Low-Cost Resonance Sensing Supporting Landform Structural Health Assessment

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1. INTRODUCTION AND OBJECTIVE

1.1 Introduction

Seismic monitoring techniques have been employed for various structural and geological engineering applications. Ambient vibrations of civil structures have been studied to assess the response of large buildings to lateral loads such as wind and seismic events (Brownjohn, 2003). These same techniques are now being employed for monitoring and characterization of unstable rock slopes. Rock slopes can be classified into two main types of instabilities, depth-controlled and volume-controlled, based on the dynamic behavior recorded using seismic monitoring equipment and modeling methods (Kleinbrod *et al.,* 2019). Measurements of the ambient vibration spectra and directional amplitude of ground motion can be used to identify changes in unstable rock slopes caused by internal damage (Burjánek *et al*., 2018). This research is key to developing accurate predictive models of time-dependent slope failure.

Currently, research is being conducted to better understand the reaction of dynamic natural structures, such as rock arches, to shifting environmental conditions. Seismic measurements show changes in rock masses due to temperature changes and other environmental and anthropogenic inputs (Moore *et al.,* 2016). The vibrational characteristics measured using these techniques are linked to material properties that allow assessment of structural health. Permanent changes in measured resonant frequencies can be related to irreversible damage of these landforms, which may in turn lead to serious hazards and conservation concerns (Starr *et al*., 2015). There is thus growing need for long-term monitoring of these features in order to detect such changes.

Ambient vibration measurements represent a non-invasive and non-destructive method to assess the changing state of health of rock landforms. These measurements can be analyzed for their frequency content to monitor the structural composition of landforms, such as arches and bridges. However, the equipment needed to make such measurements is generally expensive (in the range of ten thousand dollars), and such high cost may inhibit widespread application of the technique. There is potential for a low-cost seismometer, like the Raspberry Shake 3D, to provide accurate ambient resonance measurements for rock health assessment within the means of more organizations and individuals. However, field testing and comparison against a low-noise, broadband seismometer must be conducted in order to assess the capabilities of such a device in this demanding application.

1.2 Objective

To lay the groundwork for more widespread application of geological-structural health monitoring, tests were conducted of the ability of a low-cost seismometer, the Raspberry Shake 3D, to make accurate ambient resonance measurements on natural arches. Data collection was conducted at the Job's Crossing footbridge at the University of Utah, and at three natural arches: Owachomo Bridge and Sipapu Bridge in Natural Bridges National Monument, and Big Arrowhead Arch in White Canyon, Utah. Raspberry Shake vibration data were benchmarked against coeval measurements from a broadband seismometer in order to assess the ability of the Raspberry Shake 3D to make accurate measurements supporting landform health assessment.

2. SENSORS AND METHODS

2.1 Sensors

2.1.1 Raspberry Shake 3D

The Raspberry Shake 3D[a] is a low-cost seismometer based on Raspberry Pi hardware. It contains three, 4.5 Hz orthogonally-oriented geophones. The instrument tested was configured with an all-weather housing, 24-bit digitizer, and GPS timing capability. The sampling rate is preset at 100 Hz and the system has an estimated bandwidth of -3dB points at 0.6 to 34 Hz.

A separate power source, a simple 12 AH lithium-ion battery, was acquired to operate the Raspberry Shake 3D in the field. Deployment of the Raspberry Shake also required the use of a laptop to initiate startup and shutdown of the device through Ethernet connection. The Raspberry Shake device, including necessary power source and laptop, combined for a total weight of approximately 10 pounds (~4.5 kg) housed in a portable field case.

2.1.2 Trillium Compact 20s

The seismometer used to benchmark the Raspberry Shake 3D was a 3-component compact vault seismometer by Nanometrics. The Trillium Compact[b] 20s has a tilt tolerance of 10°, a variable sampling rate set to match the Raspberry Shake, and bandwidth of -3dB at 20 s and 108 Hz. A separate Nanometrics Centaur digitizer with GPS timing and lithium-ion battery were used in all field deployments. Combined total weight was approximately 25 pounds (~11 kg).

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[a] https://manual.raspberryshake.org/_downloads/SpecificationsforRaspberryShake3D.pdf

[b] https://www.nanometrics.ca/sites/default/files/2019-03/trillium_compact_datasheet.pdf

2.2 Methods

The ability for meaningful comparison of data from the Raspberry Shake 3D and the Trillium Compact is dependent on several factors. Three sensors in each device record vibration in the x, y, and z axes. In order to compare data collected by the Raspberry Shake, both sensors must be co-located on the structure being assessed, leveled, aligned to magnetic north, and synchronized in time. Improper alignment and leveling will result in differences in the orientation of movement recorded between the two sensors. Furthermore, vibrational data will not match if sensors are not co-located on each arch, as modal amplitude and polarization attributes are sometimes strongly dependent on location. Precise UTC timing is set using a GPS receiver on both devices to allow coeval segments of data to be compared. Without this proper setup, it is not possible to compare data accurately.

