5 Data availability

Earthquake locations and magnitudes as a result of data processing by JMA are made public by means of several ways, as follows:

- Prompt information in the case of tsunami warnings and/or felt earthquakes

If a tsunami is anticipated and/or if a seismic intensity 1 and more is observed when an earthquake occurs, JMA provides prompt information of its location and magnitude in 10-15 minutes after the detection of seismic waves. Warning information will be disseminated as a computer-readable message in a specific format to broadcasting media and to national/local government authorities who have responsibilities for emergency operations. It is also often disseminated through web-sites, including JMA's.
- Preliminary results reviewed by analysts

Preliminary determinations of earthquake parameters are available on the JMA web-site on the evening of the next day after their origin time.
- Earthquake catalogue of Japan

Results after a final review process are archived several months later as the earthquake catalogue of Japan, which is also available on the JMA web-site. The catalogue includes locations and magnitudes of earthquakes, as well as phase arrival-times and focal mechanism solutions.

The publication timeline is summarized in Table 5.2. Waveform data observed not only by JMA but also by the other institutions that have joined in seismic data sharing are available from a data management center operated by the National Institute for Earth Science and Disaster Prevention (NIED).

Table 5.2: Timeline of information and data release by JMA

| Timing after an earthquake | Title | Content |
|----------------------------|--------------------------|---|
| Several to tens of seconds | Earthquake Early Warning | Warnings of intensities of ground motions |

Table 5.2: Continued.

| Timing after an earthquake | Title | Content |
|-----------------------------|--|--|
| 1.5 to 2 minutes | Seismic Intensity Information | Indicating regions with seismic intensity of 3 or greater |
| 2 to 3 minutes | Tsunami Warning | Fast determinations of the location and magnitude of the earthquake. |
| 5 to 10 minutes | Earthquake and Seismic Intensity Information | Indicating the earthquake location and magnitude, and cities with seismic intensity of 3 or greater |
| Up to 15 minutes | Seismic Intensity Information | Indicating seismic intensities at observation stations |
| One day | Preliminary determination of earthquakes | Locations, magnitudes, phase arrivals, after review process by analysts |
| Beginning of the next month | Monthly report of seismicity of Japan | Overview of seismicity, mostly focused on felt earthquakes |
| Several months | Monthly Seismological Bulletin of Japan | Locations, magnitudes, phase arrivals, focal mechanisms, seismic intensities, after review process by analysts |

5.1.6 History of the seismic network

Before 1994, most of seismic instruments were installed at about 150 of JMA’s local offices. Although a computer system for telemetered seismic data processing had been introduced to the six regional tsunami warning centers of JMA late in 1980’s, a person in charge there at each local office was still responsible for the reading of phase arrival-times and maximum amplitudes from seismograms and reporting them to the tsunami warning centers. From 1994, the seismic network was renewed, so that seismographic instruments were installed at less noisy sites to detect weaker seismic waves, and all the waveform data were telemetered to regional tsunami warning centers of JMA. In 2004, another renovation was implemented, so as to issue earthquake early warnings following the installation of “multi-function seismic stations,” and the tsunami warning centers were centralized to the JMA Headquarters and the Osaka Regional Headquarters after a major data processing system upgrade in 2009. The progressive development of the JMA network is indicated in Figure 5.8. A chronological summary below, after Hamada (2002), has been updated to indicate more recent developments.

- 1875 The Palmieri seismograph (imported from Italy) was installed and operated by the Weather Section of the Geographical Agency Office of Interior in Tokyo
- 1892 Seismographs were installed at the 19 weather stations
- 1926 Deployment of the Wiechert seismograph and Omori’s seismograph was promoted for the development of the seismological network after the 1923 Kanto Earthquake
- 1950 Mechanical strong-motion seismographs (modified type) were manufactured by the Meteorological Instrument Plant. The number of the seismographs installed reached 104 by the end of 1959.

