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Compressor Station Noise Mapping Using Delaunay Triangulation and Natural-Neighbour Interpolation Techniques

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Abstract

Noise is generated at gas turbine-based compressor stations from a number of sources, including turbomachinery (gas turbines and compressors), airflow through inlet ducts and scrubbers, exhaust stacks, aerial coolers, and auxiliary systems. Understanding these noise sources is necessary to ensure that the working conditions on site are safe and that the audible noise at neighbouring properties is acceptable. Each noise source has different frequency content, and the overall sound pressure level (OSPL) at any location in the station yard or inside the compressor building is a multiple superposition of these noise sources. This paper presents results of multiple-point spectral noise measurements at three of TransCanada's compressor stations on the Alberta System. A method is described to determine the overall noise map of the station yard using Delaunay Triangulation and Natural-Neighbour Interpolation techniques. The results are presented in OSPL maps, as well as animated pictures of the sound pressure level (SPL) in frequency domain which will be shown on a video at the conference. The latter will be useful in future work to determine the culprit sources and the respective dominant frequency range that contributes the most to the overall OSPL.

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1.0 Introduction

Noise is generated at compressor stations from a number of sources, including turbomachinery (gas turbines and compressors), airflow through inlet ducts and filters, compressor building ventilation systems, gas scrubbers, exhaust stacks, aerial coolers, yard piping, control valves and auxiliary systems [1-6]. Several techniques are used in noise reduction depending on the source and frequency content of these noise sources. Common to these are close fitting acoustical unit enclosures which provide a significant reduction of casing radiated noise from the gas turbine driver. Acoustical rated compressor building can also be used to provide noise reduction not only of the gas turbine unit but also to control noise from other sources such as the compressor casing, interior piping and lube oil cooling skids. Gas turbine's casing radiated noise contribution as compared to the power turbine's exhaust noise contribution usually diminishes at distances greater than 0.5 km away. Then for residences more than 2.0 km away, the exhaust noise contribution is usually the sole remaining contributor [1].

Current computer noise modeling tools utilize three-dimensional topographical and construction/building databases and take into account numerous variables when performing noise calculations and predictions [2]. Among these variables are: equipment sound power levels (SPL), equipment noise source radiation type, equipment noise source elevation and radiation directivity, equipment size, geometric and physical location, building size, geometric and physical location, building wall and roof deck construction, temperature and relative humidity, ground cover, terrain elevations, topographic contours, noise control mitigation, distance dissipation parameter, ground attenuation, atmospheric absorption, barrier attenuation, wind effects, and temperature gradient effects. The output of these tools is commonly presented in isopleths which provide visual maps of potential noise impact or issues of a facility [1]. However, the main challenge with this approach is the degree of confidence in the prediction, given the enormity of the parameters required to perform these simulations and their respective uncertainties [3].

Understanding these noise sources is necessary to ensure that the working conditions on site are safe and that the audible noise at neighbouring properties is acceptable. Each noise source has different frequency content, and the overall sound pressure level (OSPL) at any location in the station yard or inside the compressor building is a multiple superposition of these noise sources. A selective detection measurement approach was suggested whereby sound emissions can be allocated to certain emission sources in a nearby plant, and hence allows for identifying cost-effective sound absorbing measures to reduce such noise [4].

The objective of this paper is to provide a novel technique to quantify and map the SPL not only as a function of location but, more importantly as a function of the individual frequency content for the purpose of determining the culprit sources and the respective dominant frequency range that contributes the most to the OSPL.

2.0 Methodology

The procedure described in this paper followed a heuristic approach in that it focused on a survey of noise sources at three compressors stations of different numbers and types of compressor units and drivers. It focused on the first aspect, which primarily involved mapping the noise sources at these stations as a first step to understand the nature and the spectral content of the various sound sources at these stations. Sound pressure measurements were taken at various locations in the yard and within each of the unit buildings at each site. One of the measurements is shown in progress in Figure 1, and the measurement locations at each station are shown in Figures 2–4, respectively. Note that a few of the measurements were taken with alternate power unit (APU) running.

The data were collected with a Brüel & Kjær instrument (B&K 7651), which passes the measured sound through a Hanning window and an FFT analyzer to obtain the sound spectra in dBA, which covered a range from 0 Hz to 16,384 Hz, in either 512 or 1024 bins of 32 or 16 Hz, respectively. One such spectrum is shown in Figure 5 as an example. The measurement of sound pressure level in units of dBA means that the data has been scaled using the standard A-weighting curve shown in Figure 6, which approximates the sensitivity of the human ear to different frequencies [7,8].