In the field, the tests proceeded as follows (Figure 1):

i. Co-locate seismometers near center of rock arch
ii. Level and orient each sensor to magnetic north
iii. Place GPS timing receiver in location with (southerly) view of sky
iv. Initiate startup sequence for each instrument
v. Ensure sensors are properly powered on and collecting data
vi. Cover sensors with a box or bucket to minimize wind contact
vii. Note experiment start time (UTC and local time)
viii. Vacate area to minimize anthropogenic vibrations
ix. Allow sensors to gather data for desired timeframe

The Job’s Crossing footbridge on the University of Utah campus was monitored for approximately 30 minutes several weeks prior to rock arch testing. Owachomo Bridge was monitored with both devices for 13.5 hours overnight, while Sipapu Bridge and Big Arrowhead Arch were monitored using both devices for approximately two hours each. Foot traffic and wind during testing at the footbridge were noted. Wind and rain occurred during measurements on Owachomo and Sipapu bridges and was also noted along with the time of rain. Conditions at Big Arrowhead Arch were nominally still and clear. Photos of each arch are shown in Appendix 1.

Figure 1. Deployed instruments covered using a box and a bucket to minimize noise from wind and rain. Trillium Compact digitizer and accessories are located in the blue case, while the Raspberry Shake is powered by a small battery in the gray case.

Data processing was performed according to normal methods. Data blocks from each sensor were precisely trimmed to concurrent intervals. The mean and trend of raw seismic data were removed, and the output converted from instrument counts to velocity using the appropriate scalar conversion factor: 3E9 counts/m/s for the Trillium Compact at the selected gain, and 3.60E8 counts/m/s for the Raspberry Shake 3D. Results are visualized as velocity power spectra, with power in decibel units relative to 1 m/s. For comparison, we show in Appendix 2 (personal communication: P. Geimer) all arch data separately processed with instrument response removed using manufacturer-supplied pole-zero information, converted to acceleration, rotated to arch perpendicular and parallel orientation, and compared to the updated low-noise model from Wolin & McNamara (2020).