- 1960 As a successor to the Wiechert seismograph, the JMA59 type electromagnetic seismographs with either an optical recorder (OP) or a visual recorder (VI, $T_0 = 5s$) were developed and deployed. The deployed number of the OP-type was 31 by the end of 1955, and 82 of the VI-type were deployed by the end of 1976.
- 1978 Ocean-bottom seismometers connected by coaxial cable were deployed off the Tokai coast and data were relayed to the JMA Headquarters
- 1983 The Seismic Array System became operational at the JMA Seismological Observatory (Matsushiro), performing backup functions of the JMA Headquarters
- 1985 Another ocean-bottom seismograph observation system was installed off the coast of the Boso Peninsula
- 1994 Deployment of 180 stations for the Tsunami and Earthquake Observation Network was approved and operation of existing seismic stations was terminated and replaced by the new network
- 1996 Start of seismic intensity meters in operation, replacing the system of reports sent by observers at meteorological offices of JMA
- 2003 Installation of multi-function seismic stations began and was completed in 2005
- 2009 The third ocean-bottom seismograph observation system was deployed in Enshu-nada Sea
- 2011 Deployment of an additional 50 multi-function seismic stations, coming into operation in 2012-2013

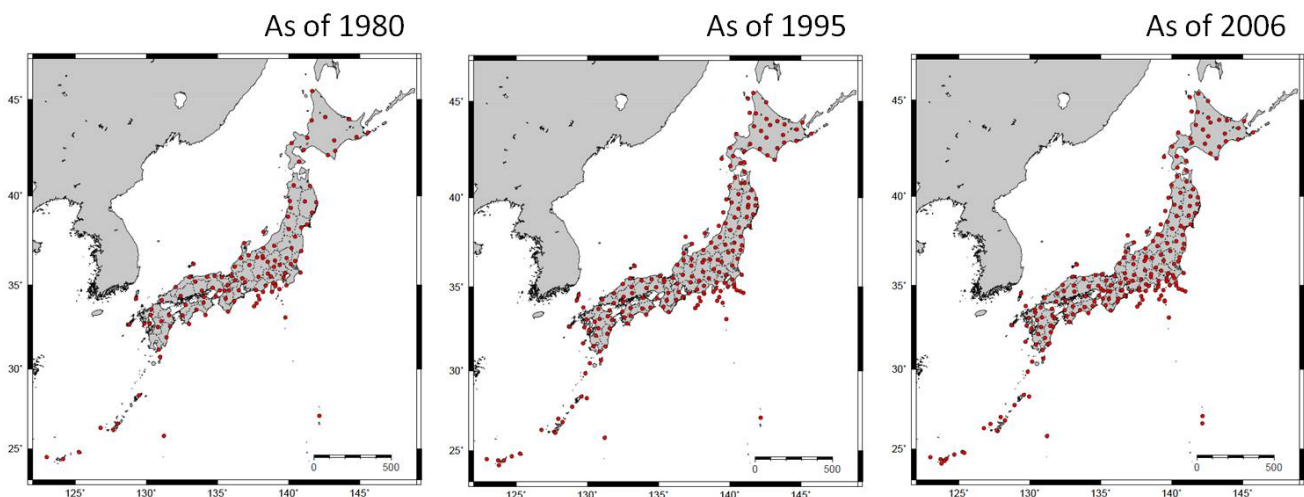


Figure 5.8: Recent development of the JMA seismic network

5.1.7 Acknowledgements

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- Note: The *Quaternary Journal of Seismology* has been published by Japan Meteorological Agency since 1925. The volumes are available on the JMA web-site.

5.1.9 Appendix: Instrumental seismic intensity

A seismic intensity represents the scale of ground motion at a particular location caused by an earthquake. It varies with the distance from the epicenter and the surface geology as well as the magnitude of the earthquake. The JMA seismic intensity scale has 10 degrees (0 (imperceptible), 1, 2, 3, 4, 5 lower, 5 upper, 6 lower, 6 upper and 7) and is calculated from the acceleration of ground motion.

The process is:

- 1 Filtering an acceleration seismogram using a band-pass filter providing similar sensitivities to human perceptions in the frequency domain (Figure 5.9)
- 2 Getting an adjusted maximum acceleration A that satisfies certain criteria with respect to the duration of the ground motion
- 3 Calculating S by $S = 2.0 * \log(A) + 0.94$
- 4 Rounding S numerically to a whole number for the seismic intensity. If $S = 2.4$, for example, then the seismic intensity becomes 2.