Figure 1: Measuring Sound with the B&K 7651

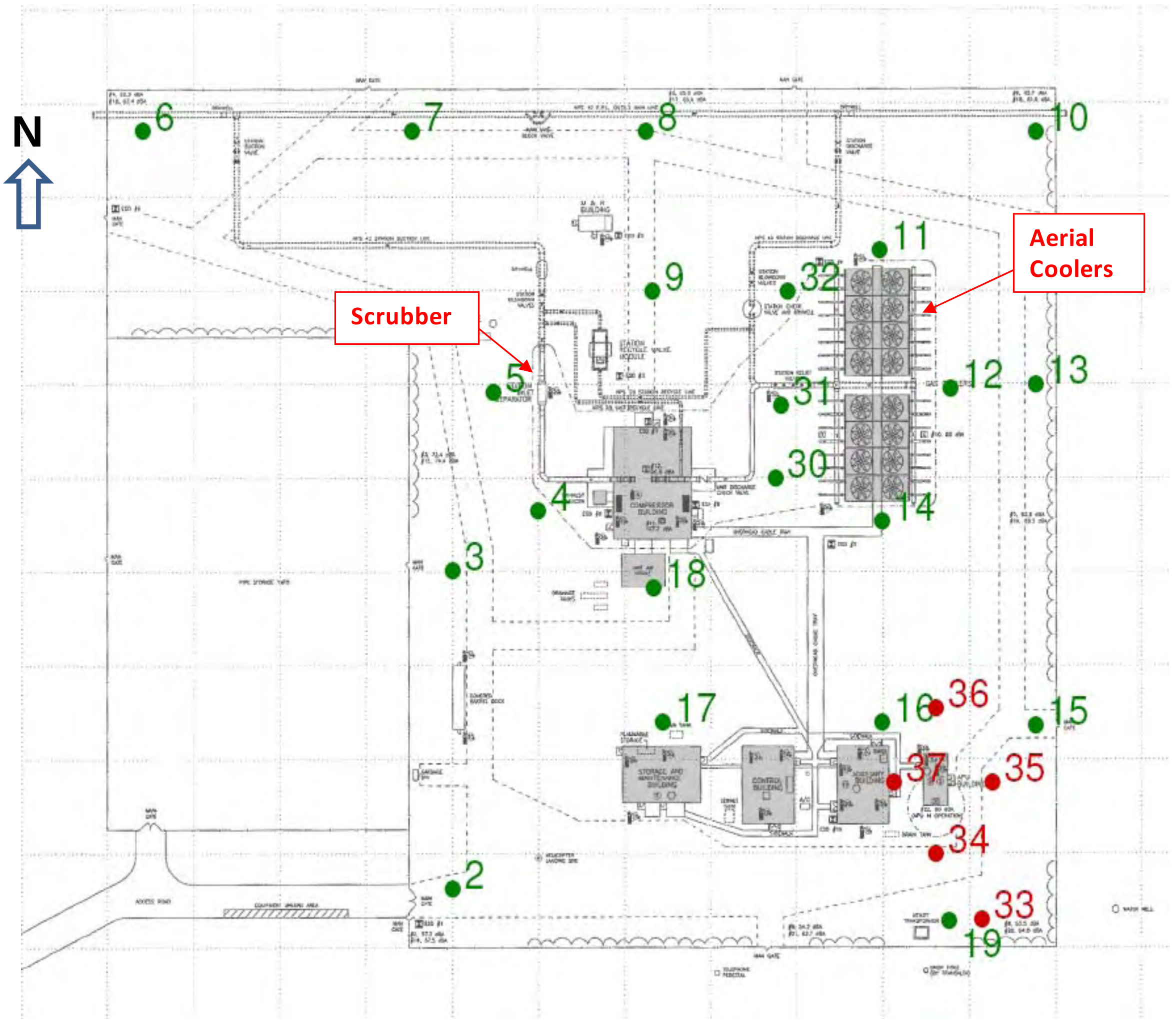


Figure 2: Measurement Locations at Compressor Station #1 (locations #33 through #37 were taken with the APU running).

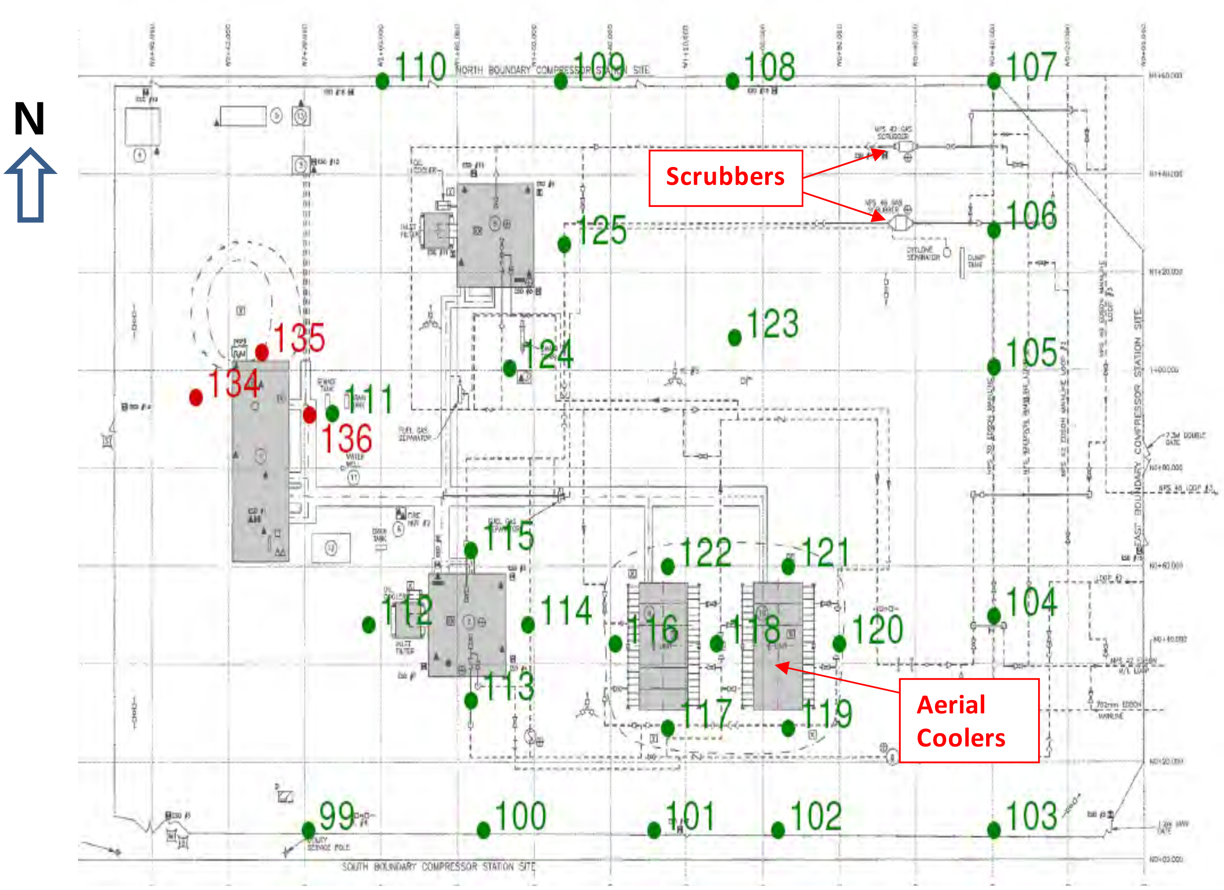


Figure 3: Measurement Locations at Compressor Station #2 (locations #134 through #136 were taken with the APU running).

