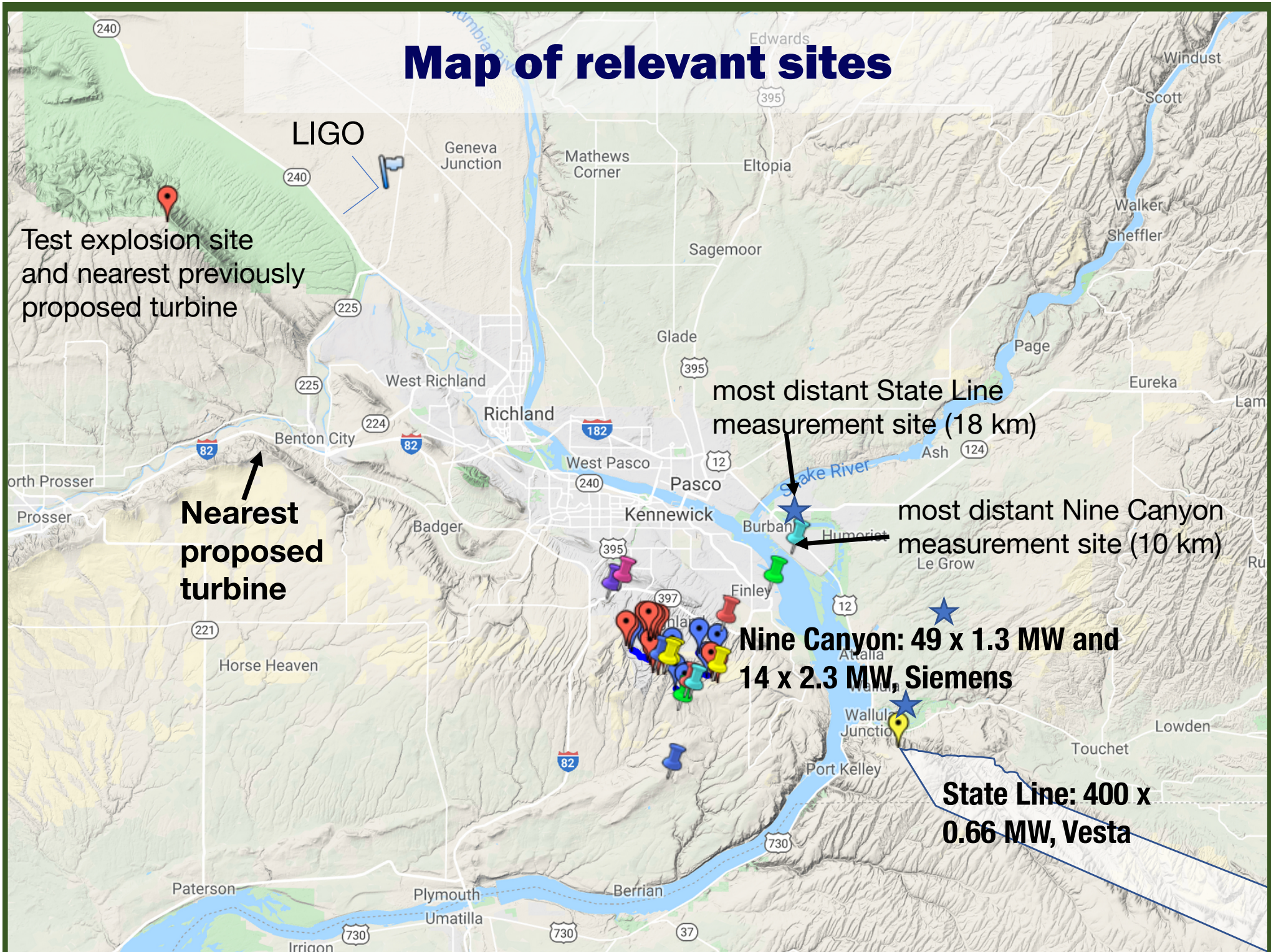


Predicting seismic noise from wind farms for a current proposal

Robert Schofield, LIGO-T1900746-v1

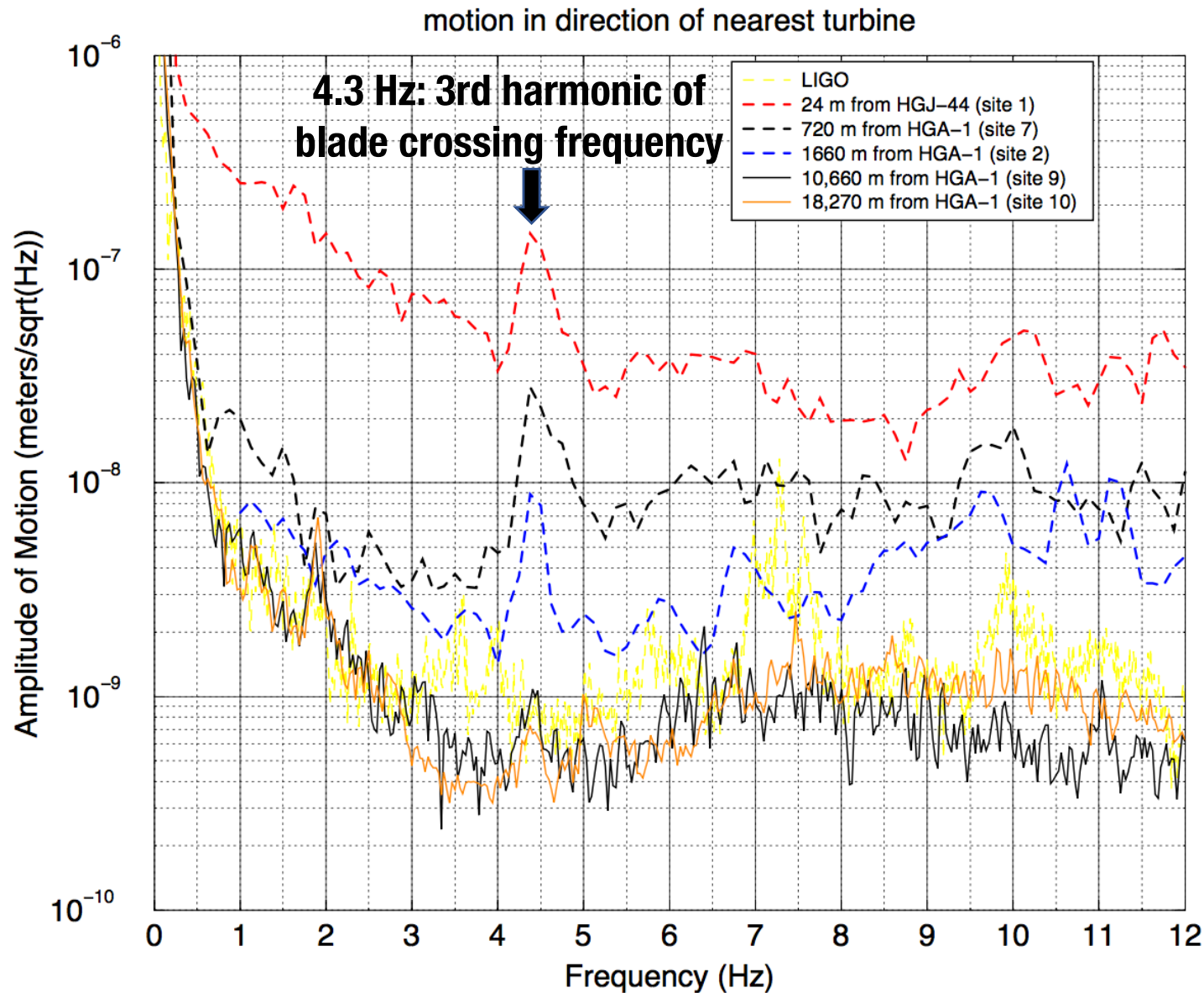


Map of relevant sites



Sample of seismic measurements around State Line wind farm (State Line report, T020104-x0)

