COMPARING INEXPENSIVE RASPBERRY SHAKES TO BROADBAND SEISMOMETERS IN ESTIMATING DEEP EARTH STRUCTURE THROUGH THE USE OF RECEIVER FUNCTIONS

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INTRODUCTION

An inexpensive, three-component Raspberry Shake and a research grade, broadband seismometer were compared in performance via receiver function analysis. The seismometers were located 33 km apart in the Black Hills (fig. 1).

A crust-mantle boundary depth (Moho) was calculated for both seismometers. The Raspberry Shake was found to be adequate in producing similar interpretations as the broadband seismometer, implying that the Shakes may have potential to be used in more advanced scientific research.

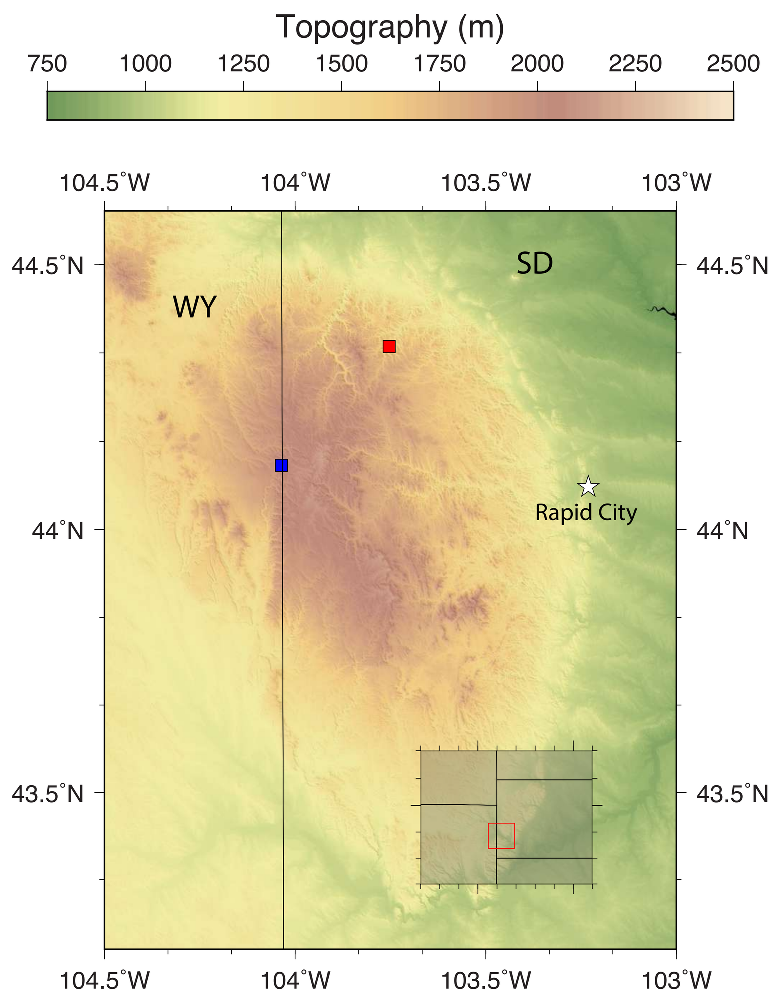

Figure 1. Location map for Raspberry Shake (red) and broadband, IU RSSD (blue) seismometers located in the Black Hills of South Dakota and Wyoming. Rapid City with a star shown for reference. (Note: all figures, excluding figures 2, 3, and 9, were created using GMT (Wessel et al., 2019)).

METHODS

Thirty four seismic events with the parameters of magnitude >5.5 and distance 30° to 90° from the seismic stations were recorded from the deployment of the Raspberry Shake (fig. 2, December 9th, 2021) until February 28th 2022. One earthquake occuring on February 03rd, 2022 in northern Peru provided sufficient data from both the Raspberry Shake and broadband seismometer.

