

**Exhibit CS-RH-3**

*Highway Noise Analysis*

# MEMO

**TO:** Brad Wilson, (Ecos Energy, LLC)

**FROM:** T. Ryan Haac, M.S. (RSG, Inc.)

**DATE:** November 16, 2017

**SUBJECT:** The effect of tree removal for the Chelsea Solar Project on traffic noise levels at  
531 Apple Hill Road

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## EXECUTIVE SUMMARY

To study the effect of removing just under 10 acres of trees for the proposed Chelsea Solar Project in Bennington, VT, sound propagation modeling and onsite sound level monitoring were conducted. The monitoring provided insight into the current sound levels at the site and quantified the attenuation provided by the site's existing physical features, including the forest. The study concluded the following:

- Total attenuation provided by the buffer between the road and the residence fluctuated considerably during the monitoring period
- Removing the proposed 9.6 acres of trees may result in up to a 3 dB increase in traffic noise levels at the southern property line of 531 Apple Hill Road
- The proposed tree removal could result in a 1.6 dB increase at the second story window of the house at 531 Apple Hill Road.
- Based on results from background sound monitoring and sound propagation modeling, post-construction background sound levels in the residential neighborhood are projected to remain well below the level at which VTrans would consider providing noise abatement measures.

## INTRODUCTION

Ecos Energy, LLC (“Ecos Energy”) is proposing the development of a 2-MW solar array in North Bennington, Vermont. The Chelsea Solar Project (“the Project”) is to be located on the hillside directly north-northeast of the US Route 7 and Route 279 interchange, as pictured in Figure 1.

The existing site is currently forested. Prior to becoming forested, the parcel was the site of a sprawling apple and/or cherry orchard that has since been abandoned.

Neighbors of the potential project have expressed concerns about the increase in traffic-related noise that would result from the removal of a portion of the existing forest that is required for the project. To further the understanding of the potential change in traffic-related sound levels at the site, Ecos Energy retained RSG to:

- measure the current sound levels in the neighborhood,
- determine the attenuation currently provided by the existing foliage, and
- estimate the change in sound levels that would result with the removal of the specified forest sections.

### *Scope of This Noise Study*

The approach used here puts the focus on the physical features defining sound propagation between the road and the monitoring location. ISO 9613-2 provides standardized methods for calculating attenuation from a variety of attenuating factors, such as air absorption, ground effect, shielding due to terrain and barriers, and foliage attenuation. FHWA’s REMEL (Reference Energy Mean Emission Levels) were used for sound power levels of traffic noise sources. Moreover, on-site sound level monitoring was performed to provide context to the current character of the area and help verify the model inputs and geometry.

## SOUND LEVEL MONITORING

Long-term sound level monitoring took place between Monday, April 3 and Wednesday, April 12. Sound level data were collected using Cesva SC-310 and Larson Davis 831 ANSI/IEC Type 1 sound level meters. All sound level meters were set to log A-weighted equivalent sound levels and 1/3 octave band sound levels once each second. All meters were attached to external digital audio recorders to aid in source identification. The sound level meters were time synced immediately prior to deployment and calibration was performed immediately prior to and following the monitoring period. Sound level meter microphones were mounted on wooden stakes at an approximate height of 1.5 meters (5 feet) and the microphones were covered with windscreens to reduce the influence of wind-caused noise on measurements. Additionally, instruments measuring wind speed and direction were installed alongside both long term sound level monitors at microphone height; the equipment reported average wind speeds and maximum wind gust every minute.

There was rain several days during the monitoring period, specifically on April 4<sup>th</sup>, 6<sup>th</sup>, and 7<sup>th</sup>. All rain periods were excluded from monitoring; time periods of rain were determined by inspecting spectrograms and verified by digital audio recordings. Periods when microphone-level wind speeds exceeded 5 m/s (11.8 mph), measured by the adjacent anemometer, were also excluded from the data analysis and long-term averages. Additionally, anomalies resulting from interactions with the monitor were excluded from the monitoring, including deployment and collection operations and instances when people or animals approached the monitor. Snow was not on the ground in and around Bennington during the study.

### *Locations*

All locations where sound level monitoring was performed are indicated on the map in Figure 1. Prior to retrieving the long-term monitors from the field, short-term monitoring was performed at a series of locations along Route 7. The short-term monitoring at distinct locations provided context to how different portions of the forest attenuate sound. Photographs of each sound level meter deployment are provided in Appendix A.

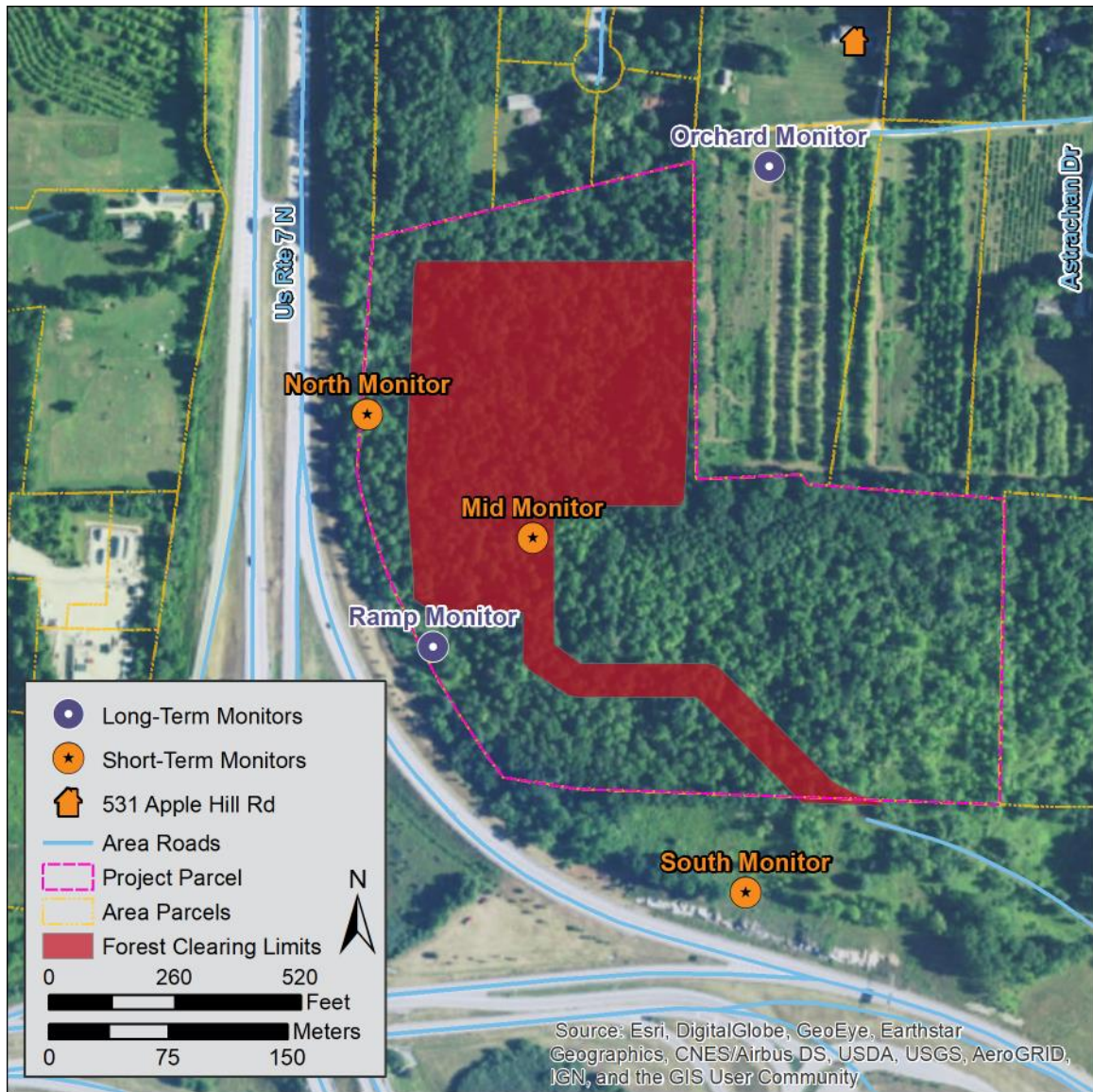


FIGURE 1. ALL SOUND MONITORING LOCATIONS ON APPLE HILL IN BENNINGTON

## LONG TERM MONITORING RESULTS

Results from sound level monitoring at the site are presented in this section. Graphical representations of the time histories are provided, as well as a statistical summary of observed sound levels. Each point on the graph represents data summarized for a single 10-minute interval. Equivalent continuous sound levels ( $L_{EQ}$ ) are the energy-average level over 10 minutes. Tenth percentile sound levels ( $L_{90}$ ) are the statistical value above which 90% of the sound levels occurred during 10 minutes. The data from periods during which data were excluded from processing (e.g., due to high wind and rain, for example) are included in the graphs but shown in lighter colors, with the bars on the lower portion of the plot designating the reason for exclusion.

