LIGO-T020104-00-Z

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 about18 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 about 20% of the r.m.s. of the frequency noise in one interferometer, prior to special servo modification. A similar amplitude signal from the Maiden Wind Project, at a resonance, could contribute much more to this r.m.s. because the peak would be wider. This could create a need for abatement modifications.

Measurements

Instrumentation

Seismic measurements were made using a Guralp CMG-40T seismometer whose outputs were fed through a Stanford SR-560 preamplifier into an HP 3857 signal analyzer. Instruments were powered by internal or external (automobile) batteries. At sites 1 and 2, the seismometer was placed on a granite slab set directly on the earth at the bottom of a meter deep pit (Figure 1). The pit was walled and capped with a wooden box. The box top was then covered with a couple of inches of earth to bring the level up to the surrounding grade. At other sites, the seismometer was shielded from wind using an overturned plastic tub instead of a pit.

Figure 1. Seismometer in pit at site 2.

Calibration

The instrumentation described above was set up, using identical instrument settings, near a LIGO seismometer. The signal level calculated from the HP 3857 output, using the manufacturer's calibration, matched the signal level output by the LIGO data system. Noise floors for each of the instrument settings used during data collection at the Stateline site were determined by replacing the seismometer with a resistor matched to the seismometer output resistance. Noise floors were below signal level for spectra shown here.

Results

Measurement Locations

Measurements were made at 10 locations. Seismometer pits were excavated at two sites. Site 1 was located 24 meters SW of the base of turbine HGJ-44 (Figure 2). Site 2 was located 1660 m (about 1 mile) from HGA-1 and is shown on the map of Figure 3. At the other locations, plastic tubs were used instead of pits. These locations were as follows: site 3, on the cement base of HGJ-44, site 4, 50 meters from HGA-1 (Fig. 3), site 5, 100 meters from HGA-1 on Hatch Grade Rd. (Fig. 3), site 6, 150 m from the base of HGA-1 at the corner of Hatch Grade and Braden Ranch roads (Fig. 3), site 7, located 710 m from HGA-1 on Hatch Grade road (Fig. 3), site 8, about 3 km from HGA-1,across the Walla Walla river (Fig. 4), site 9, about 11 km away on Dodd road (Fig. 4), and, site 10, about 18 km away in

Figure 2. Site 1: the pit was in the shadow of the mound at the lower left; the base of HGJ-44 is 24 m away in the near background

the McNary National Wildlife Refuge (Fig. 4).

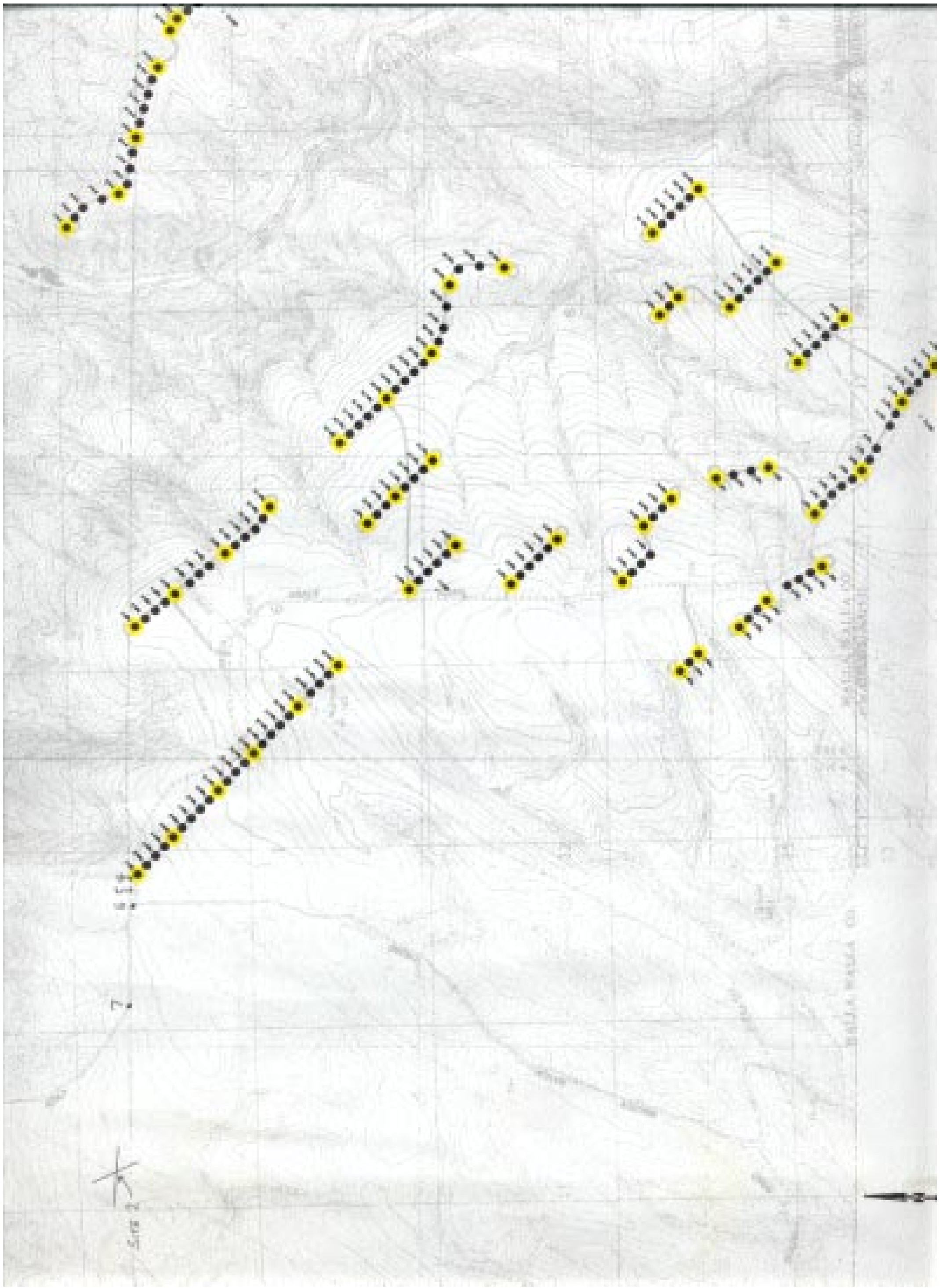


Figure 3

Figure 4.

Spectra

Figures 5 and 6 show spectra from sites 1 and 2. The figures show a low frequency and a high frequency measurement for each site. The LIGO spectra were taken the same evening as the Maiden spectra; the wind speed at LIGO for this data averaged about 8 m/s.

Figure 5.