Raw data were processed using Seismic Analysis Code (Goldstein, 2003 and Goldstein, 2005), removing the instrument response for each component of both seismometers via several steps:

- applied bandpass filter of 0.1 to 8.0 Hz
- removed the mean and trend
- tapered the ends of the waveforms
- rotated horizontals to a radial and tangential waveform in the earthquake reference frame
- applied iterative, time-domain deconvolution (Ligorría and Ammon, 1999) to radial and vertical waveforms
- applied three Gaussian filters to remove high-frequency noise

Important considerations in interpreting receiver functions:

- positive spike shows increase in velocity with depth; negative spike implies decrease (fig. 3)
- magnitude of the amplitude of the spike corresponds to magnitude of the velocity contrast
- materials making up the crust and mantle layers are very different in velocity, resulting in a large, positive amplitude spike at this boundary
- time delay of the spike is used to calculate depth at which velocity change occurs
- general rule of thumb, one second translates to about 8 km of depth
- crust-mantle boundary averages 30 to 50 km in depth for the Black Hills--should produce large amplitude spikes between about 4 and 6 seconds.

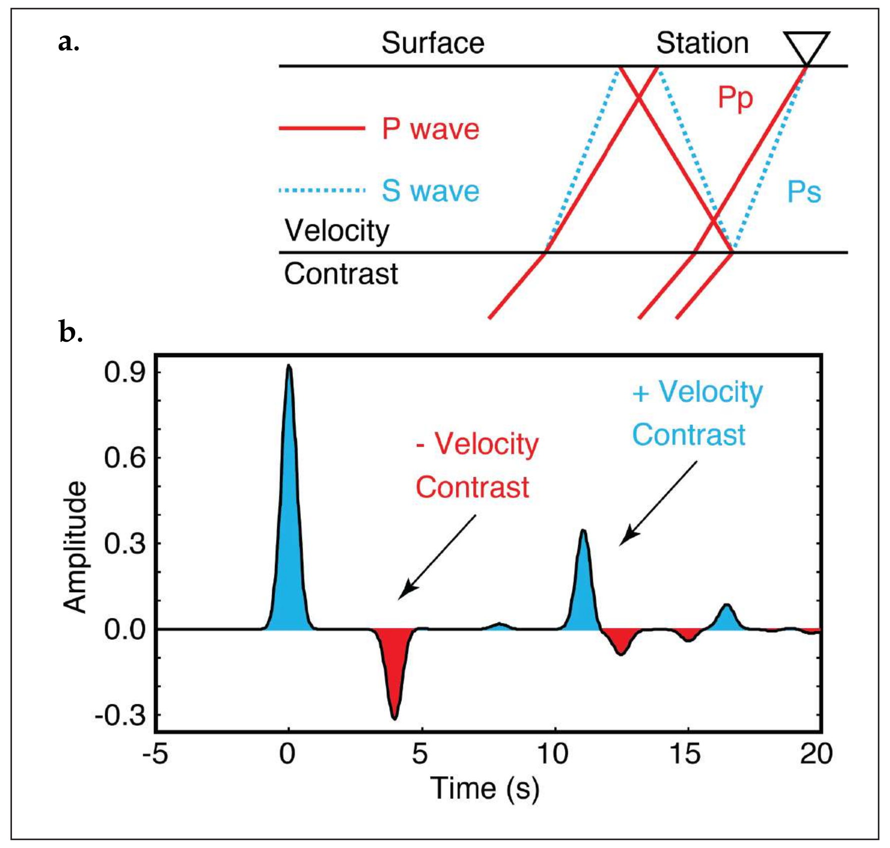

Figure 2. (below) Image of the three component, Raspberry Shake used in this study, currently active at the 4100 ft level in SURF.

Figure 3. (left) a) Illustration of P and S waves detected from a seismic station (triangle in top right of image). The difference in arrival times of the different Pp and Ps waves can be used to estimate the Moho depth. b) Expected waveform shape for imaging the crust-mantle boundary. The positive spike (blue waveform) at about 11 seconds implies an increase in velocity with depth, which may indicate the Moho (after Ward et. al., 2014).