### *Orchard Monitor*

The Orchard Monitor was placed 23 meters (75 feet) south of the northern property line abutting 531 Apple Hill Road. This location provided the best practical representation of the affected propagation path between road noise sources from the southwest and the residence at 531 Apple Hill Road, since we were not granted permission to monitor on the aforementioned property.

Results from the sound level monitoring, grouped into 10-minute averages, are presented in Figure 2. The main source of sound at this monitor was traffic noise from the Route 7 interchange. The daily pattern was diurnal, in that the levels increased during the day with human activity. Sound levels increased significantly slightly after 5:00 AM each day, indicating a sharp rise in traffic volumes at the beginning of each day. Peak-hour surges in traffic appear to occur on weekdays around 07:30 in the morning and then again around 16:30 in the evening.<sup>1</sup> The sound levels were slightly lower on the weekend (April 8<sup>th</sup> and 9<sup>th</sup>), signifying that there was likely less traffic on those days, particularly on Sunday.

### *Ramp Monitor*

The Ramp Monitor was placed at the edge of the forest approximately 50 meters from the Route 7N onramp. A preliminary sound propagation model indicated that this location resided on the sound propagation path that would be most impacted by the removal of the trees for the solar farm.

The monitoring results from the Ramp Monitor are displayed in Figure 3. The sound levels are very clearly diurnal and dominated by traffic noise, providing a representation of traffic volumes over the course of the day and night. Note that this monitor suffered a power failure after four full days of monitoring.

Table 1 summarizes the statistical sound level metrics from the monitoring period. A summary of the levels for the Orchard Monitor are included for both the entire period and for the period during which the Ramp Monitor was taking data, so that they can be compared directly.

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<sup>1</sup> Night was defined as 22:00 to 07:00, per FHWA standards.

