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Understanding Magnitude Bias in Taiwan's Earthquake Early Warning System: A Case Study of the August 2026 Taitung Offshore Earthquake

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18 Abstract

19 The earthworm-Based Earthquake Alarm Reporting (eBEAR) system is the operational
20 earthquake early warning system of Taiwan's Central Weather Administration. Offshore
21 earthquakes are its hardest class: the source lies outside the land network and all stations lie
22 on one side of the epicentre. We analyse the 25 August 2026 Taitung offshore earthquake
23 (local magnitude 5.85, depth 13.1 km, 48 km offshore) from 83 eBEAR solutions, three
24 dissemination channels and 166 intensity observations, with three archived events as controls.
25 The first alert went out 13.67 s after origin time on all three channels; 92.5% of the stations
26 that eventually reached intensity 3 were warned beforehand, and cell broadcast covered 17
27 counties against an observed footprint of 15. No station was under-warned, but the alert
28 reported magnitude 6.6, 0.75 units high. The operational magnitude relation, recovered from
29 2065 single-station records, makes reported magnitude a deterministic function of assumed
30 distance: two solutions computed in the same second from identical peak initial displacement
31 amplitudes differed by 0.89 units, and epicentral error and magnitude correlate at -0.74 . The
32 first magnitude was set by three stations spanning 12° of azimuth on the P-wave maximum,
33 where the theoretical radiation coefficient is 1.78 times the all-azimuth average, predicting
34 $+0.29$ against an observed $+0.28$; peak ground acceleration follows the theoretical S-wave
35 pattern, with no residual directivity. A further $+0.42$ persists at the best geometry and recurs
36 offshore. Magnitude error and azimuthal gap are invalid offshore quality gates; we propose
37 gates on magnitude-station azimuthal coverage and cross-stream agreement.

38 1. Introduction

39 Earthquake early warning (EEW) exploits the interval between the fast, weak P wave and the
40 slower, damaging S wave, so its performance is governed by how quickly and how accurately
41 the source can be characterised from the first seconds of P-wave data (Allen and Melgar

2019). For sources inside a dense network the problem is comparatively benign: near-source stations surround the epicentre, azimuthal coverage is good, and the hypocentre is constrained within seconds. For offshore sources, the dominant hazard class along subduction margins, none of these conditions hold: the nearest station may be tens of kilometres away, all stations occupy a limited azimuthal range on land, and both location and magnitude must be inferred from a one-sided sampling of the wavefield. Operational systems worldwide face this geometry, among them SASMEX in Mexico (Espinosa-Aranda et al. 2009), ShakeAlert on the U.S. West Coast (Given et al. 2018) and the Japan Meteorological Agency system, which adopted the wavefield-based PLUM method precisely to stay robust where source parameters are poorly constrained (Kodera et al. 2018).

Taiwan is an instructive laboratory for this problem. The island sits at the convergent boundary between the Eurasian and Philippine Sea plates (Angelier 1986; Kao and Chen 2000); a large share of its felt earthquakes originate offshore in the Ryukyu and Manila subduction systems, whereas the seismic network is necessarily concentrated on land. The Central Weather Administration (CWA) has operated an EEW system for two decades and has published performance milestones mostly for inland shallow events (Wu and Teng 2002; Hsiao et al. 2009, 2011; Chen et al. 2012, 2015, 2019). The system in operational use is the earthworm-Based Earthquake Alarm Reporting (eBEAR) system (Chen et al. 2015): it runs several parallel processing streams on the same real-time feed, pairing a geometric-centre location that is immediate and robust against non-convergence with a Geiger inversion that can resolve depth when the station geometry permits (Chen et al. 2019), and it disseminates alerts through cell broadcast, television and a dedicated school channel. Fig. 1 makes the resulting geometry explicit for the event analysed here. The 25 August 2026 Taitung earthquake (M_L 5.85) occurred 48 km east-southeast of Taitung City, outside the land network, with its nearest station 14.1 km away on Green Island and every remaining station in a single

sector to the west and northwest. An inland earthquake of the same size would be enveloped by stations, the nearest one about 5 km away.

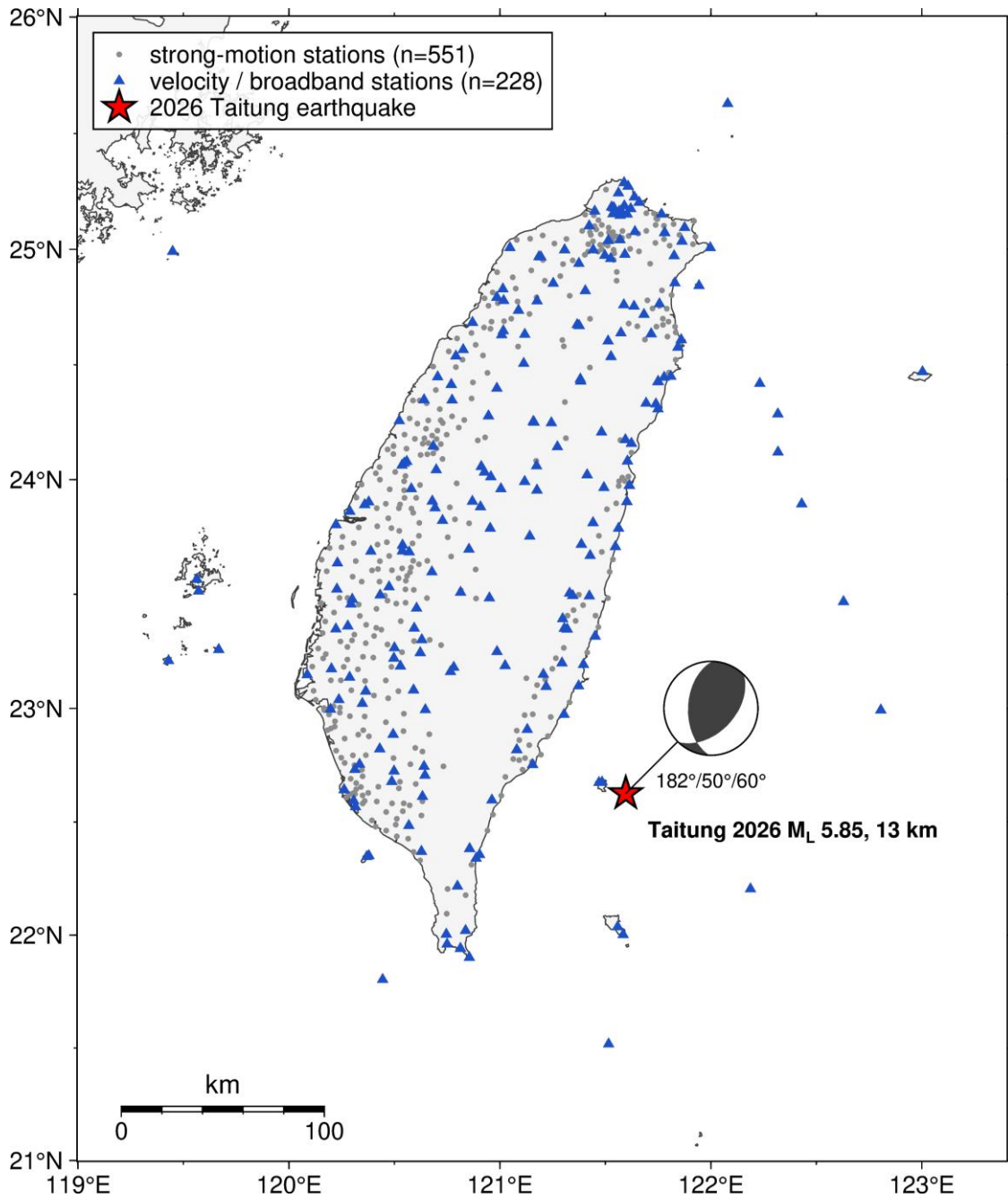


Fig. 1

Fig. 1 CWA real-time seismic network and the 25 August 2026 Taitung offshore earthquake.

Grey circles: strong-motion stations; blue triangles: velocity/broadband stations, as configured in the eBEAR instance analysed here (551 and 228 stations respectively within the map area).

Red star: the epicentre of the analysed event; the beachball, plotted offset and connected by a

line to the epicentre, shows the Real-time Moment Tensor (RMT) focal mechanism used in Section 5 (strike 182° , dip 50° , rake 60° ; Lee et al. 2014)

Most operational EEW magnitudes derive from the amplitude of the first few seconds of the P wave. The peak initial displacement Pd , measured over a fixed window of typically 3 s, scales with magnitude and distance and is widely used for real-time magnitude estimation (Wu and Kanamori 2005; Wu and Zhao 2006; Zollo et al. 2006). Three limitations are known: saturation when the window is shorter than the rupture duration (Trugman et al. 2019); strong sensitivity to the assumed hypocentral distance, because the distance-correction term is steep; and station-to-station scatter caused by site response and by the source radiation pattern. The last two interact destructively offshore. The earliest triggering stations occupy a narrow azimuth range, so the magnitude is averaged over a single sector of the focal sphere, while any epicentral error translates directly into a distance error and hence into a magnitude error. Offshore, that error is not random: mislocation is systematically toward the land network, which shortens the assumed distance and therefore lowers the reported magnitude until the location improves. The location side of this problem has been addressed directly: Hsu et al. (2018) improved the location of offshore earthquakes in the Taiwan EEW system, and Chen et al. (2019) reported the operational gain for the 2018 Hualien earthquake. The magnitude side has not been treated in the same way. To our knowledge the distance term and the azimuthal-sampling term have not previously been separated and quantified in an operational record.