MOHO DEPTH FORWARD MODEL

The Mohorovicic discontinuity (Moho, the crust and mantle boundary), produces a positive waveform spike due to changing from a higher velocity mantle to a lower velocity crust (velocity increase with depth). The general equation used to forward model this depth (Zhu and Kanamori, 2000) is:

$$h = \frac{t_{Ps}}{\sqrt{\frac{1}{V_S^2} - p^2} - \sqrt{\frac{1}{V_P^2} - p^2}}$$

The crust-mantle boundary was calculated for both seismometers via this equation, giving a depth of 47.0 km beneath the Raspberry Shake and that of 50.6 km beneath the RSSD.

RESULTS

Below are the raw waveforms, processed radial and tangential waveforms, and receiver functions. The event shown was a 6.5 magnitude earthquake at a distance of 54.1 deg, occuring on February 03 rd , 2022 in northern Peru (Crotwell and Owens, 2005 and Trabant et al., 2012.)

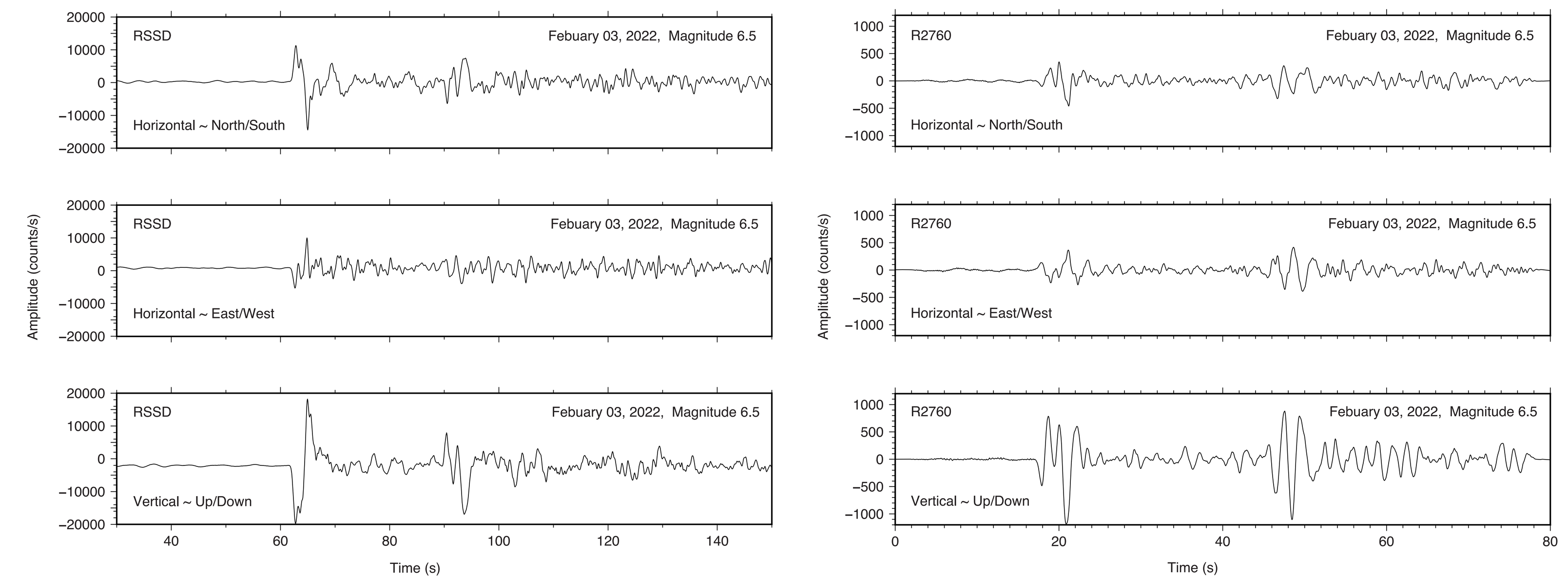

Figure 4. (above, left column) raw waveform data for February 03 rd earthquake of magnitude 6.5 in Peru recorded from the RSSD broadband station. (above, right column) raw waveform data for the same event recorded from the Raspberry Shake seismometer (note: the time axes are referenced to the theoretical P-wave arrivals).