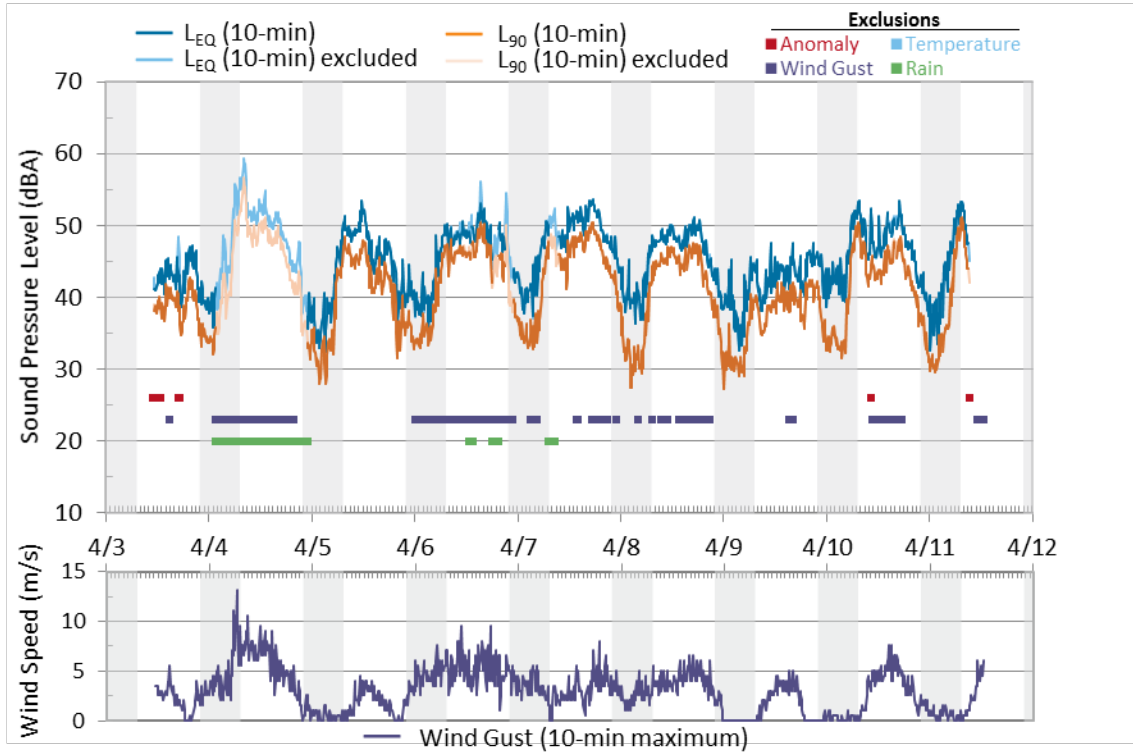


FIGURE 2. TIME HISTORY RESULTS AT THE ORCHARD MONITOR

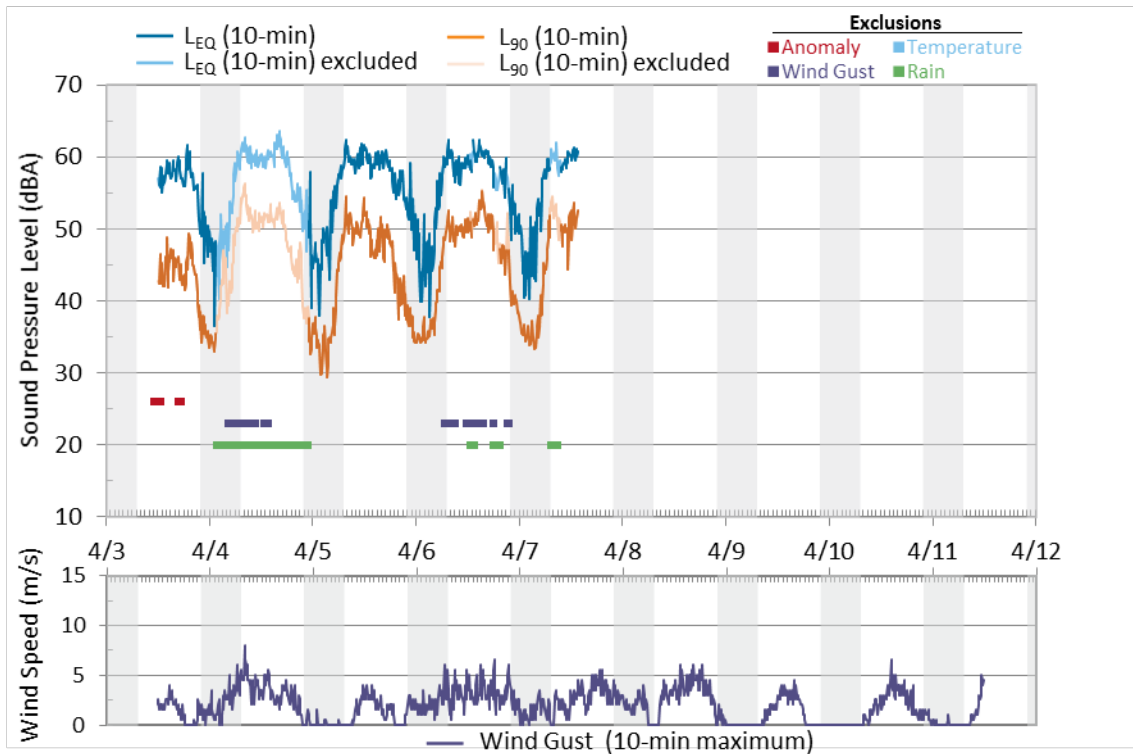


FIGURE 3. TIME HISTORY RESULTS AT THE RAMP MONITOR

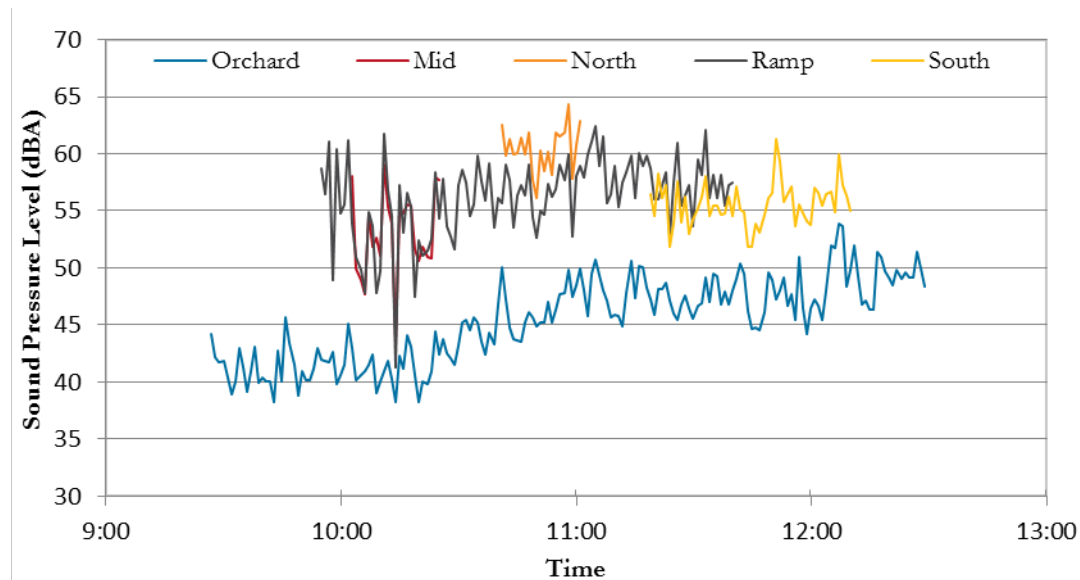
**TABLE 1. LONG TERM MONITOR SUMMARY**

| Sound Pressure Level<br>(dBA)      |         | L <sub>eq</sub> | L <sub>90</sub> | L <sub>50</sub> | L <sub>10</sub> |
|------------------------------------|---------|-----------------|-----------------|-----------------|-----------------|
| Orchard<br>Monitor                 | Day     | 48              | 40              | 47              | 51              |
|                                    | Night   | 44              | 33              | 39              | 47              |
|                                    | Overall | 47              | 35              | 44              | 50              |
| Ramp<br>Monitor                    | Day     | 59              | 46              | 54              | 63              |
|                                    | Night   | 53              | 35              | 41              | 56              |
|                                    | Overall | 57              | 37              | 51              | 61              |
| Orchard<br>Monitor<br>(4/3 to 4/7) | Day     | 48              | 40              | 46              | 51              |
|                                    | Night   | 43              | 34              | 39              | 46              |
|                                    | Overall | 46              | 35              | 44              | 50              |

### Short-Term Monitoring Locations

Supplementary short-term monitoring was performed at additional locations near the Route 7 interchange on the morning of 4/12/2017. Five monitoring locations were involved in total, including the two long-term locations and an additional three locations along Route 7. All of the locations are labeled on Figure 1.

Results from short-term monitoring are plotted in Figure 4. The Orchard Monitor was set to take data for the entirety of the short-term monitoring period, while the short-term locations along Route 7 were monitored for at least 20 minutes each. The highest levels were recorded at the North Monitor, as it was closest to the roadway. The Mid Monitor and the South Monitor exhibited sound levels quite similar to that of the Ramp Monitor, although slightly lower. The similarity in the traces suggest that all of the reference monitors were dominated by the same traffic sources.



**FIGURE 4. SHORT-TERM MONITORING RESULTS, L<sub>eq</sub> (1-MINUTE) (dBA)**

### Discussion of Monitoring Results

Besides providing context to the aural character of the area, the sound level monitoring provided the opportunity to assess the existing attenuation between the reference microphones, positioned close to the Route 7 interchange, and the proxy Orchard Monitor. In the context of this memo, “total attenuation” is defined as the difference in source sound levels and the Orchard Monitor. The total attenuation, determined from monitored sound levels, provided the ability to determine the representative conditions at the site.

To look at the difference in sound level between the reference locations and the Orchard Monitor, we considered time periods where two conditions were met:

- 1) There was traffic noise present at the reference microphones, and
- 2) There was not extraneous (non-traffic) noise at the Orchard Monitor.

When those two conditions are met, we calculated a range of attenuation values that occurred at the site as shown in Table 2. These ranges provided guidance for determining site-specific model inputs including ground absorption and canopy height. Note that the long-term daytime and nighttime averages ( $LA_{eq}$ ) presented in Table 1 only show a nine and eleven decibel difference between the monitors, respectively.

**TABLE 2. RANGE OF TOTAL ATTENUATION OBSERVED FROM MONITORING RESULTS BETWEEN EACH TRAFFIC REFERENCE MONITOR AND THE ORCHARD MONITOR**

| <i>Total Attenuation<br/>(dB)</i> | <b>Calculated from Monitoring</b> |                |
|-----------------------------------|-----------------------------------|----------------|
|                                   | <b>Minimum</b>                    | <b>Maximum</b> |
| <i>Ramp Monitor</i>               | 11                                | 21             |
| <i>North Monitor</i>              | 12                                | 17             |
| <i>Mid Monitor</i>                | 12                                | 18             |
| <i>South Monitor</i>              | 8                                 | 14             |

### MODELING METHODOLOGY

ISO 9613-2 is commonly used to model outdoor sound propagation, which is applicable to a wide variety of sources and environments. The ISO standard states:

This part of ISO 9613 specifies an engineering method for calculating the attenuation of sound during propagation outdoors in order to predict the levels of environmental noise at a distance from a variety of sources. The method predicts the equivalent continuous A-weighted sound pressure level ... under meteorological conditions favorable to propagation from sources of known sound emissions. These conditions are for downwind propagation ... or, equivalently, propagation under a well-developed moderate ground-based temperature inversion, such as commonly occurs at night.

Standard modeling methodology per ISO 9613-2 takes into account source sound power levels, surface reflections and absorption, atmospheric absorption, geometric divergence, meteorological conditions, walls, barriers, berms, terrain, and moderate downwind conditions. CadnaA®, from Datakustik GmbH, was utilized to perform the analysis.

### Noise Sources

Traffic noise was represented by line sources in the model. Separate line sources were assigned to cars, medium trucks, and heavy trucks according to FHWA classification, which provides sound power levels based on speeds at specific heights above the roadway for each vehicle type. Each source is represented by two line sources: one at pavement height for the pavement/tire interaction and the other at engine or exhaust height. The available counts from VTrans on US Route 7 just north of Exit 1 (2015, 2016) report a vehicle mix of 89% cars, 8% medium trucks, and 4% heavy trucks<sup>2</sup>. The resulting sound powers, taken at 40 mph, were then calibrated to the overall average sound levels obtained from the long-term monitoring period data. The resulting line sources provided a representation of the conditions experienced during the monitoring period and provided a quantitative method to validate the model's prediction of sound attenuation between the reference microphone(s) and the Orchard Monitor.

### Spatial Input Parameters

Terrain in the model follows digital elevations obtained from the US Geological Survey and the proposed site grading modification on a small portion of the project site. The roadways of Route 7 and the associated Route 7 interchange were modeled as hard ground ( $G=0$ ) and the remaining ground was modeled as mixed-soft ground ( $G=0.7$ ). Representations of the nearby residential buildings were placed in the model according to their locations indicated on ortho-imagery. Atmospheric absorption was based on an atmosphere of 10°C (50°F) and 70% relative humidity.

### Forest Zones

A central part of the study included the definition of forest zones. The specific section of the standard that applies is from ISO 9613-2: Annex A. Foliage:

The foliage of trees and shrubs provides a small amount of attenuation, but only if it is sufficiently dense to completely block the view along the propagation path, i.e. when it is impossible to see a short distance through the foliage. The attenuation may be by vegetation close to the source, or close to the receiver, or by both situations.