The same geometry also undermines two quality indicators that are routine for inland sources. Azimuthal gap, the largest azimuthal sector without a station, is widely used as a location-quality flag: a small gap means stations surround the source. For an offshore epicentre a correct location necessarily leaves a large gap, because every station lies on land. That gap is often greater than 180° , although it is smaller where offshore islands host stations, as in the

present case; a small gap appears only if the epicentre is wrongly placed inside the network. A rule that withholds public alerts when the gap is large would therefore block valid offshore warnings. Magnitude error is a similarly poor promotion gate. The first stations to trigger occupy a narrow landward sector of the focal sphere, so the early *Pd* magnitude samples one radiation lobe rather than an azimuthal average. An initial overestimate is then an expected geometric accident, as is an underestimate when that sector is nodal, not a diagnosis that the solution is unfit to release. A more informative test is whether the stations used for magnitude already span more than one azimuthal sector, and whether independent parallel streams agree on the location.

This paper closes that problem using the complete operational record of a moderate offshore earthquake. We document the eBEAR response report by report, covering all six parallel processing streams and all three public dissemination channels; we decompose the first-alert magnitude bias into a location-distance term, an azimuthal-sampling term and an intrinsic relation term; and we test which physical mechanism controls the azimuthal term, using the focal mechanism of the event. We then ask whether the result generalises, by recomputing identical metrics for three further Taiwan earthquakes spanning offshore and near-coast geometries, and we evaluate magnitude error and azimuthal gap as promotion gates against alternatives based on magnitude-station azimuthal coverage and cross-stream location consistency. Section 2 describes the system and data, Section 3 the evaluation metrics and analysis protocol, Sections 4 to 6 the results, and Sections 7 and 8 the discussion and conclusions.

2. System and Data

The Central Weather Administration (CWA) real-time seismic network is a mixed-sensor system that combines velocity and acceleration instruments in surface, borehole and ocean-

bottom installations. Velocity sensors provide the sensitivity to weak early P-wave motion that is decisive for offshore sources; accelerometers preserve waveform fidelity under strong shaking without clipping. Data are digitised at 24 bit, packetised at 1 s, and delivered with a typical end-to-end latency of 0.5–2 s. Real-time processing runs within the Earthworm framework (Johnson et al. 1995). The operational instance analysed here was configured with 551 strong-motion and 228 velocity/broadband stations inside the map area of Fig. 1. Their distribution is dense across the island but, as that figure shows, provides no coverage seaward of the east coast, so the epicentral region itself is unsampled. Every offshore hypocentre must therefore be located and sized from a one-sided, landward sampling of the wavefield.

The earthworm-Based Earthquake Alarm Reporting (eBEAR) system (Chen et al. 2015) runs as multiple parallel instances that share the same real-time data feed but differ in association parameters and location algorithm. Two location families operate simultaneously. The effective-epicentre (geometric-centre) method returns the centroid of triggered stations with depth fixed at 10 km; it is immediate and robust against non-convergence (Chen et al. 2019). The Geiger inversion method solves for the hypocentre iteratively and can resolve depth, but it requires a usable station geometry. For this event, six streams ran in parallel on four computers, two using the geometric-centre method and four using Geiger inversion. Each stream writes one report file (.rep) per solution, listing source parameters, the number of stations used in the location (n) and in the magnitude (n_m), azimuthal gap, and a per-station table of the peak acceleration, velocity and displacement of the early P wave (Pa , Pv , Pd), the single-station magnitude M_{Pd} and the assumed hypocentral distance R , so that the operational magnitude is fully auditable at station level (Section 5). The operational and disseminated magnitude is M_{Pd} .

Alerts are distributed through three independent channels with different thresholds: (i) the Public Warning System (PWS) cell-broadcast, nominally for $M \geq 5.0$ and predicted intensity

≥ 3 (Taipei ≥ 2); (ii) a television channel (CAP), nominally $M \geq 5.0$ and predicted intensity ≥ 2 ; and (iii) a school channel (XML via a dedicated network), nominally $M \geq 4.5$ and predicted intensity ≥ 2 . The school channel transmits successive updates, whereas PWS and TV normally issue a single message per event. The analysis uses 83 eBEAR solutions (2065 single-station records), the analyst-reviewed P-file with 290 phases and 166 intensity/PGA stations, the issue-sequence log, CAP/XML alert files (1 PWS, 1 TV, 4 school), per-second intensity for 626 stations over 120 s, and the Real-time Moment Tensor (RMT) solution of the Institute of Earth Sciences, Academia Sinica (strike 182° , dip 50° , rake 60° ; Lee et al. 2014). Three additional archived events (Section 6) provide the comparison baseline. For every event, reference hypocentre and magnitude are read from that event's analyst-reviewed P-file header so that all events are treated identically.

3. Evaluation Metrics and Analysis Protocol

The reference (ground truth) is the CWA analyst-reviewed solution. For the Taitung event this is 2026-08-25 07:00:11.33 UTC, 22.6252°N , 121.5968°E , depth 13.05 km (quoted as 13.1 km elsewhere in this paper), M_L 5.85, based on 290 phases (azimuthal gap 105° , rms 0.11 s, quality grade B) and matching CWA catalogue report No. 115057. Latency of a solution is its reporting time minus the reference origin time. Alert latency is the sent timestamp in the CAP or XML product minus that origin time: the instant the product left the warning system, excluding downstream cell-broadcast delivery, which is not recorded here. All events are measured identically, so cross-event comparisons are internally consistent. Epicentral error is the horizontal distance between the solution and the reference epicentre, and magnitude bias is $\Delta M = M_{Pd} - M_L^{\text{ref}}$. A well-located solution has epicentral error below 10 km. The converged value and the geometry penalty are both defined within a single processing stream:

172 the converged value is the median of the last three well-located solutions of that stream, and
 173 the geometry penalty is its earliest well-located magnitude minus that converged value.

174 Because each report lists Pd , assumed hypocentral distance R and single-station M_{Pd} , the
 175 operational magnitude is fully specified at station level and can be recovered by least squares
 176 over all 2065 single-station records of the event: $M_{Pd} = 4.79 + 1.16 \log_{10}(Pd) +$
 177 $1.85 \log_{10}(R)$, with Pd in cm, R in km and rms 0.13. Predicted and reported values lie on the
 178 1:1 line (Section 5), confirming that reported magnitude is a deterministic function of Pd and
 179 assumed distance, not an independent estimate. The coefficient 1.85 on $\log_{10}R$ is steep: a
 180 factor-of-two error in assumed distance produces 0.56 magnitude units of error, so any
 181 offshore mislocation toward the land network maps directly into a magnitude bias. The
 182 relation contains no path- or region-dependent term: the same distance correction is applied to
 183 offshore and inland paths. Event magnitude is the mean of the station values used in each
 184 report; therefore two solutions computed from identical Pd amplitudes can differ only
 185 through their assumed distances. The recovered relation is used only as a diagnostic
 186 description of this operational implementation, not as a proposed new scaling law.

187 Far-field P- and S-wave radiation coefficients F_P , F_{SV} and F_{SH} are computed from the Real-
 188 time Moment Tensor (RMT) focal mechanism (Lee et al. 2014) following Aki and Richards
 189 (2002, Box 4.4), with take-off angle measured from the downward vertical. Take-off angles
 190 for the 166 analyst-reviewed stations come from the P-file; for report-file stations they are
 191 interpolated from the P-file distance–take-off relation. Because observed amplitudes never
 192 vanish on nodal planes, $|F|$ is floored at 0.10. We use $|F_S| = \sqrt{F_{SV}^2 + F_{SH}^2}$ against PGA and
 193 $|F_P|$ against Pd . Coefficient uncertainties are estimated by bootstrap resampling (4000
 194 iterations); significance of an azimuthal or radiation term is assessed by permutation (4000
 195 iterations). Azimuthal structure is the amplitude $\sqrt{b^2 + c^2}$ of the best-fitting one-cycle

harmonic $y = a + b\cos\phi + c\sin\phi$. Four events with complete report archives are compared in Section 6: all metrics are recomputed from the raw report files and each event's own analyst P-file using identical code, so the offshore versus near-coast contrast is not affected by catalogue convention. A large language model was used as a coding and drafting assistant throughout this work: it helped write the analysis scripts that parse the report files and produce the figures, and it helped draft and edit the manuscript text. It was not used to generate, select or alter any measurement. Every number reported here was recomputed from the archived operational files by code that the authors reviewed, and the authors are accountable for the analysis and for the final text.