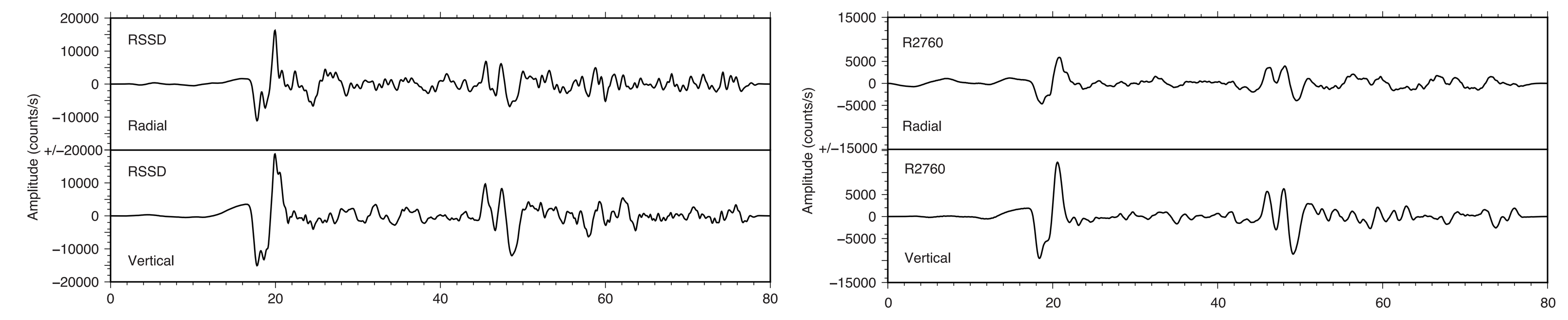

Figure 5. (above, left) radial and vertical waveforms from the February 03 rd earthquake recorded by the RSSD. The horizontals have been rotated to the earthquake reference frame and both components have had the instrument response removed and a bandpass filter applied. (above, right) similar details for the Raspberry Shake.

