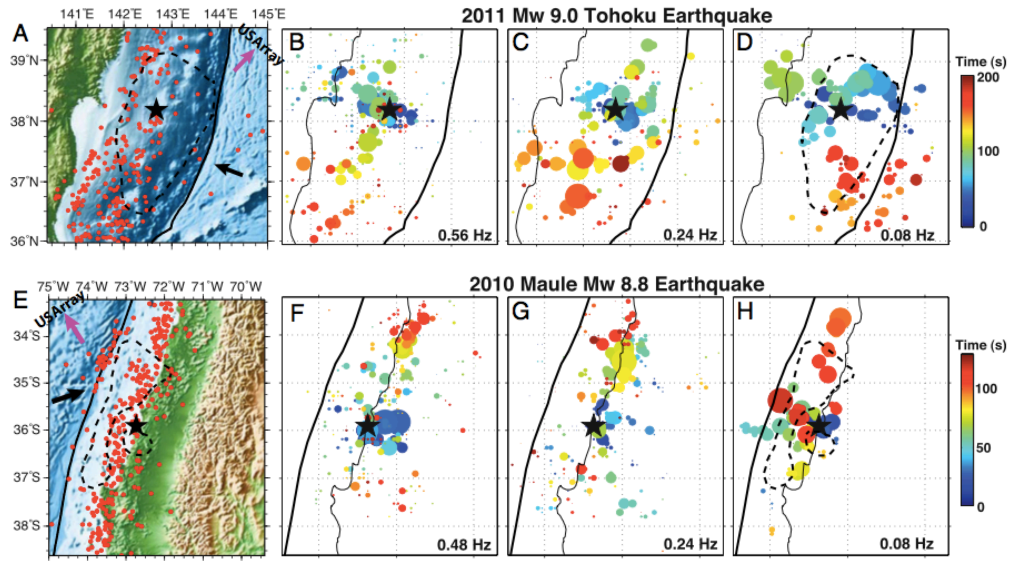
Improving Distance Metrics in Ground Motion Prediction Equations Based on Seismic Array Back-Projection

UCLA

Lingsen Meng[1] (meng@ess.ucla.edu) and Tian Feng[1]

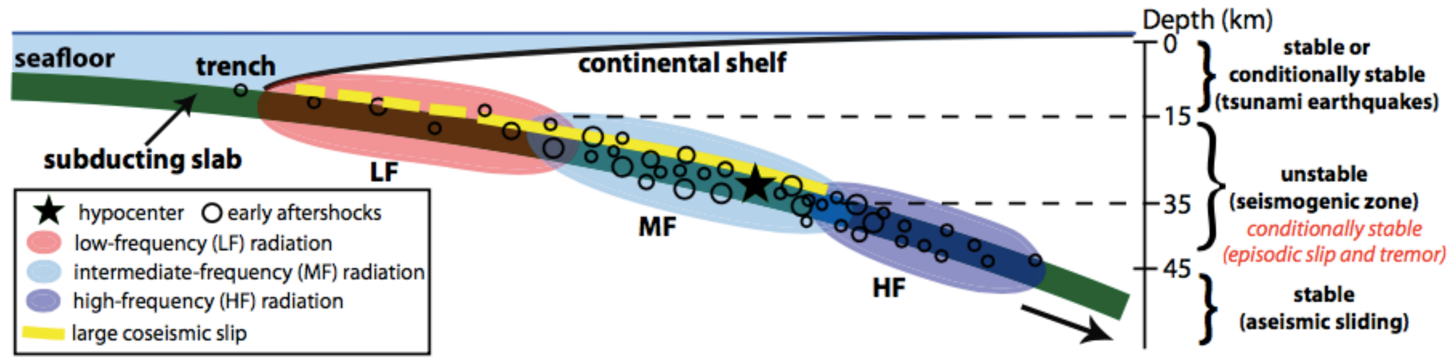
1. Earth, Planetary and Space Sciences, University of California, Los Angeles, CA 90025, USA.