**TABLE 3. OCTAVE-BAND ATTENUATION OF SOUND THROUGH DENSE VEGETATION (REPRODUCTION OF TABLE A.1 FROM ISO 9613-2)**

| <i>Propagation Distance</i> <sup>3</sup> | Units | 63 Hz | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | 8 kHz |
|------------------------------------------|-------|-------|--------|--------|--------|-------|-------|-------|-------|
| 10 – 20 meters                           | dB    | 0     | 0      | 1      | 1      | 1     | 1     | 2     | 3     |
| 20 meters+                               | dB/m  | 0.02  | 0.03   | 0.04   | 0.05   | 0.06  | 0.08  | 0.09  | 0.12  |

<sup>2</sup> VTrans count station B233

<sup>3</sup> The propagation distance is the curved downwind propagation path between the two points, which is estimated by the arc-length between two points of a circle with a five kilometer radius.

### Model Calibration

In the model, a discrete receiver was positioned at each location monitoring location. Unless otherwise noted, all reported sound levels from the model were calculated at the microphone height of 1.5 meters (5 feet). While onsite and in the forest, we estimated a common canopy height for most dominant tree types at 14 to 16 meters (45 to 53 feet). Some areas were covered in invasive understory growth, while other areas were populated with mostly mature trees and little understory growth. In the model, tree heights above 10 meters produced more attenuation than was typically observed during the monitoring. Nonetheless, the estimated actual forest height of 15 meters was used, which provides a conservative analysis. The resulting values of total attenuation observed during monitoring and calculated by the model at the monitor locations are presented in Table 4. Higher values of total attenuation characterize the forest as more absorptive, leading to larger changes in sound levels when considering the clearing of a portion of the forest.

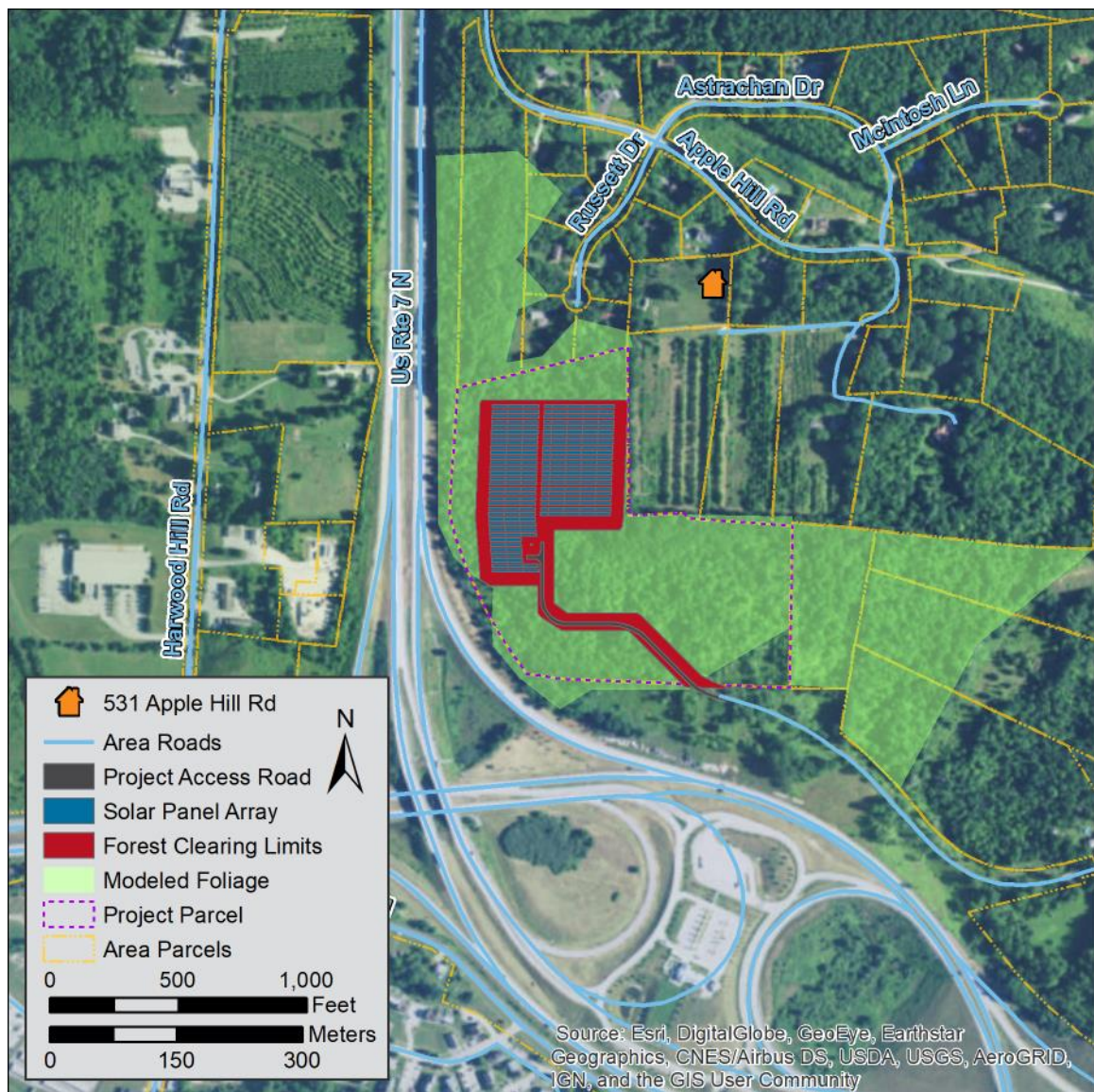


FIGURE 5. MAP OF FOREST ZONES USED IN THE MODEL.

**TABLE 4. TOTAL ATTENUATION OBSERVED FROM MONITORING RESULTS COMPARED TO THE SAME MEASURE CALCULATED BY THE MODEL**

| <i>Total Attenuation<br/>(dB)</i> | <b>Calculated from Monitoring</b> |                | <b>Value in<br/>Model</b> |
|-----------------------------------|-----------------------------------|----------------|---------------------------|
|                                   | <b>Minimum</b>                    | <b>Maximum</b> |                           |
| <i>Ramp Monitor</i>               | 11                                | 21             | 18                        |
| <i>North Monitor</i>              | 12                                | 17             | 17                        |
| <i>Mid Monitor</i>                | 12                                | 18             | 15                        |
| <i>South Monitor</i>              | 9                                 | 14             | 17                        |

### ***Model Results***

Changes in sound levels were explored for discrete receivers at three key locations and as a grid surrounding the immediate project area. The three key locations examined were the Orchard Monitor location, the center of the southern property line of 531 Apple Hill Road, and the second story of the residence at 531 Apple Hill Road (the “Residence”) at 4 meters (13 feet) above ground level.

Spectral attenuation provided by the existing foliage at the three key locations is listed in Table 5. Note that 8 kHz is excluded because the model indicated that such high frequency noise from the highway did not reach the discrete receivers, i.e. all high-frequency energy produced by the traffic above the 4 kHz 1/3-octave band was attenuated by the forest, ground, and/or atmosphere prior to reaching the discrete receivers. Table 6 represents the spectral attenuation provided by the retained forest in the model. The data in Table 5 and Table 6 are reproduced in graphical format in Figure 6.

The change in sound levels from highway noise sources are presented for the surrounding area in Figure 7. The iso-dB contour lines represent the change in A-weighted sound levels from the existing forest conditions to the proposed forest conditions. The existing forest condition included the “Modeled Foliage” and “Project Clearing Limits” shown on the maps in Figure 5 and Figure 7. The scenario for the removal of 9.6 acres of forest required for the Chelsea Solar Project included only the “Modeled Foliage.”