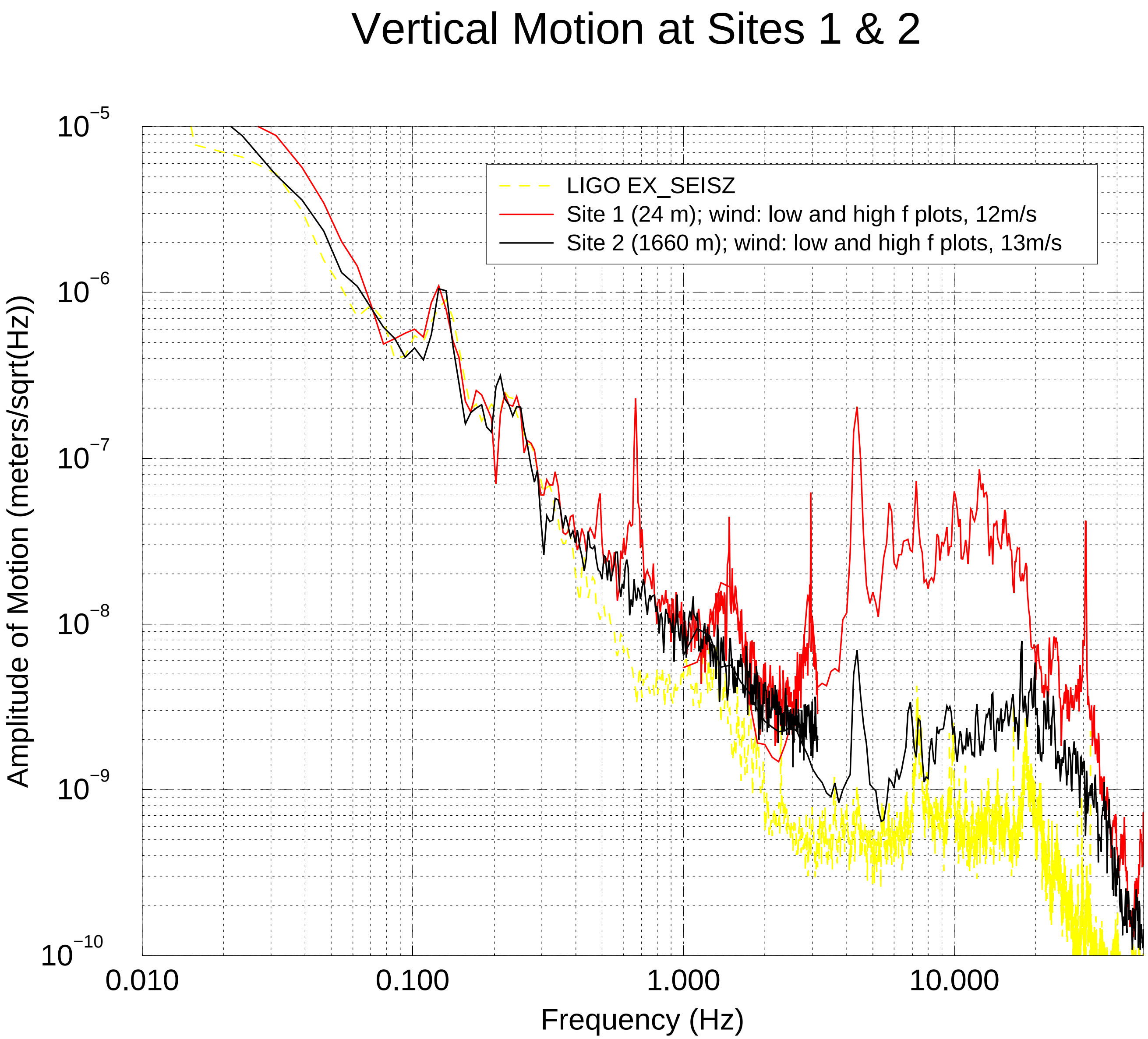
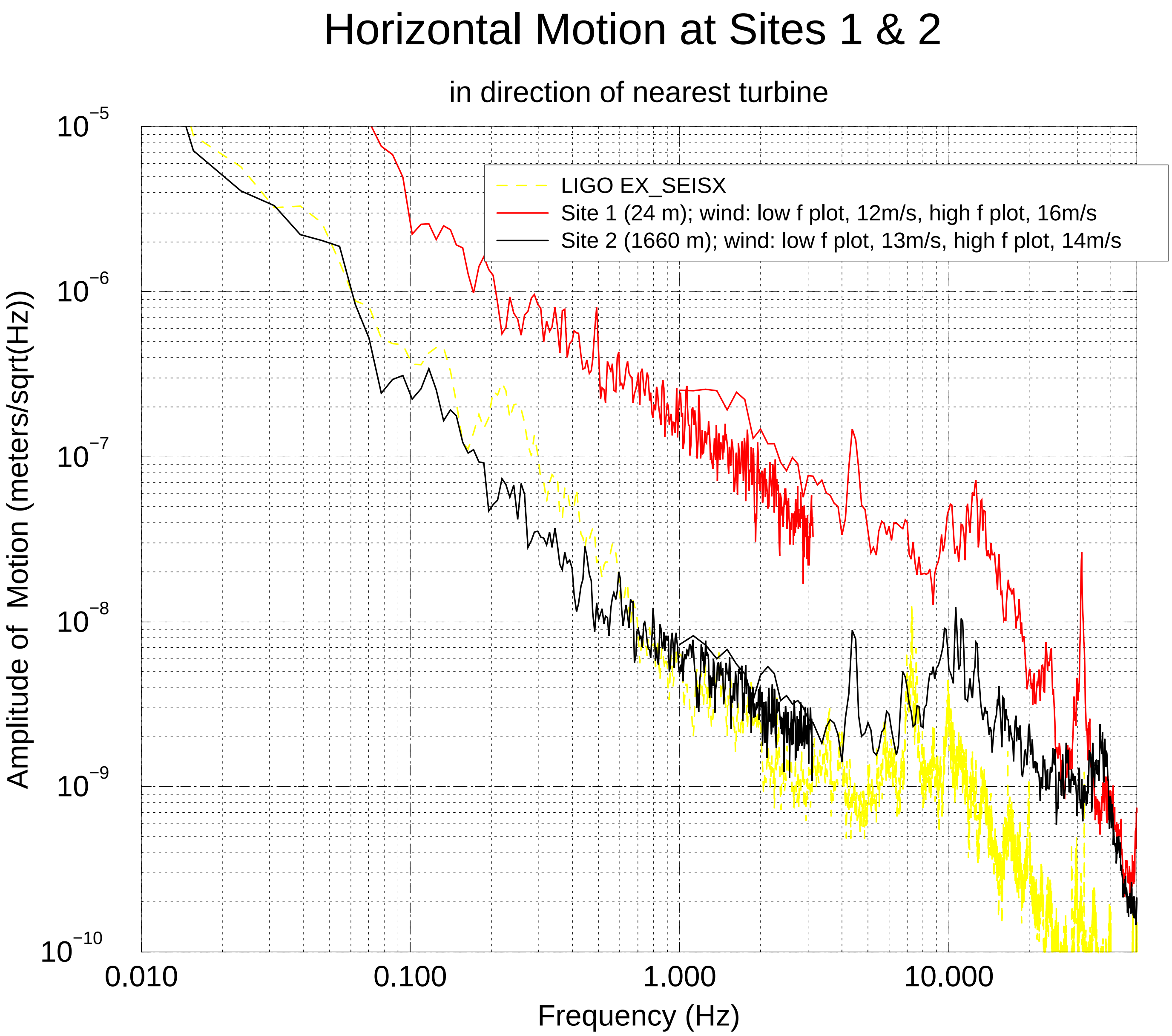

Vertical Motion at Sites 1 & 2
LIGO EX_SEISZ
Site 1 (24 m); wind: low and high f plots, 12m/s
Site 2 (1660 m); wind: low and high f plots, 13m/s
Amplitude of Motion (meters/sqrt(Hz))
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.010
0.100
1.000
10.000
Frequency (Hz)

Figure 6.


Horizontal Motion at Sites 1 & 2
in direction of nearest turbine
LIGO EX_SEISX
Site 1 (24 m); wind: low f plot, 12m/s, high f plot, 16m/s
Site 2 (1660 m); wind: low f plot, 13m/s, high f plot, 14m/s
Amplitude of Motion (meters/sqrt(Hz))
Frequency (Hz)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.010
0.100
1.000
10.000

Signal Identification

Signals were attributed to the turbines if they were relatively larger nearer to the base of the tower. Two types of peaks were identified, stationary frequency peaks, presumably associated with structural resonances, and peaks whose frequency varied with turbine rotation rate. To discriminate between these two types, a seismometer was set up on the base of a turbine tower (site 3) during a period of low wind velocity, when many turbines were not moving. The peaks identified below as stationary were observed at the same frequency as during high wind velocity periods. The peaks identified as varying were observed to increase in frequency as the rotation rate of the turbine increased. At higher wind velocities these varying frequencies stabilize because the turbine is designed to run at a nearly constant rotation rate (OptiSlip-equipped induction generators allow about a 10% variation in rate).

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

Spectra at Varying Distances

Figure 7.