Frequency-dependent and Depth-varying Seismic Radiation

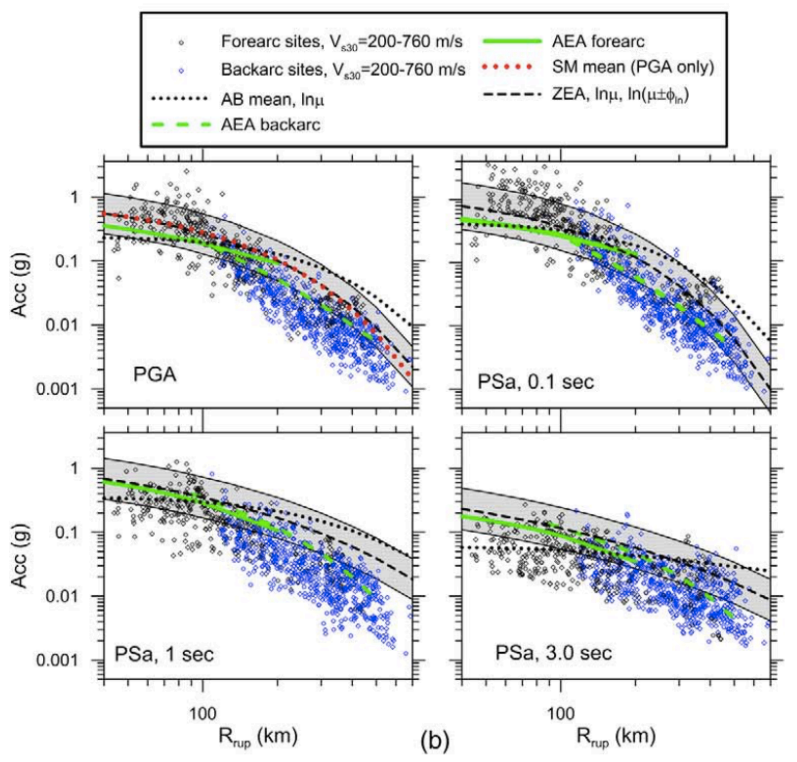


Recent advances in earthquake source imaging of major subduction earthquakes highlight the frequency-dependent and depth-varying seismic radiations at the plate interfaces. Low-frequency energy mainly emanated from the shallower portion of the megathrusts while dominant high-frequency energy often radiates from the deeper portion of the megathrust (Meng et al., 2011; Lay et al., 2012; Yao et al., 2013).

Yao et al., PNAS, 2013



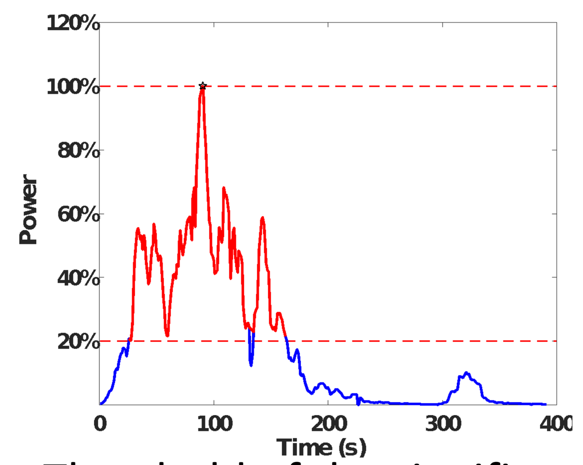
Distance Metrics of GMPEs



Stewart J P et al., Earthquake Spectra, 2013

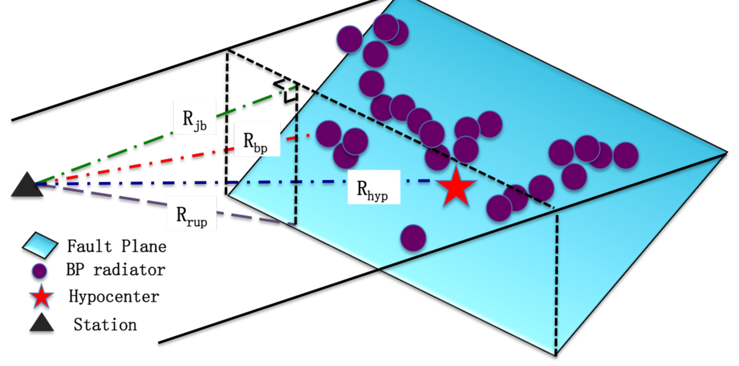
Typical Ground Motion Prediction Equations (GMPEs) measure the distances either relative to the epicenter (Repi) or the hypocenter (Rhyp) assuming point-sources, or relative to the closest point of the fault rupture (Rrup) or its surface projection (Rjb) to account for finite earthquake dimensions. For the 2011 Tohoku-Oki earthquake, all these distance metrics produce severe biases, underestimating the ground accelerations at short distances (<100km) and overestimating them at long distances (>100km). This phenomenon motivates an alternative distance metric based on the array back-projection (BP) technique that effectively captures regions releasing high-frequency energy.

