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Towards an EEW system in Greece: A Performance Study of ElarmS and VS Against the NOA Revised Bulletin

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INTRODUCTION & AIM

Earthquake Early Warning (EEW) systems provide a few to several tens of seconds of warning time using the faster propagation of P-waves relatively to the more damaging S-waves. In this study, we evaluate the overall performance of two operational EEW systems—the Earthquake Alarm Systems (ElarmS) [1] and the Virtual Seismologist (VS) [2, 3] — that are routinely used in the Institute of Geodynamics. These algorithms were tested by the use of extensive retrospective playback tests.

METHOD

ElarmS, developed at the University of California, Berkeley, and supports the ShakeAlert network in the U.S. West Coast. It rapidly associates P-wave triggers across multiple stations and uses early amplitude metrics (e.g., peak displacement) combined with empirical ground-motion scaling relationships to estimate origin time, epicenter, and magnitude.

VS, maintained by the Swiss Seismological Service (SED) at ETH Zurich, uses a Bayesian framework that combines observed picks with the earliest available ground-motion amplitudes, predefined priors, and envelope attenuation relationships to estimate earthquake magnitude, location, and the distribution of peak shaking.

We tuned, configured, and operated both systems for the Greek region. A total of 390 earthquakes of ML ≥ 4.0 that occurred between 01/01/2024 and 01/11/2025 (all NOA bulletin events), were processed through full historic playbacks. All available waveform data from 605 stations across Greece were included. For each event, only the first alert issued by each system was evaluated. We used the same playback settings, for each system respectively, for entire broader Greek region.

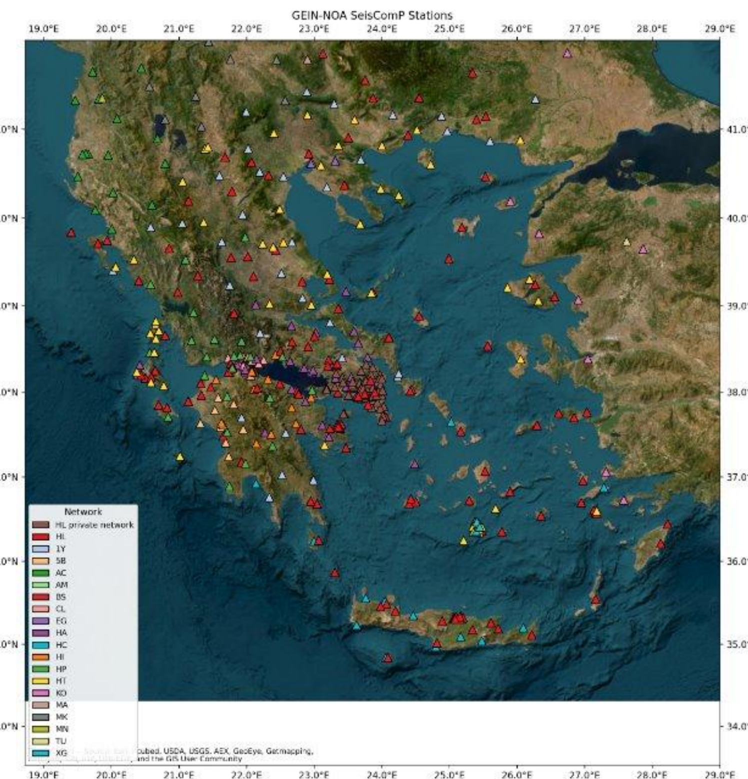


Fig. 1 Stations Map
(605 stations)