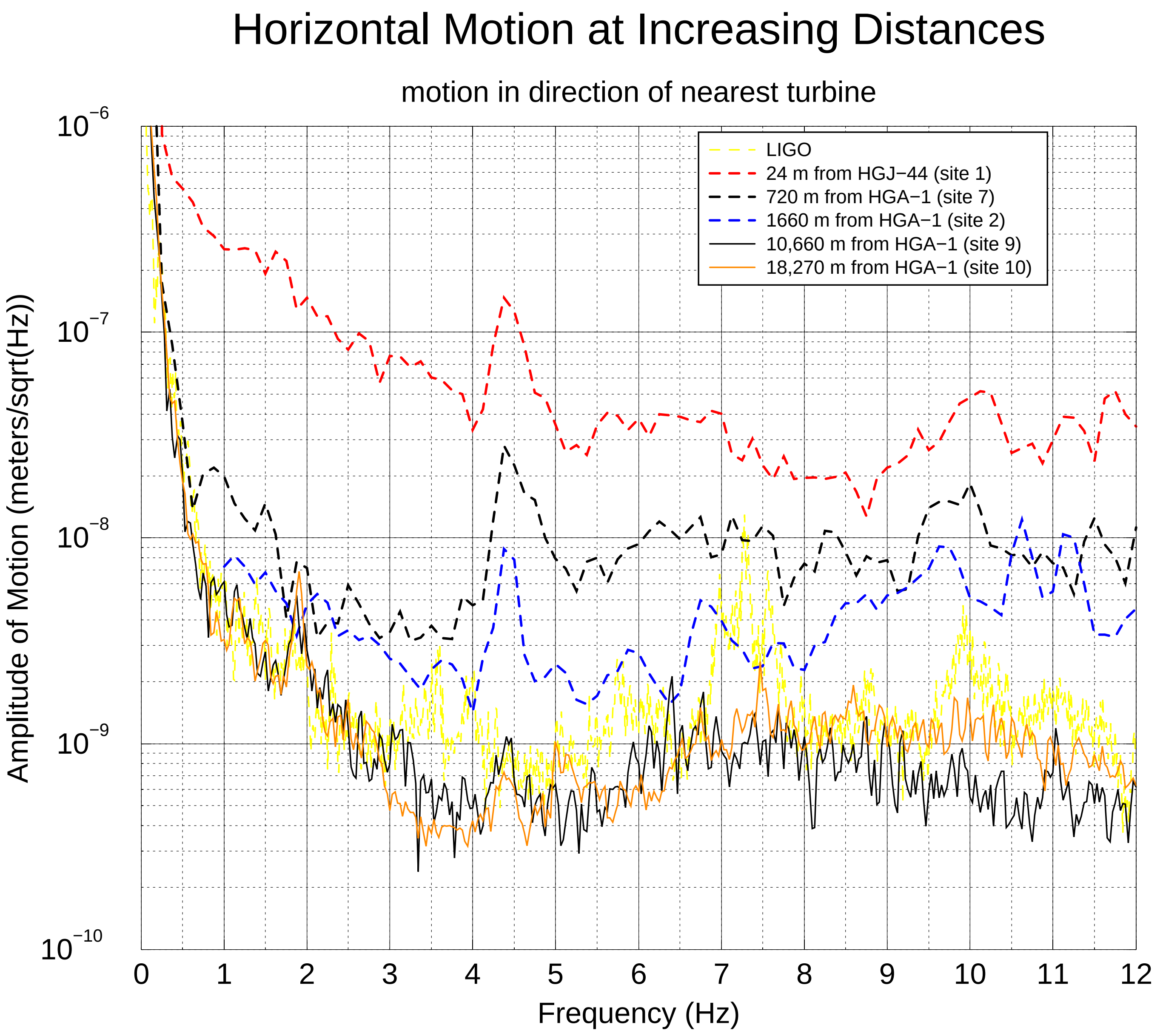


Figure 7 shows some of the spectra from sites at increasing distances from the Stateline project.

Analysis

In order to predict signal amplitudes at LIGO, assumptions or models were developed for how signals from multiple turbines at varying distances combine, how the signals propagate, and how the signals vary with different turbine designs and with wind speed.

Combining Signals from Multiple Turbines in Quadrature

For all calculations here, the signals from multiple turbines were assumed to add in quadrature. Thus, the amplitude of the signal produced by 100 identical turbines at identical distances was assumed to be sqrt(100) or 10 times the amplitude of the signal from a single turbine. If the phase angles of each of the 100 turbines were identical and the inter-turbine spacing were small compared to the seismic wavelengths, the signal would be 100 times rather than 10 times the single turbine amplitude. However, in the case of the Stateline project, the phase angles of the turbines were not all identical during power generation - visually the blades were in different positions relative to the tower. This is because the Vestas V-47 generator, while directly connected to the power grid, is an induction generator and so the position of the rotor poles varies relative to the turbine blades. Furthermore, the rotation frequency of the turbines may vary by 10% (OptiSlip) during generation.

Propagation

Three attenuation models were tested, a 1/sqrt(r) model with linear attenuation, typical of propagation at the surface of the ground, a 1/sqrt(r) model (no linear attenuation), and a 1/r model, typical of propagation through the air.

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 ~ 500 m/s and Q ~ 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.

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:

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

Obtaining Distances From the Measurement Sites to Each Individual Turbine

In order to predict the amplitude of a peak at a certain site using the above models, the distances from each site to each of the hundreds of turbines must be known. To do this, a grid was laid out on a map and the coordinates of turbines and measurement sites were entered into a computer that calculated the distance from each measurement site to each of 399 turbines. To simplify data entry, turbines that were far from measurement sites were clustered into groups and assumed to all be located at a single position. The locations of 31 individual turbines and 29 groups were entered. An uncertainty of 10% or less in the predicted amplitude was estimated by varying the coordinates entered for the groups.