4. The 25 August 2026 Taitung Offshore Earthquake

The earthquake occurred at 15:00:11.33 local time (07:00:11.33 UTC) 48 km east-southeast of Taitung City at 13.1 km depth, with M_L 5.85. It is reverse-faulting with a small strike-slip component (strike 182° , dip 50° , rake 60° ; Lee et al. 2014), the P axis nearly horizontal at azimuth 293° . The nearest station, on Green Island (LDU, 14.1 km), recorded an analyst-reviewed PGA of 150.1 gal and intensity 4, the largest ground motion of the event; the real-time Pa listed for the same station in the report files is 162.3 gal, a different measurement on the vertical channel that is used in Section 5. Of the 166 analyst-reviewed stations, 6 reached intensity 4, 13 reached intensity 3, and the rest intensity 2 or below. All three channels issued their first message at 07:00:25 UTC, 13.67 s after origin time; the first internal solution was available at 12.52 s. PWS covered 17 counties, television 11, and the school channel 12 at predicted intensity ≥ 3 , with three later updates (Fig. 2a, Table 1); the three counts are not directly comparable, because each channel applies its own magnitude and intensity thresholds to its own list of administrative units. Fifteen counties eventually recorded intensity 3 or

above, so PWS coverage exceeded the observed footprint: the alert was conservative rather than under-inclusive (Fig. 2b).

Table 1 Dissemination summary. The three channels dispatched simultaneously; the entire alert delay is therefore upstream of the publication pipeline.

Channel	Messages	First alert (s)	Coverage
PWS (cell broadcast)	1	13.67	17 counties/cities
Television (CAP)	1	13.67	11 counties/cities
School (XML)	4	13.67	12 counties at predicted intensity ≥ 3

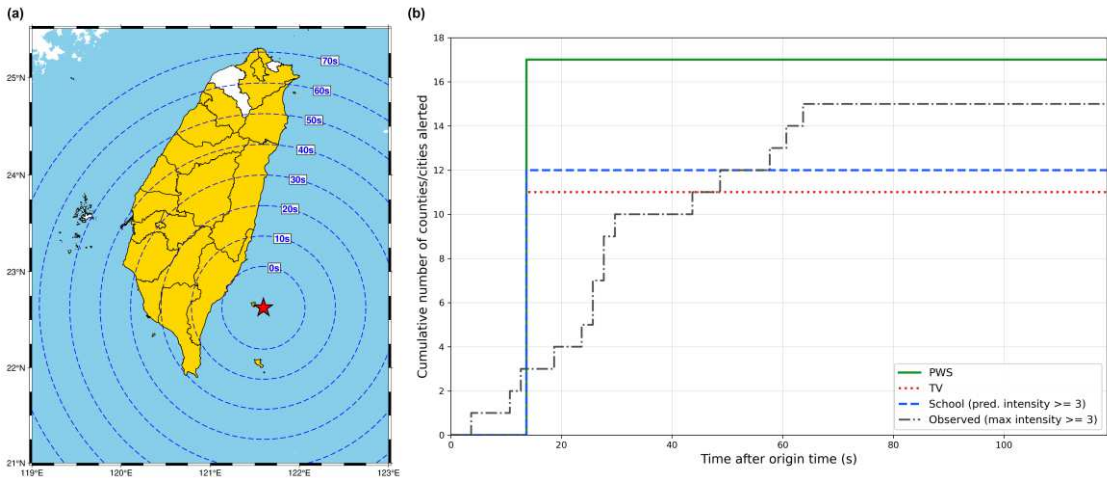


Fig. 2

Fig. 2 Coverage of the first public alert. (a) Counties reached by the cell-broadcast (PWS) message: shaded counties received the alert, white counties did not. The star is the epicentre; dashed circles are S-wave response-time contours at 10 s intervals measured from the alert instant, so the 0 s contour marks the theoretical blind-zone boundary. (b) Cumulative number of alerted counties for the three channels, compared with the observed cumulative count of counties first exceeding intensity 3 (per-second intensity data). All channels reach their final coverage at 13.7 s, whereas the observed footprint grows until about 65 s; the first county exceeded intensity 3 at about 4 s, before any alert was issued

Eighty-three solutions were produced by six streams within 40 s. Location convergence was rapid for the Geiger streams and poor for the geometric-centre streams: one Geiger stream

was within 4.6 km of the reference in its first solution at 12.5 s, whereas a geometric-centre
 stream placed the epicentre 35.4 km inland and never recovered (final error 36.1 km). Final
 errors for the four converging streams were 0.8–1.9 km. Magnitude stabilised at 6.1–6.4
 against the reference 5.85; depth remained at the 10/20/30 km grid nodes (Figs. 3, 4).
 Compared with the 166 analyst-reviewed observations, the first school report (M 6.6 at 30 km,
 a depth that identifies it as a Geiger solution because the geometric-centre streams fix depth at
 10 km) was exact at 10.2% of stations and within ± 1 intensity rank at 59.0%; later reports
 reached 80.7% within ± 1 (Table 2). First-report residuals are entirely non-negative: no station
 was under-warned, 10.2% were exact, 48.8% were over-warned by one intensity rank, 25.3%
 by two, 14.5% by three and 1.2% by four. Accuracy improved with each update, but the
 message that reached the public was the least accurate one.

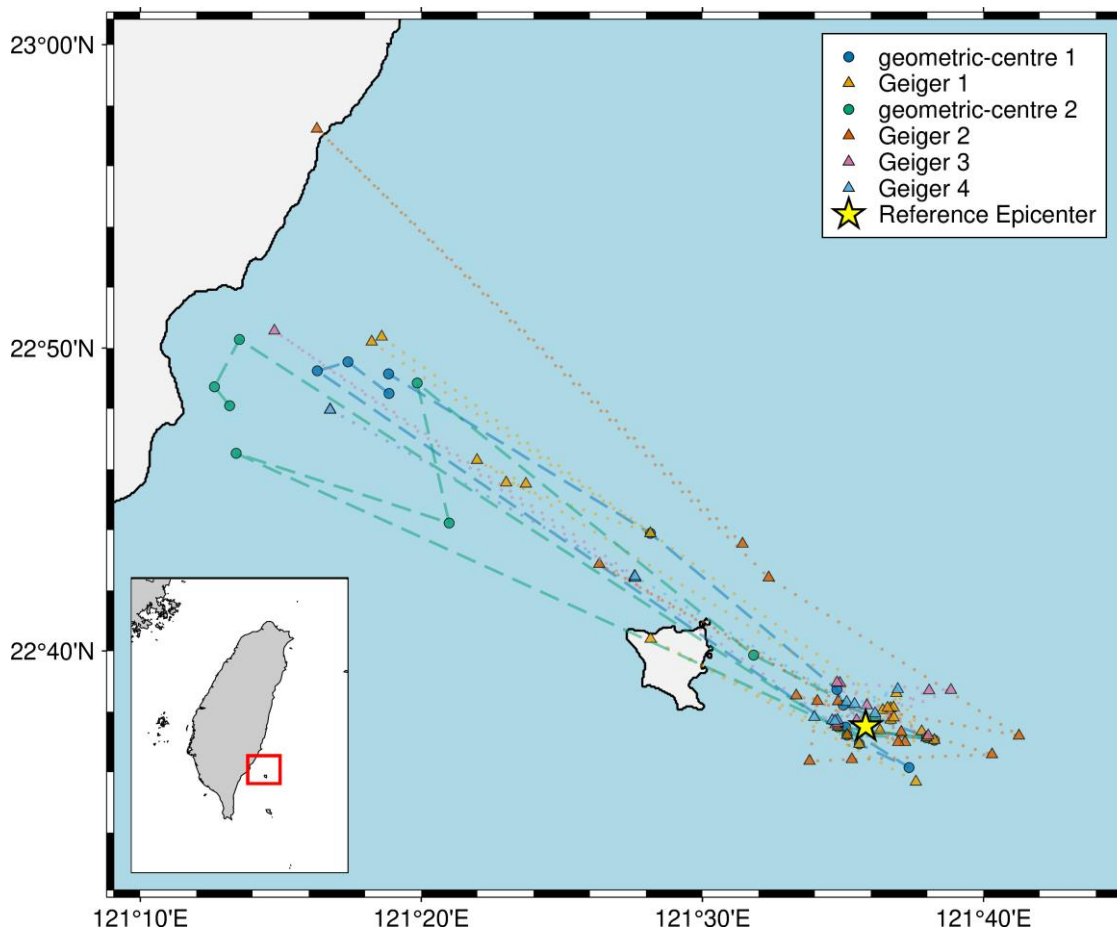


Fig. 3

Fig. 3 Epicentre convergence trajectories of the six parallel streams. The reference epicentre is the yellow star. Circles are the two geometric-centre streams; triangles are the four Geiger streams; each stream keeps the same colour and number in Figs. 3, 4, and the numbering itself is arbitrary. Early geometric-centre solutions lie on land, 35–43 km northwest of the true offshore source. The inset locates the map area (red box) within Taiwan

