AIVS INC

AIVS Inc Application Note AN-100

Spatially Filtered Sound Level Meter noise events using the ARES-100

ARES-100 is a 3-axis Acoustic Vector Sensor (AVS) that serves as an accessory to a Sound Level Meter (SLM), providing measurement of directional bearings to acoustic events. This information increases the dimensionality of noise signatures, improving the confidence of autonomously characterized sound events.

ARES can be set to send bearing results to the SLM over either RS232, USB, or BLE (wireless) interfaces, one or more of which are supported by most modern Class 1 SLMs. This note describes the ARES-100 measurement process, and how to use the computed bearings in conjunction with a sound level meter.

ARES samples four measurements (pressure, and triaxial acceleration) at a 4800 Hz rate. The sampled data is time windowed using a Hann window prior to performing a Short-Time Fourier Transform (STFT), using a 192-sample block size. The time record length is 40 msec, but since the FFT results are overlapped in time by 50%, the output of the FFT processing stage provides 50 updates per second. The frequency resolution per FFT bin is 4800/192 = 25 Hz[1]. FFT spectra are A-weighted prior to computing acoustic intensity. The noise floor of the ARES-100 accelerometer is 22 $\mu g/\sqrt{Hz}$, such that after integration of acceleration to compute particle velocity, bins ≥100 Hz provide valid measurement results, up to the rated 2 kHz bandwidth for the ARES-100 sensor (bins 4-80). Extended low frequency bandwidth is one of the major advantages of an accelerometer-based AVS compared to microphone arrays, since MEMS accelerometers are sensitive to DC, have excellent channel-to-channel phase match, and are thus limited only by the device noise floor. The core sensing elements of ARES-100 occupy an aperture of just 5 mm, consisting of the triaxial accelerometer and MEMS microphone, both within a lightweight sphere of closed cell foam. The foam enhances accelerometer sensitivity, and protects the sensor from weather.

Triaxial intensity (both active and reactive), azimuth (θ), and elevation (φ) are computed for every frequency bin (Eqn. 1). A bearing histogram collects the results per selected event time window by incrementing the measured active intensity per angular bin, per time step. At the end of the event time window (which is an integral number of 20 msec processing intervals), one or more noise events are chosen from the maximum histogram outputs.

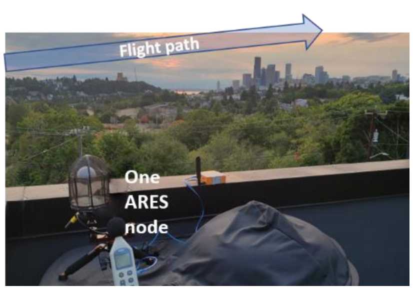

Figure 1. Example flight paths observation.

$$\vec{\boldsymbol{I}} = p\,\vec{\boldsymbol{u}}^*/2$$

$$\theta = \tan^{-1}\frac{Re[I_y]}{Re[I_x]}$$

$$\varphi = \tan^{-1}\frac{Re[I_z]}{\sqrt{{I_x}^2 + {I_y}^2}}$$

histogram over all bearing angles, for all frequency bins

Equation 1. Intensity and angle calculations per FFT bin.

Figure 1 shows an emplacement of ARES-100 near downtown Seattle, 25 km downrange along the takeoff path from Sea-Tac International Airport. The sensor is observing repeated flights over the city after takeoff, as depicted in the spectrograms of Figs 2 and 3.

[1] ARES can also be set to sample at 3840 Hz. For the same 192 sample block size, the frequency resolution is 20 Hz, and time record length is 50 msec. This results in a histogram event sample rate of 25 msec at 50% STFT overlap, which allows setting the histogram integration time (event window time) to exactly 125 msec (5 successive updates at 25 msec each), to replicate the "Fast" integration time of a integrating Sound Level Meter. The downside of using the 3840 Hz sample rate is that the measurable bandwidth of ARES-100 is limited by the Nyquist frequency to 1900 Hz (bins 5 to 95), rather than 2 kHz (bins 4-80).