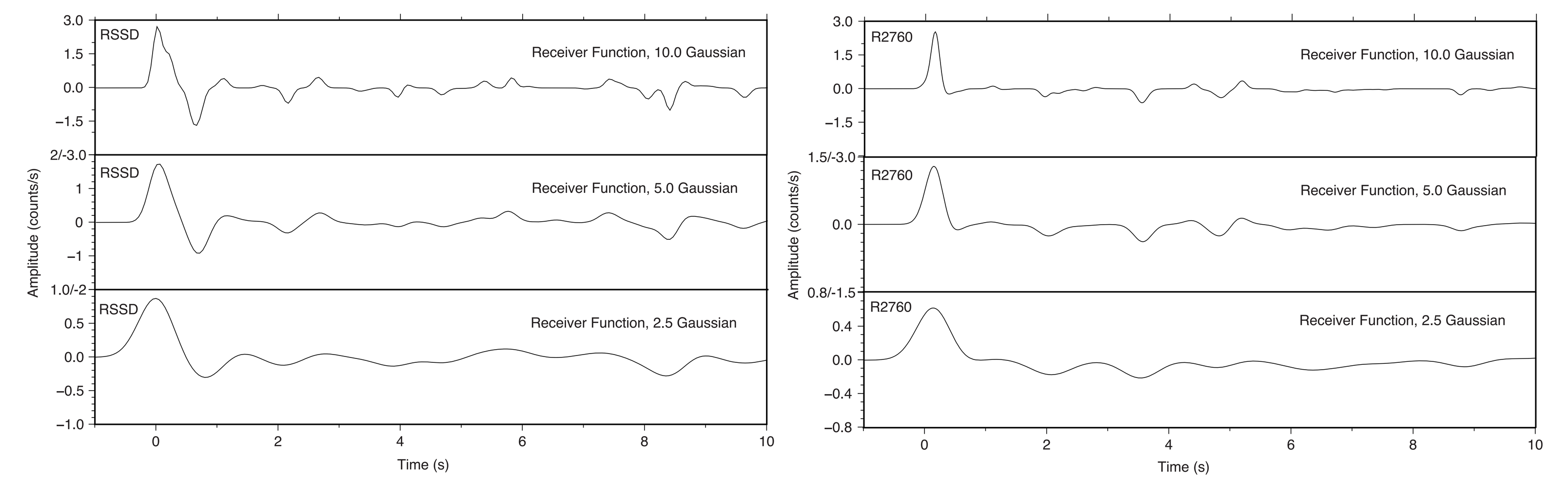

Figure 6. (above, left) receiver function results with 10.0, 5.0, and 2.5 Gaussians applied to the broadband RSSD seismometer. (above, right) receiver functions with the same Gaussians for the Raspberry Shake seismometer. Note what is interpreted as the Moho around 5.2 and 5.6 seconds for the RSSD and R2760, respectively.

ACKNOWLEDGMENTS AND CITATIONS

Thank you to Dr. Kevin Ward, who proposed the research, has taught me everything I know about seismology thus far, and has been a consistently encouraging, patient, and intentional advisor.

Thank you to the Sanford Underground Research Facility (SURF) for allowing us to use their space to deploy our Raspberry Shake seismometer (www.sanfordlab.org.)

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DISCUSSION

The waveforms in figures 4, 5, and 6, collectively suggest that a Raspberry Shake can provide similar results as that of a high grade, advanced seismometer.

The earthquake can clearly be seen in both seismometer records (fig. 4). Because the earth structure below each station is different, the horizontals are not expected to be similar, while the vertical signals are not affected by the subsurface earth structure as much, resulting in little difference between the two station recordings. This is due to the receiver function method, in which the source is on the vertical and the earth response, or conversions, are seen on the horizontals (figs. 5 & 7).

The large amplitude spikes at 5.6 seconds at the broadband and 5.2 seconds at the Raspberry Shake, in the receiver functions, are interpreted as the Moho boundary (figs. 6 & 8). This spike is observed in both the Raspberry Shake and broadband seismometers. These arrival times were used to calculate the crustal thicknesses of 47.0 and 50.6 km for the Raspberry Shake and broadband, respectively.

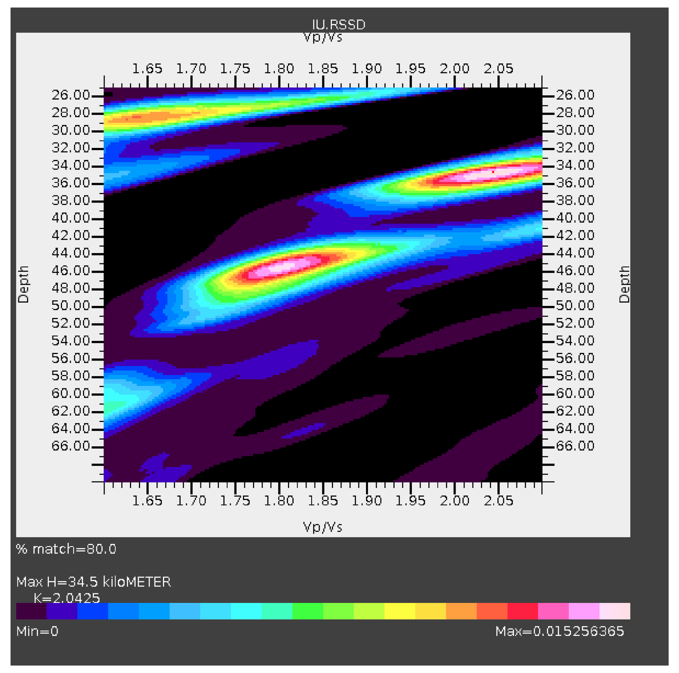


Figure 9. Parameter space for an HK stack of 200 events for the IU RSSD station. Note the two leading models set the crustal thickness (Moho depth) at about either 34 or 46 km. The thickness of the Black Hills in this area is not easily determined (see: ears.iris.washington.edu).