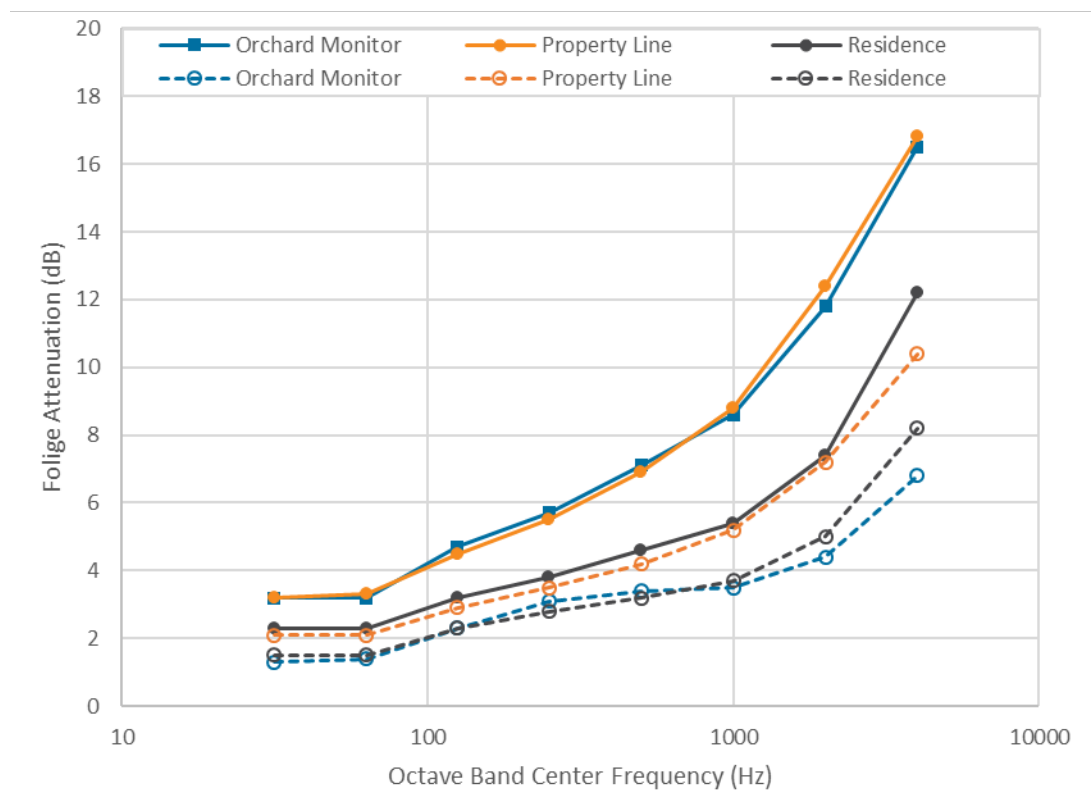
The largest change in sound levels from highway noise that could result from the removal of forest within the “Project Clearing Limits” is centered on the northeastern portion of the proposed solar array. The model predicted that the greatest change at any location on a neighboring residential parcel is about 4 dB. The maximum predicted change at any residence is less than 3 dB. Note that these results do not include the potential acoustical attenuation and scattering from the solar panels. The introduction of ground-mounted solar panels to the propagation path of traffic noise would likely increase the attenuation represented by the open ground in the model. The quantitative ability of ground-mounted solar panel arrays to impede propagating sound is unknown and would vary considerably in relation to the orientation of the panels and propagation direction. These effects were excluded from the analysis and thus the results represent a maximum possible change under the conditions tested.

**TABLE 5. ESTIMATED OCTAVE BAND ATTENUATION PROVIDED BY THE FOREST FOR HIGHWAY NOISE AT EACH LOCATION, UNDER EXISTING CONDITIONS**

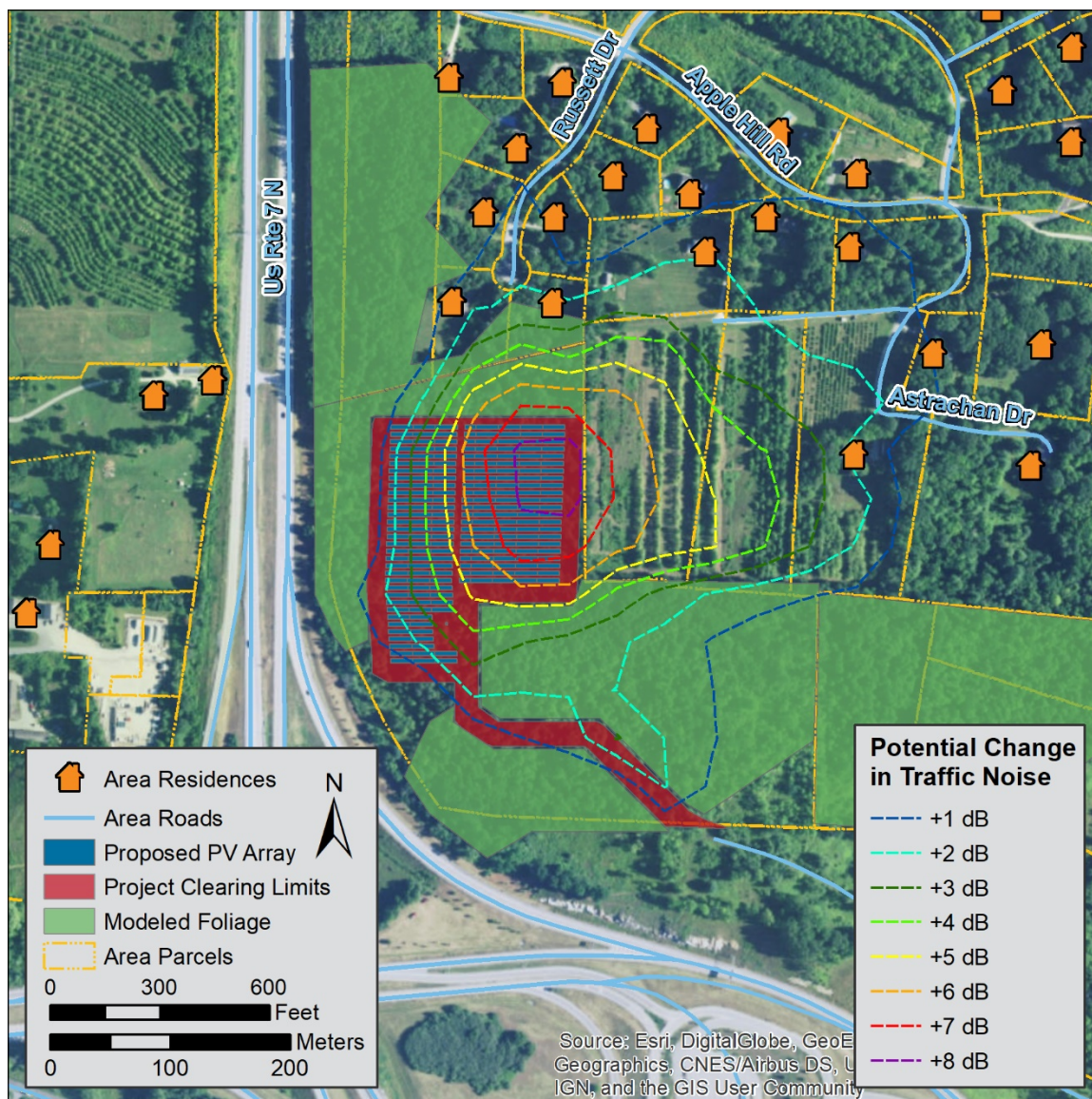
| Attenuation (dB) | 31.5<br>Hz | 63<br>Hz | 125<br>Hz | 250<br>Hz | 500<br>Hz | 1<br>kHz | 2<br>kHz | 4<br>kHz |
|------------------|------------|----------|-----------|-----------|-----------|----------|----------|----------|
| Orchard Monitor  | 3          | 3        | 5         | 6         | 7         | 9        | 12       | 17       |
| Property Line    | 3          | 3        | 5         | 6         | 7         | 9        | 12       | 17       |
| Residence        | 2          | 2        | 3         | 4         | 5         | 5        | 7        | 12       |

**TABLE 6. ESTIMATED OCTAVE BAND ATTENUATION PROVIDED BY THE FOREST FOR HIGHWAY NOISE AT EACH LOCATION, WITH THE PROPOSED FOREST CLEARING**

| Attenuation (dB) | 31.5<br>Hz | 63<br>Hz | 125<br>Hz | 250<br>Hz | 500<br>Hz | 1<br>kHz | 2<br>kHz | 4<br>kHz |
|------------------|------------|----------|-----------|-----------|-----------|----------|----------|----------|
| Orchard Monitor  | 1          | 1        | 2         | 3         | 3         | 4        | 4        | 7        |
| Property Line    | 2          | 2        | 3         | 4         | 4         | 5        | 7        | 10       |
| Residence        | 2          | 2        | 2         | 3         | 3         | 4        | 5        | 8        |



**FIGURE 6. ATTENUATION PROVIDED BY FOILAGE AT THE DISCRETE RECEIVERS. THE SOLID LINES REPRESENT EXISTING FOREST ATTENUATION AND THE DAHSED LINES REPRESENT FOREST ATTENUATION WITH JUST UNDER 10 ACRES OF FOREST ARE REMOVED FOR THE PROJECT.**



**FIGURE 7. CHANGE IN SOUND LEVELS OF HIGHWAY NOISE SOURCES CAUSED BY THE CLEARING OF TREES PROPOSED FOR THE PROJECT.**

## DISCUSSION

Sound levels at the site change over the course of the year due to traffic volume fluctuations, pavement condition, meteorological cycles, and seasonal forest composition, among other things. This study was performed during the early spring when the snow cover was gone but leaves were still not back on the trees. Therefore, the attenuation provided by the forest was likely less, to some extent, than in the summer, for instance, when there would be leaves on the trees and the change in sound levels may be greater than reported here. The model did predict total attenuation values on the higher side of the observed range, which biases the results closer to the leaf-on scenario. Regardless, the change in sound level from a different time of year may be slightly more or slightly less than determined in this study, but the resulting levels with the trees removed would likely be quite similar with comparable traffic volumes and meteorological conditions.