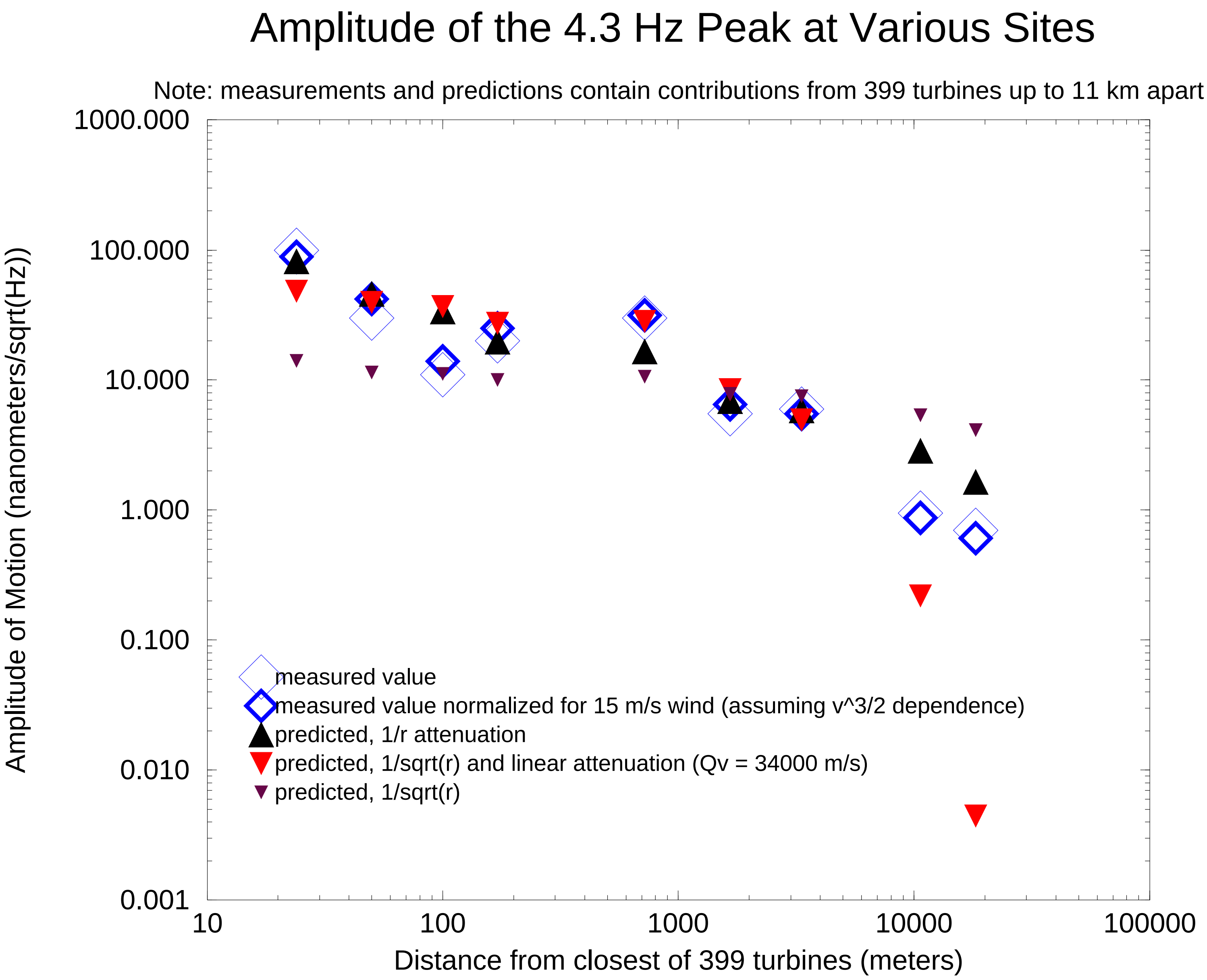
Normalizing According to Wind Speed

Since the measurements at various distances were taken at different times and different wind speeds, the measurements were normalized according to wind speed at HGA-1. This is only an approximation because the wind speeds at each turbine are different. The energy in a volume of air goes as the square of its velocity, and the number of volumes that pass by the turbine per second increases linearly with velocity. Thus the available power goes as the cube of velocity. It is assumed here that the power in the seismic signal is proportional to the wind power available to the turbine and thus that the signal amplitude goes as the wind velocity to the 3/2 power.

The 1/r Model Works Best for the 4.34 Hz Peak

An average value of the peak amplitude of the 4.34 Hz signal was obtained from multiple spectra measured at each site (some of these spectra are shown in Figure 7). These average measured values are shown in Figure 8 as blue diamonds. The 3 propagation models were used to predict the signal from each turbine, assuming that each turbine produced an identical signal. These predicted contributions from the individual turbines were added in quadrature. Rather than obtain A_{near} in

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
Amplitude of Motion (nanometers/sqrt(Hz))
1000.000
100.000
10.000
1.000
0.100
0.010
0.001
10
100
1000
10000
100000
Distance from closest of 399 turbines (meters)
measured value
measured value normalized for 15 m/s wind (assuming v^3/2 dependence)
predicted, 1/r attenuation
predicted, 1/sqrt(r) and linear attenuation (Qv = 34000 m/s)
predicted, 1/sqrt(r)

the above equations from measurements near the base of one of the turbines, where near-field effects might influence results, the predicted values were normalized as a set to the measured data. This was done “by eye”, adjusting each set of predicted values with a multiplicative constant until about half of the predicted values were above the measured values and about half were below the measured values (see Figure 8). It is clear from Figure 8 that the 1/r model is the most successful in predicting the signal amplitude over long distances. This may indicate that the signal travels partly through the air and couples locally to the ground. A coupling to the ground of a low frequency acoustic signal produced by the turbine blades would be similar to the mechanism by which helicopters shake the ground (at about 10 Hz) when in flight. One test of this hypothesis would be to determine if the propagation velocity of the Stateline signals is that of sound in air. Of course energy from the air signal would be lost to the ground so the signal would attenuate at a rate greater than 1/r. This may partly explain why the two values at the greatest distance fall below the model.

*Evidence that Infra-sound Did Not Couple Directly to the Seismomete*r

The possibility that the 4.3 Hz signal was coupling directly to the seismometer was considered. Acoustic coupling at 5 Hz was measured in the laboratory. A microphone and a seismometer were placed near a seismically isolated speaker generating a 5 Hz signal. At Stateline, microphone signals were recorded at several sites along with seismometer signals. The ratio of microphone to seismometer signals at Stateline was much lower than in the acoustic coupling measurement. This indicates that acoustic coupling directly to the seismometer could not account for the seismic signals measured at Stateline.

Differences Between the Stateline Turbines and the Proposed Maiden Turbines

The turbines for the Maiden site may differ from the Vestas V47 turbines at the Stateline site. A likely candidate for the Maiden site is the GE 1.5MW Turbine. For signal amplitude estimates, it will be assumed that the amplitude of the seismic signal increases as the square root of the turbine power output. Thus the signal produced by a 1.5 MW turbine will be assumed to be 1.51 times greater than that produced by the 660 kW Stateline turbines.

The GE turbine being considered features an indirect grid connection (AC-DC-AC conversion) and generates at rotation frequencies of 0.18 - 0.33 Hz, in contrast with the 0.47 +/- 5% rate of the V47. A possible advantage of variable rate turbines is that the rotation rates of the different turbines at the Maiden site may, at any given time, vary more than the rates of the different turbines at Stateline, producing broader, lower amplitude peaks.

Prediction of the Signal Level at LIGO Produced by the Maiden Wind Project

This prediction was for the 4.3 Hz peak, which was the largest peak attributed to the turbines that was evident at sites further than 1 km from the nearest turbine. The prediction was based on the measured value at the most distant site from Stateline, an assumption of 1/r propagation, and assumptions about scaling for wind speed and for turbine numbers and power. From the data obtained at site 10 and the distances to each turbine, it was estimated that a single Stateline turbine would produce a 0.038 nanometer per sqrt(Hz) signal at 18 km when the wind speed was 15 m/s. The signal level (nanometers per sqrt(Hz)) that the Maiden project would produce at LIGO (A_{LIGO}) was thus estimated as::

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

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 Stateline (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.

The high degree of uncertainty

The uncertainty is primarily due to differences in turbines and to geographic differences between sites.

Possible differences in the frequency and magnitude of the predominant peak.

Since the proposed Maiden turbines will be larger and operate at a lower frequency, the frequencies of the peaks will differ from the Stateline frequencies. It is not clear why the 9th harmonic of the Stateline turbine rotation rate is the predominant peak. If it is because the 4.3 Hz peak is in a band that couples well to the ground, the frequency of the peak from the Maiden turbines may be close to that of the Stateline turbines, though the 12th or 15th harmonic rather than the 9th harmonic may be emphasized. On the other hand, if the emphasis of the 9th harmonic is related to the width of the blades relative to the distance between blades, the predominant peak from the Maiden turbines may be at a lower frequency than the predominant Stateline frequency. The uncertainty in the signal amplitude due to different rotation rates was estimated to be a factor of two.

Differences in rotation rate variation.

The variable rate of the proposed turbines could result in a lower signal level at LIGO, but not in a higher level. If the frequency variation of the Maiden turbines turns out to be about 4 times that of the Stateline turbines, the peak signal would be expected to be reduced by about a factor of 2 from the estimated value.

Unknown differences in the turbines and inaccurate assumptions.

These uncertainties were estimated to be about a factor of 2. One possibility is that the signal amplitude does not scale as the square root of the generation power.

Uncertainties due to topography.

The topographic relationship of the Maiden site to the LIGO site is similar to the relationship between the Stateline and distant measurement sites. The three measurement sites most distant from Stateline were off of the basalt ridge on the alluvial plane. LIGO is similarly situated relative to the Maiden site. One difference between the Maiden and Stateline sites is that the basalt is closer to the surface at the Maiden site than at the Stateline site. It seems unlikely that topographic differences would amount to more than a factor of 2 difference in signal level.

Conclusion and Recommendation

In summary, it is likely that the largest peak produced by the Maiden project would be larger than 1/7 of the LIGO background and smaller than 7 times the LIGO background when the wind speed at the Maiden site was about 15 m/s (about 34 mph). At higher wind speeds the signal would be larger, though the background level would increase with increasing wind speed at LIGO.

Seismic measurements at a site employing the turbines that will be used for the Maiden project could significantly reduce this uncertainty and are recommended.