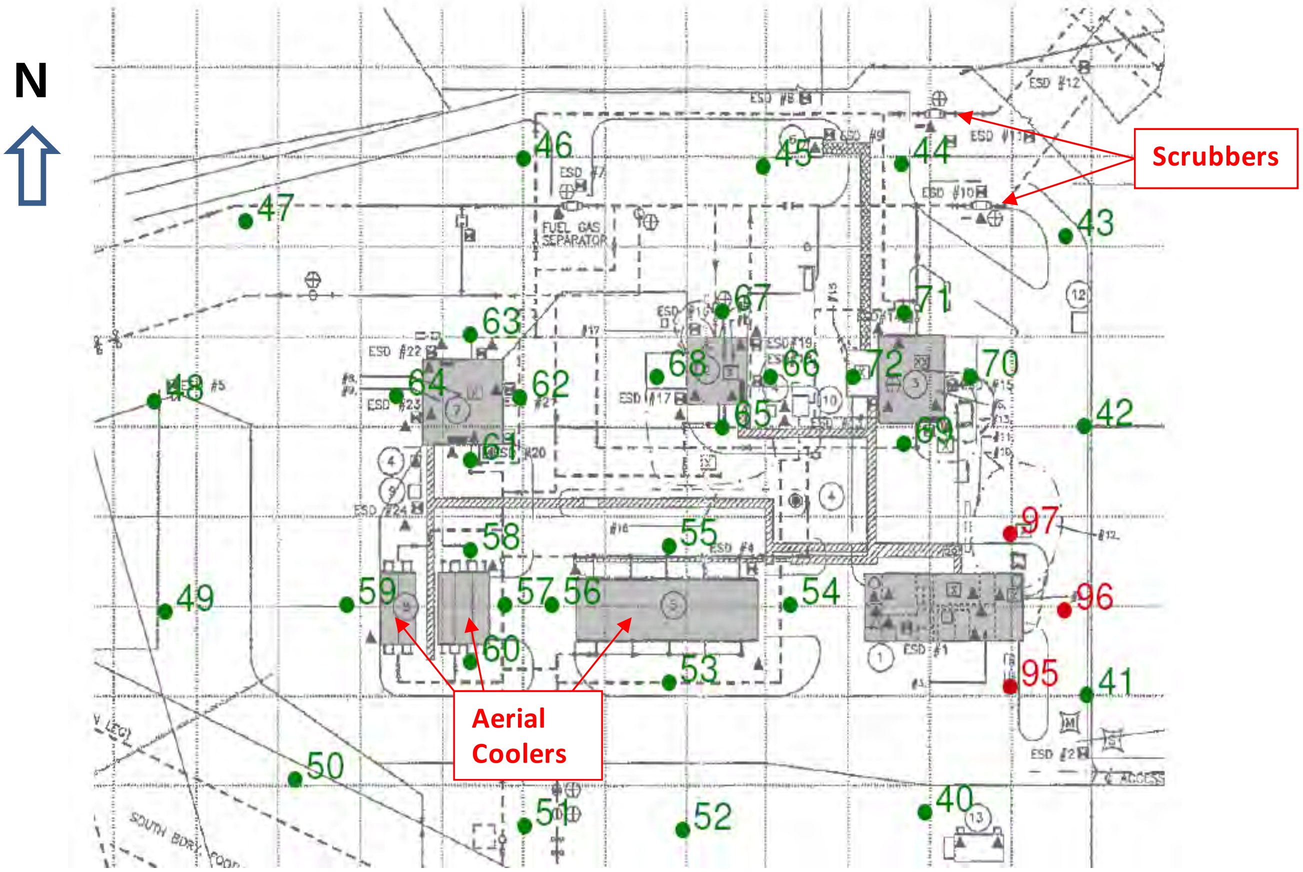


Figure 4: Measurement Locations at Compressor Station #3 (locations #95 through #97 were taken with the APU running).

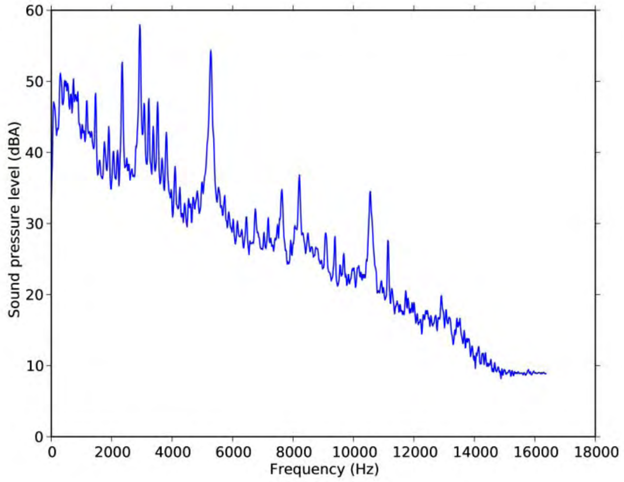


Figure 5: A Sound Spectrum Measured at Station #2 (Location 112) with 16-Hz Frequency Bins

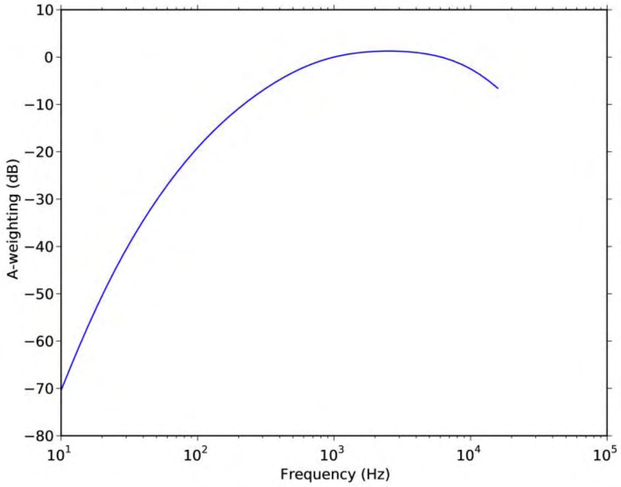


Figure 6: A-Weighting Curve Used to Approximate the Sensitivity of the Human Ear to Different Frequencies.