The ground-motion misfits are more severe in the high frequency observation (1-10Hz). Since the attenuation relation between distance and ground motion is well established, we hypothesize that the large observed errors can be attributed to a misrepresentation of the source-receiver distance in the high-frequency band. We thus defined a new type of distance measurements, Rbp, the shortest distance from receiver site to the back-projection radiators. Back Projection Radiator (BP radiator) refers to the location where peak energy is released. To avoid the effect of coda waves, we consider that only the significant radiators (with BP power larger than 20% of the maximum) are responsible for the generation of strong ground motions.



Threshold of the significant Back Projection Radiators

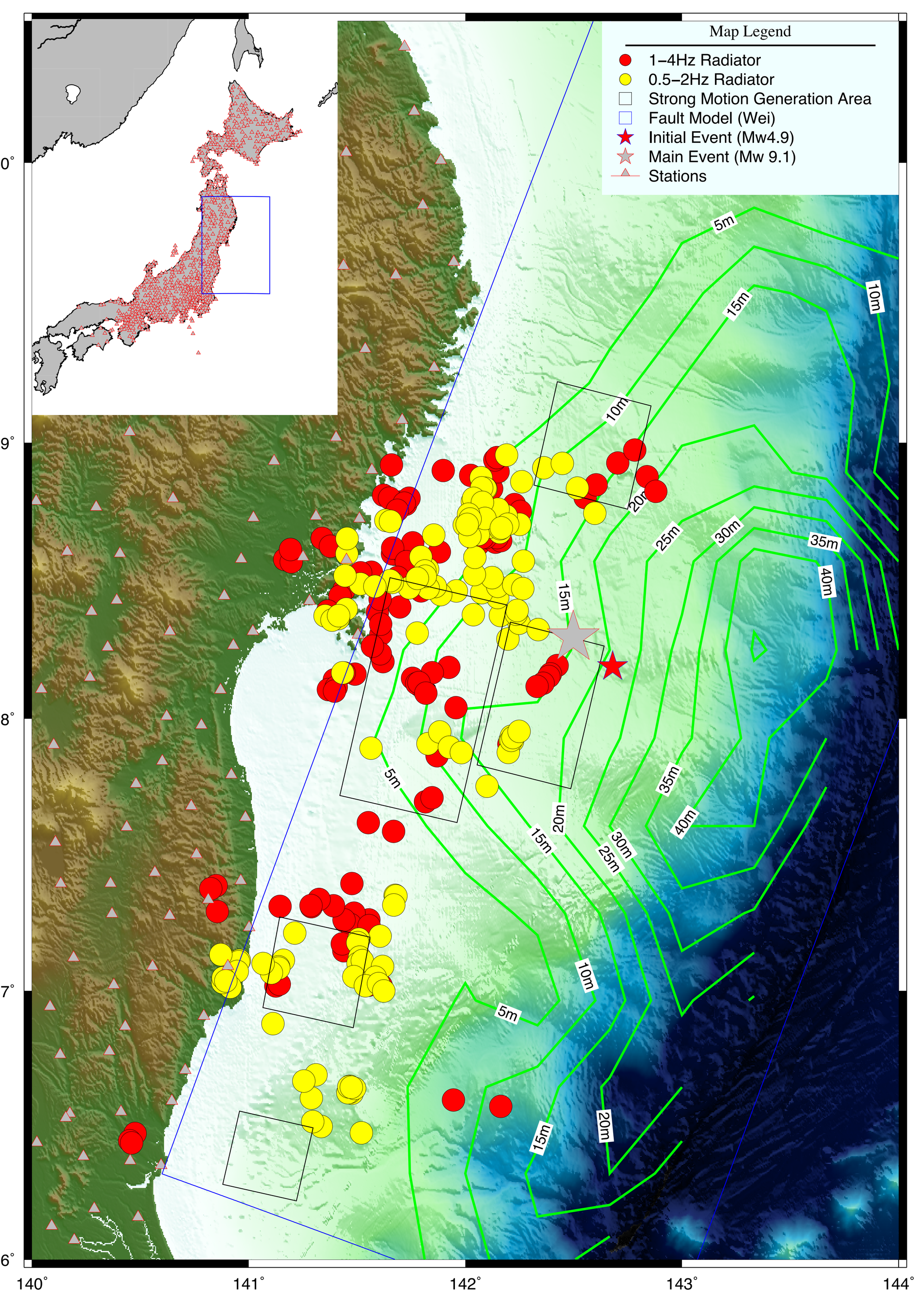
Schematic diagram of distance metrics



Events & Fault slip models selected

Event	Time	Institute	Mw	Location	Depth (km)	Fault model
Tohoku	2011/03/11	Iris	9.1	38.2963N 142.498E	19.7	Wei (2011)
		USGS		38.297N 142.373E	29	
		JMA	9.0	38.10N 142.86E	24	
