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Moment Magnitude Estimation of the July 29, 2025, Kamchatka Earthquake Based on Accelerometers Data

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Abstract: On July 29, 2025, a major earthquake with a moment magnitude of $M_W = 8.8$ occurred off the coast of Kamchatka. The most accurate and rapid estimation of the magnitude of such events is a crucial task in modern seismology, particularly in the context of earthquake and tsunami early warning systems. In this study, we propose and test an approach for rapid M_W estimation from accelerometer records based on an empirical relationship between peak ground displacement (PGD) and moment magnitude. Unlike most similar studies, we rely exclusively on accelerometric data from 13 seismic stations on Sakhalin and the Kuril Islands, without the use of GNSS observations. The final M_W estimate derived from all stations was 8.75 ± 0.2, which is consistent with values reported by international agencies. Simulating real-time data processing demonstrated that a first stable magnitude estimate of $M_W = 7.6 \pm 1.3$ could be obtained as early as 4.5 minutes after the earthquake origin time, with a value of $M_W = 8.65 \pm 0.3$ available after 8 minutes. The results indicate that, given an existing accelerometer network, this methodology can provide reliable and sufficiently rapid estimates of the moment magnitude of major earthquakes without the need for GNSS data. This opens possibilities for enhancing the timeliness of source parameter estimation and for improving tsunami early warning systems in regions with developed seismic infrastructure, without requiring major modifications to existing seismic data processing systems.

Keywords: Accelerograms, peak ground displacement, accelerometer network, warning system, great earthquakes, Kamchatka megathrust earthquake

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Research Article

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1. Introduction

On July 29, 2025, at 23:24:50 UTC, a major earthquake with a moment magnitude of $M_W = 8.8$ occurred off the coast of Kamchatka. According to the Earthquakes Early Alert Service (EEAS) of the Geophysical Survey of Russian Academy of Sciences, the epicenter (52.43°N, 160.46°E) was located 130 km from the city of Petropavlovsk-Kamchatsky.

The problem of rapid and adequate magnitude estimation for great earthquakes [*Blewitt et al.*, 2009; *Murray et al.*, 2023; *Wright et al.*, 2012] proved to be relevant for this event as well. In operational earthquake monitoring, many seismological agencies, including the EEAS, use standard magnitude types: the body-wave magnitude m_b and the surface-wave magnitude M_s. These magnitude scales have upper limits and often do not allow one to assess the true size of the largest seismic events, especially in real time.

Thus, for the Kamchatka earthquake, the final values reported by EEAS were $M_s = 8.2$ and $m_b = 7.1$, while the USGS reported $M_s = 8.0$ and $m_b = 7.0$.

The actual size of great earthquakes can be assessed by calculating the moment magnitude M_W, but this requires determining the seismic moment or using empirical relations that link M_W to other measurable quantities. Various methods are used to estimate the seismic moment, each requiring an evaluation of the earthquake source model parameters. The fastest among them are methods based on measuring coseismic displacements using Global Navigation Satellite Systems (GNSS) [*Blewitt et al.*, 2009; *Ohta et al.*, 2018]. This approach makes it possible to obtain a realistic estimate of the seismic moment and moment magnitude within the first minutes after an earthquake, but it imposes strict requirements on the observation network infrastructure. Moreover, achieving the necessary accuracy in low-latency processing (on the order of a few seconds) additionally requires continuous communication with services transmitting precise satellite clock and orbit corrections.

Among purely seismological methods, significant attention is given to approaches in which the predominant period of oscillation or the maximum displacement is determined from a short initial segment (3–5 s) of the P-wave record. These quantities, in turn, are empirically related to the earthquake's moment magnitude. Providing results very quickly, such methods often serve as the basis for earthquake and tsunami early warning systems [*Allen et al.*, 2009; *Hoshiba and Ozaki*, 2014]. However, due to the short record length [*Hoshiba and Iwakiri*, 2011] and the limitations imposed by the seismological instruments used, the maximum resolvable period is generally severely restricted in these methods, which ultimately prevents obtaining an unbiased magnitude estimate for great earthquakes [*Melgar et al.*, 2013].