3.0 Data Analysis

The sound data was processed and analyzed using SciPy, an open-source library for the Python programming language [9]. Python is an attractive environment for data analysis because it is a high-level, dynamic, interpreted language with very clean syntax. The numeric and scientific libraries provide convenient and fast n-dimensional array manipulation tools and user-friendly access to industry-standard numerical routines. To allow for proper comparison, the spectra that were binned in 32-Hz intervals were re-sampled in 16-Hz intervals. This was achieved by replacing every bin with two sub-bins with the same total mean-square sound pressure. The size of the two sub-bins relative to each other was chosen to match the slope of the original spectral curve. This procedure allowed a smooth interpolation of sound spectrum while ensuring that if it were re-sampled in 32-Hz bins it would produce the original data.

This approach also maintained the overall mean-square sound pressure p_{rms} [7] at each measurement location:

$$p_{\mathrm{rms}}^2(\mathrm{overall}) = \sum_{i=1}^{n} p_n^2 \qquad (1)$$

where the sound pressure (p) and the sound level in dBA (Lp) are related by:

$$L_p = 10 \log\left(\frac{p}{p_{\mathrm{ref}}}\right)^2 \qquad (2)$$

Where $p_{ref} = 20\ \mu Pa$.

The sound measurement locations were chosen to capture the noise sources at each compressor station, but this resulted in an irregular grid of data.

In order to plot the sound contours, the data had to be spatially interpolated onto a regular grid. This was done by the Delaunay triangulation and natural-neighbour interpolation function in matplotlib, a 2D Python plotting library [9,10]. Delaunay triangulation is a technique for connecting unordered points with a set of triangles such that the largest angle in the triangulation is maximized, which avoids producing extremely slender triangles. Any location within the data set is then contained within a single triangle and an interpolated value can be found based on only the three neighbouring points. This produces an interpolated sound field that is continuous at all points and has a continuous gradient within each of the Delaunay triangles [11].

4.0 Results

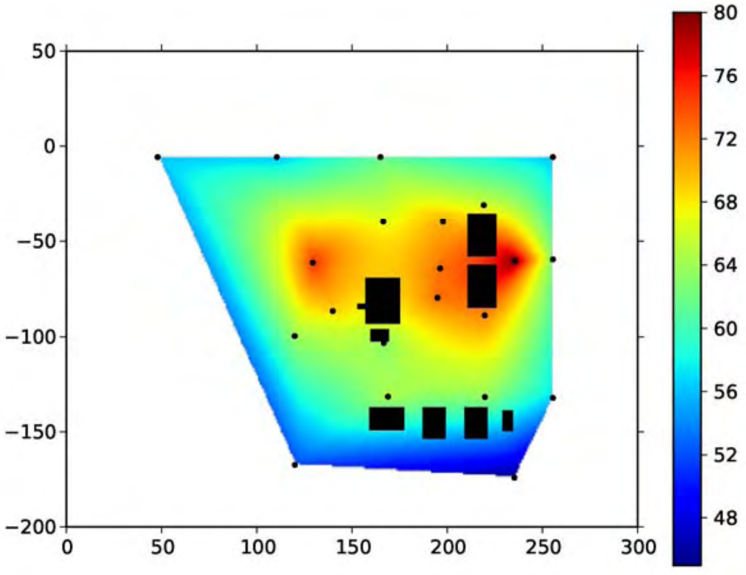
The overall sound pressure levels were calculated at each location, and the highest (maximum) and lowest (minimum) measured levels are reported for each compressor station in Table 1. The measured levels all fall below the threshold 85 dBA level that is permitted for an 8-hour exposure [8], but they are still significant.

Table 1: Summary of Measured Overall Sound Pressure Levels

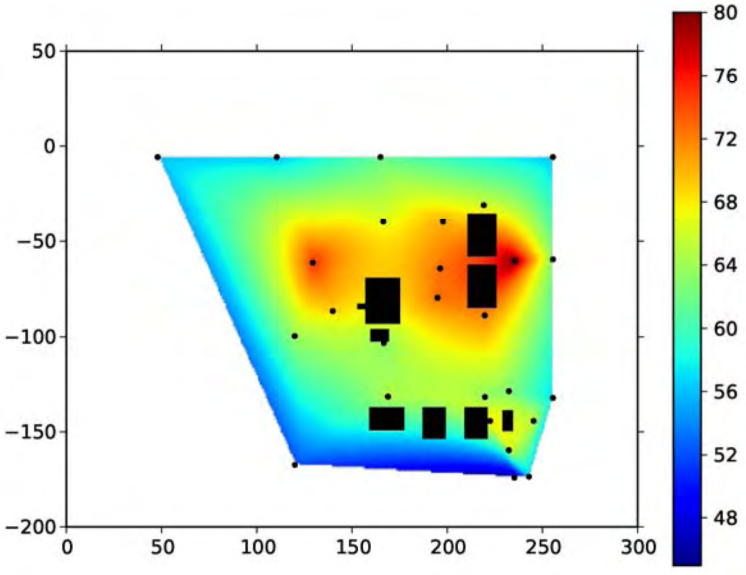
	Within the Station When APU not Operating	
	Min (dBA)	Maximum (dBA)
Station #1	45.5	79.8
Station #2	48.8	74
Station #3	52.6	78.3

	Around APU When Operating
	Maximum (dBA)
Station #1	68.3
Station #2	80
Station #3	80.7

The results of our spatial interpolation can be seen in Figure 7, which shows the overall mean-squared sound pressure levels at Station #1. The measurement locations and the buildings are shown and the axes denote distances in meters, as taken from the station drawings. The most prominent noise sources are the aerial coolers followed by the scrubber, which will be discussed further under the spectral noise results. Figure 7(a) shows all the data points that were taken without the APU. The colour contours are determined by the natural-neighbour interpolation, which results in values that are reasonable for much of the yard but which should not be taken literally. For example, the interpolation will never produce a higher SPL than the maximum measured value, even at locations that are closer to the noise source. This is because the interpolation is unaware of the locations or sizes of the noise sources. Figure 7(b) adds the measurements of the APU noise to the data, but the original data points are unmodified. This is a reasonable approximation for data points that are far from the APU, but produces some unrealistic gradients of SPL between the APU data points and the original data points. The figures are included because they serve to illustrate the intensity of the APU noise relative to the rest of the yard. At this station, the APU is not a major noise source. This is also shown in Table 1.