Horizontal Motion at Increasing Distances



(State Line report, T020104-x0)

Table 1: Peaks that decreased in frequency at low wind velocities

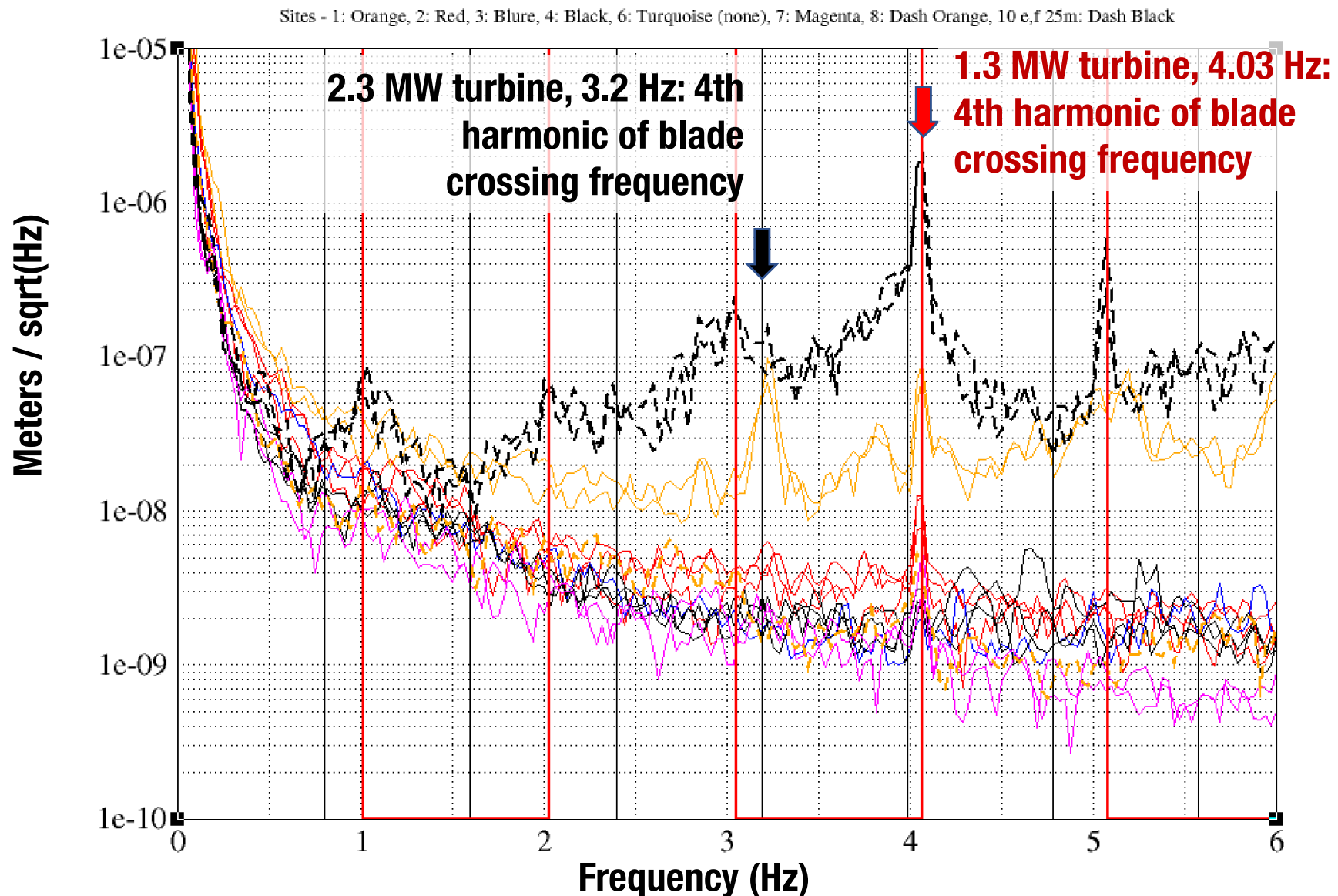
Approximate frequency at high wind velocity (Hz)	Comments
0.49	rotation frequency of turbine (29 rpm)
1.47	3rd harmonic of rotation frequency (blade pass frequency)
2.95	6th harmonic
4.34	9th harmonic (largest peak relative to background)
5.88	12th harmonic
7.35	15th harmonic
Higher harmonics appeared to be present but were difficult to distinguish	
30	generator frequency

Table 2: Fixed-frequency peaks

Peak Frequency (Hz)	Comments
0.669	
11	broad peak; 5 - 17 Hz

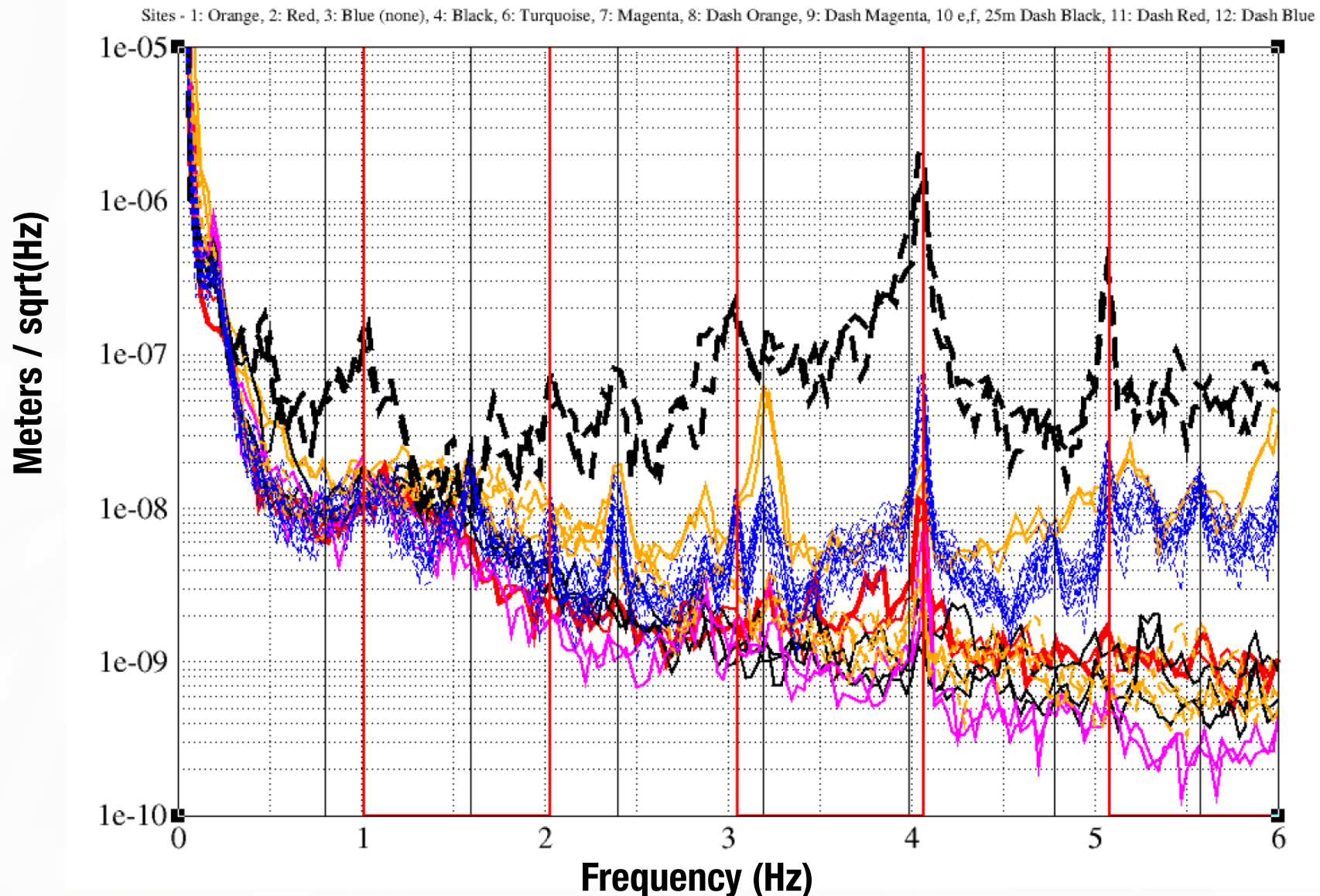
Sample of newer seismic measurements around Nine Canyon wind farm