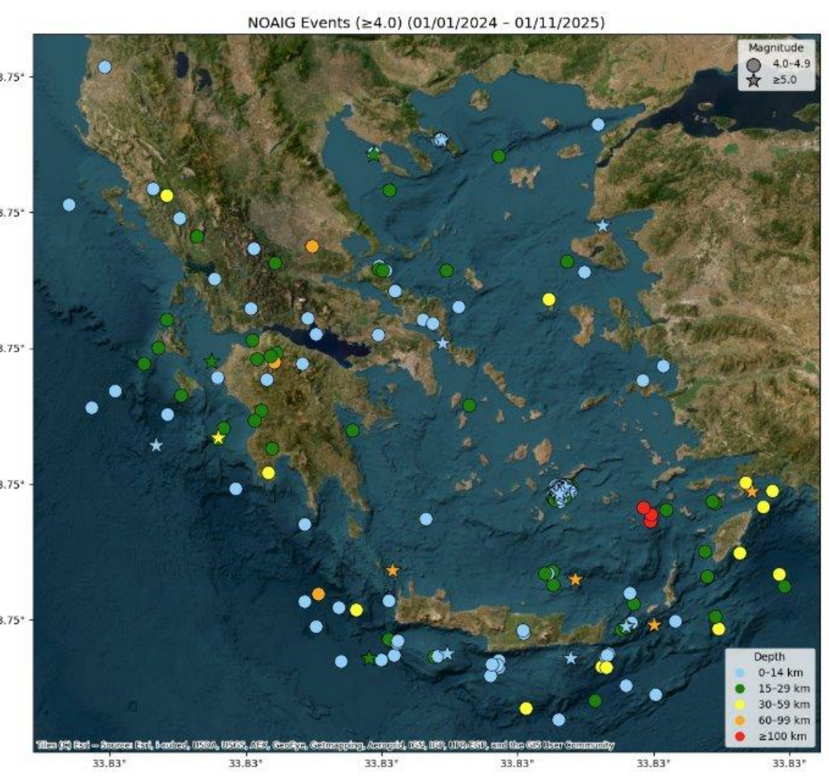


Fig. 2 Earthquakes from NOA Catalogue
(390 events)

VS was implemented within the SeisComP framework[4] (SCP); therefore, all VS playbacks were run using publicly available SCP modules. ElarmS (version E3 [5]) was run using Earthworm and its dedicated ElarmS processing chain. For both systems, identical multiplexed MiniSEED files, with 512 bytes record size length, were generated and fed into the respective playback pipelines through custom automation scripts. For VS station metadata info was read by SCP inventory, while for ElarmS the station sensitivity list was created independently for each event, before playback, by querying the same FDSN service as the VS system.

RESULTS & DISCUSSION

From the playback results, we retained only alerts where the estimated origin time (OT) differed by <10 seconds from the revised OT, and where the alert latency (Tdiff) was ≥1 second. Under these quality conditions, ElarmS produced 302 alerts and VS produced 308 alerts out of the 390 catalogue events. It is important to note that 238 of the 390 earthquakes are included in the Santorini seismic swarm. As expected, EEW systems faced difficulties during this intense swarm activity, because many events overlap temporally, leading to ambiguous picks, complex wavefields, and increased likelihood of misassociation or delayed triggering.