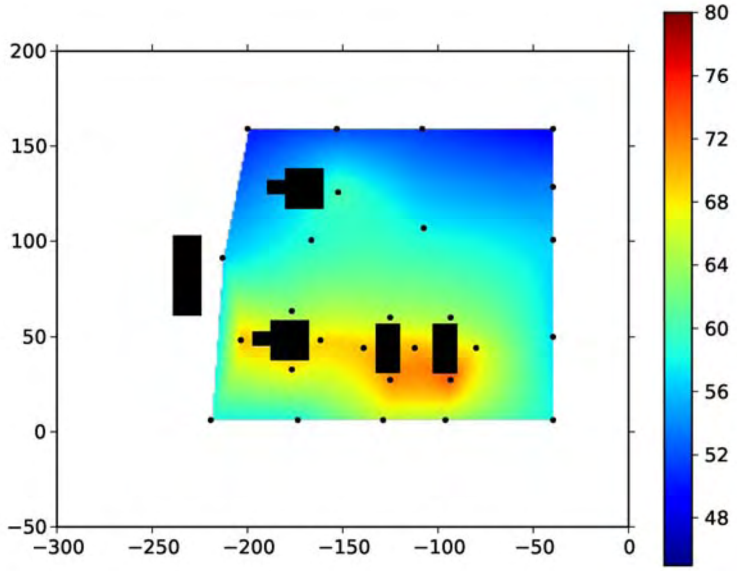


(a) No APU data

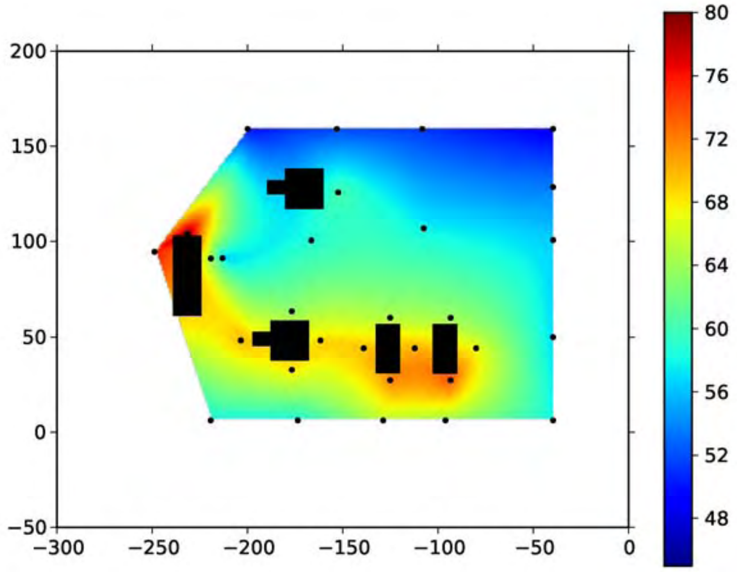


(b) APU locations added

Figure 7: Overall Sound Pressure Level (dBA) at Station #1 (Axes in meters, OSPL scale is in dBA).

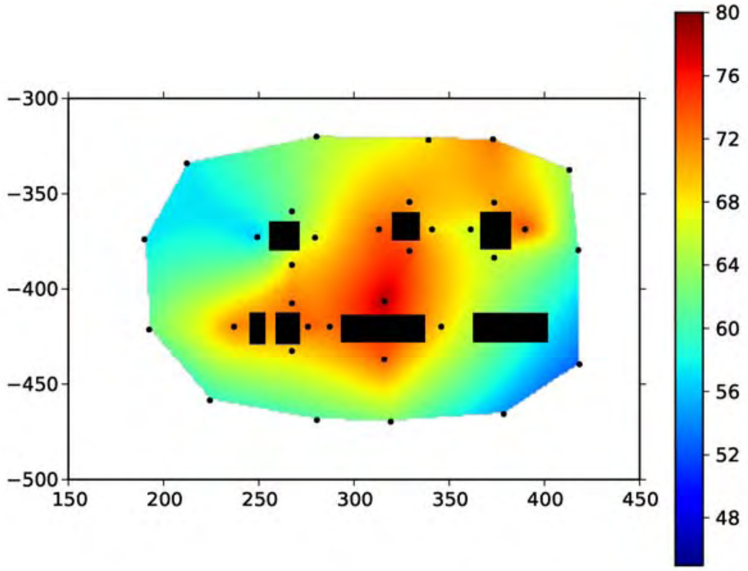


(a) No APU data

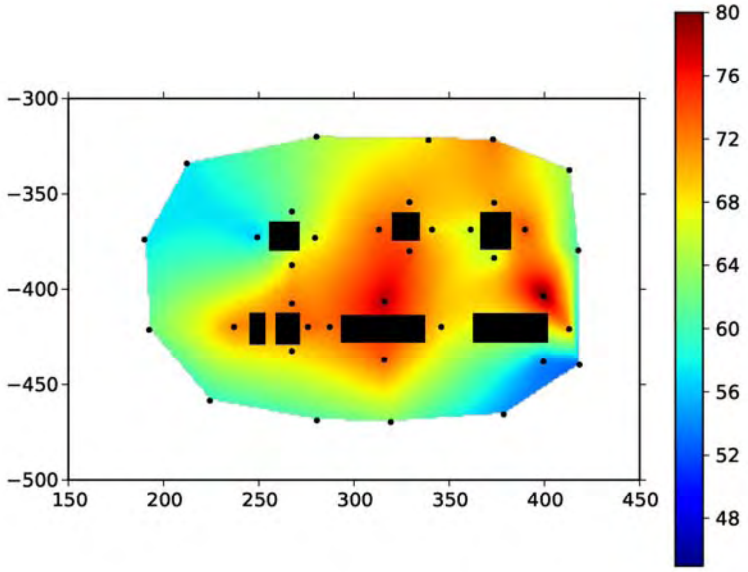


(b) APU locations added

Figure 8: Overall Sound Pressure Level (dBA) at Station #2 (Axes in meters, OSPL scale is in dBA).