3. DATA

3.1 Job’s Crossing Footbridge

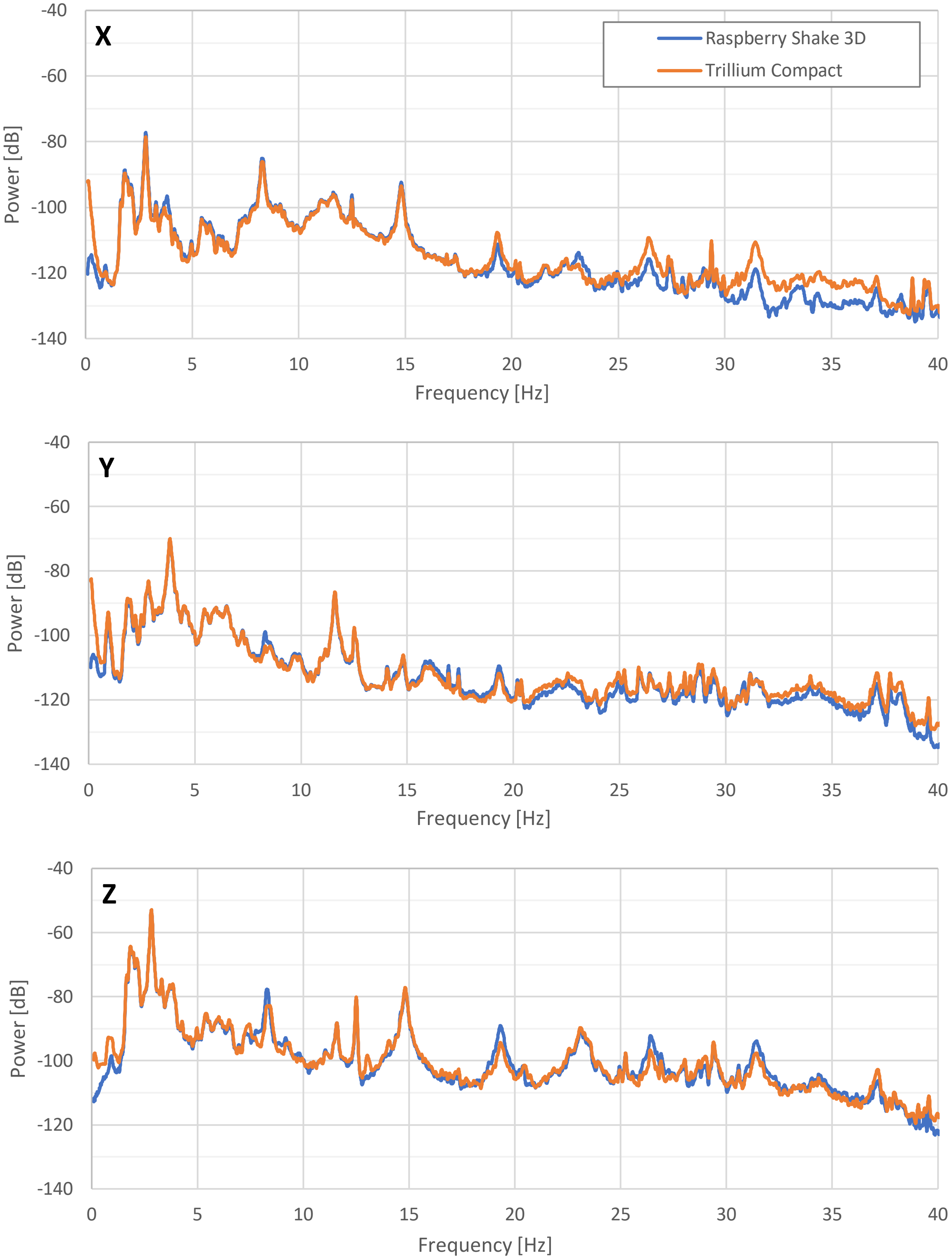

Figure 2. Job’s Crossing footbridge power spectra comparison, in decibel units relative to 1 m/s.

3.2 Owachomo Bridge

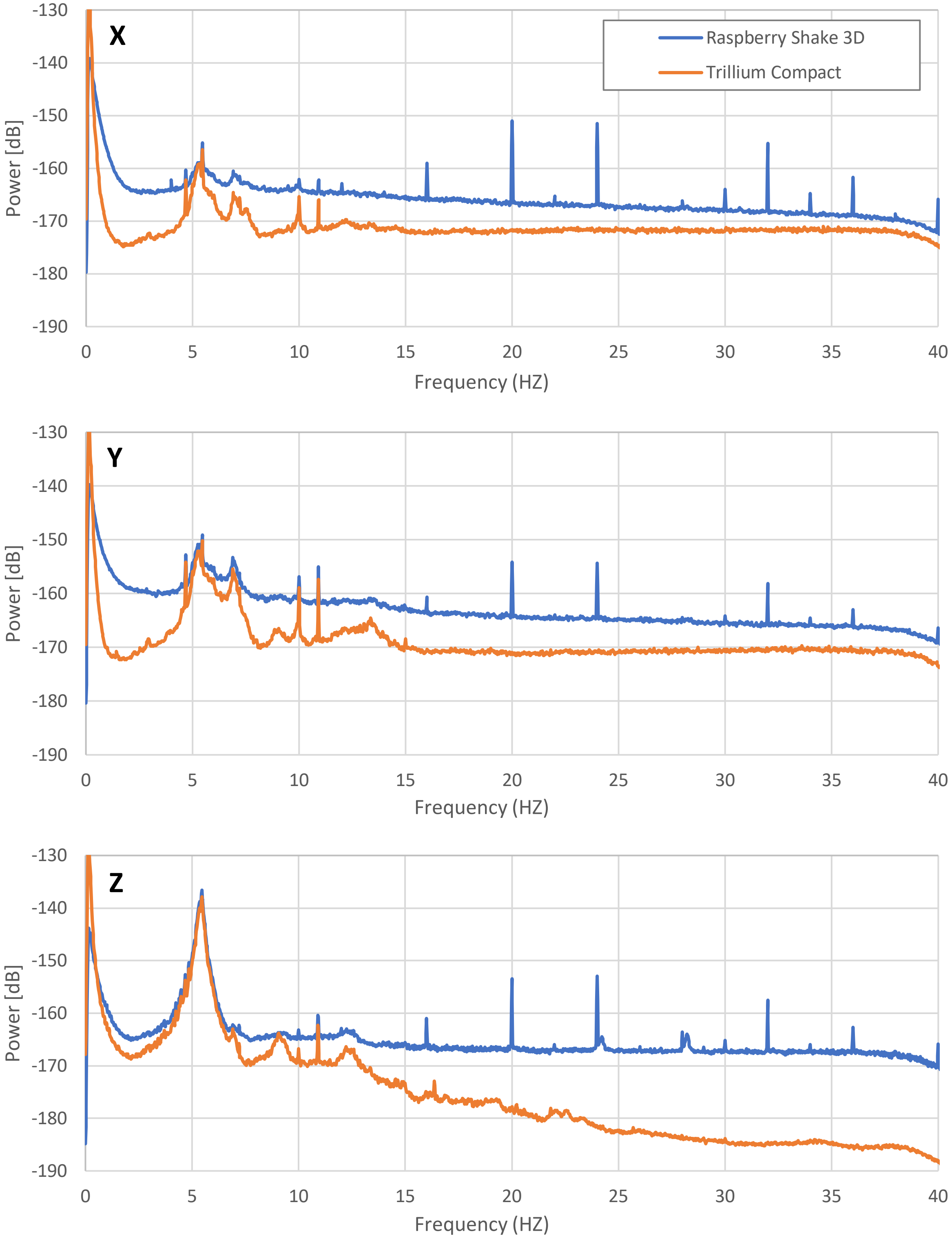

Figure 3. Owachomo Bridge power spectra comparison, in decibel units relative to 1 m/s.