Horizontal good data



Vertical amplitude similar to radial horizontal amplitude

Vertical good data



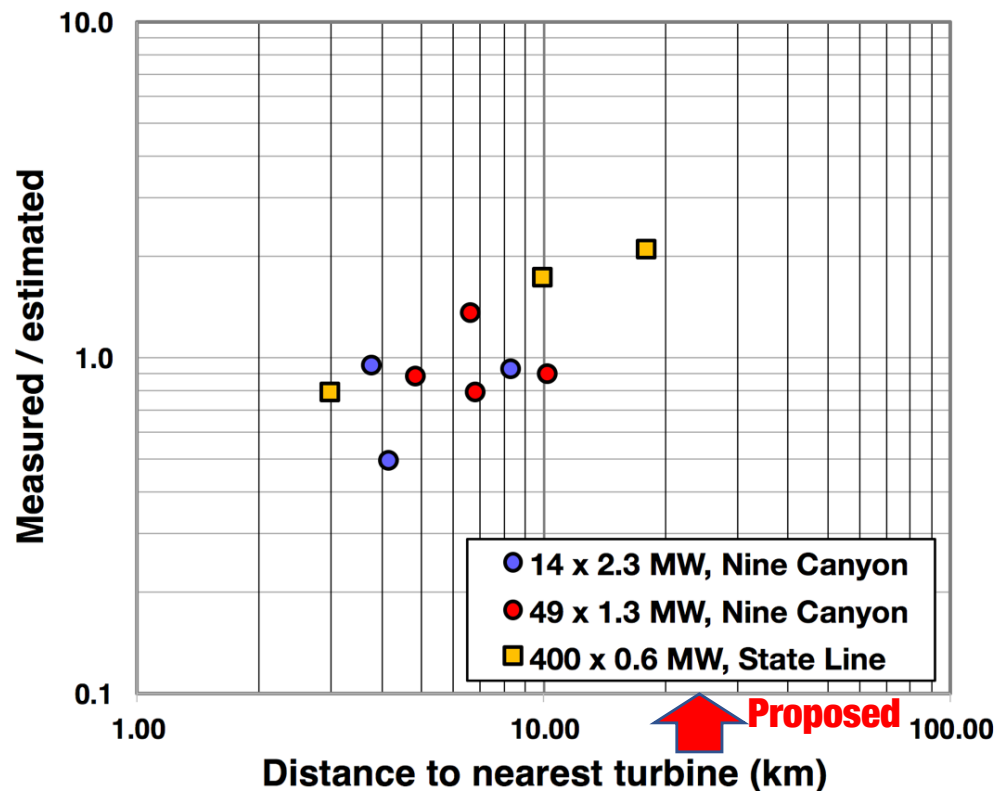
Prediction of largest peak at harmonic of blade crossing (expected in the 2.5 - 5 Hz region) for 2019 proposed wind farm

Prediction details	Prediction (nm/sqrt(Hz))	SD (nm/sqrt(Hz))	5% chance of exceeding (nm/sqrt(Hz))
1/r model using estimated mean distance	2.35E-01	1.06E-01	4.27E-01
1/r model with all turbines at nearest location (upper limit)	3.89E-01	1.75E-01	7.06E-01
1/sqrt(r) model using estimated mean distance	4.38E-01	1.92E-01	7.86E-01
1/sqrt(r) model with all turbines at nearest location (upper limit)	5.64E-01	2.47E-01	1.01E+00

Compare to 1 nm/sqrt(Hz) at LH0 in 1-7 Hz band

Uncertainty determined from scatter of measurements for 7 sites, 3km or further from 2 farms with 3 turbine types

1/r model



1/r

0.42

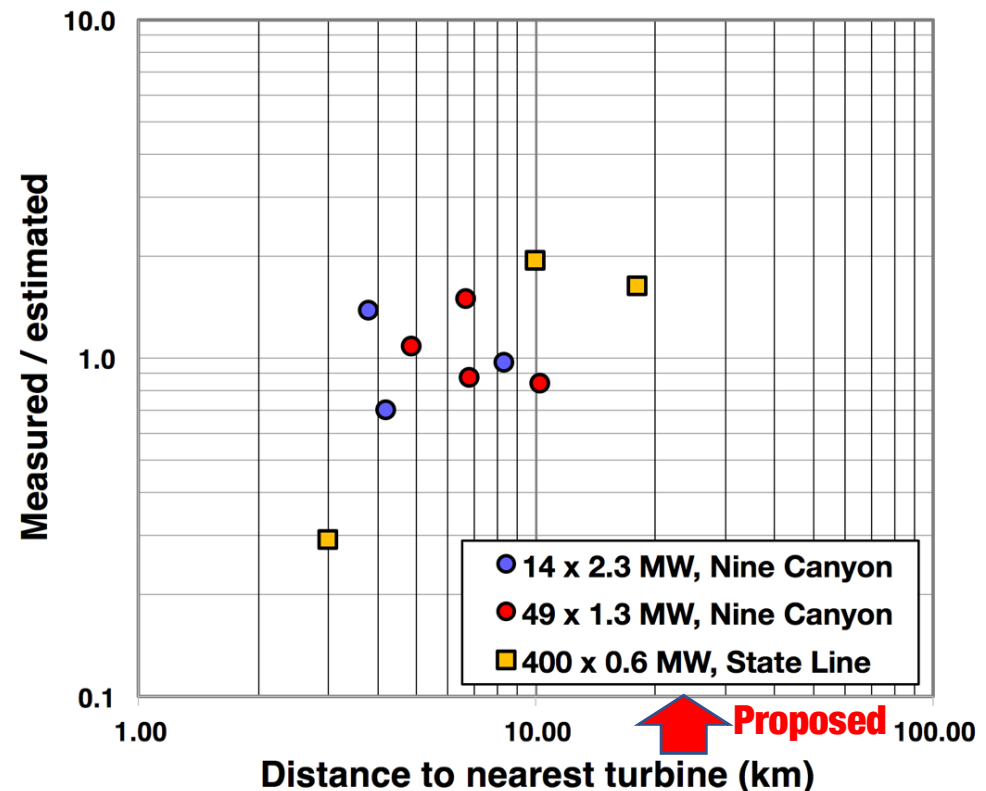
0.30

FOM: standard deviation of log of values

1/r is still slightly better

though not when SL is left out

1/sqrt(r) model



1/sqrt(r)