		Chu	4.9 Initial	38.19N 142.68E	21	
Tokachi	2003/09/26	Iris	8.3	41.7488N 143.8725E	33	Koketsu (2004)
				41.815N 143.91E	27	
		USGS				
		JMA	8.0	41.78N 144.07E	42	
Offshore Honshu (Foreshock of Tohoku Eq)	2011/03/09	Iris	7.3	38.4407N 142.9803E	26.2	Hayes (NEIC, offshore Honshu 2011)
		USGS		38.435N 142.842E	32	
		JMA		38.33N 143.28E	8	
Off Miyagi	2005/08/16	Iris	7.2	38.2013N 142.1143E	37.8	Shao and Ji (UCSB, Honshu 2005)
		USGS		38.276N 142.039E	36	
		JMA		38.15N 142.28E	42	
Iwate-Miyagi Nairiku	2008/06/13	Iris	6.9	39.1514N 140.7365E	11.6	Cultrera et.al (2013)
		USGS		39.030N 140.881E	7.8	
		JMA	7.2	39.03N 140.88E	8	

Coincidence between SMGAs and BP radiators

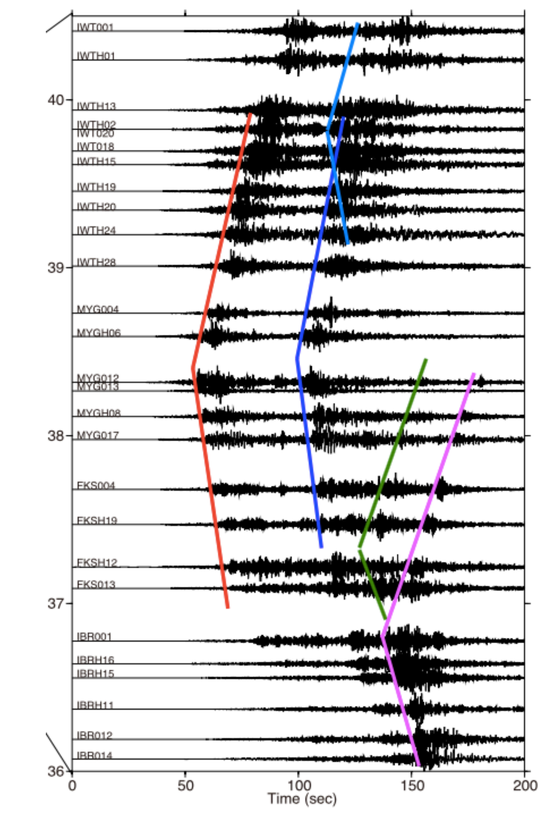


To understand the role of BP Radiators in generating high-frequency ground motions, we compare them with strong motion generation areas of the 2011 Tohoku event and the coseismic slip distribution. The 'strong motion generation area' is defined as the source area of large slip velocities and large stress release (1-10MPa), that are responsible for large amplitude of high-frequency radiation (Miyake 2003).