3.2 Sipapu Bridge

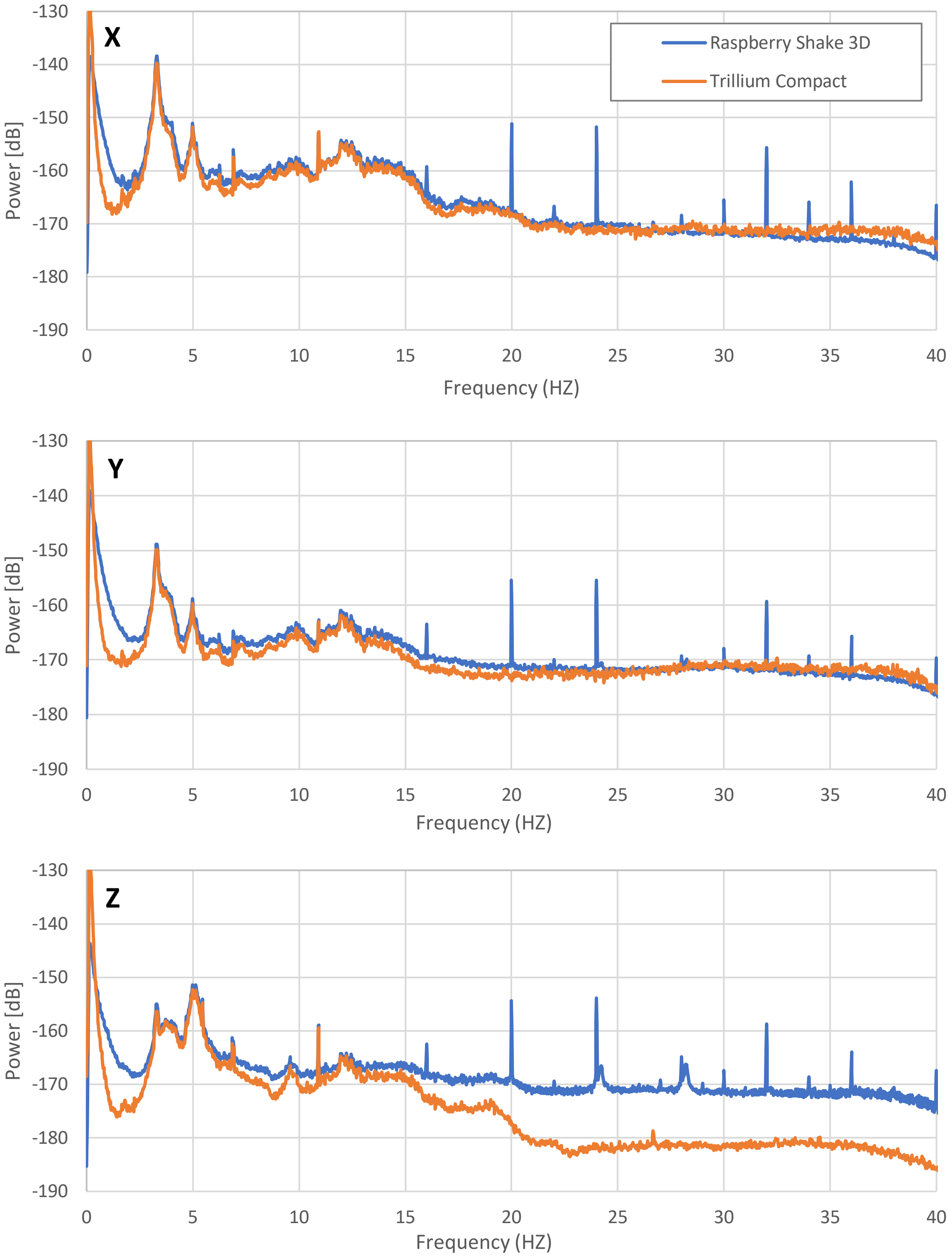

Figure 4. Sipapu Bridge power spectra comparison, in decibel units relative to 1 m/s.