(a) No APU data



(b) APU locations added

Figure 9: Overall Sound Pressure Level (dBA) at Station #3 (Axes in meters, OSPL scale is in dBA).

The overall SPL from Station #2 is shown in Figure 8. Again, the most prominent source of yard noise is the aerial coolers, but this time the APU contributes a significant amount of noise when it is running. On this particular day, one compressor was running and the other was idling. The overall SPL from Station #3 is shown in Figure 9. All three compressors were running on that day: Unit 1 (in the NE corner) was running at 16 MW, while the other two were running at 11 MW. It appears that Unit 3 and the control building offer some noise shielding, although the APU in the control building is a significant noise source when it is running.

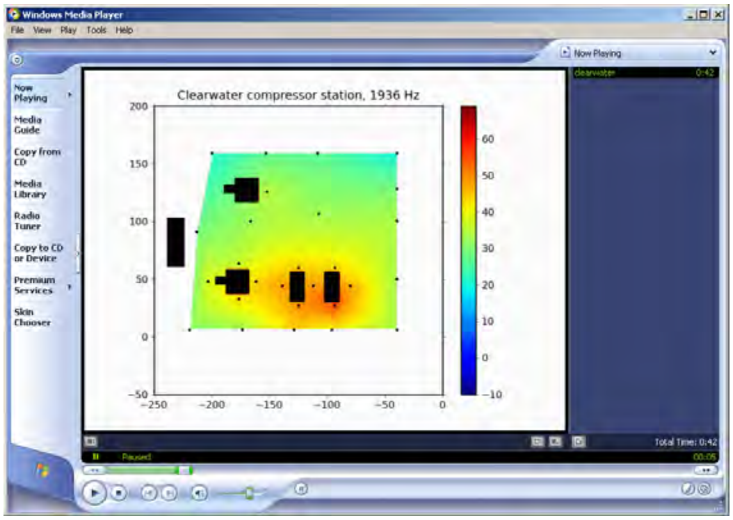


Figure 10: SPL Animation Playing (Station 2.avi)

Spectral Content

To visualize the spectral content of the noise, a noise map was produced for each of the 16-Hz frequency bins. These frames (1024 per station) were then compiled into three animation files:

Station 1.avi
Station 2.avi
Station 3.avi

These animations are included with this paper. Figure 10 shows an example from Station #2 animation. Since the noise measurements in each frequency bin are much lower than the overall SPL, the colour scale was adjusted accordingly and the same scale was used in all three movies. Comparing the noise maps at different frequencies allows us to better distinguish between the various sources of noise. For example, Figure 7 showed that the strongest noise at Station #1 comes from the aerial coolers, and that the cooler noise was most prominent on the Eastward side of the coolers. Surprisingly, the next most significant source of noise is not the compressor station, but the scrubber shown in Figure 11. It is located about 15 m North-West of compressor building, and 10 m East of measurement location 5.

The total sound pressure level at location 5 of Station #1 was only 4.9 dBA less that the maximum sound pressure level in the yard at location 12. The noise spectra from the scrubber and the coolers are compared in Figure 12. The aerial coolers have a maximum sound level at 2608 Hz, with several higher frequency harmonics. The scrubber, on the other hand, produces primarily low frequency noise with a high peak at

1328 Hz. The scrubber noise is prominent throughout the yard, as shown in Figure 13, and propagates as far as the auxiliary buildings in the South East corner. This is because sound transmission damping decreases with frequency. The sound spectra at Station #2 are sufficiently different to distinguish between the noise west of the operating compressor, near the idling compressor, and near the aerial coolers. Figure 14 shows how distinct the three measurements are from one another, and demonstrates that the only frequency peak shared by both compressor buildings occurs at 10,560 Hz. This peak was not measured near the coolers.

A similar plot from Station #3 is shown in Figure 15, where the only noise source that was clearly distinct from the others was the scrubber.

Figure 11: Scrubber at Station #1.

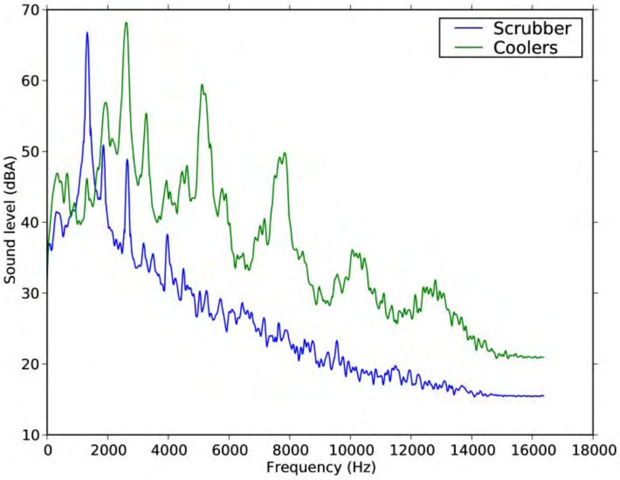


Figure 12: Comparison of Scrubber Noise and Aerial Cooler Noise at Station #1 (Locations 5 and 12).