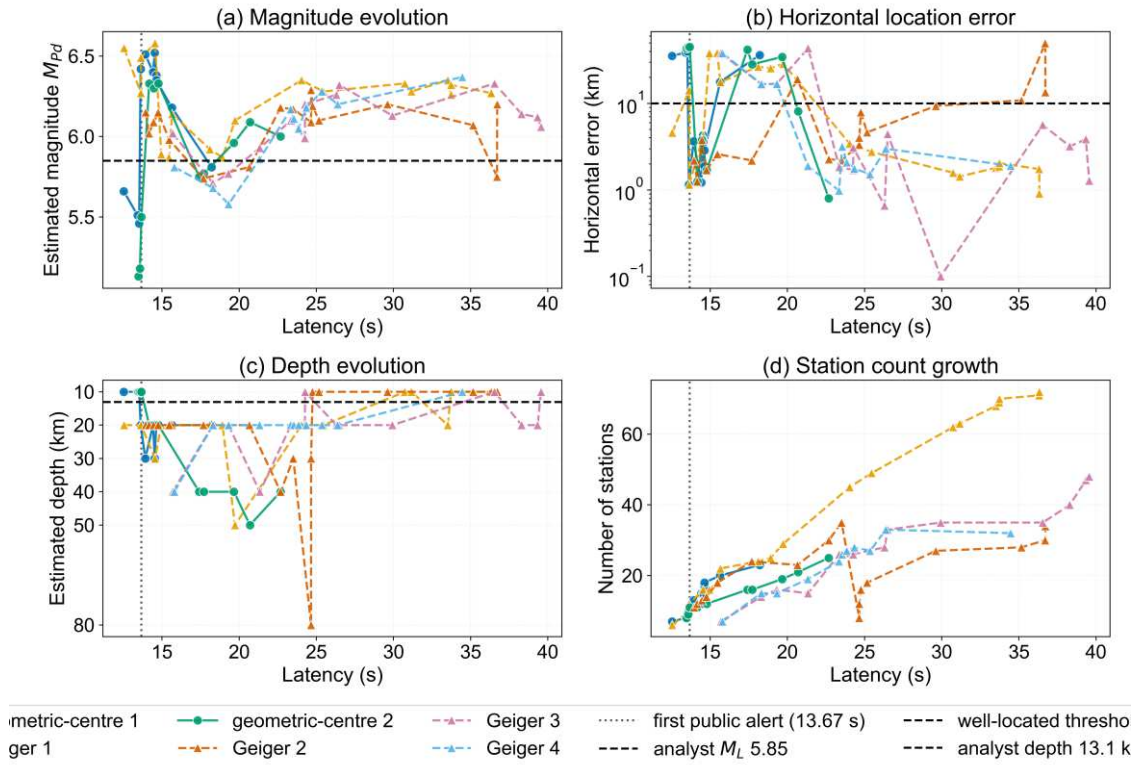


Fig. 4

Fig. 4 Evolution of (a) M_{Pd} , (b) horizontal location error, (c) depth and (d) station count versus latency, for the six streams coloured and numbered as in Fig. 3. Circles are geometric-centre streams, triangles Geiger streams. The dotted vertical line in every panel marks the first public alert at 13.67 s. Dashed horizontal lines mark the analyst M_L 5.85 in (a), the 10 km well-located threshold of Section 3 in (b), and the analyst depth of 13.1 km in (c). The error axis in (b) is logarithmic, spanning 0.09–50 km; depth in (c) is drawn on the grid nodes the system reports. Magnitude stabilises at 6.1–6.4 against the reference 5.85, and depth stays at the 10/20/30 km nodes except for brief excursions

Table 2 Intensity prediction accuracy per school-channel report (166 compared stations). All four messages originate from the same Geiger stream (reports 4, 5, 7 and 8 of that stream); reports 2 and 3 carry the same sent timestamp because two successive updates were dispatched within the same second.

Report	Magnitude / depth	Exact (%)	Within ± 1 (%)
1 (13.67 s)	<i>M</i> 6.6 / 30 km	10.2	59.0
2 (14.67 s)	<i>M</i> 5.9 / 20 km	27.1	75.9
3 (14.67 s)	<i>M</i> 6.1 / 20 km	24.7	75.9
4 (17.67 s)	<i>M</i> 5.9 / 20 km	37.4	80.7

Using the per-second observed intensity of 626 stations, the first issued solution preceded the S-wave arrival at 99.0% of stations (median lead 33.6 s) and preceded the crossing of intensity 3 at 92.5% of stations that eventually reached intensity 3 (median lead 29.1 s). Taitung City, 48.7 km from the epicentre, had a theoretical lead of only 2.1 s relative to the 13.67 s alert; Green Island and the Taitung coast exceeded intensity 4–5 within 4–13 s, before the alert was issued (Fig. 5). The blind-zone population is small, but the geometry is intrinsic: for an offshore source the closest exposed community is also the least protected (Minson et al. 2018).

Because Fig. 5 resolves intensity every second rather than reducing each site to a single peak value, it carries the duration of every intensity level as well as its maximum. Duration matters operationally: structural damage accumulates with the number of strong cycles a building absorbs, so two areas that share a peak intensity need not sustain the same damage. In the near field the 22.6–23.1°N bands held intensity 4 or above for 16–32 s and intensity 3 or above for 55–63 s, whereas the 24.4–24.9°N bands never reached intensity 4 and held intensity 3 for at most 10 s. The clearest case is the 25.0°N band containing the Taipei basin, about 280 km from the epicentre: it reached intensity 4 and held intensity 3 or above for 80 s, longer than any near-field band and the longest in the dataset, which is consistent with the long-period basin response for which the area is known. A peak-intensity map cannot express that contrast,

yet it is what tells a responder where shaking was merely felt and where it was sustained long enough to matter, so this presentation has direct value for directing inspection and search-and-rescue effort in the first minutes after an event. The per-second envelope reaches one rank above the maximum analyst-reviewed intensity of 4 because the two quantities are computed differently: the analyst value is a single rank assigned to the complete record, whereas the envelope is the running maximum of 626 continuous streams.

Three magnitudes must be kept apart in what follows. The first internal solution, available at 12.52 s, reported M_{Pd} 6.55 from three magnitude stations at a gap of 335°; the solution actually disseminated, report 4 of the same Geiger stream, reported M_{Pd} 6.58 at 30 km depth from six magnitude stations at a gap of 217°; and the public message rounded that value to M 6.6, which is 0.75 units above the analyst M_L 5.85. Section 5 decomposes the 6.55 solution, because it is the first solution of the sequence and the one whose station set can be audited completely. That M_{Pd} overestimate, not a missed warning, is the remaining operational problem.

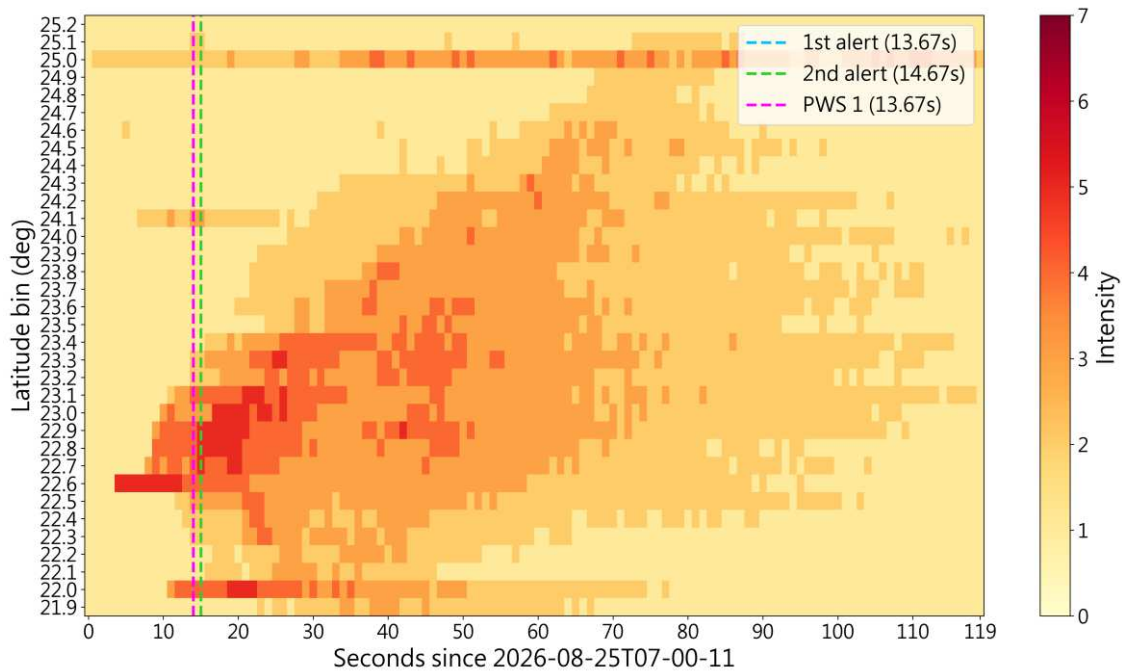


Fig. 5

Fig. 5 Per-second maximum observed intensity by latitude band, with the alert times superimposed. Reading down a column gives the shaking distribution at one instant; reading along a row gives the full time history of one latitude band, so the figure carries the duration of each intensity level as well as its peak: the horizontal extent of a colour is how long that level persisted. Intensity 4–5 is reached in the 22.6°N band within 4–13 s, before the first alert at 13.67 s. The time axis counts from the first intensity sample at 07:00:11 UTC, 0.33 s before the origin time; the alert labels are latencies measured from the origin time

5. Magnitude Bias: Decomposition and Mechanism

Reported magnitude tracks assumed distance. At 07:00:23.8 UTC two streams produced solutions in the same second from the same stations with identical Pd values; their only difference was the assumed hypocentre (Table 3). The Geiger solution reported 6.55, the geometric-centre solution 5.66. The 0.89-unit difference equals $1.85\log_{10}(60/21) = 0.84$ predicted by the operational relation. The solution that appeared accurate (M 5.66 against M_L 5.85) was the badly mislocated one (35.4 km error), while the correctly located solution (4.6 km error) over-estimated. Within a geometric-centre stream the same coupling appears: when it briefly converged to within 1.1 km, magnitude jumped from 5.46 to 6.42, then fell to 5.81 as the epicentre drifted inland. Over all 83 solutions, epicentral error and reported magnitude correlate at $r = -0.74$, with a slope of -0.15 units per 10 km of location error (Fig. 6). The regression crosses the reference magnitude at an epicentral error of about 30 km: the apparently most accurate magnitudes were produced by solutions mislocated by 30 km.