A series of studies [*Crowell et al.*, 2013; *Melgar et al.*, 2015; *Ruhl et al.*, 2018] described and further developed a rapid method for estimating the moment magnitude of large earthquakes through empirical relationships linking it to the peak recorded displacement amplitude and the epicentral distance. In [*Crowell et al.*, 2013], this was done using a formal generalization of the Gutenberg–Richter formula, while in [*Melgar et al.*, 2015] the regression was expressed in a more general form and optimal coefficient values were evaluated using records of several great earthquakes. These and subsequent studies demonstrated that moment-magnitude estimates close to the true value can be obtained literally within the first minutes after the event [*Crowell et al.*, 2018; *Melgar et al.*, 2015].

In the studies mentioned above, GNSS data were used to calculate the peak displacement amplitude. When processed in kinematic mode, GNSS observations at permanent stations allow one to directly obtain a time series of relative displacements of a point on the Earth's surface, with centimeter-level accuracy and a sampling rate of 1 Hz or higher. For great earthquakes, this accuracy is sufficient, since peak displacements within hundreds of kilometers of the epicenter range from tens of centimeters to several meters [*Melgar et al.*, 2015].

While the use of GNSS data enables the recording of the full displacement spectrum, including low-frequency oscillations and static coseismic offsets, it introduces practical challenges. First, high-precision, near-real-time GNSS processing depends on continuous access to real-time data streams from external providers. Second, when ground motion amplitudes are moderate, the inherent low-frequency trends and generally higher noise levels in GNSS coordinate time series can significantly distort the determination of peak displacement amplitude, thereby reducing the accuracy of the resulting moment magnitude estimate.

In the aforementioned studies, as in many others, the potential for estimating moment magnitude from peak displacement using accelerometers alone is not explored. Typically, researchers either forgo accelerometers entirely or employ them only in tandem with GNSS equipment to produce a combined seismogeodetic displacement record [*Crowell et al.*, 2013; *Melgar et al.*, 2013; *Shu et al.*, 2018; *Xin et al.*, 2021].

In the present study, using the Kamchatka earthquake as an example, we show that accelerometer records alone may be sufficient for applying this approach to rapid moment-magnitude estimation. The development of seismological networks equipped with accelerometers in regions where earthquakes of magnitude 8 and above are possible would make it possible to rapidly obtain M_W estimates using a simple processing procedure and without significantly complicating the existing infrastructure of seismological observation networks.

2. Data and Methods

Accelerometric records from 13 stations deployed across Sakhalin Island and the Kuril Islands [*Kostylev*, 2021] were used as input data (Figure 1). The selection of stations situated at epicentral distances exceeding 1000 km is justified by the negligible amplitude of coseismic displacements at such ranges, which consequently do not introduce substantial distortion into the waveforms following the processes of integration and filtering. Only one seismic station, SKR, is located 358 km from the epicenter within the nearfield of the seismic source.

The analyzed records include approximately 30 minutes before and after the earthquake.

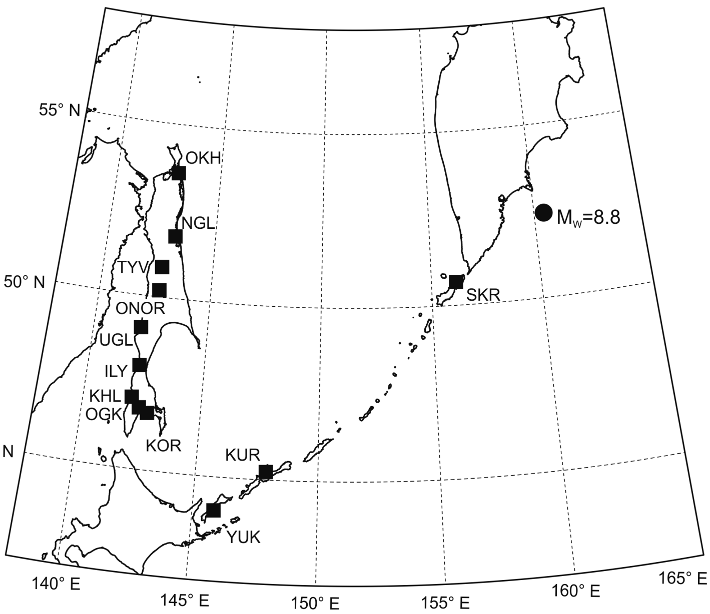


Figure 1. Map showing the location of the Kamchatka earthquake (black circle) and the seismic stations equipped with accelerometers (black squares) used in this study.