3.3 Big Arrowhead Arch

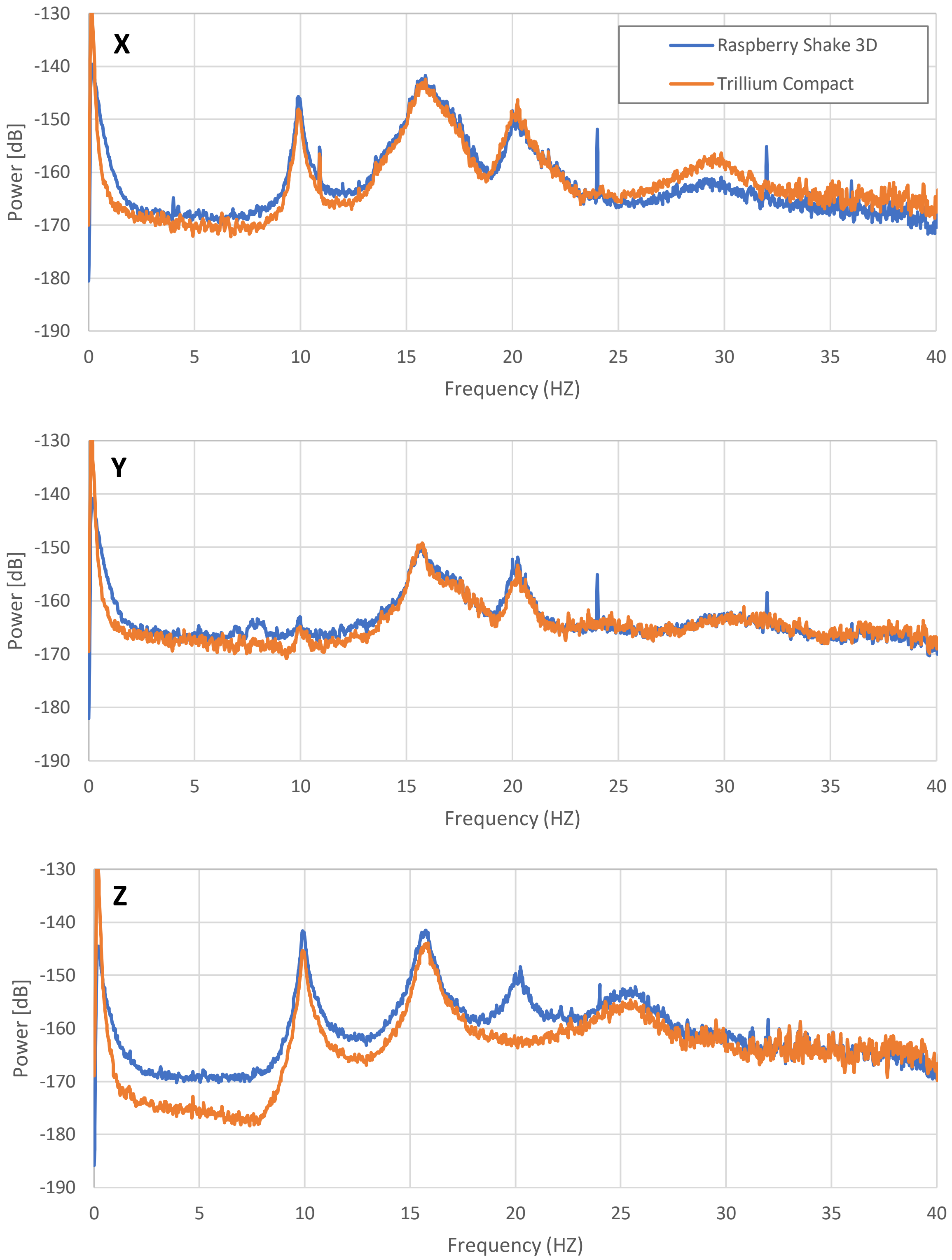

Figure 5. Big Arrowhead Arch power spectra comparison, in decibel units relative to 1 m/s.

4. RESULTS & DISCUSSION

Data from both instruments were compared with velocity power spectra. Peaks in each data set represent resonant frequencies of the feature. Peaks measured by the Raspberry Shake 3D closely match those measured by the Trillium Compact in all but one noticeable case on the vertical component of Big Arrowhead Arch (Figure 5). This is potentially due to narrowness of the arch and inability to precise co-locate the instruments. The instruments were roughly 0.5 m apart, which can lead to different modal displacements on a small feature like Big Arrowhead Arch. Several peaks are present in data from the Raspberry Shake that are not present in data from the Trillium compact. These peaks are all at frequencies greater than 15 Hz and have a very narrow width. These may result from self-noise of the instrument, as most cultural noise sources are unlikely in these remote locations.

The best fit is seen in data gathered on the Job's Crossing footbridge. The bridge had high levels of excitation during deployment and the data from the Raspberry Shake closely match that from the Trillium Compact. Several larger deviations do occur at higher frequencies (above 25 Hz), however. Compared to previous tests done at this same location, results were greatly improved by covering the Raspberry Shake with a box to shield the instrument from wind. This proved effective in reducing noise levels at all frequencies.