Although traffic noise was the dominant source, the measured sound levels were not purely a result of the traffic noise. The model assumes that the predicted sound level is comprised entirely by traffic noise, leading to the potential of over-estimating the effect on any time-averaged level.

### ***Regulatory Context and Practical Implications***

The modeled increase in traffic sound levels at the property line of 531 Apple Hill Road, resulting from the removal of trees for the Project, is 3 dB. The maximum change at any other residential property line is 4 dB. The modeled increase in traffic sound levels at all residences in the area is projected to be less than 3 dB.

For context, a doubling of one's perceived loudness of a sound is produced with a 10 dB increase, a change of 3 dB in broadband sound levels is just perceptible by most people, and less than 3 dB of change is typically imperceptible. For comparison with traffic noise policy, a "substantial noise increase" is defined in the Vermont Agency of Transportation (VTrans) Noise Analysis and Abatement Policy<sup>5</sup> as an increase of "15 dB(A) above the existing noise level." The 3 dB or 4 dB increase at a property line would not be considered a "substantial noise increase" per VTrans Policy.

In addition, the average sound levels at 531 Apple Hill Road and the surrounding residences are below the levels for which VTrans would consider implementing noise mitigation. For example, the maximum  $L_{eq1-hr}$  measured during the long-term monitoring period at the Orchard Monitor was 53 dBA. The maximum  $L_{eq1-hr}$  was likely lower on the 531 Apple Hill Road parcel than measured at the Orchard Monitor parcel because it was farther from the highway than the monitoring location. Nonetheless, projecting an increase of 3 dB over the maximum monitored one-hour average level from the Orchard Monitor location produces a maximum one-hour equivalent sound level of 56 dBA. This is more than 10 dB below the VTrans Noise Abatement Criteria for residential land uses (67 dBA  $L_{eq1-hr}$ ), which is the level for which they would consider implementing noise mitigation for Type I highway projects.

### **SUMMARY**

The conclusions of the study are as follows:

- Traffic noise attenuation across the Project parcel is constantly changing due to factors such as source type, meteorology, and season.
- The existing total attenuation from the roadway to the property of interest is between 9 and 21 dB, depending on what section of roadway the sound is coming from and the other previously stated factors
- The sound propagation model indicated that the removal of the trees for the proposed solar project could result in an increase of 3 dB increase at the southern property line of 531 Apple Hill Road and a 1.6 dB increase at the second story of the residence.
- The estimated increase at all residences in the area is predicted to be less than 3 dB: a 3 dB increase in broadband sound levels is just perceptible by most people and the change in sound levels is not considered substantial by VTrans nor is the overall sound level considered actionable by VTrans.

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<sup>5</sup> VTrans, Noise Analysis and Abatement Policy, July 13, 2011.

## APPENDIX A: MONITORING LOCATION PICTURES

This section provides photographs of each monitoring location used for collecting acoustic and wind data.



FIGURE A 1. ORCHARD MONITORING LOCATION, LOOKING SOUTH



FIGURE A 2. RAMP MONITORING LOCATION, LOOKING SOUTHWEST



FIGURE A 3. SOUTH MONITORING LOCATION, LOOKING SOUTH



FIGURE A 4. MID MONITORING LOCATION, LOOKING SOUTHWEST



FIGURE A 5. NORTH MONITORING LOCATION, LOOKING WEST

## APPENDIX B: SOUND PRIMER

Sound consists of tiny, repeating fluctuations in ambient air pressure. The strength, or amplitude, of these fluctuations determines the sound pressure level (SPL). “Noise” can be defined as “a sound of any kind, especially when loud, confused, indistinct, or disagreeable.”

### *Expressing Sound in Decibel Levels*

The varying air pressure that constitutes sound can be characterized in many different ways. The human ear is the basis for the metrics that are used in acoustics. Normal human hearing is sensitive to sound fluctuations over an enormous range of pressures, from about 20 micropascals (the “threshold of audibility”) to about 20 pascals (the “threshold of pain”).<sup>7</sup> This factor of one million in sound pressure difference is challenging to convey in engineering units. Instead, sound pressure is converted to sound “levels” in units of “decibels” (dB, named after Alexander Graham Bell). Once a measured sound is converted to dB, it is denoted as a level with the letter “L”.

The conversion from sound pressure in pascals to sound level in dB is a four-step process. First, the sound wave’s measured amplitude is squared and the mean is taken. Second, a ratio is taken between the mean square sound pressure and the square of the threshold of audibility (20 micropascals). Third, using the logarithm function, the ratio is converted to factors of 10. The final result is multiplied by 10 to give the decibel level. By this decibel scale, sound levels range from 0 dB at the threshold of audibility to 120 dB at the threshold of pain.

Typical sources of noise, and their sound pressure levels, are listed on the scale in Figure 8.

### *Human Response to Sound Levels: Apparent Loudness*

For every 20 dB increase in sound level, the sound pressure increases by a *factor* of 10; the sound *level* range from 0 dB to 120 dB covers 6 factors of 10, or one million, in sound *pressure*. However, for an increase of 10 dB in sound *level* as measured by a meter, humans perceive an approximate doubling of apparent loudness: to the human ear, a sound level of 70 dB sounds about “twice as loud” as a sound level of 60 dB. Smaller changes in sound level, less than 3 dB up or down, are generally not perceptible.

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<sup>7</sup> The pascal is a measure of pressure in the metric system. In Imperial units, they are themselves very small: one pascal is only 145 millionths of a pound per square inch (psi). The sound pressure at the threshold of audibility is only 3 one-billionths of one psi; at the threshold of pain, it is about 3 one-thousandths of one psi.