LIGO-T020104-00-Z

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 about18 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 about 20% of the r.m.s. of the frequency noise in one interferometer, prior to special servo modification. A similar amplitude signal from the Maiden Wind Project, at a resonance, could contribute much more to this r.m.s. because the peak would be wider. This could create a need for abatement modifications.

Measurements

Instrumentation

Seismic measurements were made using a Guralp CMG-40T seismometer whose outputs were fed through a Stanford SR-560 preamplifier into an HP 3857 signal analyzer. Instruments were powered by internal or external (automobile) batteries. At sites 1 and 2, the seismometer was placed on a granite slab set directly on the earth at the bottom of a meter deep pit (Figure 1). The pit was walled and capped with a wooden box. The box top was then covered with a couple of inches of earth to bring the level up to the surrounding grade. At other sites, the seismometer was shielded from wind using an overturned plastic tub instead of a pit.

Figure 1. Seismometer in pit at site 2.

Calibration

The instrumentation described above was set up, using identical instrument settings, near a LIGO seismometer. The signal level calculated from the HP 3857 output, using the manufacturer's calibration, matched the signal level output by the LIGO data system. Noise floors for each of the instrument settings used during data collection at the Stateline site were determined by replacing the seismometer with a resistor matched to the seismometer output resistance. Noise floors were below signal level for spectra shown here.

Results

Measurement Locations

Measurements were made at 10 locations. Seismometer pits were excavated at two sites. Site 1 was located 24 meters SW of the base of turbine HGJ-44 (Figure 2). Site 2 was located 1660 m (about 1 mile) from HGA-1 and is shown on the map of Figure 3. At the other locations, plastic tubs were used instead of pits. These locations were as follows: site 3, on the cement base of HGJ-44, site 4, 50 meters from HGA-1 (Fig. 3), site 5, 100 meters from HGA-1 on Hatch Grade Rd. (Fig. 3), site 6, 150 m from the base of HGA-1 at the corner of Hatch Grade and Braden Ranch roads (Fig. 3), site 7, located 710 m from HGA-1 on Hatch Grade road (Fig. 3), site 8, about 3 km from HGA-1,across the Walla Walla river (Fig. 4), site 9, about 11 km away on Dodd road (Fig. 4), and, site 10, about 18 km away in

Figure 2. Site 1: the pit was in the shadow of the mound at the lower left; the base of HGJ-44 is 24 m away in the near background

the McNary National Wildlife Refuge (Fig. 4).

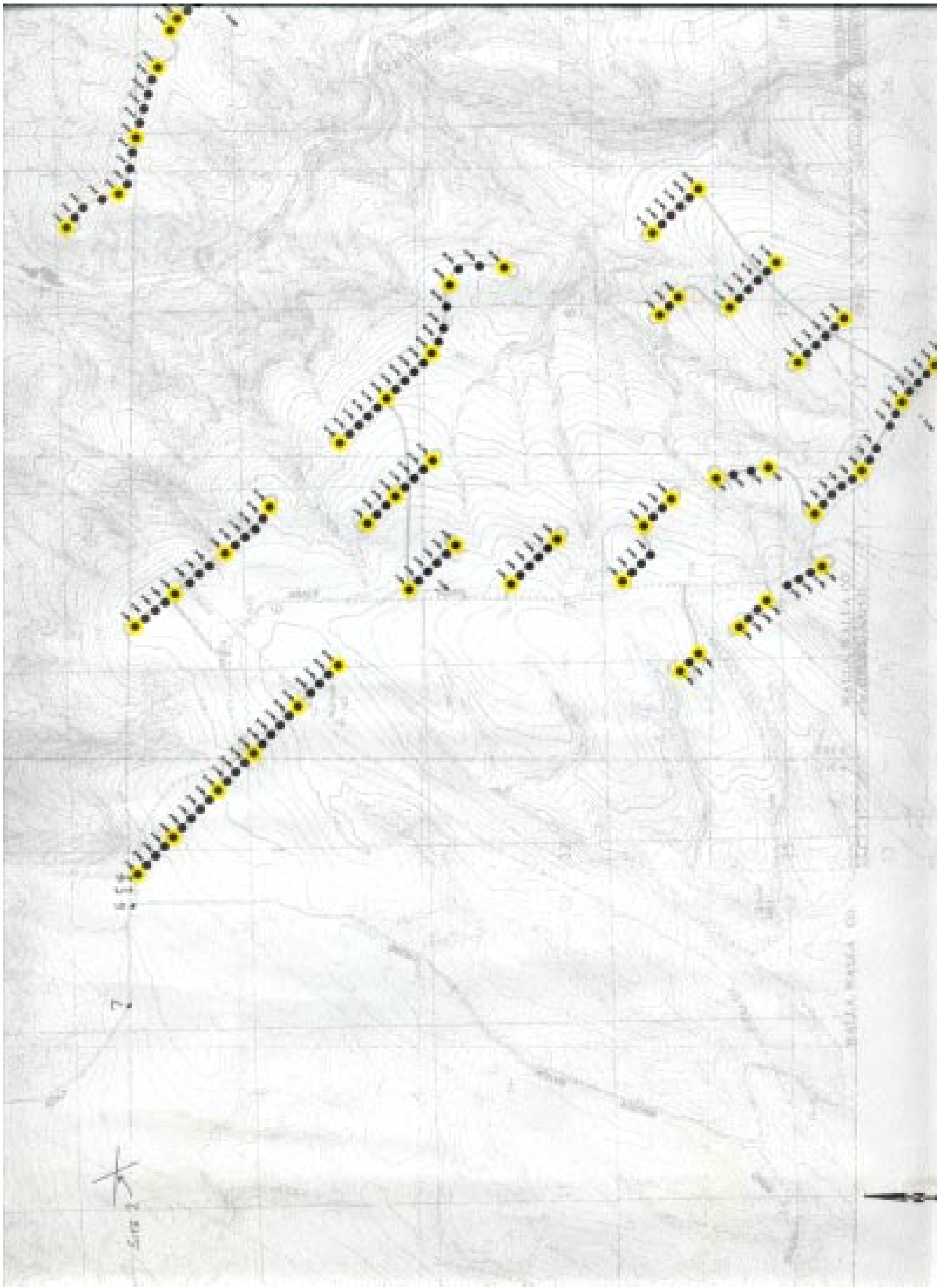


Figure 3

Figure 4.

Spectra

Figures 5 and 6 show spectra from sites 1 and 2. The figures show a low frequency and a high frequency measurement for each site. The LIGO spectra were taken the same evening as the Maiden spectra; the wind speed at LIGO for this data averaged about 8 m/s.

Figure 5.