On Owachomo Bridge, the longest bridge measured, the fit of the spectral peaks closely matched between instruments, but the power spectra differ by ~10 dB or more at some frequencies. It could be that the length of the bridge and subsequent low frequency vibrations challenged the Raspberry Shake's ability to make accurate spectral measurements without relatively high levels of excitation from wind during quiet overnight hours

Several challenges arose during deployment of the Raspberry Shake 3D. Compared to the Trillium Compact, the Raspberry Shake has a relatively large footprint, making leveling difficult on rough terrain. This could potentially cause issues in future sensor deployments where level terrain is minimal, but is in turn easily addressed through case modifications. Another challenge is the Raspberry Shake startup and shutdown processes. The requirement of an on-site computer to initiate both startup and shutdown of the instrument lengthens the deployment process and can be difficult in inclement weather. Rain during teardown on Owachomo Bridge and setup on Sipapu Bridge, for example, proved challenging while attempting to shield the computer from water.

5. CONCLUSION

The Raspberry Shake 3D has several limitations. Relatively inconvenient deployment, larger footprint, and higher levels of self-noise could potentially limit the use of the device in some applications. However, in structural health assessment applications for large rock arches, as tested here, the Raspberry Shake appears to be a viable option supporting low-cost resonance sensing. The measured natural frequencies closely matched those measured by an industry-leading broadband seismometer. With some modifications for field deployment, the Raspberry Shake could be improved, extending its usefulness for a variety of settings and measurement purposes.

DATA AVAILABILITY

Data generated in this study are available for download from our group website, and are reusable with attribution (CC BY-SA): geohazards.earth.utah.edu/data/CR_archdata.zip. Site and measurement metadata are found in Appendix 3.

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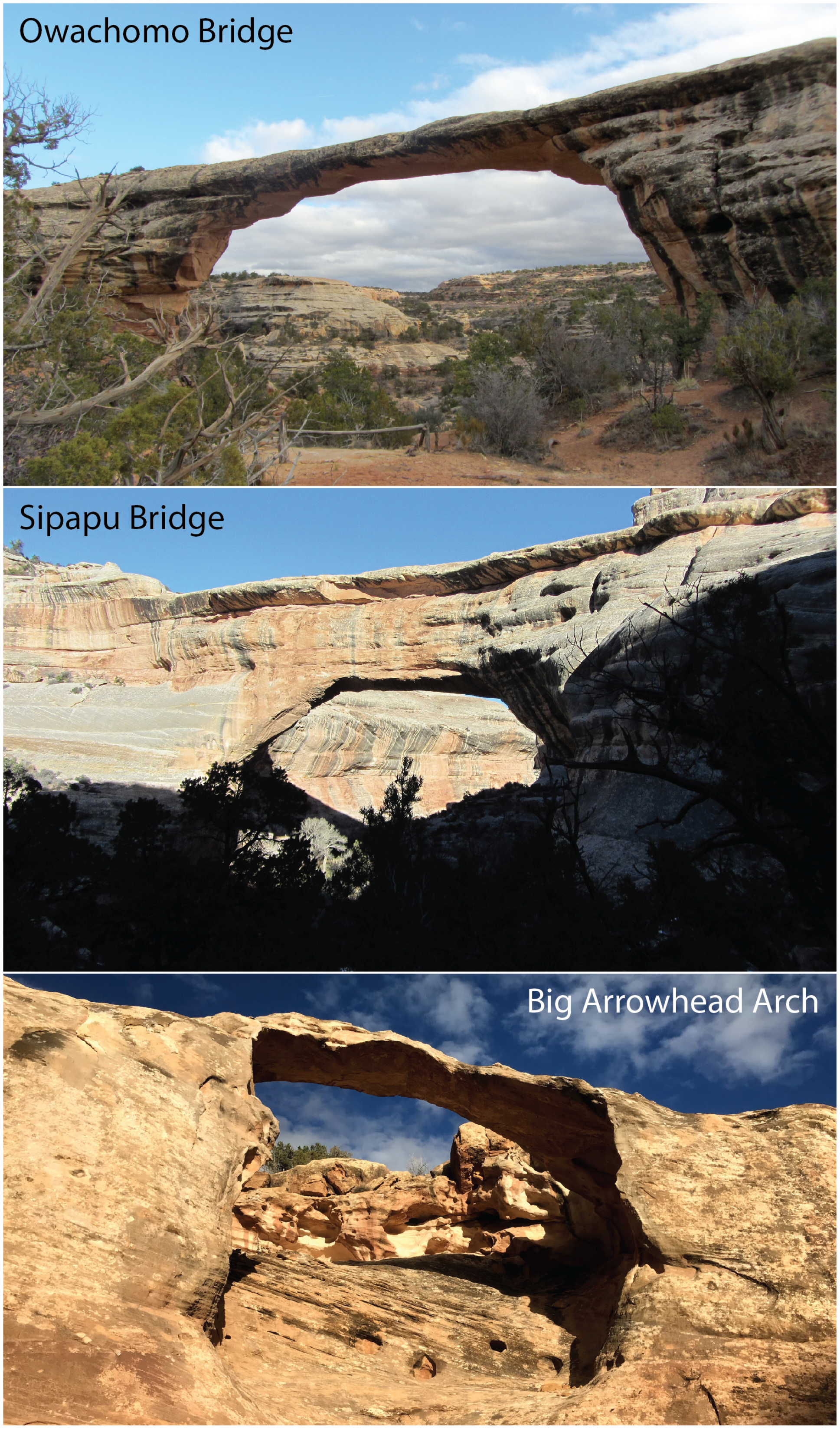
Kleinbrod U. Burjánek J., and Fäh D. 2019. Ambient vibration classification of unstable rock slopes: A systematic approach, *Eng. Geol.* **249**, 198–217.