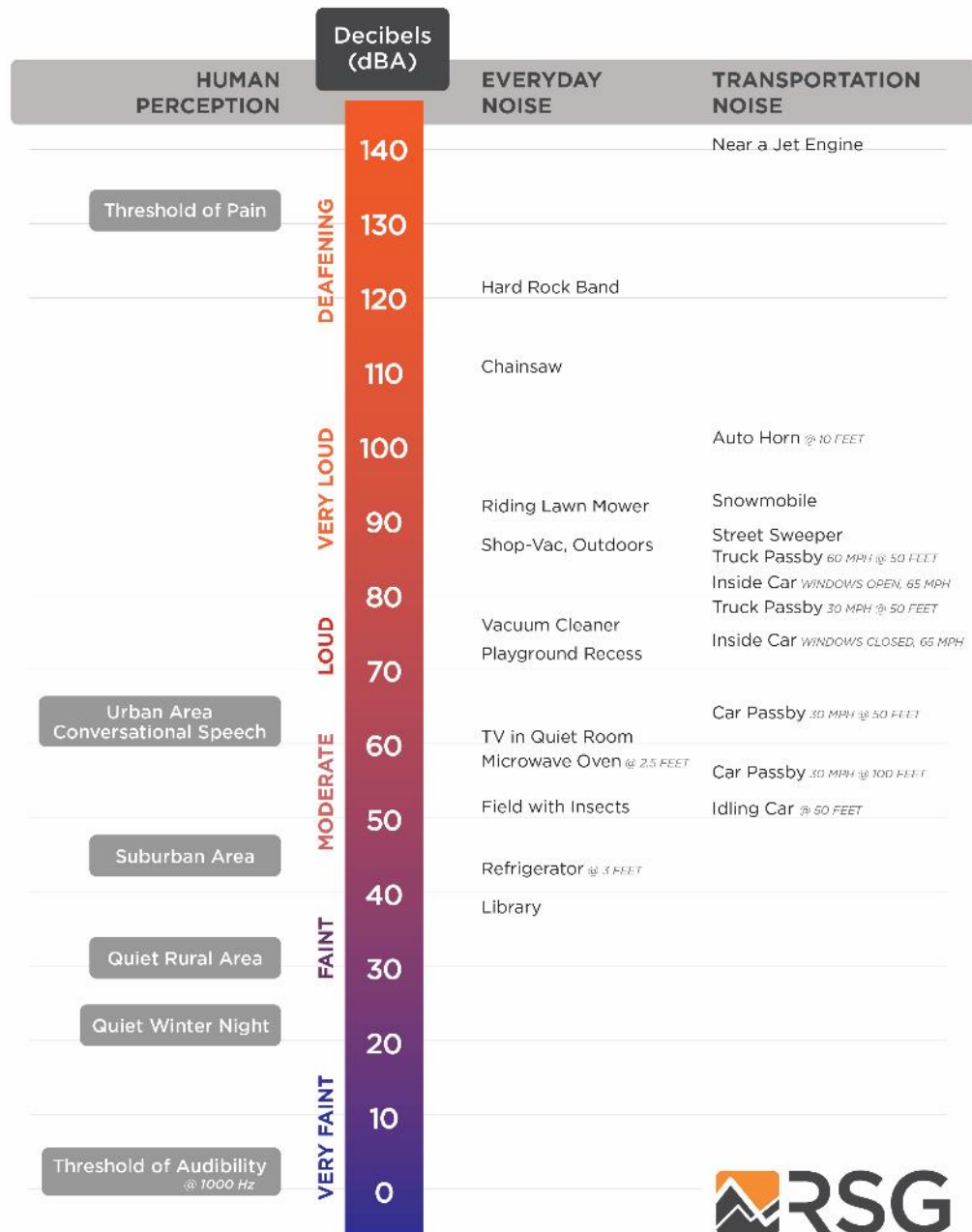


FIGURE 8: A SCALE OF SOUND PRESSURE LEVELS FOR TYPICAL NOISE SOURCES

### Frequency Spectrum of Sound

The “frequency” of a sound is the rate at which it fluctuates in time, expressed in Hertz (Hz), or cycles per second. Very few sounds occur at only one frequency: most sound contains energy at many different frequencies, and it can be broken down into different frequency divisions, or bands. These bands are similar to musical pitches, from low tones to high tones. The most common division is the standard octave band. An octave is the range of frequencies whose upper frequency limit is twice its lower frequency limit, exactly like an octave in music. An octave band is identified by its

center frequency: each successive band's center frequency is twice as high (one octave) as the previous band. For example, the 500 Hz octave band includes all sound whose frequencies range between 354 Hz (Hertz, or cycles per second) and 707 Hz. The next band is centered at 1,000 Hz with a range between 707 Hz and 1,414 Hz. The range of human hearing is divided into 10 standard octave bands: 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz, 8,000 Hz, and 16,000 Hz. For analyses that require finer frequency detail, each octave-band can be subdivided. A commonly-used subdivision creates three smaller bands within each octave band, or so-called 1/3-octave bands.

### ***Human Response to Frequency: Weighting of Sound Levels***

The human ear is not equally sensitive to sounds of all frequencies. Sounds at some frequencies seem louder than others, despite having the same decibel level as measured by a sound level meter. In particular, human hearing is much more sensitive to medium pitches (from about 500 Hz to about 4,000 Hz) than to very low or very high pitches. For example, a tone measuring 80 dB at 500 Hz (a medium pitch) sounds quite a bit louder than a tone measuring 80 dB at 60 Hz (a very low pitch). The frequency response of normal human hearing ranges from 20 Hz to 20,000 Hz. Below 20 Hz, sound pressure fluctuations are not “heard”, but sometimes can be “felt”. This is known as “infrasound”. Likewise, above 20,000 Hz, sound can no longer be heard by humans; this is known as “ultrasound”. As humans age, they tend to lose the ability to hear higher frequencies first; many adults do not hear very well above about 16,000 Hz. Most natural and man-made sound occurs in the range from about 40 Hz to about 4,000 Hz. Some insects and birdsongs reach to about 8,000 Hz.

To adjust measured sound pressure levels so that they mimic human hearing response, sound level meters apply filters, known as “frequency weightings”, to the signals. There are several defined weighting scales, including “A”, “B”, “C”, “D”, “G”, and “Z”. The most common weighting scale used in environmental noise analysis and regulation is A-weighting. This weighting represents the sensitivity of the human ear to sounds of low to moderate level. It attenuates sounds with frequencies below 1000 Hz and above 4000 Hz; it amplifies very slightly sounds between 1000 Hz and 4000 Hz, where the human ear is particularly sensitive. The C-weighting scale is sometimes used to describe louder sounds. The B- and D- scales are seldom used. All of these frequency weighting scales are normalized to the average human hearing response at 1000 Hz: at this frequency, the filters neither attenuate nor amplify. When a reported sound level has been filtered using a frequency weighting, the letter is appended to “dB”. For example, sound with A-weighting is usually denoted “dBA”. When no filtering is applied, the level is denoted “dB” or “dBZ”. The letter is also appended as a subscript to the level indicator “L”, for example “L<sub>A</sub>” for A-weighted levels.

### ***Time Response of Sound Level Meters***

Because sound levels can vary greatly from one moment to the next, the time over which sound is measured can influence the value of the levels reported. Often, sound is measured in real time, as it fluctuates. In this case, acousticians apply a so-called “time response” to the sound level meter, and this time response is often part of regulations for measuring noise. If the sound level is varying slowly, over a few seconds, “Slow” time response is applied, with a time constant of one second. If the sound level is varying quickly (for example, if brief events are mixed into the overall sound),

“Fast” time response can be applied, with a time constant of one-eighth of a second.<sup>8</sup> The time response setting for a sound level measurement is indicated with the subscript “S” for Slow and “F” for Fast:  $L_S$  or  $L_F$ . A sound level meter set to Fast time response will indicate higher sound levels than one set to Slow time response when brief events are mixed into the overall sound, because it can respond more quickly.

In some cases, the maximum sound level that can be generated by a source is of concern. Likewise, the minimum sound level occurring during a monitoring period may be required. To measure these, the sound level meter can be set to capture and hold the highest and lowest levels measured during a given monitoring period. This is represented by the subscript “max”, denoted as “ $L_{max}$ ”. One can define a “max” level with Fast response  $L_{Fmax}$  (1/8-second time constant), Slow time response  $L_{Smax}$  (1-second time constant), or Continuous Equivalent level over a specified time period  $L_{EQmax}$ . Note that, in the precedents set by the former Environmental Board under Vermont Act 250, the time response is not specified, but in the Barre Granite case which set the 55 dBA  $L_{max}$  precedent the metric  $L_{Smax}$  (a 1-second response time) was used. Since that time, maximum  $L_{eq}$  1-second has also been used as it is comparable to the  $L_{Smax}$ .