The values are in the acceptable range for the average crustal thickness. However, the thicknesses are dissimilar to those calculated from an HK stack of events for the broadband station (fig. 9). This is because our results are from a single event, whereas the HK stack solutions include >200 events. Presumably, the HK solutions are more robust measurements. However, HK stack solutions still show a bimodal distribution of Moho depths.

Figure 7. An overlay of both seismometers (RSSD in blue and Raspberry Shake in red) tangential and radial components. The radial waveforms are not very similar, as expected. Note the vertical waveforms appear very similar for the two stations even though they are at different distances.

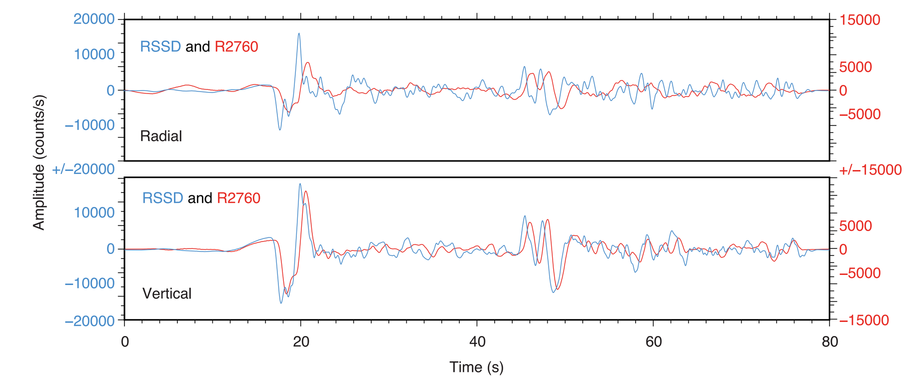
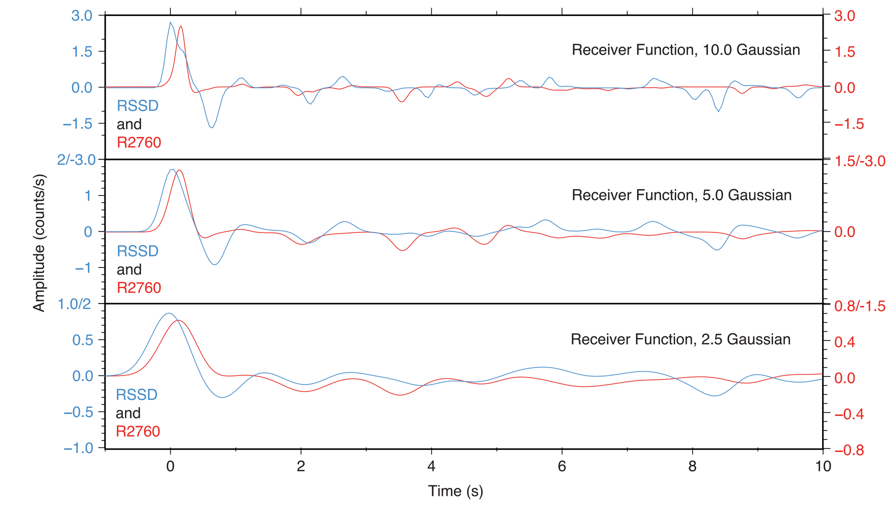


Figure 8. Overlay of all three Gaussians for the RSSD (blue) and R2760 (red) receiver functions. Receiver functions with 5.0 and 10.0 Gaussians most clearly show a positive spike in velocity contrast around 5.2 to 5.6 seconds, with the Raspberry Shake spike occurring earlier. This is interpreted as the Moho.



CONCLUSIONS

This novel and exciting research suggests that Raspberry Shakes have strong potential as instruments capable of more advanced research in the geosciences.

However, more work is needed to statisically and robustly confirm the findings presented here. It is suggested that the following parameters are investigated, which include:

- co-locating the Raspberry Shakes with broadband stations
- changing the study area to a tectonically less complex region
- adding more events to the Raspberry Shake analysis