People often associate the SMGAs with asperities of large slip. The locations of the SMGAs are estimated through the onset times of the wave-packets at near field stations (Susumu Kurahashi and Kojiro Irikura, EPS, 2011).

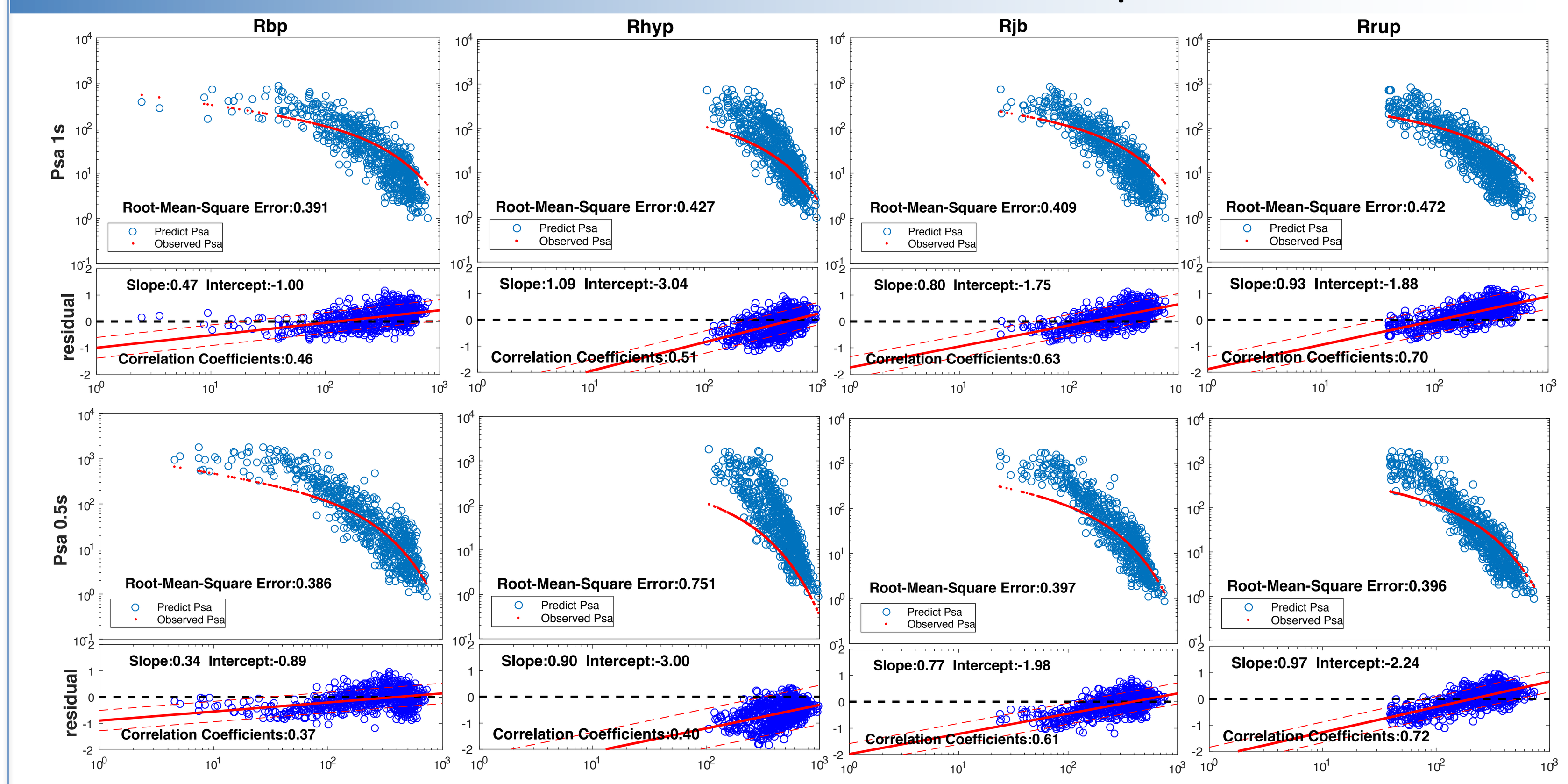
However, in the case of the Tohoku Earthquake, we found that five SMGAs don't coincide with large slips, but coincide with high frequency radiators. This coincidence between Back Projection Radiators and Strong motion generation areas demonstrates the capability of Back Projection Radiators in locating high frequency earthquake source.