The empirical relationship linking peak displacement to moment magnitude has the following general form [*Melgar et al.*, 2015]:

$$\log_{10} PGD = A + B \cdot M_W + C \cdot M_W \cdot \log_{10} R, \tag{1}$$

where R is the epicentral distance (km), PGD is the peak ground displacement (cm), and A, B, and C are coefficients.

The optimal coefficient values ($A = -4.434$, $B = 1.047$, $C = -0.138$) were estimated in [*Melgar et al.*, 2015] using 10 earthquakes with moment magnitudes from 5.9 to 9.1 that occurred between 2003 and 2014. Using these values, expression Equation 1 for M_W can be written as:

$$M_W = \frac{\log_{10} PGD + 4.434}{1.047 - 0.138 \cdot \log_{10} R}.$$

The magnitude estimate calculated in this way is denoted by some authors as M_{PGD} [*Murray et al.*, 2023].

The peak amplitude was determined from the full three-component displacement vector:

$$PGD = \max\left(\sqrt{X(t)^2 + Y(t)^2 + Z(t)^2}\right),$$

where X, Y, and Z are the three orthogonal displacement components of the seismogram.

To obtain low-frequency, near-full-spectrum displacement records from the accelerograms, the original signal was double-integrated. To mitigate artifacts caused by low-frequency trends inherent in the records, including those resulting from sensor tilts and rotations, a linear trend was removed prior to each integration. Additionally, before the first integration, the records were high-pass filtered with a cutoff frequency of 0.003 Hz.

In addition to estimating moment magnitude from the full hour-long accelerograms, we performed analogous calculations in a sequential mode to simulate real-time processing. At each 1-second time step, only the portions of the accelerograms available up to that moment were used to determine the current PGD and corresponding M_W value for each station. This approach allowed us to reconstruct the evolution of the magnitude estimate over time.

The final magnitude value at each time step for the entire network was calculated by averaging all individual station estimates that exceeded a pre-earthquake background level by at least one magnitude unit. The background level was computed from the pre-event segment of the records. No final magnitude was assigned for time intervals where fewer than three such estimates were available.

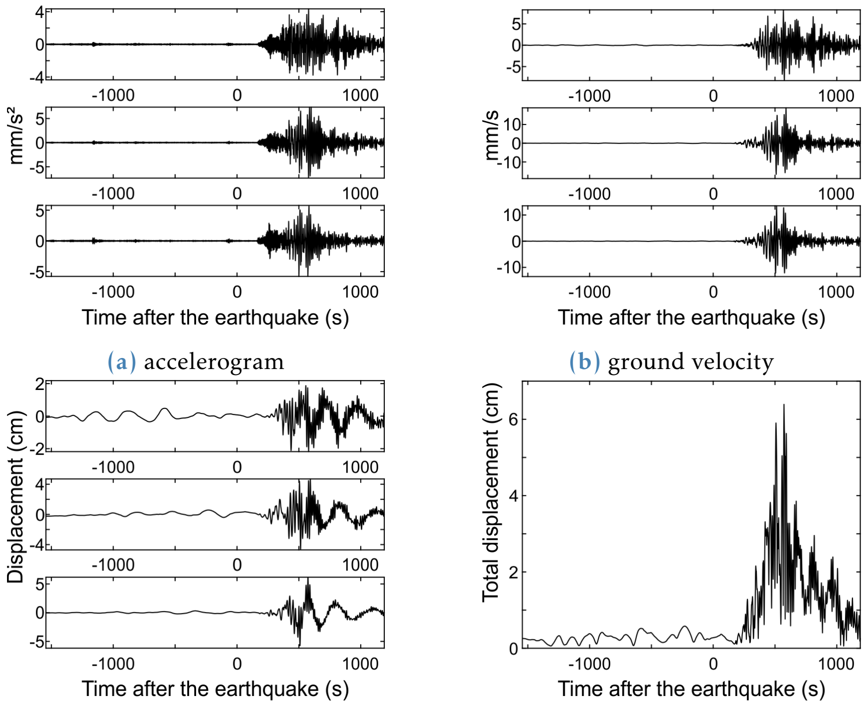
3. Results

Figure 2 illustrates, for the OKH "Okha" seismic station, an example of the recorded accelerograms and the sequence of their processing: the filtered accelerogram, the velocity seismogram, the displacement seismogram, and the plot of total displacement amplitudes. In the example shown in Figure 2, the PGD is 6.38 cm, which, for an epicentral distance of 1173 km, corresponds to a moment magnitude of $M_W = 8.6$. Figure 3 shows the plots of total displacements for all other seismic stations.