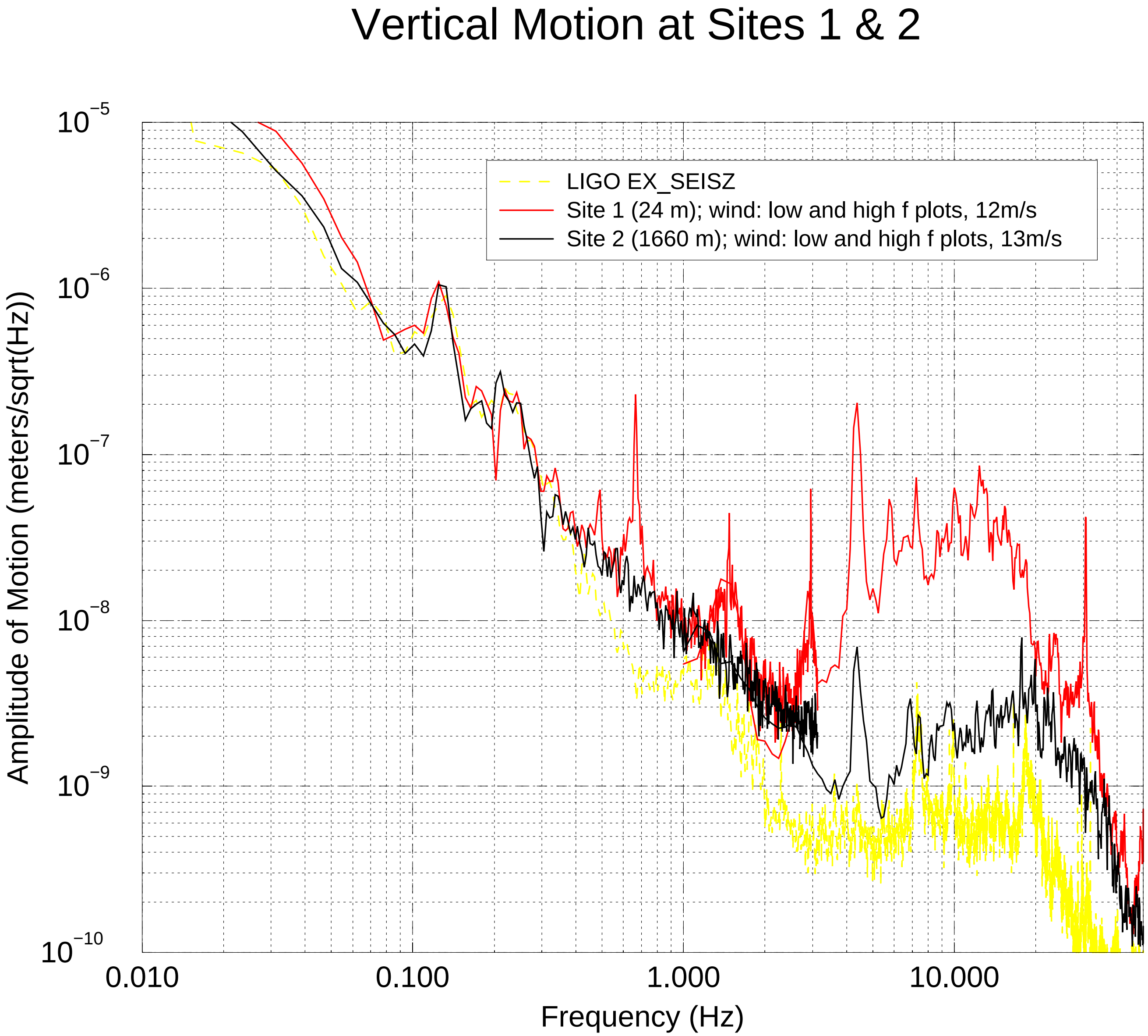
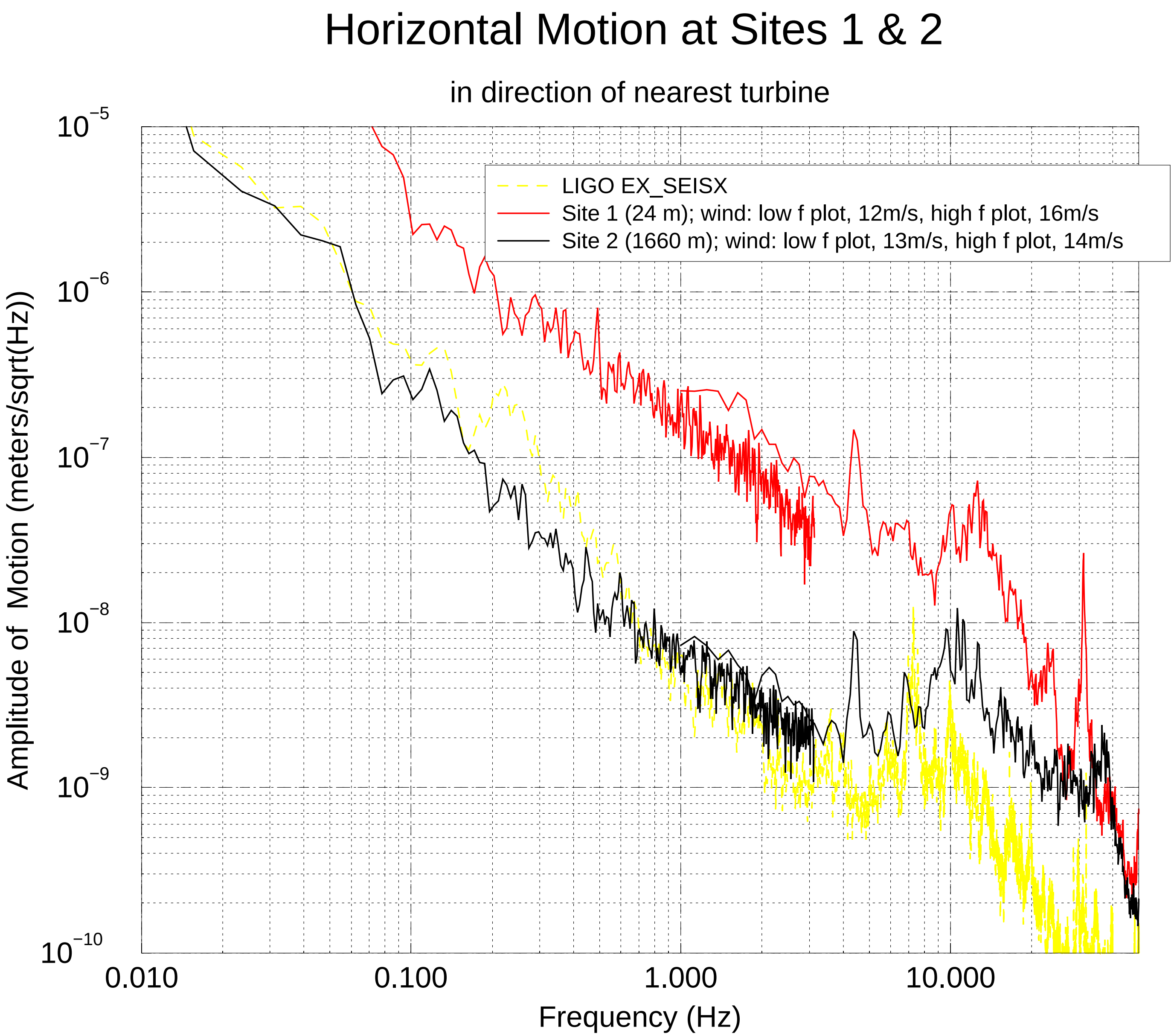

Vertical Motion at Sites 1 & 2
LIGO EX_SEISZ
Site 1 (24 m); wind: low and high f plots, 12m/s
Site 2 (1660 m); wind: low and high f plots, 13m/s
Amplitude of Motion (meters/sqrt(Hz))
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.010
0.100
1.000
10.000
Frequency (Hz)

Figure 6.


Horizontal Motion at Sites 1 & 2
in direction of nearest turbine
LIGO EX_SEISX
Site 1 (24 m); wind: low f plot, 12m/s, high f plot, 16m/s
Site 2 (1660 m); wind: low f plot, 13m/s, high f plot, 14m/s
Amplitude of Motion (meters/sqrt(Hz))
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.010
0.100
1.000
10.000
Frequency (Hz)

Signal Identification

Signals were attributed to the turbines if they were relatively larger nearer to the base of the tower. Two types of peaks were identified, stationary frequency peaks, presumably associated with structural resonances, and peaks whose frequency varied with turbine rotation rate. To discriminate between these two types, a seismometer was set up on the base of a turbine tower (site 3) during a period of low wind velocity, when many turbines were not moving. The peaks identified below as stationary were observed at the same frequency as during high wind velocity periods. The peaks identified as varying were observed to increase in frequency as the rotation rate of the turbine increased. At higher wind velocities these varying frequencies stabilize because the turbine is designed to run at a nearly constant rotation rate (OptiSlip-equipped induction generators allow about a 10% variation in rate).

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

Spectra at Varying Distances

Figure 7.