Table 3 Identical amplitudes, different assumed distances. The 0.89-unit difference equals $1.85\log_{10}(60/21) = 0.84$ predicted by the operational relation. Both event values are the mean of the $n_m = 3$ stations actually used (G035, G036 and G047); G046 is listed for

comparison and entered neither. The mean of the three rounded values printed here is 6.56 and 5.66; the reported event magnitudes use the unrounded station values.

Station	Pd (cm)	Geiger R (km)	Geiger M_{Pd}	Geometric-centre R (km)	Geometric-centre M_{Pd}
G035	0.06748	55	6.63	15	5.66
G036	0.06561	54	6.59	16	5.67
G047	0.04337	60	6.45	21	5.64
G046	0.02910	60	6.23	21	5.43
Event magnitude			6.55		5.66

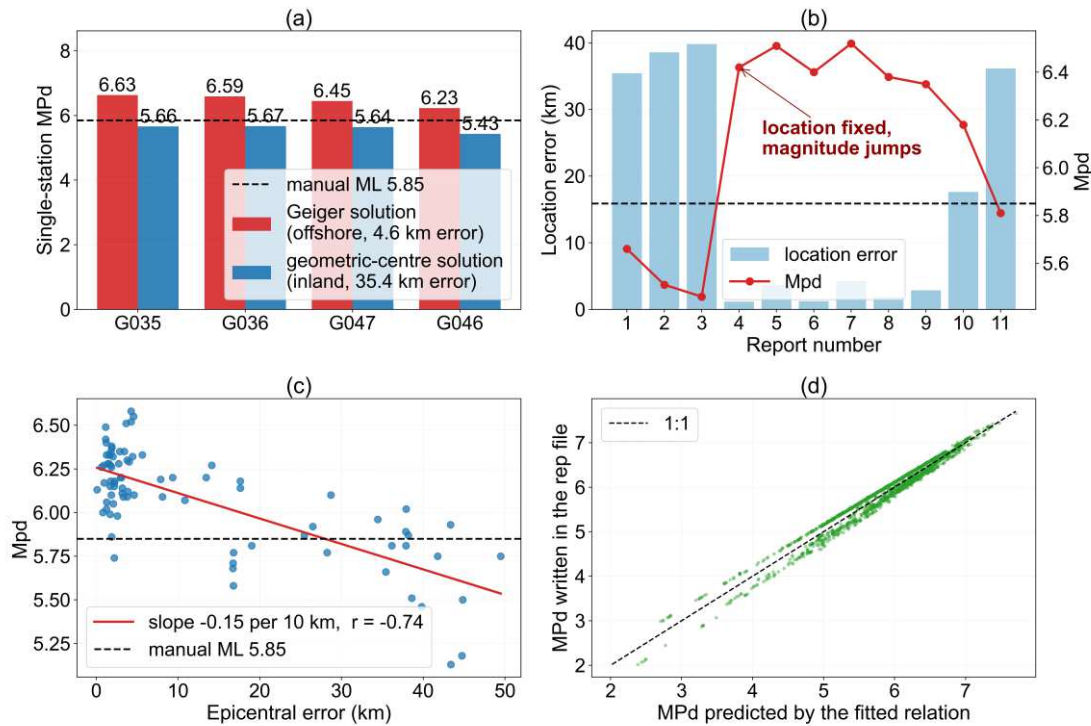


Fig. 6

Fig. 6 Evidence that reported magnitude tracks assumed distance. (a) Two solutions computed in the same second from identical Pd values. (b) Magnitude and location error report by report for a geometric-centre stream. (c) All 83 solutions, $r = -0.74$. (d) Recovered operational relation, 2065 single-station records, rms 0.13

The first internal solution used only three magnitude stations at azimuths 295–307° from the epicentre, a 12° sector; the solution actually disseminated used six and still reported 6.58. The

334 nearest station, LDU (14.1 km, azimuth 292°), recorded a real-time vertical Pa of 162.3 gal
335 but $Pd = 0.0006$ cm, yielding magnitude 3.46. This is an integration or saturation failure at
336 the one station that could have anchored the estimate downward. Among 72 single-station
337 magnitudes of the final well-located solution, estimates vary by 0.3–0.5 units between sectors
338 at the same distance; the west-northwest sector used by the first internal solution (< 60 km) is
339 the highest (median 6.54). Stations beyond 150 km yield 5.4–5.9 but join only after the
340 eleventh report (Fig. 7). Three different azimuthal gaps appear in this paper and should not be
341 compared with one another: the analyst solution, computed from the full 290-phase set
342 including the offshore-island stations, has a gap of 105°; the eBEAR solutions of this stream
343 have gaps of 335° for the first internal solution and 100–101° after convergence; and Fig. 7a
344 shows the azimuth distribution of the 166 analyst-reviewed intensity stations about the
345 reference epicentre, which is empty between 45° and 180°. Within the eBEAR solutions,
346 azimuthal gap is a weak predictor when the location is correct ($r = 0.23$) and only matters at
347 the extreme ($> 300^\circ$, $n_m \leq 4$). Among poorly located solutions the correlation is strong ($r =$
348 0.76) but spurious: the six smallest-gap solutions (125–139°) are the six worst-located (mean
349 41 km), because an inland epicentre artificially improves apparent coverage.

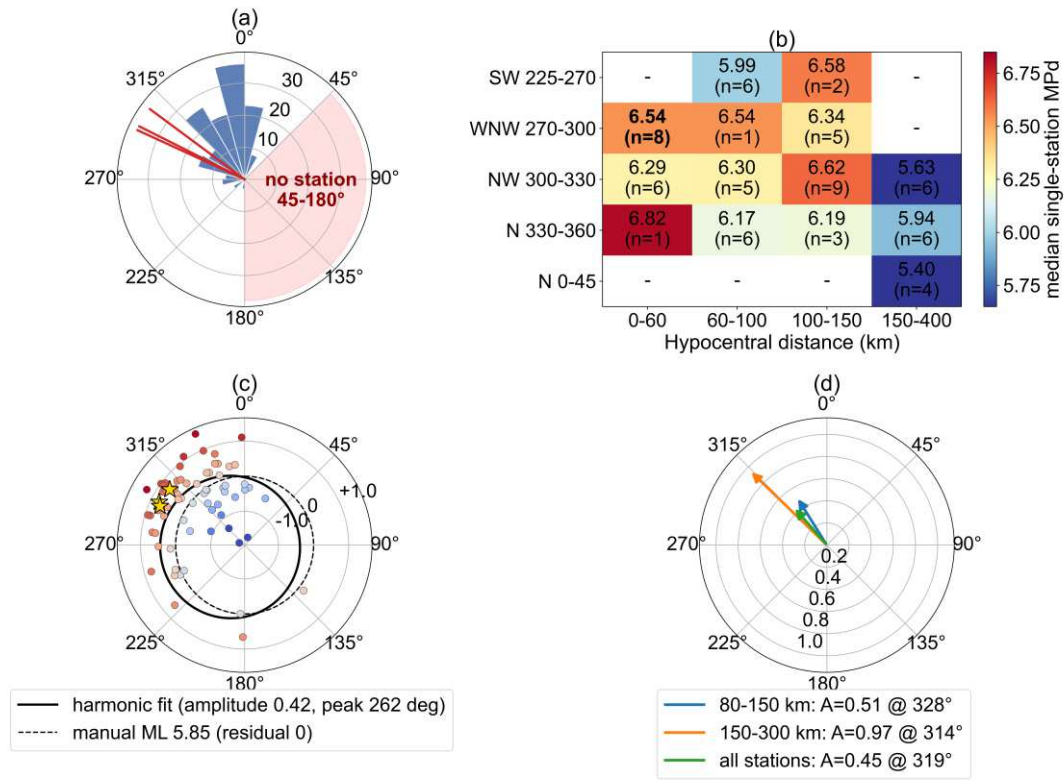


Fig. 7

Fig. 7 Azimuthal evidence. (a) Azimuth coverage of the 166 analyst-reviewed stations about the reference epicentre: no station exists between 45° and 180°; red lines mark the three stations that set the first magnitude. (b) Median single-station magnitude by azimuth sector and distance band. (c) Azimuth versus single-station magnitude residual for the final solution. (d) Direction of the strongest distance-corrected observed PGA per distance band