Moore J. R. Thorne M. S. Koper K. D. Wood J. R. Goddard K. Burlacu R. Doyle S. Stanfield E., and White B. 2016. Anthropogenic sources stimulate resonance of a natural rock bridge, *Geophys. Res. Lett.* **43**, 9669–9676.

Starr A. M. Moore J. R., and Thorne M. S. 2015. Ambient resonance of Mesa Arch, Canyonlands National Park, Utah, *Geophys. Res. Lett.* **42**, 6696–6702.

Wolin, E., and McNamara, D. E. 2020. Establishing high-frequency noise baselines to 100 Hz based on millions of power spectra from IRIS MUSTANG, *Bull. Seis. Soc. Am.* **110**, 270-278.

APPENDIX 1: Overview photos of study sites (all photos Clayton Russell). Sensors at arch center.



APPENDIX 2: Instrumented-corrected ambient vibration acceleration power spectra, rotated to arch perpendicular and parallel orientations, and plotted together with high and low noise models (personal communication: P. Geimer).

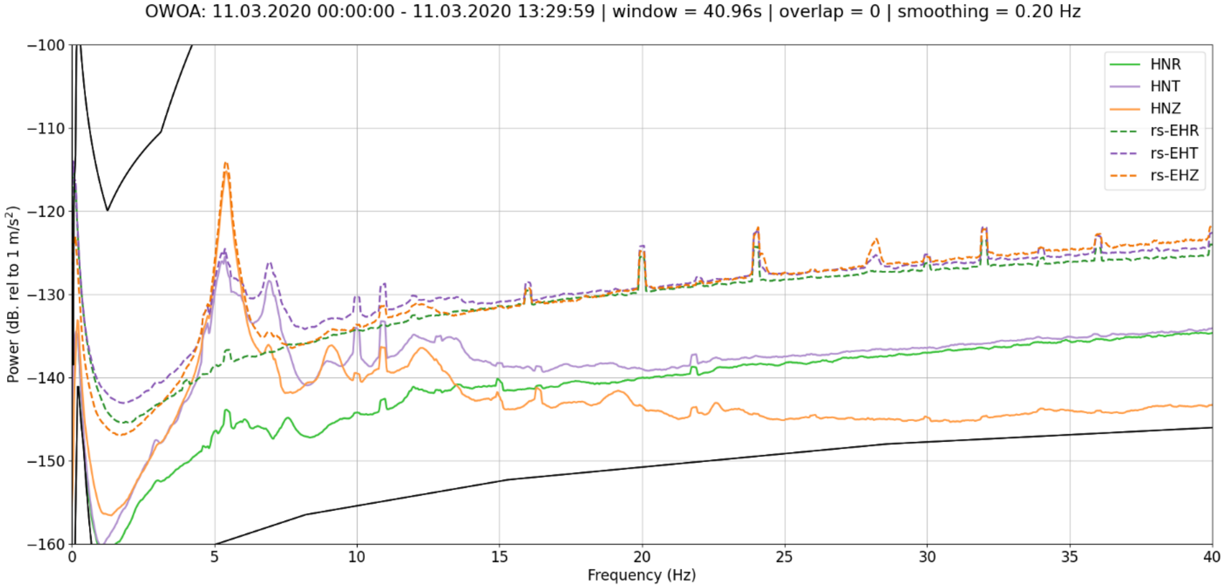


Figure A1. Owachomo Bridge (rs = Raspberry Shake 3D)