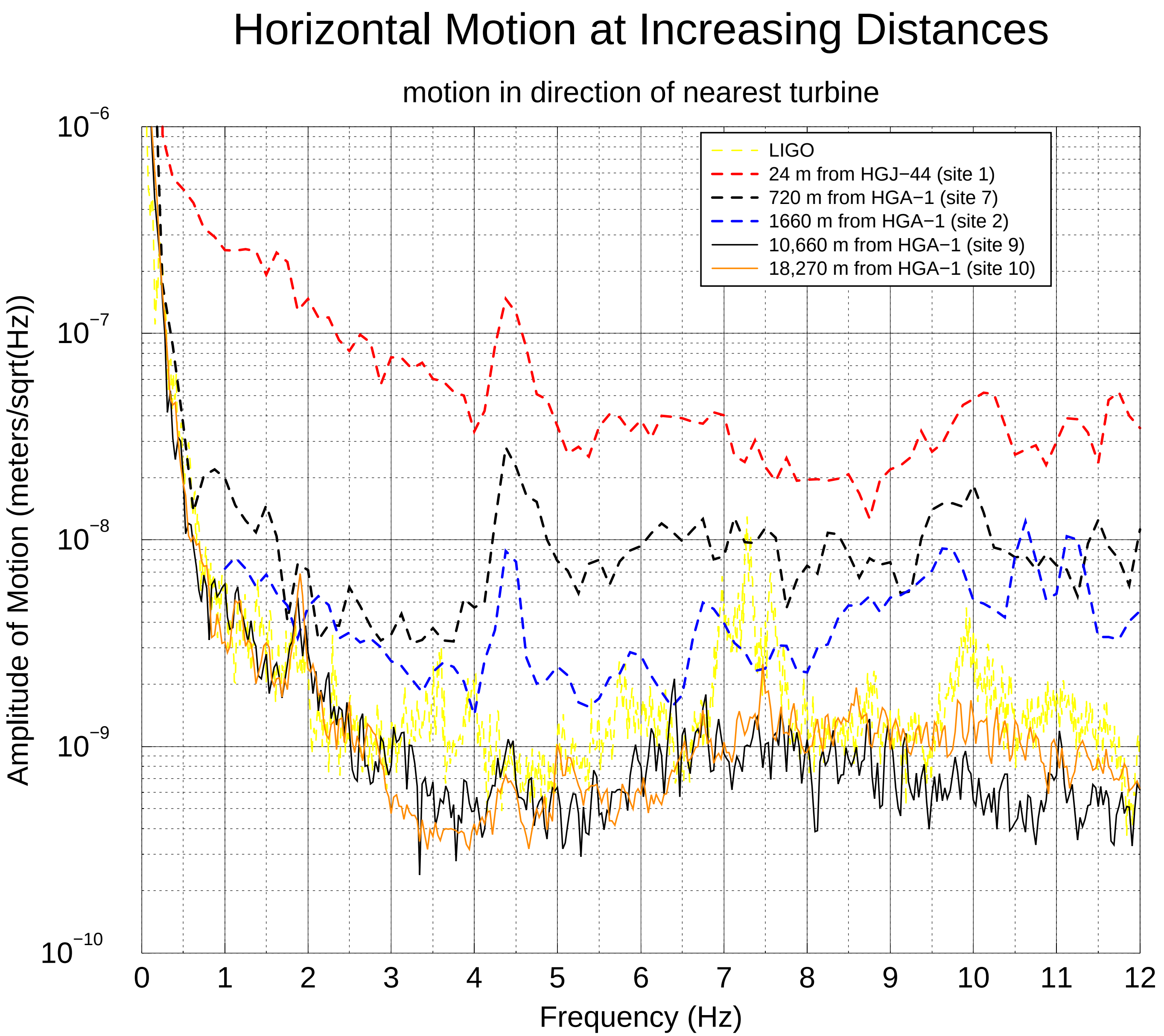


Figure 7 shows some of the spectra from sites at increasing distances from the Stateline project.

Analysis

In order to predict signal amplitudes at LIGO, assumptions or models were developed for how signals from multiple turbines at varying distances combine, how the signals propagate, and how the signals vary with different turbine designs and with wind speed.

Combining Signals from Multiple Turbines in Quadrature

For all calculations here, the signals from multiple turbines were assumed to add in quadrature. Thus, the amplitude of the signal produced by 100 identical turbines at identical distances was assumed to be sqrt(100) or 10 times the amplitude of the signal from a single turbine. If the phase angles of each of the 100 turbines were identical and the inter-turbine spacing were small compared to the seismic wavelengths, the signal would be 100 times rather than 10 times the single turbine amplitude. However, in the case of the Stateline project, the phase angles of the turbines were not all identical during power generation - visually the blades were in different positions relative to the tower. This is because the Vestas V-47 generator, while directly connected to the power grid, is an induction generator and so the position of the rotor poles varies relative to the turbine blades. Furthermore, the rotation frequency of the turbines may vary by 10% (OptiSlip) during generation.

Propagation

Three attenuation models were tested, a 1/sqrt(r) model with linear attenuation, typical of propagation at the surface of the ground, a 1/sqrt(r) model (no linear attenuation), and a 1/r model, typical of propagation through the air.

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 ~ 500 m/s and Q ~ 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.

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:

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

Obtaining Distances From the Measurement Sites to Each Individual Turbine

In order to predict the amplitude of a peak at a certain site using the above models, the distances from each site to each of the hundreds of turbines must be known. To do this, a grid was laid out on a map and the coordinates of turbines and measurement sites were entered into a computer that calculated the distance from each measurement site to each of 399 turbines. To simplify data entry, turbines that were far from measurement sites were clustered into groups and assumed to all be located at a single position. The locations of 31 individual turbines and 29 groups were entered. An uncertainty of 10% or less in the predicted amplitude was estimated by varying the coordinates entered for the groups.