The RMT mechanism (Lee et al. 2014) places the P axis (azimuth 293°, plunge 1°) on the three stations of the first internal solution. Their mean $|F_P|$ is 0.699 against an all-azimuth average of 0.392, a ratio of 1.78 that predicts +0.29 magnitude units (Table 4). Observed PGA at the 117 stations with a recorded value follows the theoretical S-wave radiation pattern: regressed on $\log_{10}|F_S|$ after distance correction, the exponent is +1.11 univariate and +1.13 in the joint fit with distance, against a theoretical 1.0 ($p < 0.001$ by permutation), and adding

363 $|F_S|$ reduces the residual scatter from 0.308 to 0.277 $\log_{10}$ units. After removing distance and
 364 radiation, the residual one-cycle azimuthal harmonic falls from 0.453 to 0.028 $\log_{10}$ units
 365 ($p = 0.92$), so no rupture-directivity signal remains within the sampled azimuth range. The
 366 predicted +0.29 matches the +0.28 geometry penalty measured as a well-located Geiger
 367 stream improved from three magnitude stations to thirty-two. That stream reported 6.55 at
 368 first and converged to 6.27, the median of its last three well-located solutions, which used 29
 369 to 32 magnitude stations at a gap of about 100° . It did not converge to the analyst M_L 5.85.
 370 The budget for that solution is therefore $5.85 + 0.42$ (Pd relation) $+0.28$ (one-sided
 371 sampling) = 6.55 (Fig. 8). The distance term of Table 3 does not enter this budget: the
 372 solution was already well located (epicentral error 4.6 km), so its assumed distances were
 373 close to correct. That term explains why the badly mislocated solutions appeared accurate, not
 374 why the released one was high. The +0.42 residual persists at the best geometry the event
 375 achieved and is a property of the Pd relation for this offshore path; improving the network
 376 cannot remove it, only calibration can.

377 **Table 4** The three stations that set the first magnitude sat on the maximum lobe of the P-wave
 378 radiation pattern. The ratio $0.699/0.392 = 1.78$ predicts a magnitude bias of
 379 $1.16\log_{10}(1.78) = +0.29$.

Station	Azimuth	Take-off	$ F_P $
G036	295°	68°	0.748
G047	297°	70°	0.790
G035	307°	65°	0.559
Mean of the three			0.699
Network median (72 stations)			0.447
All-azimuth average			0.392

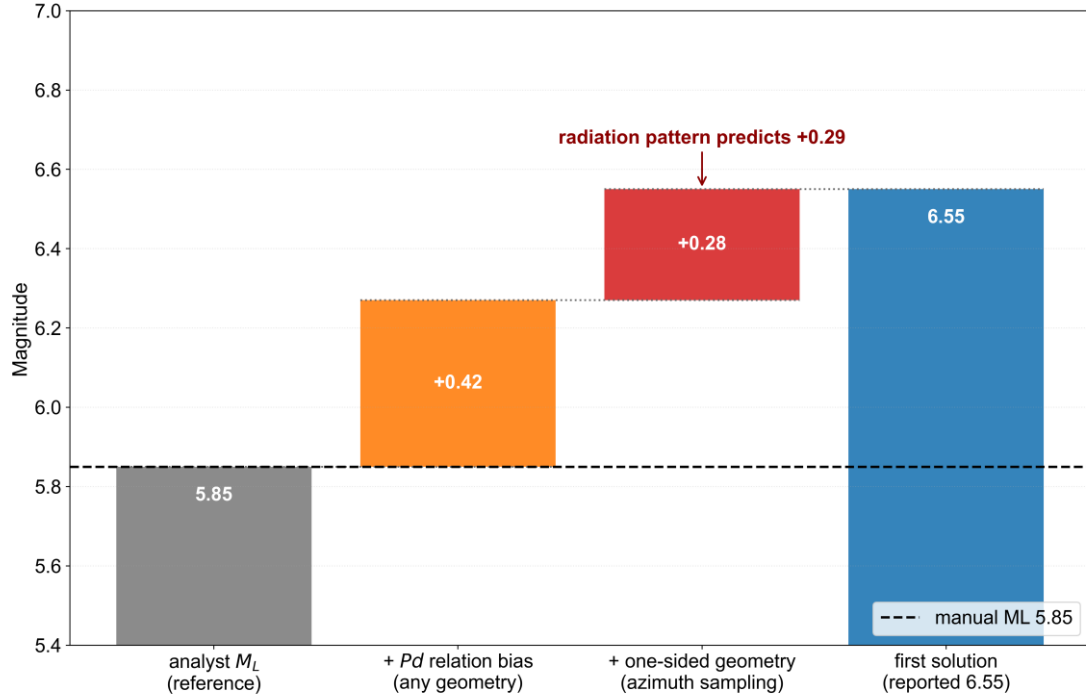


Fig. 8

Fig. 8 Error budget of the first alert. The +0.42 term is independent of station geometry; the +0.28 term is the azimuthal-sampling penalty, quantitatively explained by the radiation pattern (+0.29 predicted)

6. Cross-Event Comparison

To test whether the offshore bias is event-specific, we recomputed all metrics for three further Taiwan events with complete report archives, using each event's own analyst P-file as reference and identical code, so that catalogue convention cannot explain the contrast (Table 5). Besides the Taitung 2026 offshore M_L 5.85 shock (nearest station 14.1 km; 83 solutions), the set comprises the deep offshore Yilan 2025 M_L 7.01 event (67.7 km depth; nearest station 15.8 km; 104 solutions), the near-coast Hualien 2026a M_L 5.74 event (nearest station 5.0 km; 81 solutions) and the inland Hualien 2026b M_L 5.01 event (nearest station 5.2 km; 67 solutions). First public alert is the earliest sent timestamp among the three channels. For Taitung and Yilan all channels dispatched simultaneously; for Hualien 2026b the school

channel led at 8.26 s and PWS followed at 17.26 s. The comparison is a case-controlled contrast of two sources outside the network against two at its edge or inside it.

Table 5 Cross-event comparison. All reference parameters are read from each event’s analyst-reviewed P-file; all metrics are recomputed with identical code. “First public alert” is the earliest sent timestamp among the three channels; for the Taitung and Yilan events all channels dispatched simultaneously, whereas for Hualien 2026b the school channel led (8.26 s) and the PWS message followed at 17.26 s.

	Taitung 2026	Yilan 2025	Hualien 2026a	Hualien 2026b
Source class	offshore	offshore, deep	near-coast	inland
Epicentre (°N, °E)	22.6252, 121.5968	24.6622, 122.0043	24.0437, 121.6313	24.0235, 121.6170
M_L (analyst)	5.85	7.01	5.74	5.01
Depth (km)	13.1	67.7	25.4	15.8
Nearest station (km)	14.1	15.8	5.0	5.2
Analyst azimuthal gap (°)	105	70	86	100
Solutions analysed	83	104	81	67
First internal solution (s)	12.52	14.07	7.97	7.90
First public alert (s)	13.67	13.77	8.27	8.26
Well-located solutions	54	31	80	60
Mean ΔM, well located	+0.38 ± 0.17	+0.45 ± 0.14	−0.08 ± 0.17	−0.07 ± 0.16
r (epicentral error, M_{Pd})	−0.74	−0.55	+0.23	+0.46
First-report intensity within ±1 (%)	59.0	88.1	92.6	92.4
Stations warned before intensity 3 (%)	92.5	82.6	92.5	64.2

Three patterns emerge (Fig. 9). The magnitude bias is a property of offshore geometry, not of the system. Both offshore events over-estimate among well-located solutions ($+0.38 \pm 0.17$ and $+0.45 \pm 0.14$); the two events whose nearest station is about 5 km away, Hualien 2026a at the network edge and Hualien 2026b inside it, are unbiased (-0.08 ± 0.17 and -0.07 ± 0.16). The discriminating variable is the distance to the nearest station, that is, whether the source lies inside or outside the network (Fig. 9a). Yilan is deep and larger than Taitung, yet the over-estimate has the same sign. The mislocation–magnitude compensation is likewise specific to offshore sources. Only Taitung and Yilan show negative correlation between epicentral error and reported magnitude ($r = -0.74$ and -0.55), because their mislocations

are systematically directed toward the network. The two Hualien events, whose mislocations are unsystematic, show weak positive correlations ($r = +0.23$ and $+0.46$; Fig. 9c). First-report intensity within ± 1 is 59.0% for Taitung against 88.1, 92.6 and 92.4% for the other three events, consistent with the larger first-alert over-estimate of the Taitung case.