S waves propagating from SMGAs to Stations



Susumu Kurahashi and Kojiro Irikura, EPS, 2011

The 2011 Mw 9.0 Tohoku Earthquake



Original Boore's GMPE equation (Boore and Atkinson, 2007):

$$lnY = F_M(M) + F_D(R,M) + F_S(Vs30,R,M)$$

Where Y can be PSA, PGA and PGV, F_M, F_D and F_S represent the magnitude scaling, source-receiver distance, and site amplification factor. After transferring the F_S term from GMPE to left hand side, the observed accelerations after site effect correction is $PSA' = \frac{PSA}{e^{Fs}}$ and the GMPE becomes:

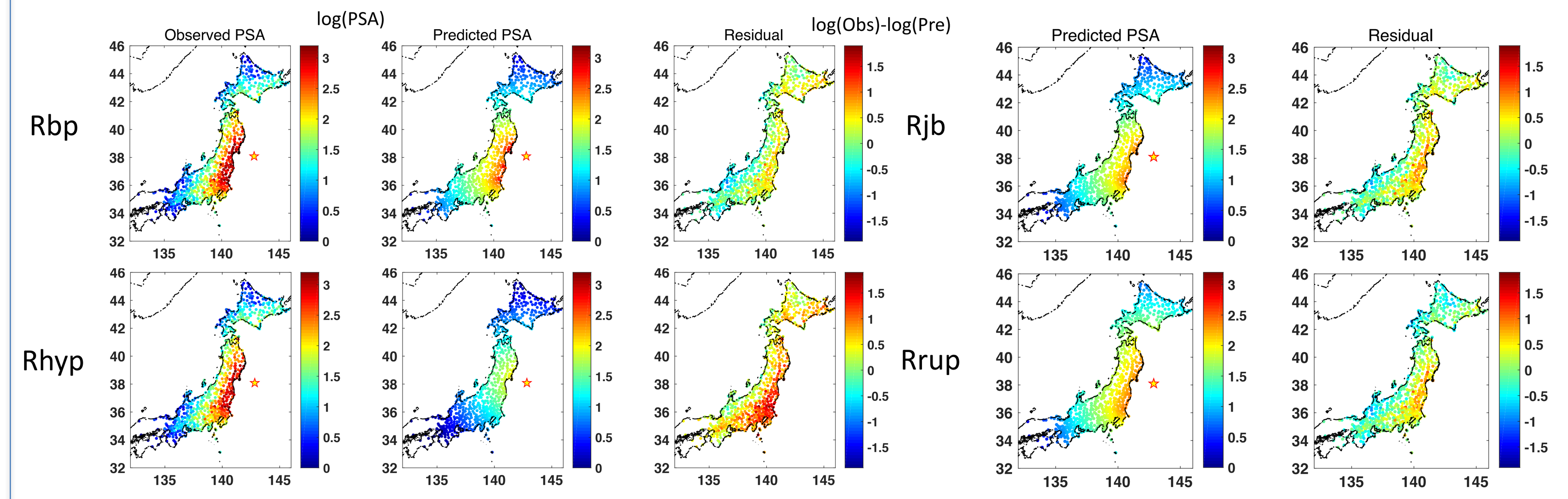
$$lnY = F_M(M) + F_D(R,M)$$

The residual between observation PSA' and prediction $exp(Y)$ describes the accuracy of different measurements.

We compare the performances of the distance metrics in predicting the ground motions of the Tohoku earthquake. For PSA (Pseudo Spectral Acceleration) at the period of 1s, Rbp metric made the best prediction among the four metrics, with the smallest RMSE (Root-mean-square error).