All obtained magnitude values are presented in Table 1, which also includes M_s values from the EEAS for comparison. The average value calculated from all stations was $M_W = 8.75 \pm 0.20$.

Table 1. Moment magnitude estimates for the Kamchatka earthquake, obtained independently from each strong-motion station

Station	Code	Lat (°)	Lon (°)	R (km)	M_W	Delay (s)	M_s
Severo-Kurilsk	SKR	50.67	156.12	358	9.09	301	7.8
Okha	OKH	53.60	142.95	1173	8.6	574	–
Nogliki	NGL	51.78	143.13	1181	8.51	565	–
Kurilsk	KUR	45.23	147.87	1215	8.88	392	–
Tymovskoye	TYV	50.86	142.68	1234	8.45	575	–
Onor	ONOR	50.19	142.68	1255	8.49	518	–
Uglegorsk	UGL	49.08	142.07	1340	8.73	509	–
Il'inskoye	ILY	47.99	142.21	1383	8.63	492	–
Yuzhno-Sakhalinsk	SSH	46.96	142.76	1404	8.83	510	8.0
Yuzhno-Kurilsk	YUK	44.03	145.86	1421	8.97	519	8.0
Korsakov	KOR	46.65	142.77	1422	8.79	533	–
Ogon'ki	OGK	46.78	142.40	1438	8.85	521	–
Kholmsk	KHL	47.05	142.05	1444	8.97	523	–



(a) accelerogram
(b) ground velocity
(c) ground displacement
(d) total ground displacement values

Figure 2. Kamchatka earthquake waveforms from accelerometer in OKH station.

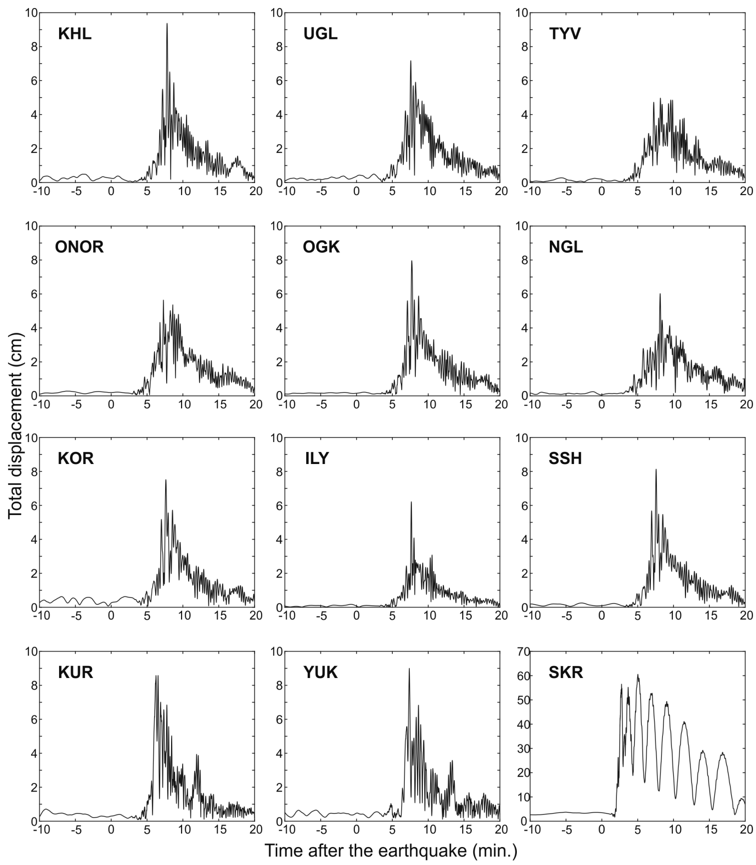


Figure 3. Total displacement values for all seismic stations except OKH. Note the different scale for SKR station.

Figure 4 illustrates the temporal evolution of the moment magnitude estimates derived from the recordings of each individual station. The magnitude was recalculated at one-second intervals, using only the data available up to each respective point in time. Figure 5 shows the corresponding progression of the network-averaged magnitude estimate, computed using the methodology described above. It is important to note that with a limited sample size, a formal error estimate for M_W would not be statistically representative.