0.54

0.27

Models used to make calculations are from State Line report, T020104-x0, prepared for BPA

Seismic Measurements at the Stateline Wind Project And A Prediction of the Seismic Signal that the Proposed Maiden Wind Project Would Produce at LIGO

Robert Schofield, Ph.D., University of Oregon

Summary

Measurements of ground vibration were made at 10 sites around the Stateline Wind Project. The 3-bladed turbines produce seismic peaks mainly at multiples of 3 times their rotation frequency. The strongest peak (4.3 Hz) was detected at a site about 18 km from Stateline where it reached 0.7 nm/sqrt(Hz) of ground motion. Signal amplitudes were fit best with a $1/r$ attenuation model, suggesting that the propagation path is partly through the air. The signal level that the Maiden project (both phases) would produce at the LIGO site (about 20 km distant) was estimated, with a high degree of uncertainty, to be about equal to the present background level at LIGO.

The accuracy of the predictions could be improved by measurements at a site that uses the turbines planned for the Maiden project. For example, it is possible that the rotation rate of the Maiden turbines would vary to a degree that the peaks from the individual turbines did not “pile up” as much at a particular frequency. Measurements at a site that employs the proposed Maiden turbines are recommended.

Motivation

The Laser Interferometric Gravitational wave Observatory (LIGO) on the Hanford reservation is concerned that the seismic signal from the Maiden wind project may shake precisely positioned mirrors. Perhaps the greatest danger to LIGO is that one (or more) of the potential peaks from the Maiden site match the frequency of a resonance in the seismic isolation system. An example of such an unlucky coincidence is a 2.3 Hz peak (from cooling tower fans at a nearby nuclear power plant) that exceeds the surrounding background at LIGO by only a factor of about 5. Because it matches a seismic isolation system resonance, this peak is responsible for nearly 25% of the r.m.s. of the frequency noise in one interferometer. A similar signal from the Maiden Wind Project could create a need for abatement modifications.

Measurements

Ground surface propagation model

(State Line report, T020104-x0)

The 1/sqrt(r) with linear attenuation model

The amplitude of the signal from a single turbine at a distant location, A_{far} , was assumed to be related to the amplitude at a location closer to the turbine, A_{near} , by:

$$A_{far} = A_{near} \sqrt{\frac{R_{near}}{R_{far}}} e^{-\frac{\pi f}{Qv}(R_{far} - R_{near})}$$

where R_{near} and R_{far} are the distances from the source to the near and far locations, respectively, Q is a factor giving the non-geometrical attenuation of the wave with distance travelled, f is the frequency of the signal and v is its propagation velocity. This formula is applicable to the degree that the waves are surface waves radiating out from the source uniformly (e.g. that there are no reflectors etc.).

Values of $v \sim 500$ m/s and $Q \sim 68$ have been measured near LIGO for frequencies of about 5 Hz. For the calculations here, Qv was assumed to be 34,000 m/s.

Q of 68 is high compared to published values, so I do not attempt to improve prediction from this model by arbitrarily increasing Q.

Alternate models

(State Line report, T020104-x0)

The 1/sqrt(r) model

This model is a variant of the above model, with no linear attenuation:

$$A_{far} = A_{near} \sqrt{\frac{R_{near}}{R_{far}}}$$

The 1/r model

This model is typical of propagation through a volume (as opposed to along a surface), such as air, in which there is minimal linear attenuation:

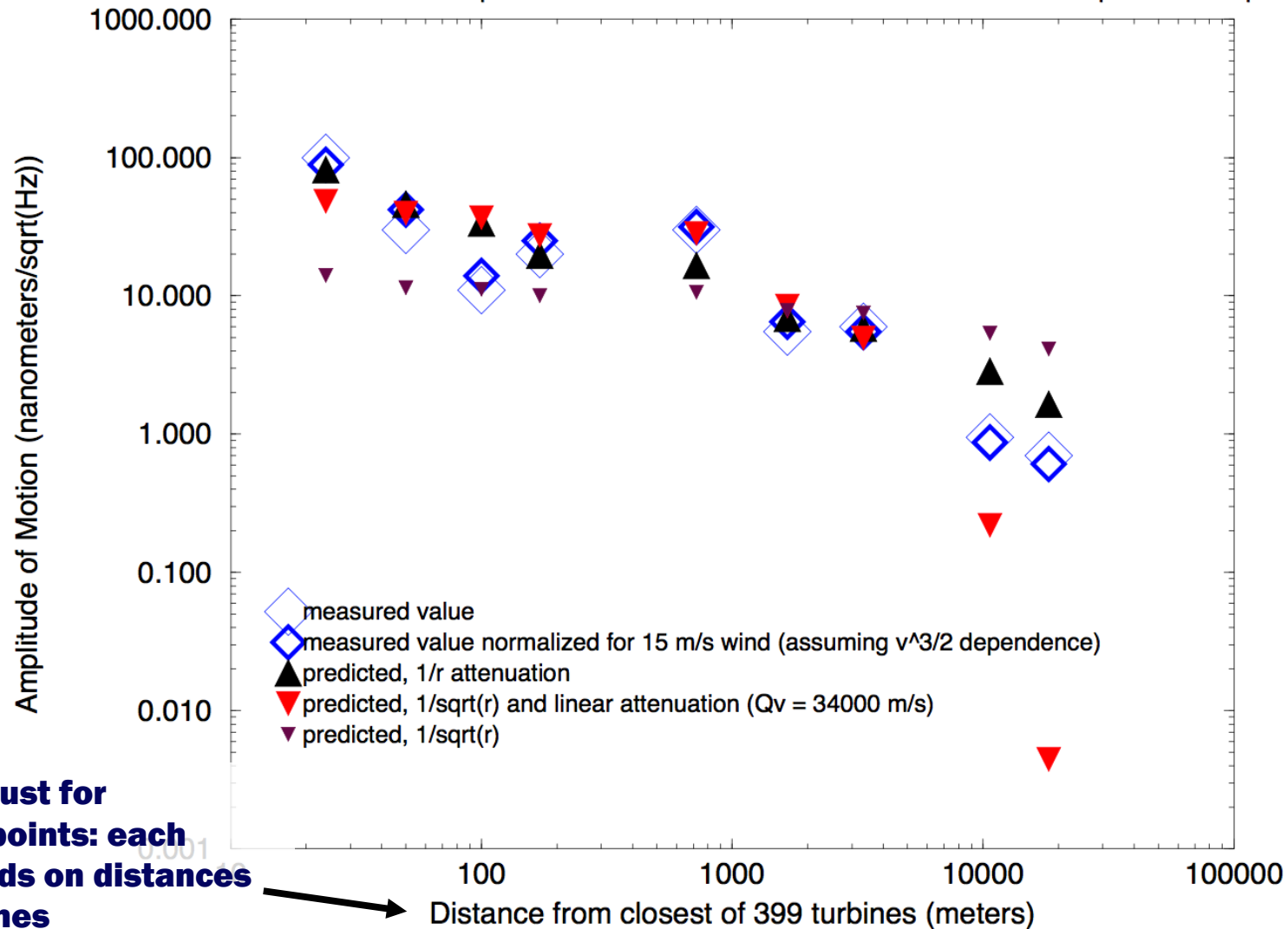
$$A_{far} = A_{near} \frac{R_{near}}{R_{far}}$$

Comparison of State Line measurements to 3 models

Figure 8.