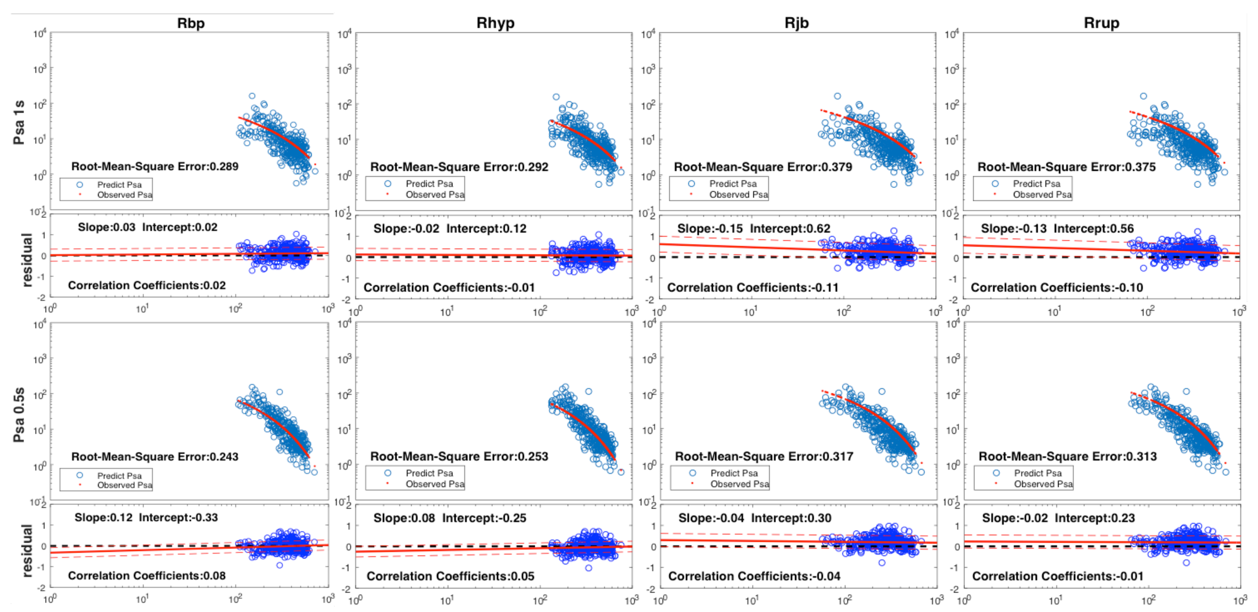
For PSA of 0.5 s, the RMSE of Rbp, Rrup and Rjb are quite small compared with Rhyp. The Rhyp measurement generates large bias and is not suitable for GMPE in high frequency. The misfit of Rrup and Rjb are also strongly depending on the distance. Also, the slopes of the best-fit lines for Rhyp, Rrup and Rjb's the are much larger than that for Rbp.

In summary, the performance of Rbp measurement in predicting ground motion intensity of high frequency is more accurate and more stable than traditional distance metrics.



For PSA 0.5s, we could find that Rbp prediction's residual is smallest among 4 distance metrics while Rhyp underestimates the PSA near the coast (about 10 times smaller), Rjb and Rrup overestimate the PSA away from hypocenter (about 10 times larger). For most stations, the residual of Rbp prediction is quite small (within 3 times).