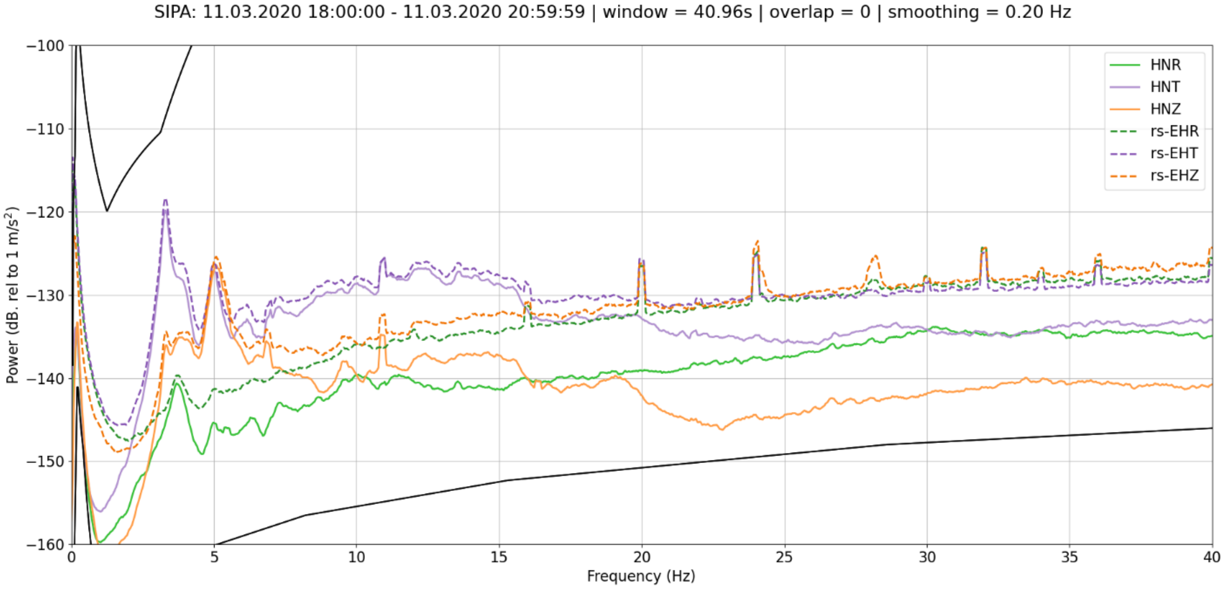


Figure A2. Sipapu Bridge (rs = Raspberry Shake 3D).

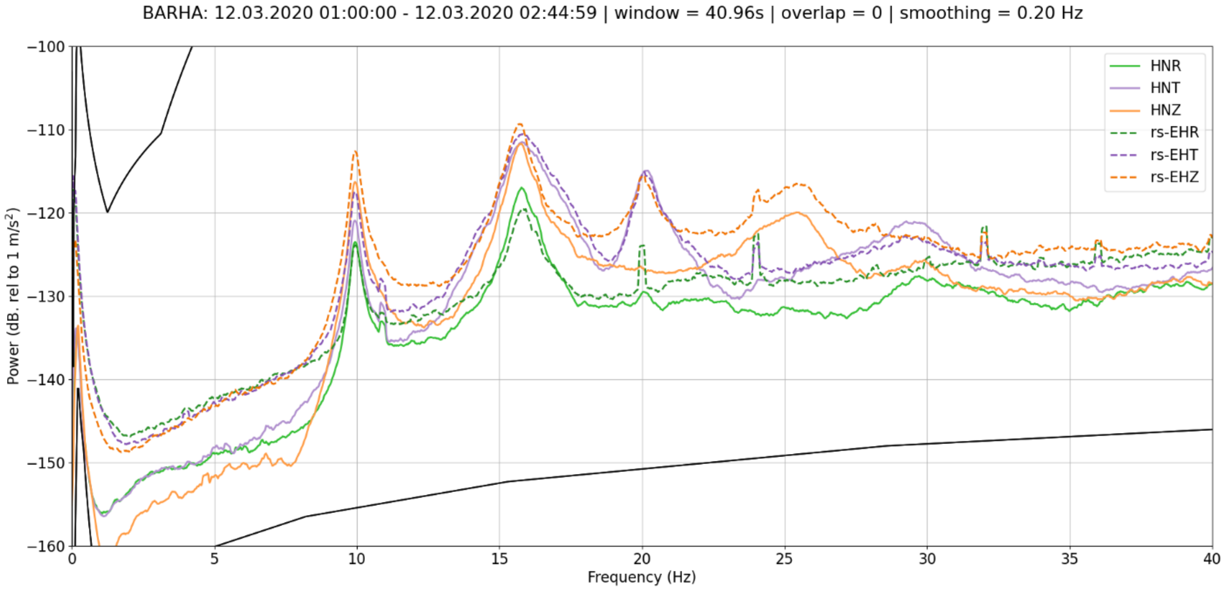


Figure A3. Big Arrowhead Arch (rs = Raspberry Shake 3D).

APPENDIX 3: Site and measurement metadata for natural arches assessed in this study.

Site Details					***Measurement Metadata***				
Name	**Latitude (°N)**	**Longitude (°W)**	**Span (m)**	**Orientation (° from MN)**	**Start Date (UTC)**	**Start Time (UTC)**	**Duration (hh:mm)**	**Mean Air Temp (°C)**	**Mean Rock Temp (°C)**
Owachomo Bridge	37.5823	110.0141	55	69	2020-03-11	0:00:00	13:30	6.8	7.2
Sipapu Bridge	37.6161	110.0113	69	164	2020-03-11	18:00:00	03:00	9.1	11.1
Big Arrowhead Arch	37.7396	110.2708	7	150	2020-03-12	0:01:00	01:45	13.4	13.4