Amplitude of the 4.3 Hz Peak at Various Sites

Note: measurements and predictions contain contributions from 399 turbines up to 11 km apart



Prediction

(based on State Line report T020104-x0, updated with Nine Canyon data)

This constant is updated so that the geometrical mean of all measured/predicted remains equal to 1

$$A_{LIGO} = A_{1SL} \left(\frac{v}{15} \right)^{1.5} \sqrt{N_M} \sqrt{\frac{P_M}{P_{SL}}} \frac{r_1}{R_{MtoLIGO}}$$

Diagram illustrating the prediction formula for A_{LIGO} based on State Line report T020104-x0, updated with Nine Canyon data. The formula is:

$$A_{LIGO} = A_{1SL} \left(\frac{v}{15} \right)^{1.5} \sqrt{N_M} \sqrt{\frac{P_M}{P_{SL}}} \frac{r_1}{R_{MtoLIGO}}$$

The variables in the formula are defined by the following boxes:

- wind velocity (used 15 m/s)**: v
- number of turbines**: N_M
- turbine max power**: P_M
- effective distance, LIGO to turbines (also used sqrt(r) model)**: r_1

The constant A_{1SL} is updated so that the geometrical mean of all measured/predicted remains equal to 1.

Where A_{1SL} is the amplitude of the signal from 1 stateline turbine at 18 km (0.038 nm/sqrt(Hz)), v is the wind speed in m/s (15), N_M is the number of proposed turbines at Maiden (330), P_M is the power rating of the turbines at Maiden (1.5 MW), P_{SL} is the power rating of the turbines at State-line (0.66 MW), r_1 is the distance to the turbine producing the A_{1SL} signal (18 km), and $R_{MtoLIGO}$ is the distance from the Maiden site to LIGO (all Maiden turbines were assumed to be at a distance of 20 km). The estimate produced in this manner was 0.94 nm/sqrt(Hz), close to the current LIGO level (about 0.8 nm/sqrt(Hz)) at this frequency.

Calculation is modified to sum individual contributions in quadrature when location of each turbine is known

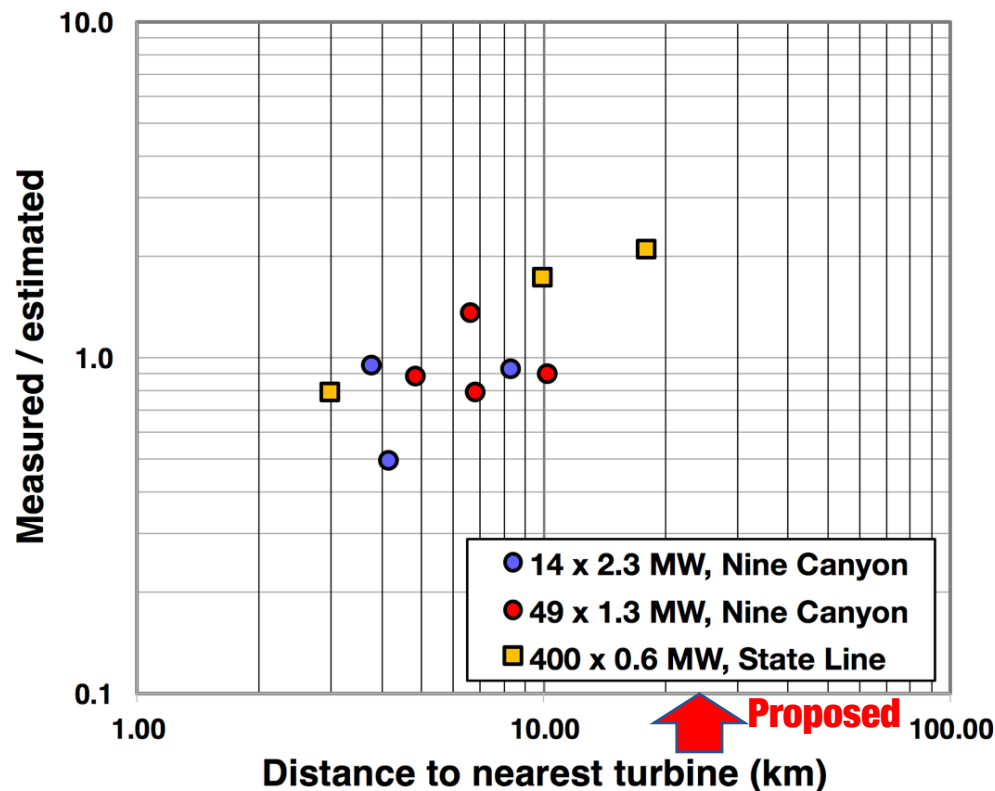
Prediction of largest peak at harmonic of blade crossing (expected in the 2.5 - 5 Hz region) for 2019 proposed wind farm

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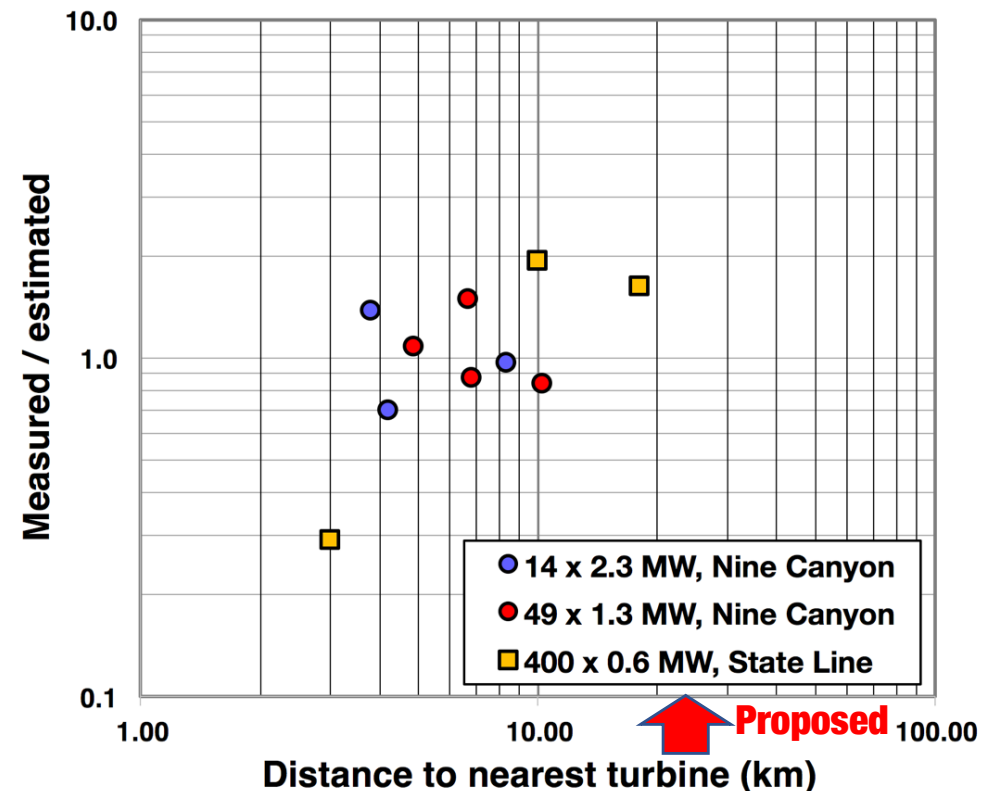
0.30