Largest Foreshock of Tohoku Earthquake

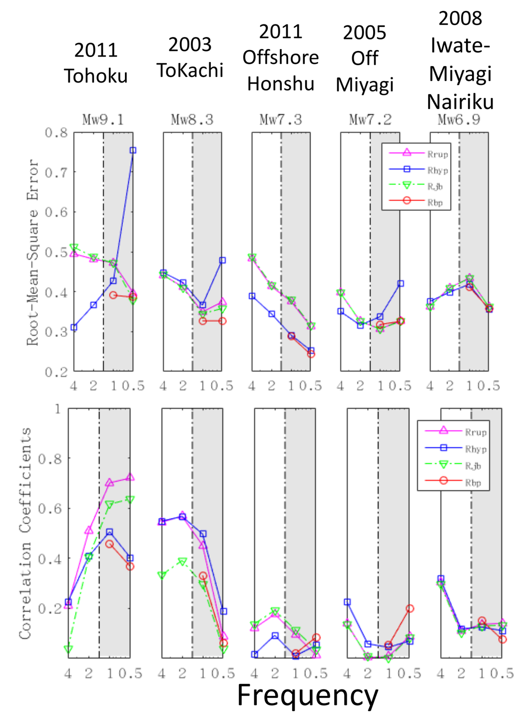


For both PSA of 1 s and PSA of 0.5 s, the RMSE of Rbp metric is smallest, while both Rrup and Rjb metrics overestimate PSA. Thus, Rrup and Rjb metrics may not be suitable for predicting PSA of high frequency in a smaller earthquake (Mw<7.3). We can also find that the predictions of Rbp and Rhpy are very close in small earthquakes, in which scales of rupture length are quite small.

Comparison of RMSE and Corrcoef

Based on the two case studies above, Rbp metric's performance in predicting ground motion intensity of high frequency is the best while other traditional distance metrics' performance less accurate or stable. We also study the 2003 Tokachi, 2011 Offshore Honshu, 2005 Off Miyagi and 2008 Iwate-Miyagi Nairiku earthquakes. we observed that Rbp metric's average RMSE is the smallest for PSA of 1s and 0.5s while Rhyp measurement's average RMSE is smallest for PSA of 4s and 2s.

The absolute correlation coefficients of residual with distance drop fast as the magnitude decrease. For earthquakes smaller than Mw 7.3, residual could be considered not relevant to distance. However, for large earthquakes, the high correlation coefficients indicate that the residual comes from oversimplification of distance metrics.



To develop an automatically early-ground–motion-prediction system, we combine two distance metrics: Rbp for high frequency and Rhyp for low frequency. This system doesn't depend on the finite fault model, which couldn't be available immediately after the earthquake. This system only requires the location and depth of event, which could be determined automatically in real-time by existing earthquake early warning system. This system could also provide more accurate ground motion prediction in difference frequencies.

Summary

In this project, we utilize the back-projection methodl to locate energy radiators (BP radiator), which are colocated with strong ground motion generation area (SMGA). We define the new metric of distance as the distance between nearest BP radiator and station, R_{BP}. We studied five large earthquakes in Japan from 2003 to 2011, and found that Rbp outperforms conventional distance metrics in predicting the Psa (Pseudo Spectral Acceleration) in the high-frequency band (0.5-4 Hz). At low frequencies (0.1-0.5Hz), we find that Rhyp produces better fits to the Psa spectrum. Thus, we propose to combine Rhyp and Rbp in low-frequency (0.1-0.5Hz) and high-frequency (0.5-4 Hz) range to improve the GMPEs. We consider that Rbp reflects the high-frequency aspects of the rupture that are complementary to conventional GMPE distance metrics and a more suitable ground motion predictors in many cases.

Reference

Atkinson G M, Boore D M. Boore-Atkinson NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters[M]. Pacific Earthquake Engineering Research Center, 2007.

Kurahashi S, Irikura K. Source model for generating strong ground motions during the 2011 off the Pacific coast of Tohoku Earthquake[J]. Earth, planets and space, 2011, 63(7): 11.

Lay T, Kanamori H, Ammon C J, et al. Depth-varying rupture properties of subduction zone megathrust faults[J]. Journal of Geophysical Research: Solid Earth, 2012, 117(B4).

Meng L, Inbal A, Ampuero J P. A window into the complexity of the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake[J]. Geophysical Research Letters, 2011, 38(7).

Miyake H, Iwata T, Irikura K. Source characterization for broadband ground-motion simulation: Kinematic heterogeneous source model and strong motion generation area[J]. Bulletin of the Seismological Society of America, 2003, 93(6): 2531-2545.

Stewart J P, Midorikawa S, Graves R W, et al. Implications of the Mw9. 0 Tohoku-Oki Earthquake for Ground Motion Scaling with Source, Path, and Site Parameters[J]. Earthquake Spectra, 2013, 29(s1): S1-S21.

Yao H, Shearer P M, Gerstoft P. Compressive sensing of frequency-dependent seismic radiation from subduction zone megathrust ruptures[J]. Proceedings of the National Academy of Sciences, 2013, 110(12): 4512-4517.