| JMA seismic intensity | instrumental seismic intensity (S) | JMA seismic intensity | instrumental seismic intensity (S) |
|-----------------------|--|-----------------------|--|
| 0 | $S < 0.5$ | 5 lower | $4.5 \leq S < 5.0$ |
| 1 | $0.5 \leq S < 1.5$ | 5 upper | $5.0 \leq S < 5.5$ |
| 2 | $1.5 \leq S < 2.5$ | 6 lower | $5.5 \leq S < 6.0$ |
| 3 | $2.5 \leq S < 3.5$ | 6 upper | $6.0 \leq S < 6.5$ |
| 4 | $3.5 \leq S < 4.5$ | 7 | $S \geq 6.5$ |

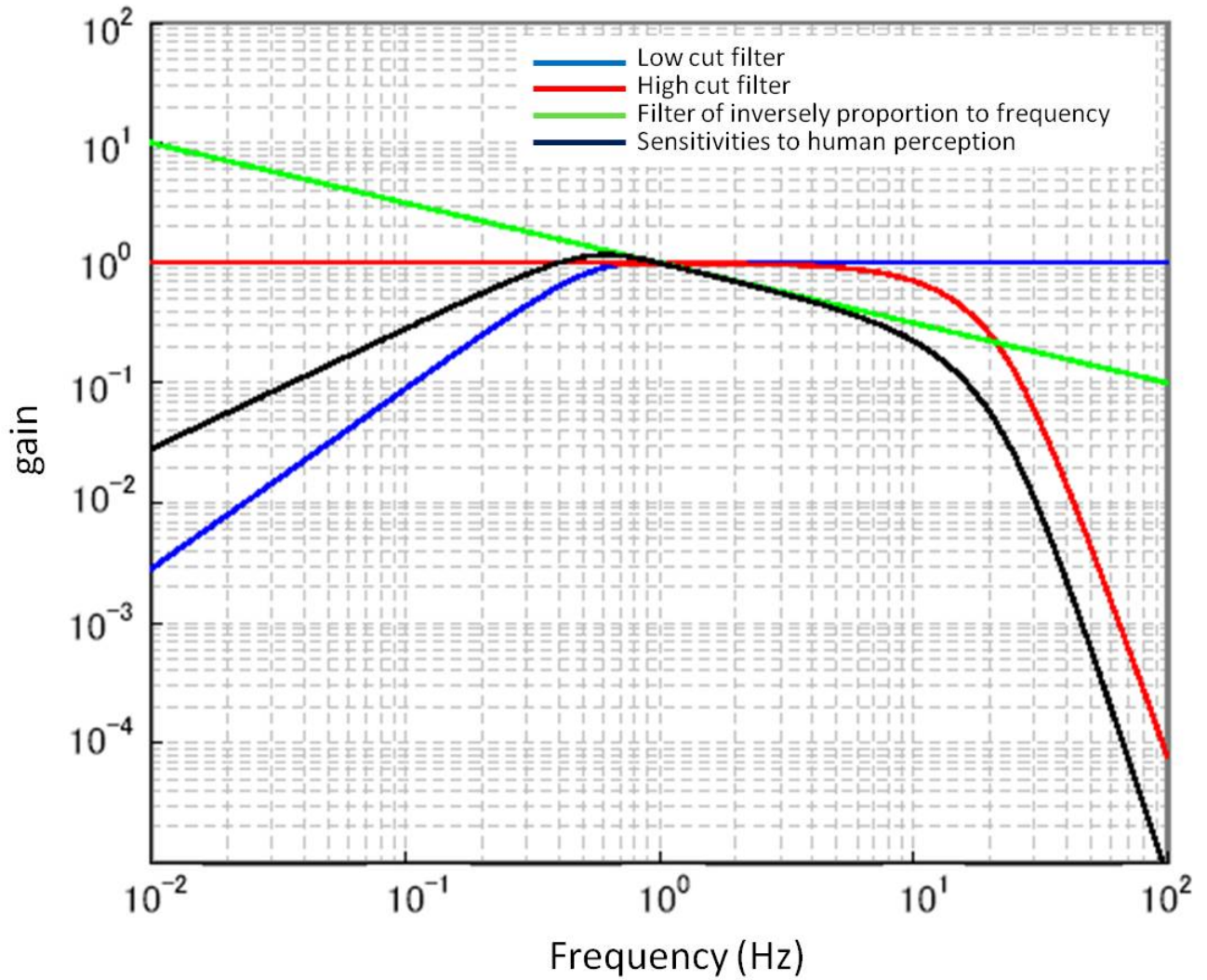


Figure 5.9: A band-pass filter providing similar sensitivities to human perceptions (black line)