FOM: standard deviation of log of values

1/r is still slightly better

though not when SL is left out

1/sqrt(r) model



1/sqrt(r)

0.54

0.27

Other questions

- 1) Can ground propagation alone account for signal? **Unlikely**
- 2) What is the ground propagation velocity of the emphasized harmonic signal? **About the speed of sound**
- 3) What accounts for the emphasized harmonic? **Best guess: frequency at which ground propagation velocity matches speed of sound**
- 4) Will infrasound coupling to buildings shake them and significantly increase ground motion? **I don't think so**

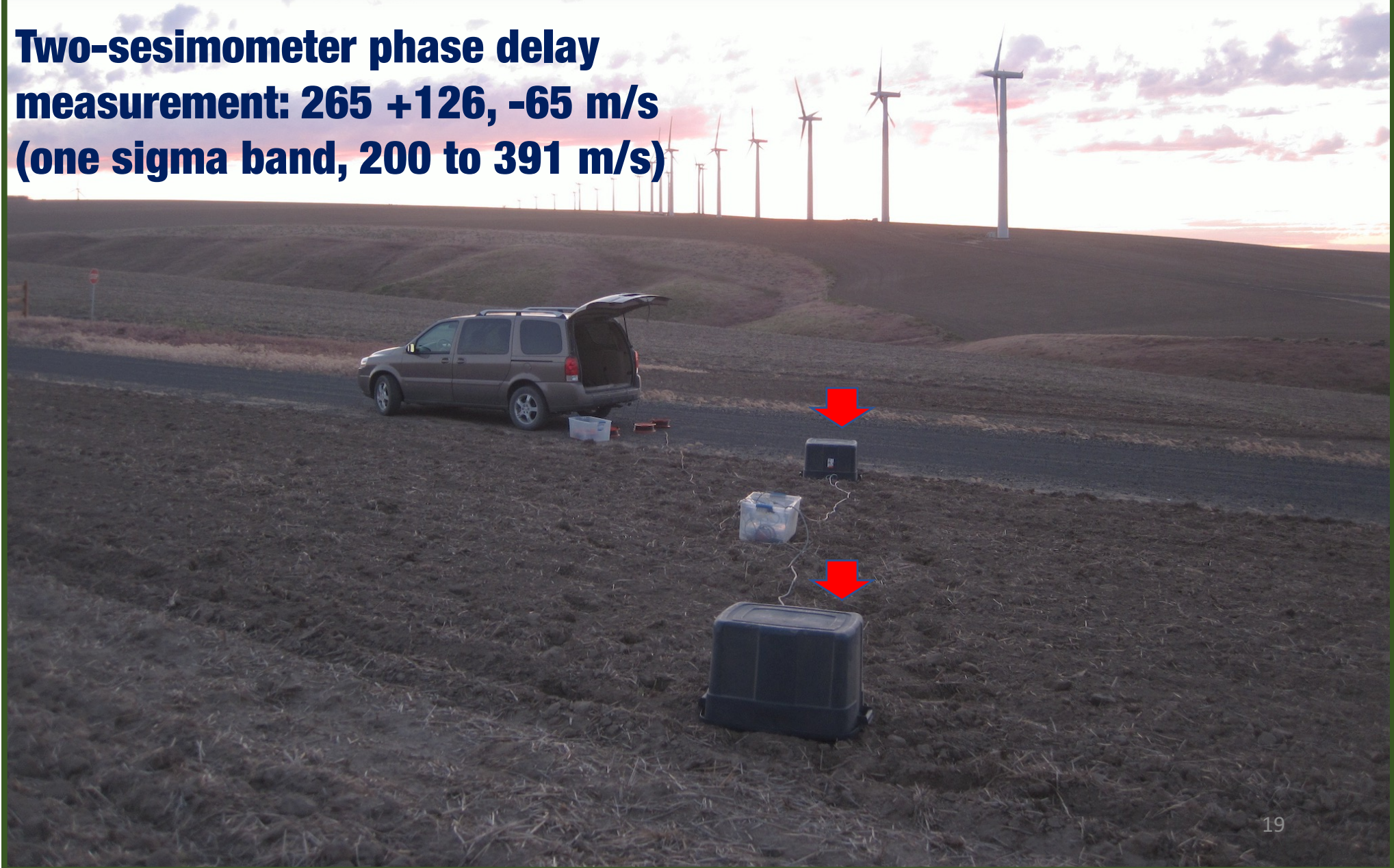
1) Can ground propagation alone account for the signal?

Several non-blade crossing peaks measured on and near the towers at both farms attenuated with distance faster than the peaks seen far away. For example, a peak at 2.87Hz dropped by 65 while the peak at 3.2 dropped by 30. Also, the blade-crossing harmonic attenuation can not be explained by normal ground attenuation.



2) What is the propagation velocity of the emphasized harmonic signal?

**Two-sesimometer phase delay
measurement: $265 \pm 126, -65$ m/s
(one sigma band, 200 to 391 m/s)**



3) What accounts for the emphasized harmonic?