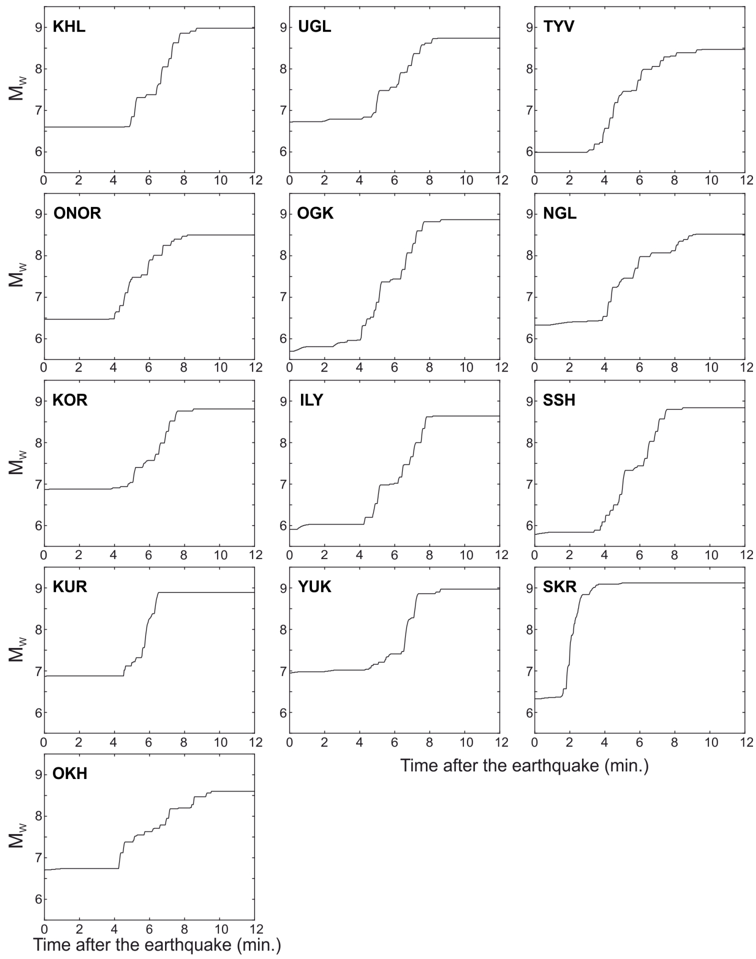


Figure 4. Evolution of moment magnitude estimates at each seismic station.

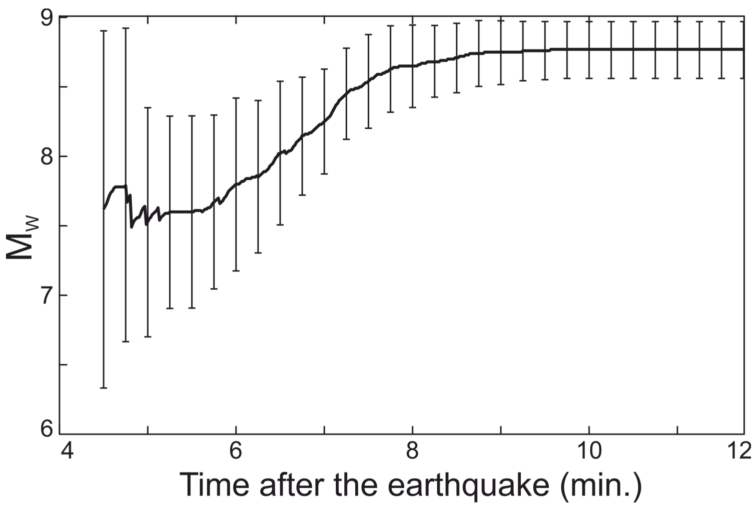


Figure 5. Evolution of the averaged magnitude estimate based on data from the entire station network.

4. Discussion

The final magnitude value obtained from all stations, $M_W = 8.75 \pm 0.2$, was achieved 574 seconds (9.4 minutes) after the earthquake origin time. Assuming equally rapid determination of the epicenter coordinates, the first magnitude estimates of $M_W = 7.62 \pm 1.28$ could have been obtained in less than 4.5 minutes. One minute later, as strong shaking reached a larger number of seismic stations, the magnitude estimate began to increase rapidly, accompanied by a reduction in scatter: $M_W = 7.8 \pm 0.62$ at 6 minutes, $M_W = 8.25 \pm 0.38$ at 7 minutes, and $M_W = 8.65 \pm 0.3$ at 8 minutes.

