Incorporating real-time GNSS-based earthquake early warning in the ShakeAlert system

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The ShakeAlert® earthquake early warning (EEW) system is designed to warn users of imminent Modified Mercalli Intensity (MMI) VI+ ground motion due to an ongoing earthquake before the shaking reaches them. ShakeAlert has provided public alerts within California since 2019 and in Oregon and Washington since 2021 using data from regional seismic networks (Kohler et al., 2018; Lux et al., 2024; McGuire et al., in review). The seismic data are highly sensitive and have low noise levels, allowing magnitude estimates for small magnitude earthquakes whose displacements are below the noise level of real-time Global Navigation Satellite System (GNSS) positions. However, seismic magnitude estimates based on P-wave amplitudes saturate for large earthquakes (e.g., >M8.0), and when only the first few seconds of the P-wave are used to estimate magnitude, as is the case in ShakeAlert, saturation begins around M7.0 (Trugman et al., 2019). GNSS data directly record arbitrarily large displacements, enabling calculation of non-saturating magnitude. This is critically important to timely alerting for large earthquakes such as anticipated subduction interface events in Cascadia. In March 2024 ShakeAlert incorporated its first algorithm utilizing positions from real-time GNSS data, GFAST-PGD, into the production system (Crowell et al., 2016; Murray et al., 2023; McGuire et al., in review). Currently positioning is carried out using raw data from the Global Positioning System (GPS), but additional constellations may be used in the future. Here we 1) report on GFAST-PGD's performance since deployment within the ShakeAlert production system and 2) evaluate the potential improvement to alert performance offered by more complex GNSS-based real-time distributed slip models.

GNSS data are affected by sources of noise that introduce drift, offsets, and increased scatter into time series, especially in real-time. Inaccurate positions can arise from problems with ambiguity resolution, the availability of high-quality real-time clock corrections, models for atmospheric delay, and satellite geometry. GFAST-PGD only contributes a magnitude estimate when ShakeAlert's seismic algorithms report a M6.0+ earthquake. However, noise signals like those described above, if mistaken for earthquake-driven displacement, could result in spuriously large magnitude estimates. These, in turn, could lead to alerting a large geographic area that did not experience MMI VI+ shaking. To reduce the likelihood of inaccurate magnitude estimates due to noisy GNSS data, we developed criteria that define when GFAST-PGD's magnitude estimates contribute to ShakeAlert's source characterization (Murray et al., 2023). We continue to investigate additional methods to mitigate the effect of noisy data on GFAST-PGD's results.

While GFAST-PGD offers non-saturating magnitudes, it characterizes the earthquake as a point source. For large subduction interface earthquakes with extensive rupture areas, more accurate ground motion predictions, and thus alerting, might be achieved using a three-dimensional finite fault representation. We carried out simulated real-time replays of GPS-derived positions and seismic data through the ShakeAlert algorithms as well as BEFORES (Minson et al., 2014), an algorithm that estimates distributed slip from geodetic position time series, to evaluate the potential impact of the more complex source characterization on alert outcomes. We found that, depending on choice of MMI threshold for issuing alerts, BEFORES has the potential to substantially increase the amount of warning time users receive, but with this comes the possibility of alerting areas that might not experience strong (e.g., MMI VI+) shaking.

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