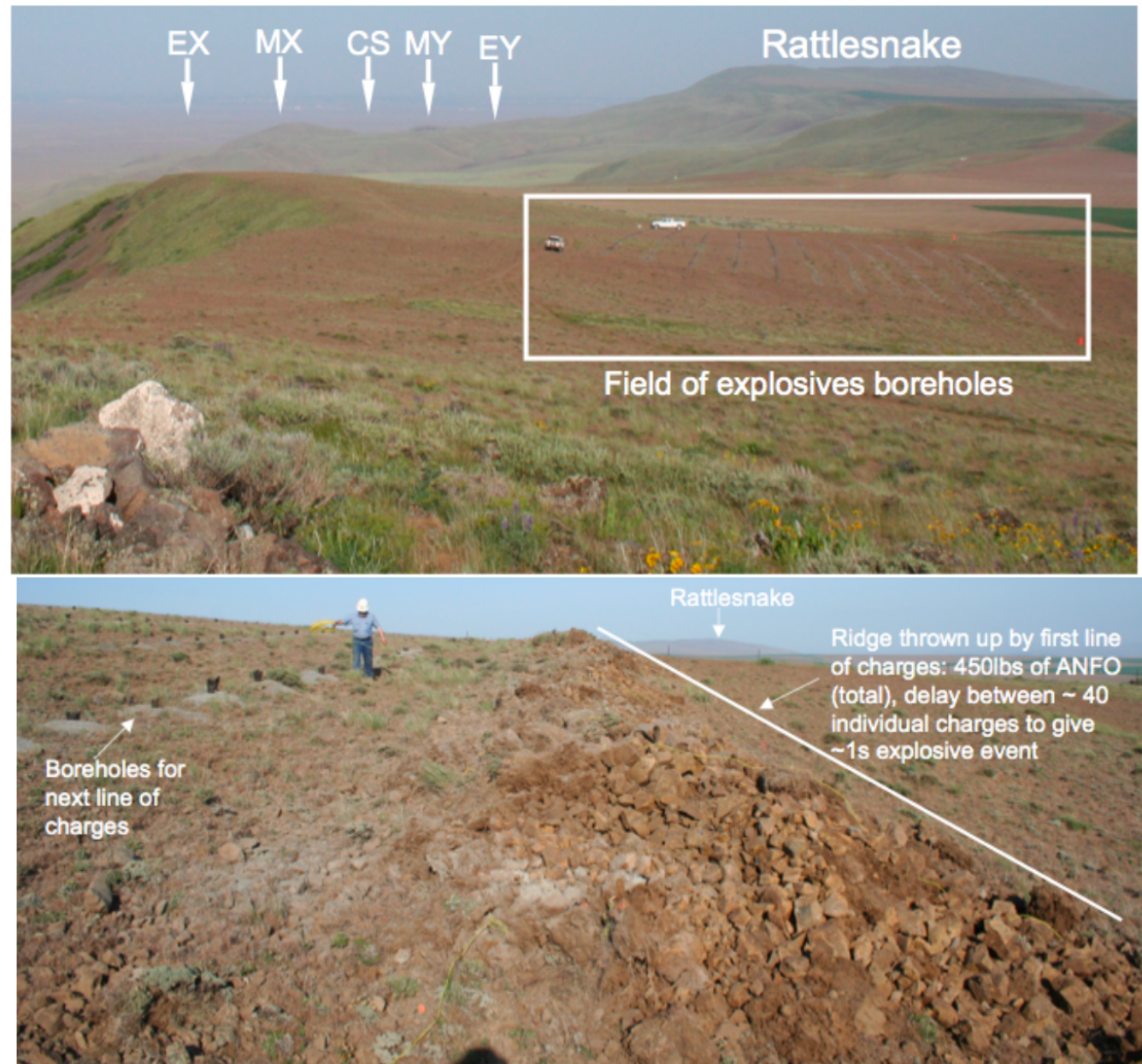
1) Used emphasized frequency from these 3 turbine types and 3 others from my Scottish collaborators, and could not predict emphasis based on hub height or rotor diameter and the wavelength of the infrasound.

2) Could not predict harmonic from blade width relative to tangential distance between blades

3) Attenuation acts like band pass, other harmonics drop more rapidly with distance. Surface waves propagate slower at higher frequencies and faster at lower frequencies.

4) Will infrasound coupling to buildings greatly increase ground motion?

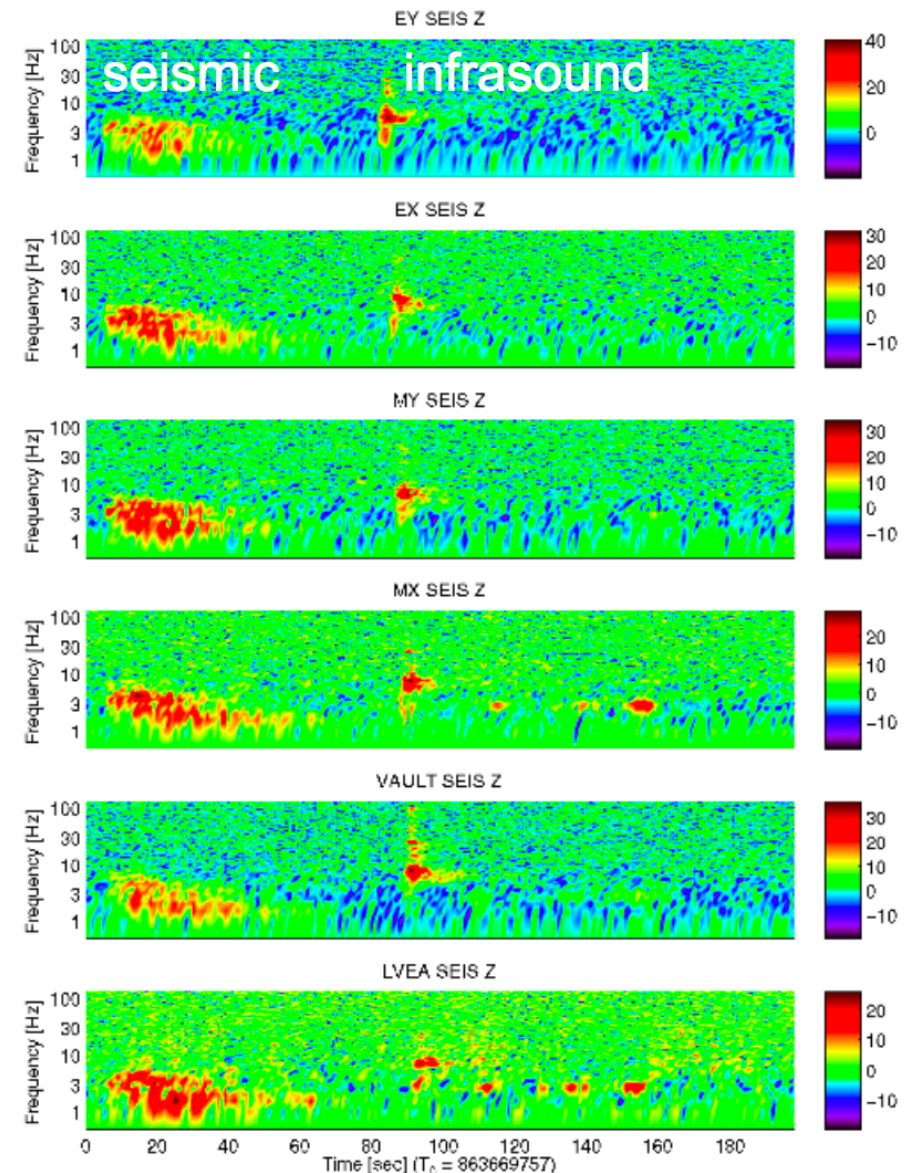
**Test explosions
set off to study
infrasound
coupling (2007)**