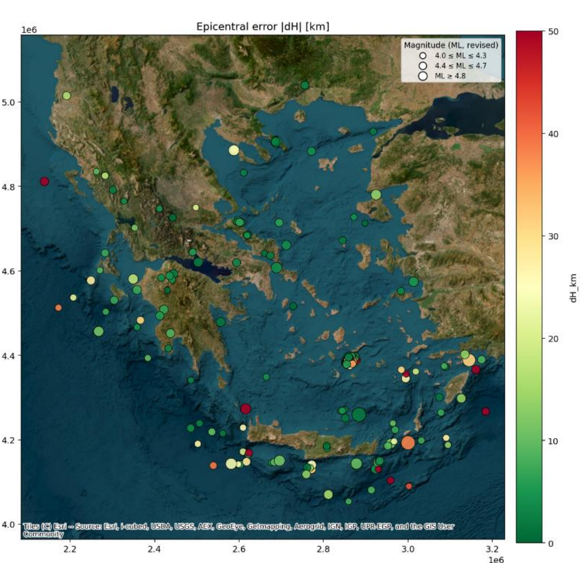


Fig. 3 VS Epicentral Error

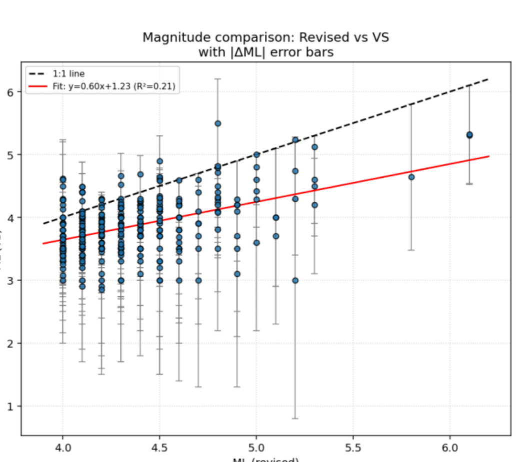


Fig. 4 ML_{VS} - $ML_{Revised}$

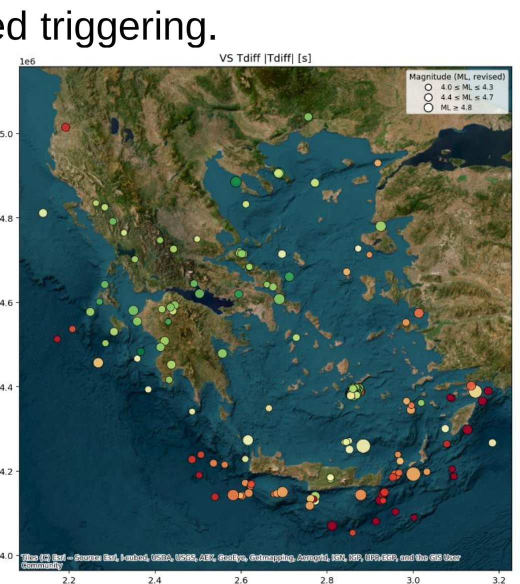


Fig. 5 VS Alert Time

- Across both systems, 255 events were matched as common alerts.
- Additionally. 46 events produced an alert only in ElarmS and 57 events produced an alert only in VS
- Regarding the relative alert speed: ElarmS was faster for 70.6% of the matched events (180 events) with median advantage: 2.8 seconds.
- VS was faster for 29.0% of the matched events (74 events) with median advantage: 4.35 seconds.

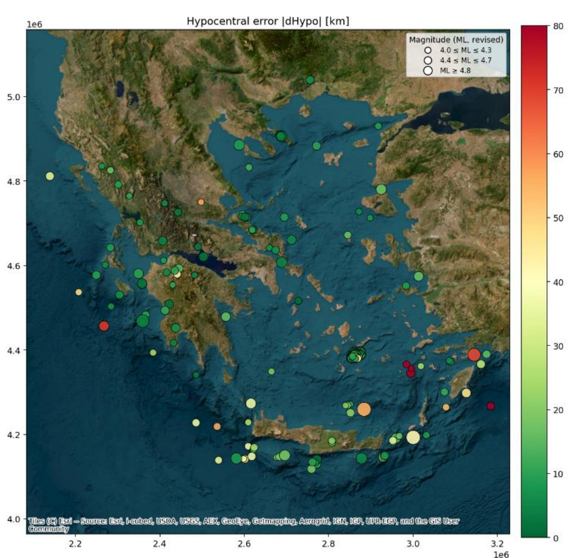


Fig. 6 ElarmS Epicentral Error

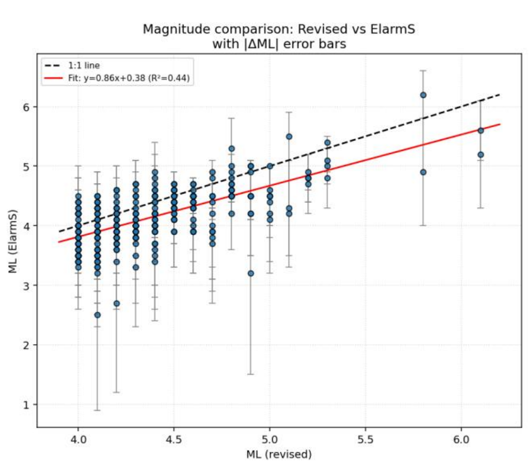


Fig. 7 ML_{ElarmS} - $ML_{Revised}$

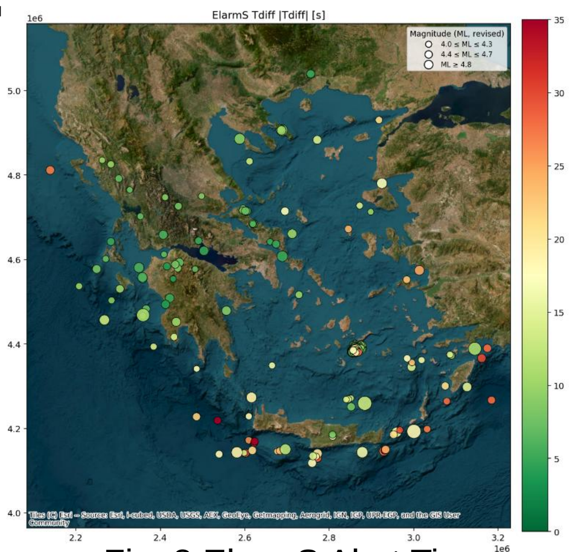


Fig. 8 ElarmS Alert Time

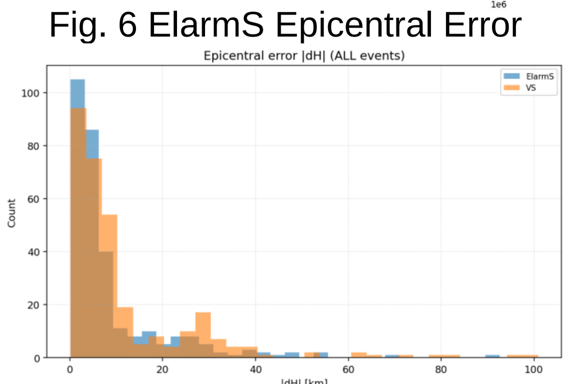


Fig. 9 Epicentral Error
(ElarmS, VS)