It should be noted that, according to USGS, the total seismic moment was released over approximately 270 s, with the highest moment release rate occurring between 90 and 170 s. This unusually long source-process duration may account for several additional minutes of delay in obtaining the final magnitude estimate.

As seen in Figure 4, the pre-earthquake background magnitude levels at individual stations range from approximately 6 to 7. This limits the method's applicability to earthquakes with magnitudes below 7.5–8. However, this limitation can be partially mitigated by increasing the high-pass filter's corner frequency during initial accelerogram processing. For example, when the cutoff frequency is increased to 0.01 Hz, the final magnitude estimate decreases to $M_W = 8.47 \pm 0.23$, while the background magnitude level drops by two units to the 4.1–5.3 range.

The time delay inherent in this method is significantly greater than that typical for moment magnitude estimates derived from P-wave onset analysis. Nevertheless, it remains acceptable for scenarios where earthquake record processing and epicenter location are performed manually or in a semi-automatic mode. Furthermore, when using stations located at large distances (on the order of a thousand kilometers) from the epicenter, potential inaccuracies in the epicentral location are unlikely to introduce significant errors into the magnitude estimate.

Using accelerometer records instead of GNSS data for the rapid estimation of the moment magnitude of the strongest earthquakes has both advantages and disadvantages. A primary advantage is the absence of a need for the complex, real-time processing of GNSS data, which depends on external sources and stable communication links.

The methodology described in [*Melgar et al.*, 2015] assumes that PGD is calculated from distortion-free displacement records with a full frequency range, including static coseismic offsets. When accelerometer records are used, this condition cannot be fully met. Due to the need for filtering, it is not possible to preserve the entire spectrum of seismic motions; however, in this study, this did not lead to a significant underestimation of the magnitude.

It should be noted that one reason for obtaining M_W estimates so close to the moment magnitude values subsequently calculated by international agencies could be a favorable combination of the spatial distribution of the stations used and the earthquake's source mechanism. Previous studies have shown significant azimuthal variability in magnitude estimates, which can be on the order of 0.2–0.3 and, in some cases, even greater.

Several studies discussing the estimation of seismic moment and moment magnitude from GNSS data have argued that it is fundamentally impossible to obtain rapid, non-saturating magnitude estimates for the largest earthquakes using seismic methods alone [*Blewitt et al.*, 2009; *Melgar et al.*, 2015; *Ruhl et al.*, 2018]. While using GNSS data, either independently or in combination with accelerometer data, can indeed yield more accurate, complete, and faster results, our findings demonstrate that accelerograms can also provide sufficiently accurate early estimates of magnitude for major M 8–9 class earthquakes. Importantly, this methodology can and should be implemented already in the operational processing of seismic data in the Kamchatka and Sakhalin branches of the Geophysical Survey of Russian Academy of Sciences.

5. Conclusion

This study estimated the moment magnitude of the major Kamchatka earthquake of July 29, 2025, using an empirical method that relates magnitude to recorded peak ground displacement. In contrast to similar studies, only records from accelerometers installed at permanent seismic monitoring stations on Sakhalin Island and the Kuril Islands were utilized. The results demonstrate that the proposed methodology, based on accelerometric data, is simple, effective, and capable of providing a rapid and robust estimate of the moment magnitude of a major earthquake.

A retrospective analysis showed that an initial estimate of $M_W = 7.62 \pm 1.28$ was obtained just 4.5 minutes after the earthquake origin time. This estimate gradually increased, converging to a final value of $M_W = 8.75 \pm 0.2$, which aligns with the moment magnitude estimates reported by the USGS and GCMT agencies.

The methodology described in this study can be implemented in a test mode with virtually no additional cost, using the existing infrastructure of the Geophysical Survey of Russia Academy of Sciences. Utilizing accelerometer data from Sakhalin Island will enable the rapid acquisition of non-saturating moment magnitude estimates for major earthquakes along at least the entire Kuril-Kamchatka subduction zone. The early acquisition of objective and sufficiently accurate magnitude estimates within the first 10 minutes after the earthquake can significantly enhance the effectiveness of tsunami early warning and improve the planning of initial response measures for catastrophic earthquakes.

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