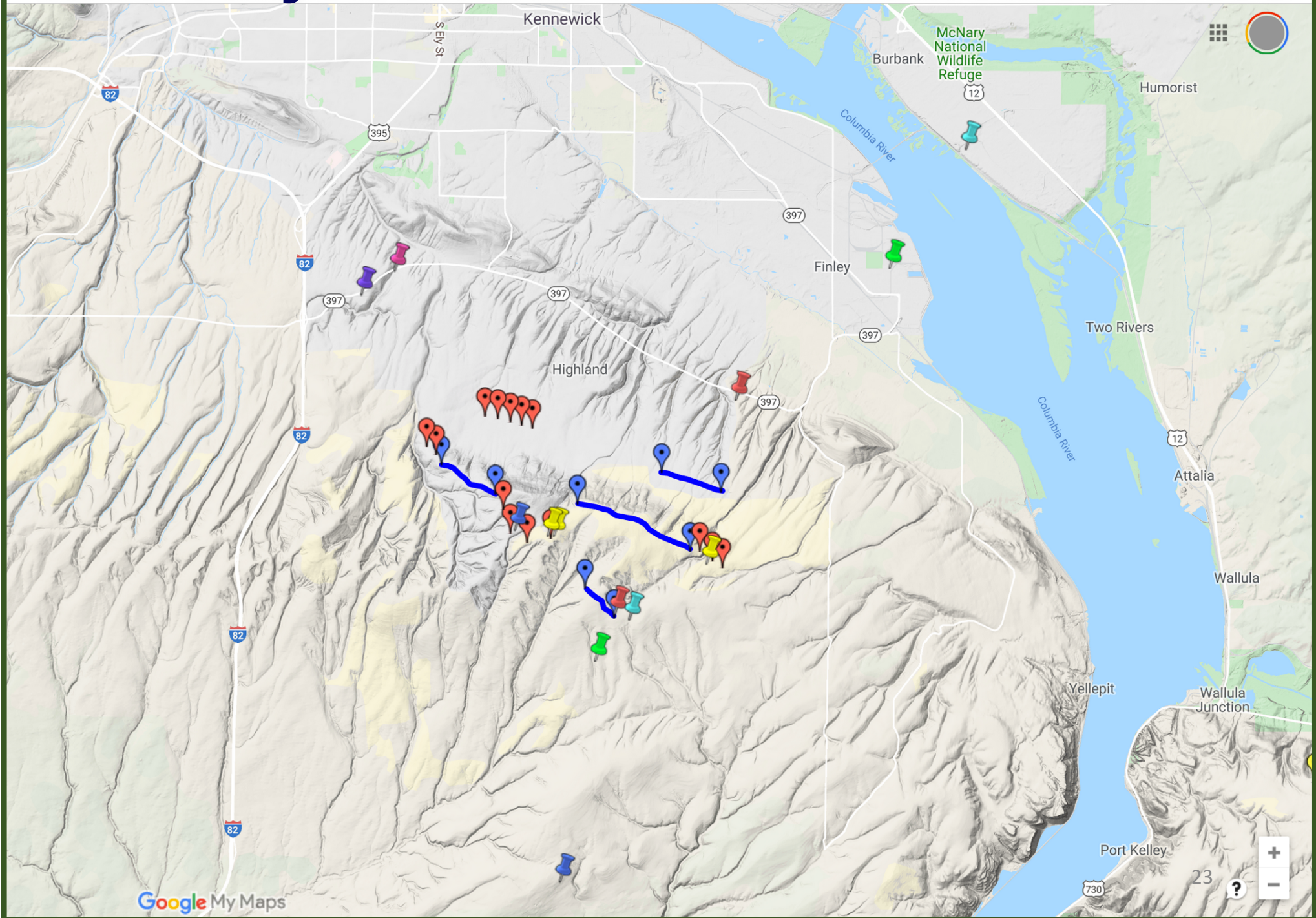
4) Will infrasound coupling to buildings greatly increase ground motion?

Seismometer in vault (no building) registers roughly the same amplitude signal from the explosion's infrasound as building seismometers register.

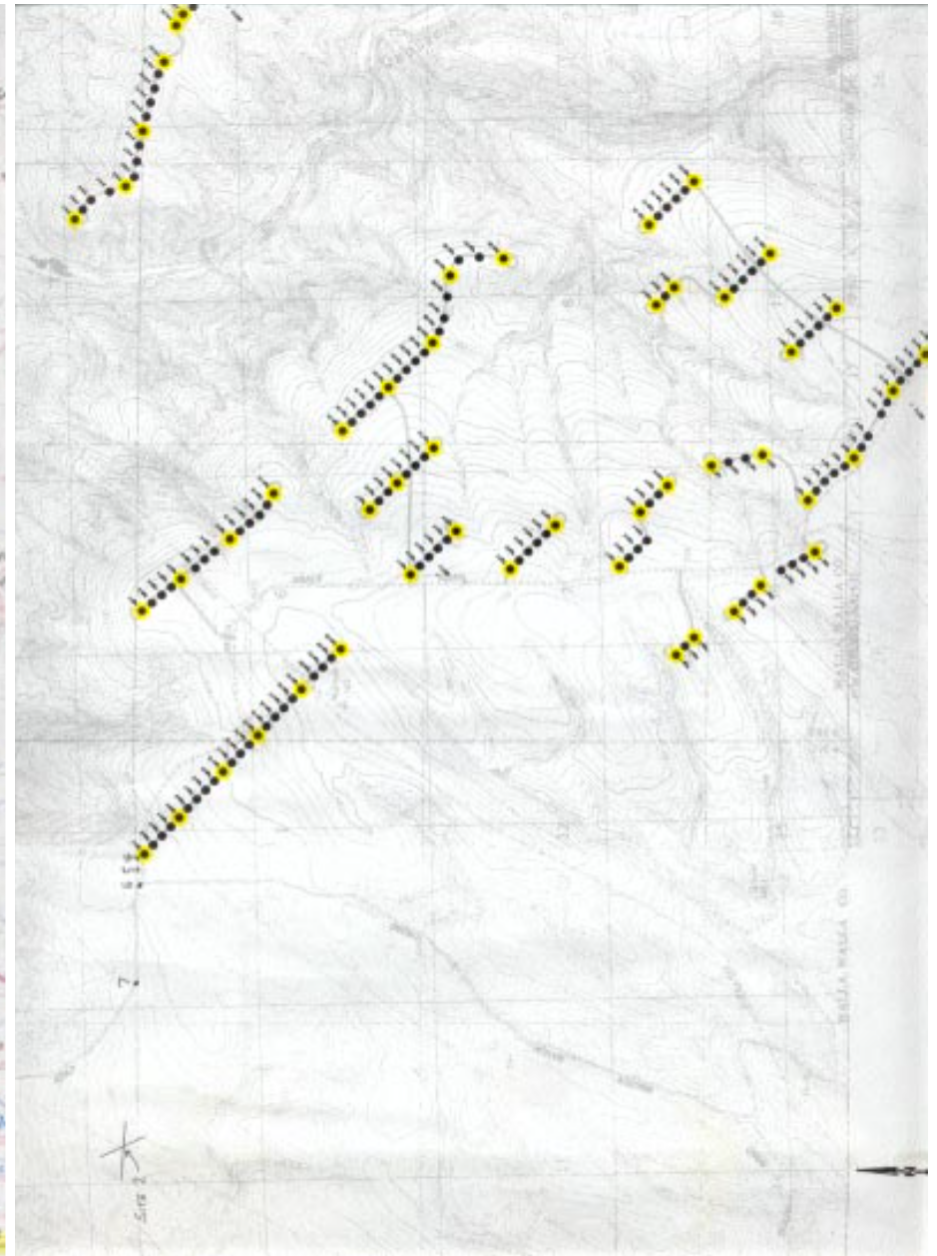
Explosion signals arriving at LHO



Nine Canyon turbines and measurement sites



State Line measurement sites and some turbines



Huddle test: Thick Ivea, thin mobile; BLUE:vertical, RED: horizontal (Ivea Y)
 $x=x/32$; $y = (0.8) * (2*\sqrt{2}*y)/(400*2*3.14157*(x+0.000000000001))$