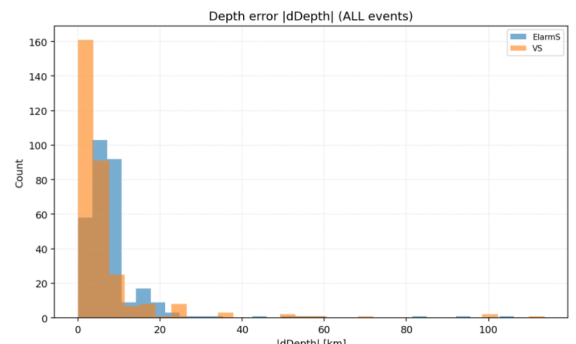


Fig. 10 Depth Error
(ElarmS, VS)

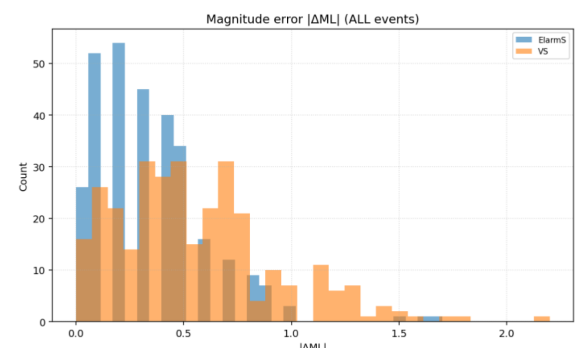


Fig. 11 Magnitude Error
(ElarmS, VS)

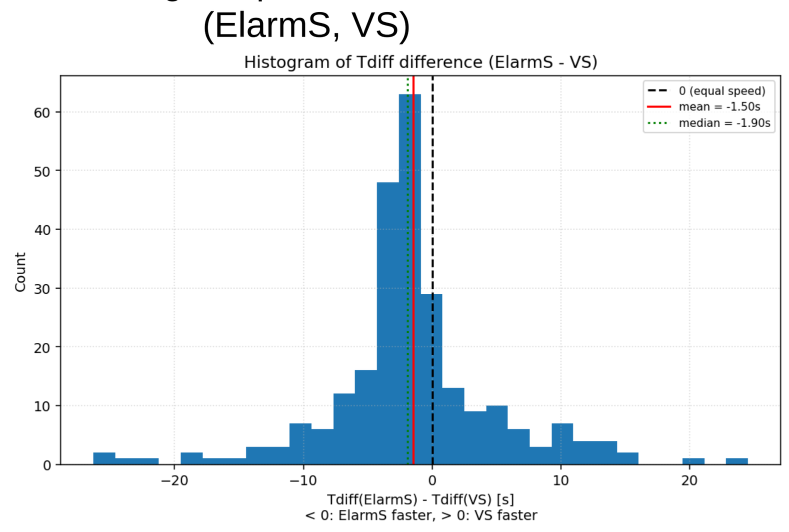


Fig. 12 Alert Time Difference
(ElarmS, VS)

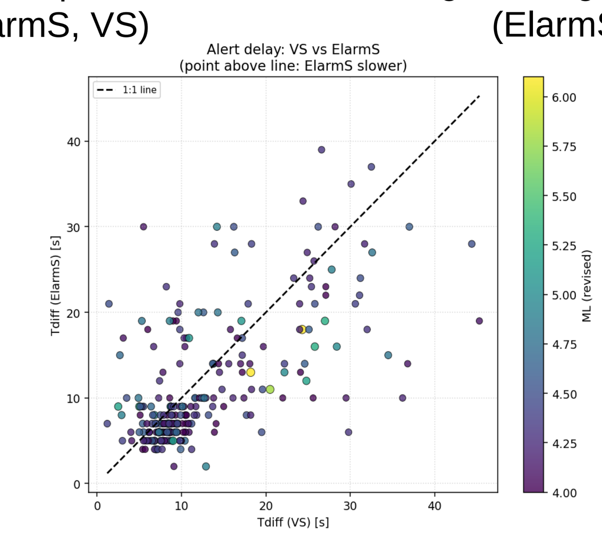
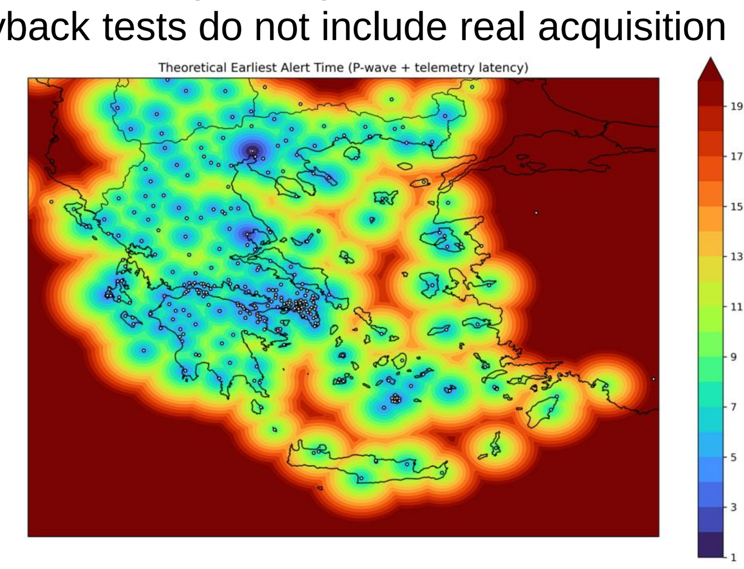