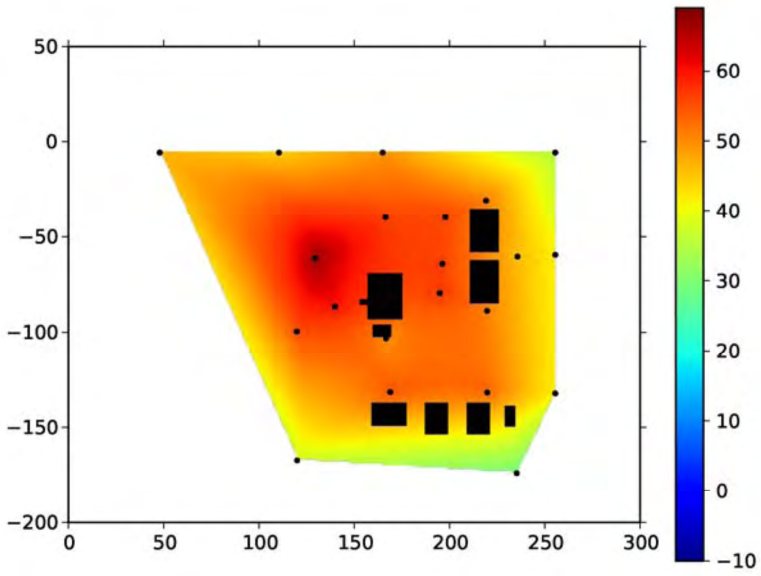


Figure 13: Sound Level Map for Station #1 in the 1328–1344 Hz Frequency Range, Showing the Prominence of the Scrubber Noise Across the Yard (Axes in meters, OSPL scale is in dBA).

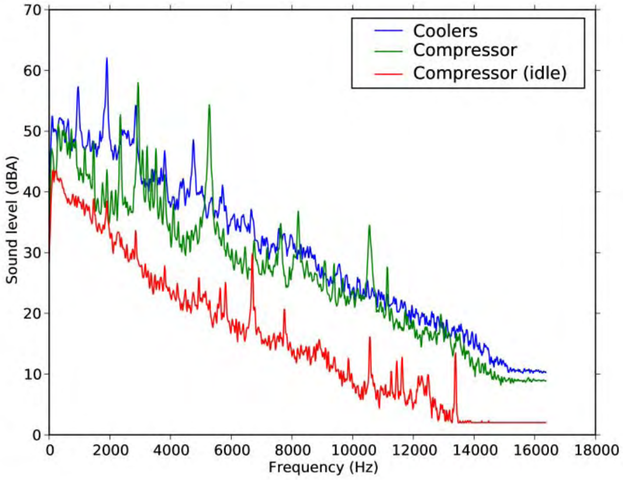


Figure 14: Three Sources at Station #2.

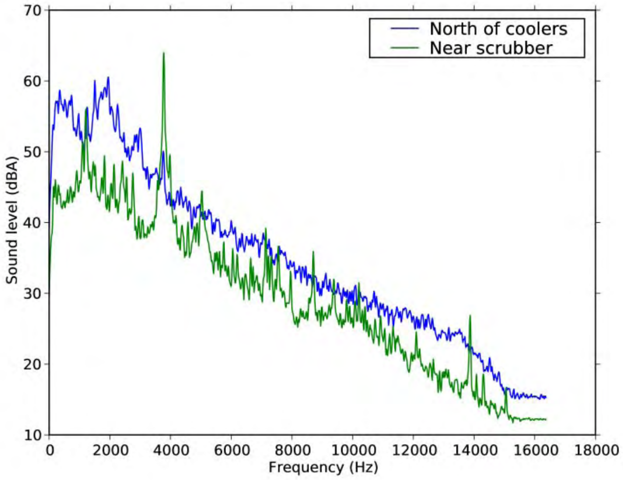


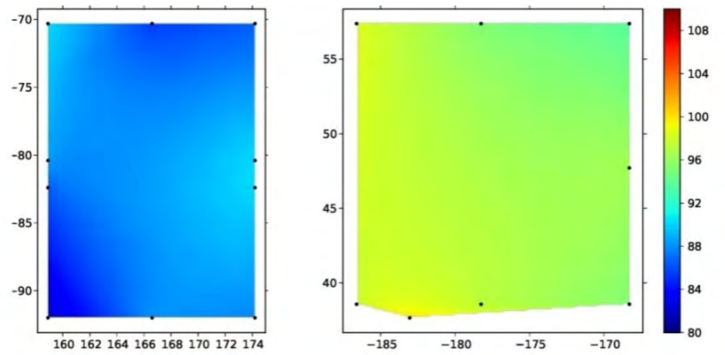
Figure 15: Scrubber Noise at Station #3 Compared to Aerial Cooler Noise.

Unit buildings:

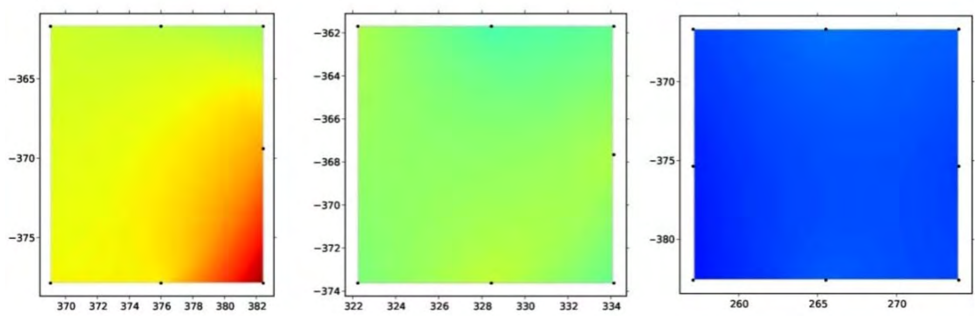
A number of noise measurements were also made inside each unit building, as reported in the Tables A1–A3 in Appendix A. This data was used to create the interpolated noise maps shown in Figure 16, although the interpolation carries very little meaning here. The local sound levels would be strongly influenced by the location of the equipment in each unit building, which is not accounted for in the interpolation.