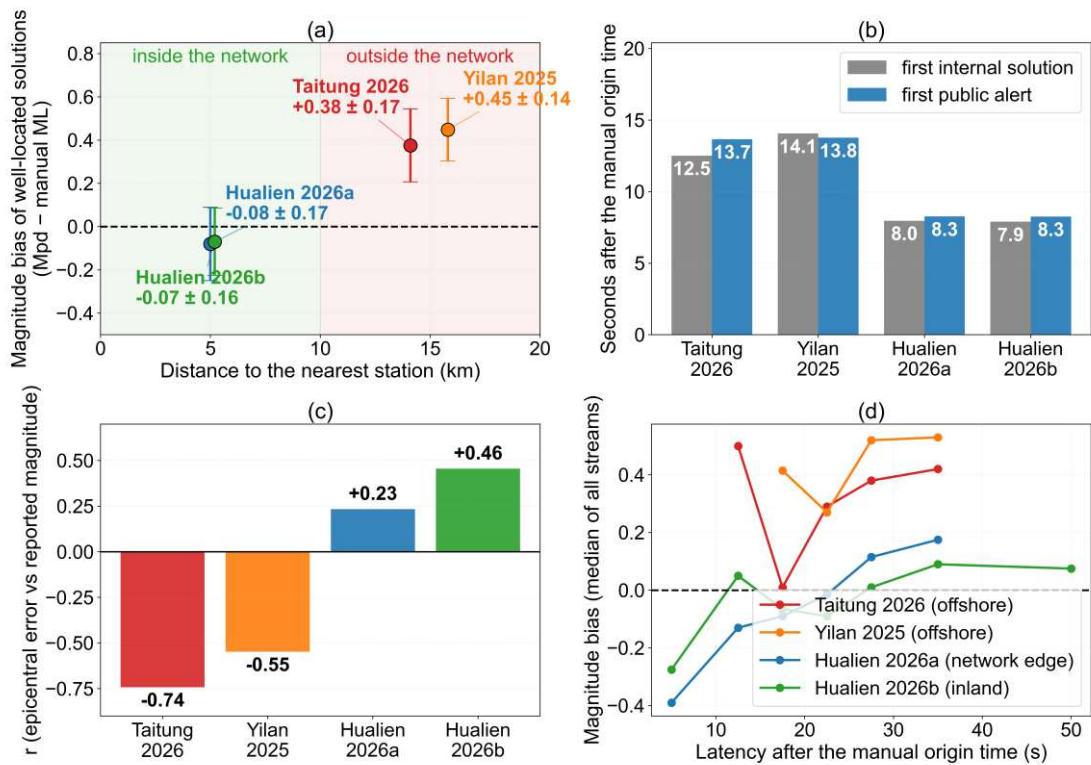


Fig. 9

Fig. 9 Cross-event comparison. (a) Magnitude bias of well-located solutions versus the distance to the nearest station. (b) First internal solution and first public alert latency. (c) Correlation between epicentral error and reported magnitude. (d) Magnitude bias versus latency for well-located solutions only

Offshore geometry also costs 4–6 s of alert latency, consistently: first internal solutions at 12.5–14.1 s and first public alerts at 13.7 s for the two offshore events, versus 7.9–8.0 s internal and 8.3 s public for the two 5 km events (Fig. 9b). Stations warned before intensity 3 remain high for Taitung, Yilan and Hualien 2026a (92.5, 82.6 and 92.5%), whereas Hualien

2026b falls to 64.2% because that smaller inland shock produced a smaller intensity-3 footprint. Four events cannot establish a population statistic; the design is a case-controlled contrast intended to test whether the Taitung mechanism generalises within Taiwan's own operational record. It does so at the level of sign and of latency, not of a transferable numerical correction: the two offshore residuals differ, Yilan is much deeper than Taitung, and the two 5 km events are unbiased despite sharing the same processing system. A larger offshore sample would be required before an operational correction of -0.3 to -0.4 is deployed.

7. Discussion

The three bias terms act together offshore and in different directions inland. Offshore mislocation is systematically toward the land network, so it lowers the assumed distance and therefore the magnitude; any location improvement then raises the magnitude. Inland mislocations have no preferred direction, so the distance term averages out (Table 5). The earliest offshore stations occupy one sector of the focal sphere, and whether the magnitude is biased high or low is set by where that sector falls on the radiation pattern. Here it fell on the P-axis lobe ($+0.29$); a nodal sample (azimuth 210° , $|F_p| = 0.01$) would have under-estimated, with a risk of missed warning. Two distinct statistics point the same way. The mean bias of all well-located solutions is $+0.38 \pm 0.17$ for Taitung and $+0.45 \pm 0.14$ for Yilan (Table 5), while the relation term of the single stream decomposed in Section 5 is $+0.42$; the first is an average over streams and reports, the second a residual of one stream at convergence, and they should not be quoted interchangeably. Both indicate that the operational Pd scaling over-predicts for offshore paths, which is expected given that the relation carries no path-dependent term (Section 3). The sign of the initial bias is not universal: the two 5 km events start below

the reference and rise toward it, whereas Taitung starts above and falls toward a biased plateau (Fig. 9d).

Magnitude error alone is not a valid quality metric. In the Taitung event the absolute magnitude error of the poorly located solutions (mean 0.21) was smaller than that of the well located solutions (0.38), because distance under-estimation cancelled the relation bias. Ranking by magnitude error would therefore select the worst solutions; location and magnitude error must be reported as a pair. Azimuthal gap is similarly misleading offshore: a correct offshore solution necessarily has a large gap (minimum 100° here), whereas an incorrect inland placement acquires a small gap, and the six smallest-gap solutions were the six worst-located. Operators should apply an offshore-specific magnitude correction (here -0.3 to -0.4), require a minimum magnitude-station count and azimuthal spread before public dissemination, detect Pd integration failures at near-source high-gain stations in real time, and use cross-stream location consistency rather than gap as the promotion gate. A median of station M_{Pd} values, rather than the mean of a few stations, further limits early outliers. Table 6 collects these recommendations with the evidence supporting each.

Table 6 Operational recommendations for offshore earthquake early warning, ordered by priority, with the evidence from this study that supports each.

Priority	Recommendation	Evidence
High	Apply an offshore-specific magnitude correction (here -0.3 to -0.4), validated on additional events before deployment	Mean ΔM of well-located solutions is $+0.38$ (Taitung) and $+0.45$ (Yilan), Table 5
High	Require a minimum magnitude-station count and azimuthal spread (e.g. $n_m \geq 5$ spanning ≥ 2 quadrants) before promoting a magnitude to public dissemination	$n_m \leq 4$ solutions have ΔM scatter 0.41 versus 0.23 for $n_m \geq 5$; first alert used $n_m = 3$ within a 12° sector
High	Detect and repair Pd integration/saturation failures at near-source high-gain stations in real time	LDU returned a real-time Pa of 162 gal but $Pd = 0.0006$ cm, removing the only near-source constraint
Medium	Use cross-stream location consistency (e.g. two independent streams within 15 km) as the promotion gate instead of gap	At 07:00:24 two streams on the same computer differed by 35 km, a detectable inconsistency
Medium	Report location error and magnitude error jointly in verification	Poorly located solutions had smaller magnitude error than well-located ones

Priority	Recommendation	Evidence
Medium	Use median or trimmed-mean station M_{Pd} rather than the mean of a few stations	With three stations, a single 0.5-unit outlier shifts the event magnitude by 0.17

Three aspects of the CWA implementation performed well. Parallel geometric-centre and Geiger streams supplied both immediate solutions and the only accurate offshore locations; simultaneous PWS, television and school dispatch meant that the entire 13.67 s was source-estimation time; and PWS coverage of 17 counties against an observed intensity-3 footprint of 15 produced over-alerting rather than missed alerting, the preferable failure direction, although repeated over-alerting carries a long-term cost in public credibility. The mechanism analysis nevertheless rests on a single event and a single focal mechanism; azimuths between 45° and 180° contain no stations, so an east-southeast directivity lobe could not be detected; site response is not modelled separately; four events cannot establish a population statistic; and the recovered Pd coefficients describe this operational implementation only. Where a mechanism is available within seconds, weighting station magnitudes by the theoretical radiation coefficient would remove the sampling term directly; otherwise azimuthal-spread requirements achieve much of the same effect, because the four-lobed pattern averages out over quadrants.

8. Conclusions

We analysed the complete operational record of the 25 August 2026 Taitung offshore M_L 5.85 earthquake: 83 eBEAR solutions from six parallel streams, three dissemination channels, 166 analyst-reviewed intensity observations and per-second intensity for 626 stations.

Operationally the system performed as designed for an offshore source. The first public alert was issued 13.67 s after origin time simultaneously on all three channels; 92.5% of stations that reached intensity 3 were warned beforehand, with a median lead of 29.1 s; PWS coverage of 17 counties exceeded the observed intensity-3 footprint of 15. The blind zone was confined

to Green Island, the Taitung coast and Taitung City, where theoretical lead was only 2.1 s. The public message rounded the disseminated M_{Pd} 6.58 to M 6.6. Geometric-centre streams provided immediate inland solutions; Geiger streams provided the only accurate offshore locations. The remaining problem is not missed warning but a systematic over-estimate of M_{Pd} and of intensity.