### ***Accounting for Changes in Sound over Time***

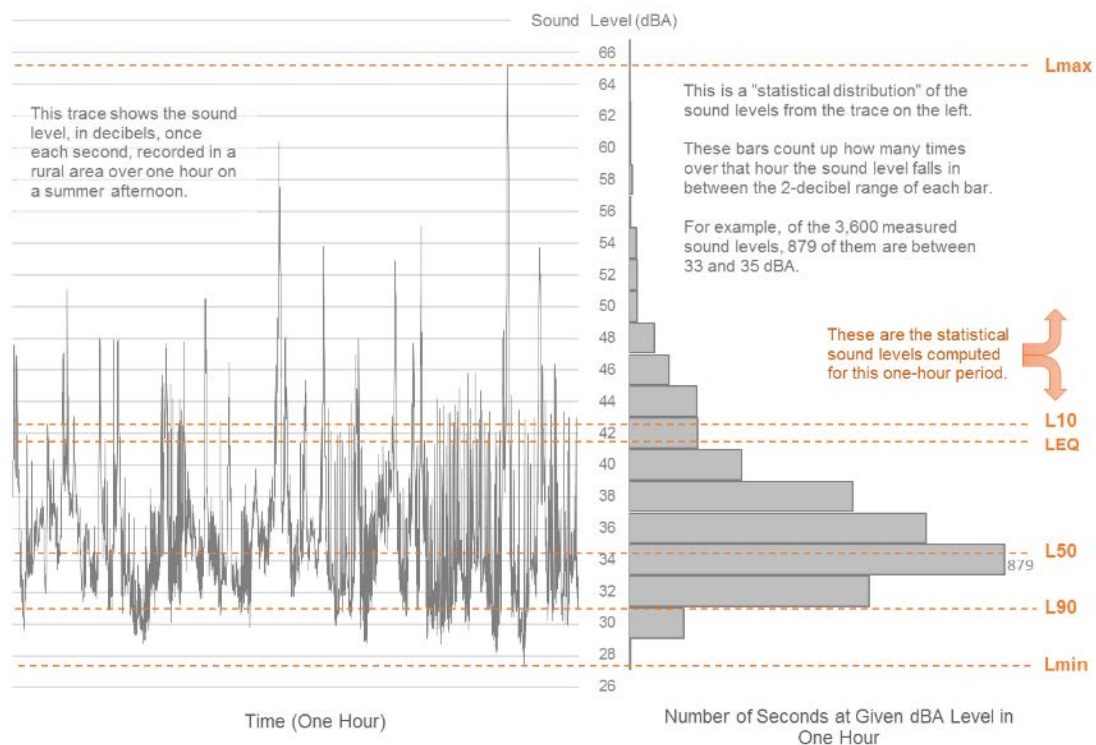
A sound level meter’s time response settings are useful for continuous monitoring. However, they are less useful in summarizing sound levels over longer periods. To do so, acousticians apply simple statistics to the measured sound levels, resulting in a set of defined types of sound level related to averages over time. An example is shown in Figure 9. The sound level at each instant of time is the grey trace going from left to right. Over the total time it was measured, the sound energy spends certain fractions of time near various levels, ranging from the minimum (about 28 dB in the figure) to the maximum (about 65 dB in the figure). The simplest descriptor is the average sound level, known as the Equivalent Continuous Sound Level. Statistical levels are used to determine for what percentage of time the sound is louder than any given level. These levels are described in the following sections.

### ***Equivalent Continuous Sound Level - $L_{eq}$***

One straightforward, common way of describing sound levels is in terms of the Continuous Equivalent Sound Level, or  $L_{eq}$ . The  $L_{eq}$  is the average sound pressure level over a defined period of time, such as one hour or one day.  $L_{eq}$  is the most commonly used descriptor in noise standards and regulations.  $L_{eq}$  is representative of the overall sound to which a person is exposed. Because of the logarithmic calculation of decibels,  $L_{eq}$  tends to favor higher sound levels: loud and infrequent sources have a larger impact on the resulting average sound level than quieter but more frequent noises. For example, in Figure 9, even though the sound levels spends most of the time near about 34 dBA, the  $L_{eq}$  is 41 dBA, having been “inflated” by the maximum level of 65 dBA.

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<sup>8</sup> There is a third time response defined by standards, the “Impulse” response. This response was defined to enable use of older, analog meters when measuring very brief noises; it is no longer in common use.



**FIGURE 9: EXAMPLE OF DESCRIPTIVE TERMS OF SOUND MEASUREMENT OVER TIME**

### ***Percentile Sound Levels – $L_n$***

Percentile sound levels describe the statistical distribution of sound levels over time. “ $L_N$ ” is the level above which the sound spends “ $N$ ” percent of the time. For example,  $L_{90}$  (sometimes called the “residual base level”) is the sound level exceeded 90% of the time: the sound is louder than  $L_{90}$  most of the time.  $L_{10}$  is the sound level that is exceeded only 10% of the time.  $L_{50}$  (the “median level”) is exceeded 50% of the time: half of the time the sound is louder than  $L_{50}$ , and half the time it is quieter than  $L_{50}$ . Note that  $L_{50}$  (median) and  $L_{eq}$  (mean) are not always the same, for reasons described in the previous section.

$L_{90}$  is often a good representation of the “ambient sound” in an area. This is the sound that persists for longer periods, and below which the overall sound level seldom falls. It tends to filter out other short-term environmental sounds that aren’t part of the source being investigated.  $L_{10}$  represents the higher, but less frequent, sound levels. These could include such events as barking dogs, vehicles driving by and aircraft flying overhead, gusts of wind, and work operations.  $L_{90}$  represents the background sound that is present when these event noises are excluded.

Note that if one sound source is very constant and dominates the noise in an area, all of the descriptive sound levels mentioned here tend toward the same value. It is when the sound is varying widely from one moment to the next that the statistical descriptors are useful.

### ***Sound Levels from Multiple Sources: Adding Decibels***

Because of the way that sound levels in decibels are calculated, the sounds from more than one source do not add arithmetically. Instead, two sound sources that are the same decibel level increase the total sound level by 3 dB. For example, suppose the sound from an industrial blower registers 80 dB at a distance of 2 meters (6.6 feet). If a second industrial blower is operated next to the first one, the sound level from both machines will be 83 dB, not 160 dB. Adding two more blowers (a total of four) raises the sound level another 3 dB to 86 dB. Finally, adding four more blowers (a total of eight) raises the sound level to 89 dB. It would take eight total blowers, running together, for a person to judge the sound as having “doubled in loudness”.

Recall from the explanation of sound levels that a difference of 10 decibels is a factor of 20 in sound pressure and a factor of 10 in sound power. (The difference between sound pressure and sound power is described in the next Section.) If two sources of sound differ individually by 10 decibels, the louder of the two is generating *ten times* more sound. This means that the loudest source(s) in any situation always dominates the total sound level. Looking again at the industrial blower running at 80 decibels, if a small ventilator fan whose level alone is 70 decibels were operated next to the industrial blower, the total sound level increases by only 0.4 decibels, to 80.4 decibels. The small fan is only 10% as loud as the industrial blower, so the larger blower completely dominates the total sound level.

### ***The Difference between Sound Pressure and Sound Power***

The human ear and microphones respond to variations in sound *pressure*. However, in characterizing the sound emitted by a specific source, it is proper to refer to sound *power*. While sound pressure induced by a source can vary with distance and conditions, the power is the same for the source under all conditions, regardless of the surroundings or the distance to the nearest listener. In this way, sound power levels are used to characterize noise sources because they act like a “fingerprint” of the source. An analogy can be made to light bulbs. The bulb emits a constant amount of light under all conditions, but its perceived brightness diminishes as one moves away from it.

Both sound power and sound pressure levels are described in terms of decibels, but they are not the same thing. Decibels of sound pressure are related to 20 micropascals, as explained at the beginning of this primer. Sound power is a measure of the acoustic power emitted or radiated by a source; its decibels are relative to one picowatt.

### ***Sound Propagation Outdoors***

As a listener moves away from a source of sound, the sound level decreases due to “geometrical divergence”: the sound waves spread outward like ripples in a pond and lose energy. For a sound source that is compact in size, the received sound level diminishes or attenuates by 6 dB for every doubling of distance: a sound whose level is measured as 70 dBA at 100 feet from a source will have a measured level of 64 dBA at 200 feet from the source and 58 dBA at 400 feet. Other factors, such as walls, berms, buildings, terrain, atmospheric absorption, and intervening vegetation will also further reduce the sound level reaching the listener.

The type of ground over which sound is propagating can have a strong influence on sound levels. Harder ground, pavement, and open water are very reflective, while soft ground, snow cover, or

grass is more absorptive. In general, sounds of higher frequency will attenuate more over a given distance than sounds of lower frequency: the “boom” of thunder can heard much further away than the initial “crack”.

Atmospheric and meteorological conditions can enhance or attenuate sound from a source in the direction of the listener. Wind blowing from the source toward the listener tends to enhance sound levels; wind blowing away from the listener toward the source tends to attenuate sound levels.

Normal temperature profiles (typical of a sunny day, where the air is warmer near the ground and gets colder with increasing altitude) tend to attenuate sound levels; inverted profiles (typical of nighttime and some overcast conditions) tend to enhance sound levels.