Fig. 13 Alert Delay (ElarmS, VS) and Revised Magnitude

- For 0.4% (1 event) both systems issued the alert simultaneously.
- An additional delay of approximately 2 or more seconds—depending on the station latencies—should be expected in real-time operation, as playback tests do not include real acquisition and network transmission delays.

Fig.14 The map shows the theoretical earliest alert time for any point in Greece, computed only from straight-line P-wave travel times (constant $V_P = 6$ km/s) and real station latencies. No complex geometry or 3-D velocity structure is used. It represents the best-case EEW capability based purely on network coverage and telemetry performance. Only active stations with latency ≤ 60 sec were used for this plot.



CONCLUSION

Overall, the performance of the two EEW systems is comparable. ElarmS shows a clear advantage in alert speed, whereas the VS system has substantial potential for improvement through the integration of commercial SCP modules (e.g., scanloc) and the inclusion of FinDer (Mfd magnitude). Such enhancements could significantly increase both the responsiveness and accuracy of VS. A consistent pattern in the results is that VS tends to systematically underestimate magnitude—an effect that must be considered during operational use. This underestimation can be partially corrected by adjusting SCP playback parameters, which improves the ML fit (increasing R^2 to 0.48), but at the cost of alert latency: under these playback settings, ElarmS increases its median advantage to 4.4 seconds, outperforming VS in 91.6% of the events. Possibly, further tuning of SCP parameters could result to a better scale between magnitude errors and alert times. ElarmS also showed more reliable performance for larger earthquakes preceded by foreshocks, whereas VS underestimated the magnitude for several of these sequences. This limitation may be mitigated through improved association tools and the integration of FinDer. Finally, Fig. 14 demonstrates that alert speed is strongly dependent on station coverage. Dense azimuthal coverage and nearby stations substantially reduce alert latency, underscoring the importance of continued network expansion and densification to further enhance EEW performance in Greece.

FUTURE WORK / REFERENCES

This work will be expanded by performing historic playbacks of all NOA bulletin events with ML ≥ 4.0 since 2020, integrating the SCP Finder module, and applying region-specific criteria. In addition, the Santorini swarm will be examined separately from an EEW perspective.

References: 1. Allen, R.M. (2007); The ElarmS Earthquake Early Warning Methodology and Application across California. In: Gasparini, P., Manfredi, G., Zschau, J. (eds) Earthquake Early Warning Systems. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-72241-0_3, 2. Behr, Y.et al (2016); The Virtual Seismologist in SeisComP: A New Implementation Strategy for Earthquake Early Warning Algorithms, Seismological Research Letters, March/March 2016, v. 87, p. 363-373, https://doi.org/10.1785/0220150235., 3. Cua, G., Heaton, T. (2007); The Virtual Seismologist (VS) Method: a Bayesian Approach to Earthquake Early Warning. In: Gasparini, P., Manfredi, G., Zschau, J. (eds) Earthquake Early Warning Systems. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-72241-0_7, 4. Helmholtz-Centre Potsdam - GFZ German Research Centre for Geosciences and gempa GmbH (2008). The SeisComP seismological software package. GFZ Data Services http://dx.doi.org/10.5880/GFZ.2.4.2020.003, 5. Angela I. Chung et al; Optimizing Earthquake Early Warning Performance: ElarmS-3. Seismological Research Letters 2019;; 90 (2A): 727–743. https://doi.org/10.1785/0220180192