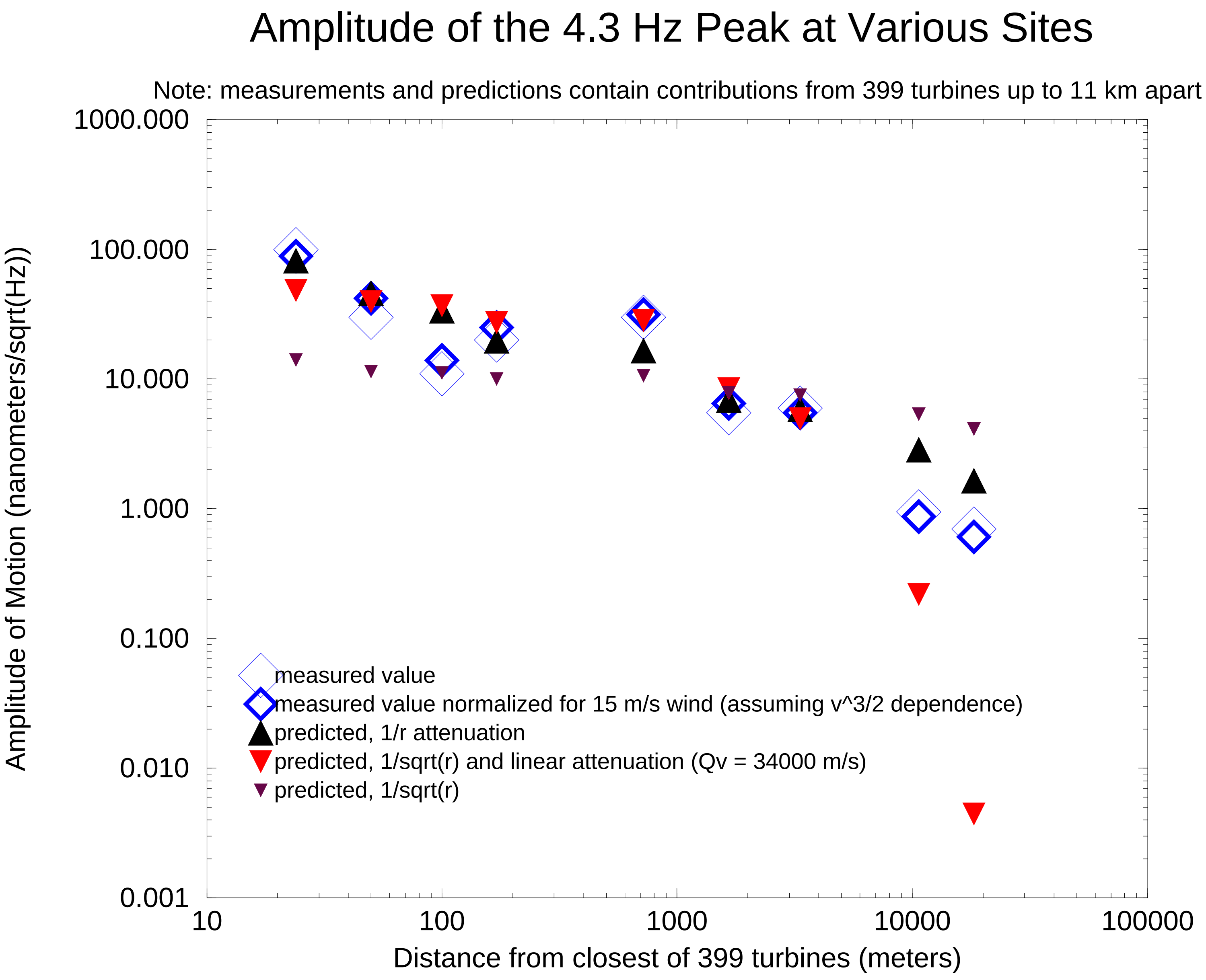
Normalizing According to Wind Speed

Since the measurements at various distances were taken at different times and different wind speeds, the measurements were normalized according to wind speed at HGA-1. This is only an approximation because the wind speeds at each turbine are different. The energy in a volume of air goes as the square of its velocity, and the number of volumes that pass by the turbine per second increases linearly with velocity. Thus the available power goes as the cube of velocity. It is assumed here that the power in the seismic signal is proportional to the wind power available to the turbine and thus that the signal amplitude goes as the wind velocity to the 3/2 power.

The 1/r Model Works Best for the 4.34 Hz Peak

An average value of the peak amplitude of the 4.34 Hz signal was obtained from multiple spectra measured at each site (some of these spectra are shown in Figure 7). These average measured values are shown in Figure 8 as blue diamonds. The 3 propagation models were used to predict the signal from each turbine, assuming that each turbine produced an identical signal. These predicted contributions from the individual turbines were added in quadrature. Rather than obtain A_{near} in

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
Amplitude of Motion (nanometers/sqrt(Hz))
1000.000
100.000
10.000
1.000
0.100
0.010
0.001
10
100
1000
10000
100000
Distance from closest of 399 turbines (meters)
◇ measured value
◇ measured value normalized for 15 m/s wind (assuming v^3/2 dependence)
▲ predicted, 1/r attenuation
▼ predicted, 1/sqrt(r) and linear attenuation (Qv = 34000 m/s)
▼ predicted, 1/sqrt(r)

the above equations from measurements near the base of one of the turbines, where near-field effects might influence results, the predicted values were normalized as a set to the measured data. This was done “by eye”, adjusting each set of predicted values with a multiplicative constant until about half of the predicted values were above the measured values and about half were below the measured values (see Figure 8). It is clear from Figure 8 that the 1/r model is the most successful in predicting the signal amplitude over long distances. This may indicate that the signal travels partly through the air and couples locally to the ground. A coupling to the ground of a low frequency acoustic signal produced by the turbine blades would be similar to the mechanism by which helicopters shake the ground (at about 10 Hz) when in flight. One test of this hypothesis would be to determine if the propagation velocity of the Stateline signals is that of sound in air. Of course energy from the air signal would be lost to the ground so the signal would attenuate at a rate greater than 1/r. This may partly explain why the two values at the greatest distance fall below the model.

*Evidence that Infra-sound Did Not Couple Directly to the Seismomete*r

The possibility that the 4.3 Hz signal was coupling directly to the seismometer was considered. Acoustic coupling at 5 Hz was measured in the laboratory. A microphone and a seismometer were placed near a seismically isolated speaker generating a 5 Hz signal. At Stateline, microphone signals were recorded at several sites along with seismometer signals. The ratio of microphone to seismometer signals at Stateline was much lower than in the acoustic coupling measurement. This indicates that acoustic coupling directly to the seismometer could not account for the seismic signals measured at Stateline.

Differences Between the Stateline Turbines and the Proposed Maiden Turbines

The turbines for the Maiden site may differ from the Vestas V47 turbines at the Stateline site. A likely candidate for the Maiden site is the GE 1.5MW Turbine. For signal amplitude estimates, it will be assumed that the amplitude of the seismic signal increases as the square root of the turbine power output. Thus the signal produced by a 1.5 MW turbine will be assumed to be 1.51 times greater than that produced by the 660 kW Stateline turbines.

The GE turbine being considered features an indirect grid connection (AC-DC-AC conversion) and generates at rotation frequencies of 0.18 - 0.33 Hz, in contrast with the 0.47 +/- 5% rate of the V47. A possible advantage of variable rate turbines is that the rotation rates of the different turbines at the Maiden site may, at any given time, vary more than the rates of the different turbines at Stateline, producing broader, lower amplitude peaks.

Prediction of the Signal Level at LIGO Produced by the Maiden Wind Project

This prediction was for the 4.3 Hz peak, which was the largest peak attributed to the turbines that was evident at sites further than 1 km from the nearest turbine. The prediction was based on the measured value at the most distant site from Stateline, an assumption of 1/r propagation, and assumptions about scaling for wind speed and for turbine numbers and power. From the data obtained at site 10 and the distances to each turbine, it was estimated that a single Stateline turbine would produce a 0.038 nanometer per sqrt(Hz) signal at 18 km when the wind speed was 15 m/s. The signal level (nanometers per sqrt(Hz)) that the Maiden project would produce at LIGO (A_{LIGO}) was thus estimated as::

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

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 Stateline (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.

The high degree of uncertainty

The uncertainty is primarily due to differences in turbines and to geographic differences between sites.

Possible differences in the frequency and magnitude of the predominant peak.

Since the proposed Maiden turbines will be larger and operate at a lower frequency, the frequencies of the peaks will differ from the Stateline frequencies. It is not clear why the 9th harmonic of the Stateline turbine rotation rate is the predominant peak. If it is because the 4.3 Hz peak is in a band that couples well to the ground, the frequency of the peak from the Maiden turbines may be close to that of the Stateline turbines, though the 12th or 15th harmonic rather than the 9th harmonic may be emphasized. On the other hand, if the emphasis of the 9th harmonic is related to the width of the blades relative to the distance between blades, the predominant peak from the Maiden turbines may be at a lower frequency than the predominant Stateline frequency. The uncertainty in the signal amplitude due to different rotation rates was estimated to be a factor of two.

Differences in rotation rate variation.

The variable rate of the proposed turbines could result in a lower signal level at LIGO, but not in a higher level. If the frequency variation of the Maiden turbines turns out to be about 4 times that of the Stateline turbines, the peak signal would be expected to be reduced by about a factor of 2 from the estimated value.

Unknown differences in the turbines and inaccurate assumptions.

These uncertainties were estimated to be about a factor of 2. One possibility is that the signal amplitude does not scale as the square root of the generation power.

Uncertainties due to topography.

The topographic relationship of the Maiden site to the LIGO site is similar to the relationship between the Stateline and distant measurement sites. The three measurement sites most distant from Stateline were off of the basalt ridge on the alluvial plane. LIGO is similarly situated relative to the Maiden site. One difference between the Maiden and Stateline sites is that the basalt is closer to the surface at the Maiden site than at the Stateline site. It seems unlikely that topographic differences would amount to more than a factor of 2 difference in signal level.

Conclusion and Recommendation

In summary, it is likely that the largest peak produced by the Maiden project would be larger than 1/7 of the LIGO background and smaller than 7 times the LIGO background when the wind speed at the Maiden site was about 15 m/s (about 34 mph). At higher wind speeds the signal would be larger, though the background level would increase with increasing wind speed at LIGO.

Seismic measurements at a site employing the turbines that will be used for the Maiden project could significantly reduce this uncertainty and are recommended.