



ABSTRAK

Gempa bumi merupakan bencana alam yang berpotensi menimbulkan kerugian besar terhadap keselamatan jiwa, infrastruktur, serta stabilitas sosial dan ekonomi. Salah satu pendekatan yang dapat dikembangkan untuk mendukung sistem peringatan dini gempa bumi adalah pemanfaatan fluktuasi konsentrasi gas radon sebagai prekursor aktivitas seismik. Namun, prakiraan gempa bumi berbasis radon masih menghadapi tantangan berupa keterbatasan data, sifat nonstasioner sistem seismik, derau lingkungan, serta keterbatasan spasial stasiun pemantauan.

Penelitian ini bertujuan mengembangkan kerangka komputasi prakiraan gempa bumi berbasis prekursor radon yang mampu bekerja pada kondisi data terbatas, adaptif terhadap perubahan pola sistem, tahan terhadap derau, serta memberikan informasi spasial kejadian gempa. Metode yang dikembangkan meliputi deteksi anomali radon menggunakan *Kalman Filter*, prakiraan parameter gempa menggunakan *Monte Carlo Aggregating* (MCA) dan *Real-Time Monte Carlo Aggregating* (RTMCA), prakiraan waktu kejadian menggunakan *LSTM-Kalman Filter*, serta estimasi spasial menggunakan trilaterasi dan *Markov Chain Monte Carlo* (MCMC). Penelitian ini diuji menggunakan multi-dataset global (Jepang, Italia, dan Indonesia) untuk menunjukkan validitas model secara spasial.

Hasil penelitian menunjukkan bahwa MCA dapat digunakan untuk memprakirakan parameter gempa bumi berbasis prekursor radon pada kondisi data terbatas. MCA menghasilkan kinerja terbaik pada radius 300–400 km, serta memperoleh galat ternormalisasi terendah dan nilai *fitness* tertinggi, meskipun keunggulannya terhadap LR dan Bagging tidak selalu signifikan. RTMCA menghasilkan RMSE terendah pada magnitudo sebesar 0,5994 M dan waktu kejadian sebesar 50,3682 jam, tetapi MCA masih lebih baik pada jarak episenter. *Kalman Filter* meningkatkan persentase anomali radon yang diikuti gempa dari 61,68% menjadi 72,13% pada jendela kurang dari 3 minggu, dengan *lead time* 1–19 hari. *LSTM-Kalman Filter* menurunkan RMSE waktu kejadian menjadi 10,26 hari pada Jepang dan 10,93 hari pada Jawa. Trilaterasi berbasis MCA belum stabil, sehingga MCMC digunakan sebagai pelengkap estimasi spasial dengan *success rate* 65,23% di Indonesia dan 81,47% di Italia. Secara keseluruhan, kerangka ini mendukung prakiraan gempa probabilistik berbasis radon secara lebih adaptif, dengan mempertimbangkan ketidakpastian data pemantauan.

Kata kunci— *Prekursor gas radon, prakiraan gempa bumi, Kalman Filter, LSTM-Kalman Filter, Monte Carlo Aggregating, Markov Chain Monte Carlo.*

ABSTRACT

Earthquakes are natural hazards that can cause substantial losses to human safety, infrastructure, and social and economic stability. One approach that can be developed to support earthquake early warning systems is the use of fluctuations in radon gas concentration as a precursor of seismic activity. However, radon-based earthquake forecasting still faces several challenges, including limited data availability, the nonstationary nature of seismic systems, environmental noise, and the limited spatial coverage of monitoring stations.

This study aims to develop a computational framework for radon-precursor-based earthquake forecasting that can operate under limited data conditions, adapt to changes in system patterns, remain robust against noise, and provide spatial information on earthquake occurrence. The developed methods include radon anomaly detection using the *Kalman Filter*, earthquake parameter forecasting using *Monte Carlo Aggregating* (MCA) and *Real-Time Monte Carlo Aggregating* (RTMCA), earthquake occurrence time forecasting using the *LSTM–Kalman Filter*, and spatial estimation using trilateration and *Markov Chain Monte Carlo* (MCMC). This study was evaluated using global multi-datasets from Japan, Italy, and Indonesia to demonstrate the spatial validity of the model.

The results show that MCA can be used to forecast earthquake parameters based on radon precursors under limited data conditions. MCA produced the best performance at radii of 300–400 km and achieved the lowest normalized error and the highest *fitness* value, although its advantage over LR and Bagging was not always statistically significant. RTMCA yielded the lowest RMSE for magnitude, at 0.5994 M, and for occurrence time, at 50.3682 hours, but MCA still performed better for epicentral distance. The *Kalman Filter* increased the percentage of radon anomalies followed by earthquakes from 61.68% to 72.13% within a window of less than three weeks, with a *lead time* of 1–19 days. The *LSTM–Kalman Filter* reduced the RMSE of occurrence time forecasting to 10.26 days for Japan and 10.93 days for Java. MCA-based trilateration was not yet stable; therefore, MCMC was used as a complementary spatial estimation method, achieving a *success rate* of 65.23% in Indonesia and 81.47% in Italy. Overall, this framework supports a more adaptive radon-based probabilistic earthquake forecasting approach by accounting for uncertainty in monitoring data.

Keywords— *Radon Gas Precursor, Earthquake Forecasting, Kalman Filter, LSTM–Kalman Filter, Monte Carlo Aggregating, Markov Chain Monte Carlo.*