5.0 Conclusions

Sound measurements were taken at various locations at three compressor stations. The overall sound pressure levels (OSPLs) in the yards were high (up to 81 dBA), and the highest sources are consistently at locations near the aerial coolers and scrubbers. The OSPLs inside the unit buildings were in the range of 80–110 dBA. The Delaunay Triangulation and Natural-Neighbour Interpolation techniques are demonstrated to be useful in determining the overall noise map of the entire station yard based on measurements of scattered locations within the yard. When the results are presented in OSPL maps, as well as animated pictures of the sound pressure level (SPL) in frequency domain will be useful in future work to determine the culprit sources and the respective dominant frequency range that contributes the most to the overall OSPL. The examples presented in this paper indicate that the scrubbers seem to be generating lower-frequency noise with high SPL levels than other surrounding equipment.



a) Station #1 b) Station #2



c) Station #3 (unit1) d) Station #3 (unit 2) e) Station #3 (unit3)

Figure 16: Overall SPL (dBA) Inside the Unit Buildings - The interpolation Does not Consider any Sources of Noise (Axes in meters, OSPL scale is in dBA).

6.0 Acknowledgments

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7.0 References

1. Frank, L.: “NOISE CONTROL ENGINEERING OBJECTIVES FOR COMPRESSOR STATION TURBO-COMPRESSOR UNITS”, Presented at the 16th Symposium on Industrial Application of Gas Turbines (IAGT) Banff, Alberta, Canada, October, 12-14, 2005.
2. Marks, T.: “NOISE CONTROL AT GAS-FIRED COMPRESSOR STATIONS”, Australian Acoustical Society Conference, Melbourne 24-26 November 1999.

3. Liu, Z., Jahnke, B., Marczak, M. and Kiteck, P.: "REDUCING COMPRESSOR STATION AMBIENT NOISE LEVEL BY CONTROLLING COMPRESSOR INTERNAL NOISE SOURCE", Proceedings of International Pipeline Conference IPC 2002, Calgary, Alberta, Canada, September 29 - October 3, 2002.
4. Zirnig, W. and Schmücker, A.: "NOVEL MEASUREMENT TECHNIQUE FOR A SELECTIVE DETECTION OF SOURCES OF SOUND IN NATURAL GAS TRANSMISSION PLANT", Proceedings of the 2001 International Gas Research Conference IGRC, p. 8, Amsterdam, Netherland, 2001.
5. Gužas, D. and Jotautienė, E.: "Estimation of sound power of centrifugal machines based on sound intensity measurements", ISSN 1392-2114 ULTRAGARSAS, Nr.1(31). 1999.
6. G. Kudernatsch, "Combustion Turbine Exhaust Systems-Low Frequency Noise Reduction," Proc. INTER-NOISE 2000, edited by Didier Cassereau, Noise Control Foundation, Poughkeepsie, New York, 2000.
7. Beranek, L. and Vér, I., *Noise and Vibration Control Engineering: Principles and Applications*, Wiley-Interscience, 1992.
8. Province of Alberta, Occupational Health and Safety Code (2006), Alberta Queen's Printer.
9. Jones, E., Oliphant, T. Peterson, P.: SciPy - Open source scientific tools for Python, http://www.scipy.org/, 2001.
10. Hunter, J. matplotlib, http://matplotlib.sourceforge.net/index.html.
11. The matplotlib.mlab.griddata function in the web site provided in ref. 10 above.

APPENDIX A

OVERALL SOUND PRESSURE DATA

Table A1: Overall Sound Pressure Levels for Station #1.

(a) Without APU running

Loc.	OSPL (dBA)	Loc.	OSPL (dBA)
2	52.0	13	62.9
3	63.9	14	71.9
4	69.2	15	56.9
5	74.9	16	63.6
6	56.1	17	64.6
7	56.3	18	63.3
8	61.4	19	45.5
9	66.9	30	72.8
10	56.1	31	72.5
11	65.9	32	70.5
12	79.8		

(b) With APU running

Loc.	OSPL (dBA)
33	56.6
34	66.7
35	65.6
36	62.7
37	68.3

(c) Unit Building

Loc.	OSPL (dBA)
20	87.8
21	90.2
22	90.2
23	86.5
24	85.6
25	90.1
26	88.4
27	86.6
28	82.1
29	88.0

Table A2: Overall Sound Pressure Levels for Station #2.

(a) Without APU running

Loc.	OSPL (dBA)	Loc.	OSPL (dBA)
99	58.3	113	68.6
100	58.5	114	68.9
101	65.6	115	63.2
102	64.5	116	69.5
103	58.0	117	72.1
104	57.0	118	70.0
105	56.5	119	74.0
106	53.8	120	67.1
107	48.8	121	63.7
108	51.2	122	64.5
109	51.8	123	57.7
110	50.0	124	58.6
111	56.5	125	60.4
112	69.9		

(b) With APU running

Loc.	OSPL (dBA)
134	75.7
135	78.0
136	64.3

(c) Unit Building

Loc.	OSPL (dBA)
126	95.3
127	96.5
128	93.7
129	95.3
130	98.6
131	97.9
132	97.3

(d) Near the ejector

Ejector	Loc.	OSPL (dBA)
Running	133	97.2
Off	137	97.4
Off	138	96.8
Running	139	100.2
Running	140	100.1

Table A3: Overall Sound Pressure Levels for Station #3.

(a) Without APU running

Loc.	OSPL (dBA)	Loc.	OSPL (dBA)
40	54.5	57	73.3
41	52.6	58	72.6
42	60.1	59	72.0
43	63.8	60	69.2
44	72.4	61	69.2
45	68.4	62	66.7
46	64.4	63	62.3
47	57.5	64	56.5
48	57.4	65	74.2
49	62.2	66	68.6
50	59.6	67	71.3
51	60.8	68	73.6
52	63.2	69	65.8
53	73.6	70	74.1
54	69.1	71	70.8
55	78.3	72	66.0
56	72.7		

(b) With APU running

Loc.	OSPL (dBA)
95	53.9
96	71.3
97	80.7

(c) Unit 1

Loc.	OSPL (dBA)
73	109.1
74	102.1
75	96.4
76	97.3
77	98.1
78	99.3
79	99.6

(d) Unit 2

Loc.	OSPL (dBA)
80	94.3
81	96.8
82	94.0
83	93.2
84	96.8
85	95.1
86	97.6

(e) Unit 3

Loc.	OSPL (dBA)
87	85.8
88	85.6
89	86.5
90	87.2
91	85.6
92	84.6
93	84.3
94	86.4