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Increasing magnitude scale consistency by combining multiple waveform features through machine learning

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Amplitude measurements at single stations are naturally noisy, due to radiation patterns, inhomogeneous ground structure and ambient noise. To improve the accuracy of magnitude estimations, measurements from multiple stations are combined. As many measurements are often not available for near real time applications, we developed a method to achieve consistent magnitude estimations even in the presence of only few stations. We achieve this by combining optimization and machine learning methods aggregating multiple waveform features.

The analysis is based on a catalog of >100,000 events between 2007 and 2014 in Northern Chile from Sippl et al. 2018[1]. The catalog contains variety of earthquake types, include different types of subduction events and shallow crustal events. It covers a depth range of 250 km and an area of about 6° times 5°. The magnitudes range from < 2 to 8.1.

For each event and station we extract multiple features, spanning peak velocity, acceleration and displacement, coda-derived statistics and trace energy. All features are extracted on all relevant components and component combinations. We derive a non-parametric attenuation and geometric spreading function based on distance and event depth for each extracted feature. Using a k-nearest neighbor approach we develop a station and source dependent correction function. For each feature all correction functions are optimized concurrently using quadratic programming. The magnitude scales are normalized to approximate moment magnitude for events with M_w between 5.0 and 6.0.

We compare the resulting magnitude scales on an independent validation data set. We evaluate their value range, including possible saturation effects, and quantitatively analyze the residuals between single station measurements and the mean across all stations using RMSE. We show that all components and their combinations yield similar residuals. Residuals are lowest for scales based on velocity and acceleration with RMSE around 0.23. Scales based on displacement have a RMSE of approximately 0.31. The RMSE is reduced by approximately 20% through the station specific source correction terms.

We compare the scales against the 88 events with M_w ranging from 4.8 to 7.7 from the validation data set. We show that acceleration scales saturate at magnitudes around 6.0, while velocity scales slightly underestimate the magnitudes of the biggest events and displacement scales slightly overestimate them.

We further reduce the RMSE significantly using boosting trees on all features and components of single stations, reaching a RMSE of 0.13. By analyzing the feature importance we show that while coda- and P-wave-derived features yield less consistent magnitude scales themselves, they are key factors for reducing residuals. This matches the intuition that coda-derived features are less susceptible to radiation patterns, while the P-wave on the vertical component is less affected by local site amplification effects.

Using boosting trees we additionally build a multi-feature magnitude scale using only features from the P-wave. We show that with the combinations of P-wave features only, a RMSE slightly lower than from any single full waveform feature can be achieved.

[1] https://doi.org/10.1002/2017JB015384