The public alert over-estimated magnitude by 0.75 units, and the bias decomposes cleanly on the internal solution that opened the sequence (M_{Pd} 6.55, +0.70). A +0.42 term arises from the Pd scaling relation itself and survives at the best achievable geometry; a +0.28 term arises from one-sided azimuthal sampling. Two solutions computed in the same second from identical Pd amplitudes differed by 0.89 units because their assumed distances differed, and over all 83 solutions epicentral error and reported magnitude correlate at $r = -0.74$. The sampling term is controlled by the source radiation pattern. The three stations that set the first magnitude lay on the P-wave maximum lobe of the RMT mechanism (Lee et al. 2014), with $|F_p|$ 1.78 times the all-azimuth average, predicting +0.29 against an observed +0.28.

Observed PGA follows the theoretical S-wave radiation pattern with exponent 1.13 (theoretical 1.0), and no residual azimuthal signal remains, excluding rupture directivity. The same offshore over-estimate recurs for the deep Yilan event (+0.45 among well-located solutions), whereas the two events with a nearest station of about 5 km are unbiased.

Two widely used quality indicators fail for offshore sources. Magnitude error alone selects the worst-located solutions, because mislocation toward the network compensates the relation bias; azimuthal gap alone rewards solutions incorrectly placed inside the network. For subduction-margin EEW operators the practical implications are to calibrate magnitude separately for offshore paths (here -0.3 to -0.4 , pending a larger sample), to gate dissemination on the number and azimuthal spread of magnitude stations rather than on gap, to verify location and magnitude jointly, to use cross-stream location consistency as a

promotion check, and to monitor near-source high-gain channels for Pd integration failures. A median of station M_{Pd} values further limits early outliers. These measures are inexpensive relative to network expansion and address the dominant error terms identified here. Four events are a case-controlled contrast, not a population statistic; the radiation-pattern control is demonstrated for this geometry, not claimed as a universal rule.

Statements and Declarations

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Conflict of Interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability The eBEAR operation logs (83 report files for the Taitung event and 252 for the three comparison events), the analyst-reviewed P-files, the alert products (CWA-EEW115006201-204 and the corresponding PWS and TV CAP files) and the per-second intensity files are maintained by the Central Weather Administration and are available from the corresponding author on reasonable request. Report No. 115057 is the CWA earthquake-catalogue number of the event, whereas CWA-EEW115006201 is the identifier of the first EEW alert product; the two numbering systems are independent. The focal mechanism is from the Real-time Moment Tensor Monitoring System of the Institute of Earth Sciences, Academia Sinica (<https://rmt.earth.sinica.edu.tw/>; Lee et al. 2014). Derived data tables underlying every figure are provided as supplementary material.

Code availability The analysis code that produces every figure and table in this paper is available from the corresponding author on reasonable request.

Author contributions D.-Y.C. designed the study, performed the analysis and wrote the manuscript. Y.-H.C. contributed to data curation. G.-Y.S. contributed to the analysis. All authors reviewed and approved the final manuscript.

Use of generative AI Generative AI tools were used to assist with drafting and language editing of the manuscript text, with the development of the analysis code, and with the production of the figures. They were not used to generate or alter any data. The authors verified all data, analyses, figures and interpretations, and take full responsibility for the content of this article.

References

- Aki K, Richards PG (2002) Quantitative seismology, 2nd edn. University Science Books, Sausalito
- Allen RM, Melgar D (2019) Earthquake early warning: advances, scientific challenges, and societal needs. *Annu Rev Earth Planet Sci* 47(1):361-388. <https://doi.org/10.1146/annurev-earth-053018-060457>
- Angelier J (1986) Geodynamics of the Eurasia-Philippine Sea plate boundary: preface. *Tectonophysics* 125:IX-X
- Chen DY, Lin TL, Wu YM, Hsiao NC (2012) Testing a P-wave earthquake early warning system by simulating the 1999 Chi-Chi, Taiwan, M_w 7.6 earthquake. *Seismol Res Lett* 83(1):103-108. <https://doi.org/10.1785/gssrl.83.1.103>
- Chen DY, Hsiao NC, Wu YM (2015) The Earthworm based earthquake alarm reporting system in Taiwan. *Bull Seismol Soc Am* 105(2A):568-579. <https://doi.org/10.1785/0120140147>

556 Chen DY, Lin TL, Hsu HC, Hsu YC, Hsiao NC (2019) An approach to improve the
 557 performance of the earthquake early warning system for the 2018 Hualien earthquake in
 558 Taiwan. *Terr Atmos Ocean Sci* 30(3):423-433. <https://doi.org/10.3319/TAO.2018.12.23.02>
 559 Espinosa-Aranda JM, Cuellar A, Garcia A, Ibarrola G, Islas R, Maldonado S, Rodriguez FH
 560 (2009) Evolution of the Mexican seismic alert system (SASMEX). *Seismol Res Lett*
 561 80(5):694-706. <https://doi.org/10.1785/gssrl.80.5.694>
 562 Given DD, Allen RM, Baltay AS, Bodin P, Cochran ES, Creager K, de Groot RM, Gee LS,
 563 Hauksson E, Heaton TH, Hellweg M, Murray JR, Thomas VI, Toomey D, Yelin TS (2018)
 564 Revised technical implementation plan for the ShakeAlert system - an earthquake early
 565 warning system for the West Coast of the United States. *US Geol Surv Open-File Rep* 2018-
 566 1155. <https://doi.org/10.3133/ofr20181155>
 567 Hsiao NC, Wu YM, Shin TC, Zhao L, Teng TL (2009) Development of earthquake early
 568 warning system in Taiwan. *Geophys Res Lett* 36:L00B02.
 569 <https://doi.org/10.1029/2008GL036596>
 570 Hsiao NC, Wu YM, Zhao L, Chen DY, Huang WT, Kuo KH, Shin TC, Leu PL (2011) A new
 571 prototype system for earthquake early warning in Taiwan. *Soil Dyn Earthq Eng* 31(2):201-
 572 208. <https://doi.org/10.1016/j.soildyn.2010.01.008>
 573 Hsu HC, Chen DY, Tseng TL, Wu YM, Lin TL, Pu HC (2018) Improving location of
 574 offshore earthquakes in earthquake early warning system. *Seismol Res Lett* 89(3):1101-1107.
 575 <https://doi.org/10.1785/0220170212>
 576 Johnson CE, Bittenbinder A, Bogaert B, Dietz L, Kohler W (1995) Earthworm: a flexible
 577 approach to seismic network processing. *IRIS Newsl* 14(2):1-4

578 Kao H, Chen WP (2000) The Chi-Chi earthquake sequence: active, out-of-sequence thrust
579 faulting in Taiwan. *Science* 288(5475):2346-2349.
580 <https://doi.org/10.1126/science.288.5475.2346>

581 Kodera Y, Yamada Y, Hirano K, Tamaribuchi K, Adachi S, Hayashimoto N, Morimoto M,
582 Nakamura M, Hoshiba M (2018) The propagation of local undamped motion (PLUM) method:
583 a simple and robust seismic wavefield estimation approach for earthquake early warning. *Bull*
584 *Seismol Soc Am* 108(2):983-1003. <https://doi.org/10.1785/0120170085>

585 Lee SJ, Liu Q, Tromp J, Komatitsch D, Liang WT, Huang BS (2014) Toward real-time
586 regional earthquake simulation II: Real-time Online earthquake Simulation (ROS) of Taiwan
587 earthquakes. *J Asian Earth Sci* 87:56-68. <https://doi.org/10.1016/j.jseaes.2014.02.009>

588 Minson SE, Meier MA, Baltay AS, Hanks TC, Cochran ES (2018) The limits of earthquake
589 early warning: timeliness of ground motion estimates. *Sci Adv* 4(3):eaq0504.
590 <https://doi.org/10.1126/sciadv.aaq0504>

591 Trugman DT, Page MT, Minson SE, Cochran ES (2019) Peak ground displacement saturates
592 exactly when expected: implications for earthquake early warning. *J Geophys Res Solid Earth*
593 124(5):4642-4653. <https://doi.org/10.1029/2018JB017093>

594 Wu YM, Kanamori H (2005) Experiment on an onsite early warning method for the Taiwan
595 early warning system. *Bull Seismol Soc Am* 95(1):347-353.
596 <https://doi.org/10.1785/0120040097>

597 Wu YM, Teng TL (2002) A virtual subnetwork approach to earthquake early warning. *Bull*
598 *Seismol Soc Am* 92(5):2008-2018. <https://doi.org/10.1785/0120010217>

599 Wu YM, Zhao L (2006) Magnitude estimation using the first three seconds P-wave amplitude
600 in earthquake early warning. *Geophys Res Lett* 33:L16312.
601 <https://doi.org/10.1029/2006GL026871>

602 Zollo A, Lancieri M, Nielsen S (2006) Earthquake magnitude estimation from peak
603 amplitudes of very early seismic signals on strong motion records. *Geophys Res Lett*
604 33:L23312. <https://doi.org/10.1029/2006GL027795>