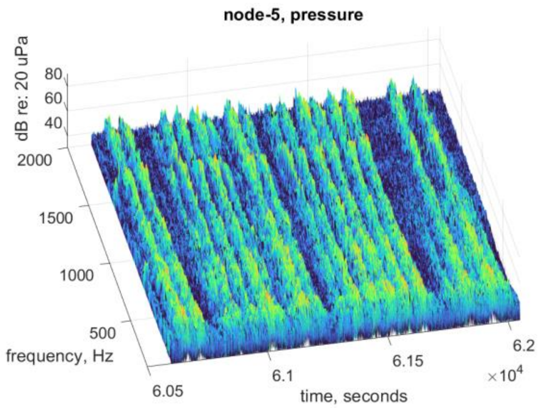

Figure 2. Pressure for a series of jet fly-bys.

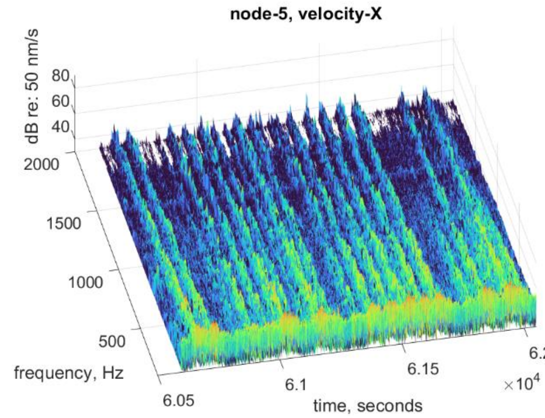

Figure 3. Velocity in X-direction for a series of jet fly-bys.

The velocity spectra for the Y and Z channels are not shown. All pressure and velocity spectra are amplitude and phase corrected to have a flat response in the specified 2000 Hz bandwidth, to offset the effects of encasing the sensors in closed cell foam. While ARES-100 does not equal the bandwidth of a Class 1 SLM, or even a Class-2 instrument, as long as the source event(s) have some acoustic energy within the frequency range [100 Hz to 2 kHz], automatic estimation of the bearing angles is possible.

Eqn. 1 shows how ARES-100 estimates bearing angles, and Eqn. 2 exposes how ARES-100 estimates the immission directivity[2], i.e., the proportion of acoustic power immitted to the sensor from one or more the source events.

$$L_{A,eq,T} = 20\ log\frac{1}{T}\sum_{t=0}^{T}\sum_{\varphi=-\frac{\pi}{2}}^{\frac{\pi}{2}}\sum_{\theta=-\pi}^{\pi}\sum_{b=4}^{80}\frac{|p(t,\varphi,\theta,f_b)|}{p_0\sqrt{\Delta f_b}} \quad \text{(Eqn. 2)}$$

Eqn. 2 shows that the summed absolute pressure from all sources over all elevation and azimuth angles, and over all frequency bins (bins 4 – 80 represent frequencies from 100 Hz to 2 kHz), must equal the SLM output over the same integration time, with the caveat that ARES-100 can only observe signals below 2 kHz. The quantity p is the measured acoustic pressure in each FFT bin, p_0 is the reference sound pressure of 20 μPa, and Δf_b is the bandwidth of the FFT bin, multiplied by the Hann window equivalent noise bandwidth (~1.5).

After every overlapped FFT, the measurement process computes the bearing angles per Equation 1. Then, three angle histograms, all with an azimuth value on the x-axis, are incremented with the measured acoustic pressure and intensity (active and reactive) per angle increment. After the designated integration time T, one or more sources are detected by selecting the largest outputs of the active intensity histogram in terms of sorted maximum power. The intensity in this case is in the radial direction from the source(s) to the sensor, since each integrated intensity estimate is confined to a single angular increment.

For the fly-by data depicted in Figs 2 and 3, Figure 4 clearly shows several flyover tracks as generated by outputs of the bearing histogram, for an event time window of 200 msec. There is roughly a 50 second interval between jet flyovers of the city (200 seconds per division on the plot). The sensor was oriented such that a westerly direction refers to zero degrees azimuth. Measured azimuths range from -90° (South, from the airport) to about +100° (NNE). Elevations of each fly-by start at near zero, and rise to a maximum of 50° to 60°, in accordance with visual observations. The color of each bearing output represents the signal level in dBA.

[2] Extended to the frequency domain from Prezelj,J., "Directivity measurements of environmental noise immission", Euronoise 2018 Conference Proceedings, Crete, Greece

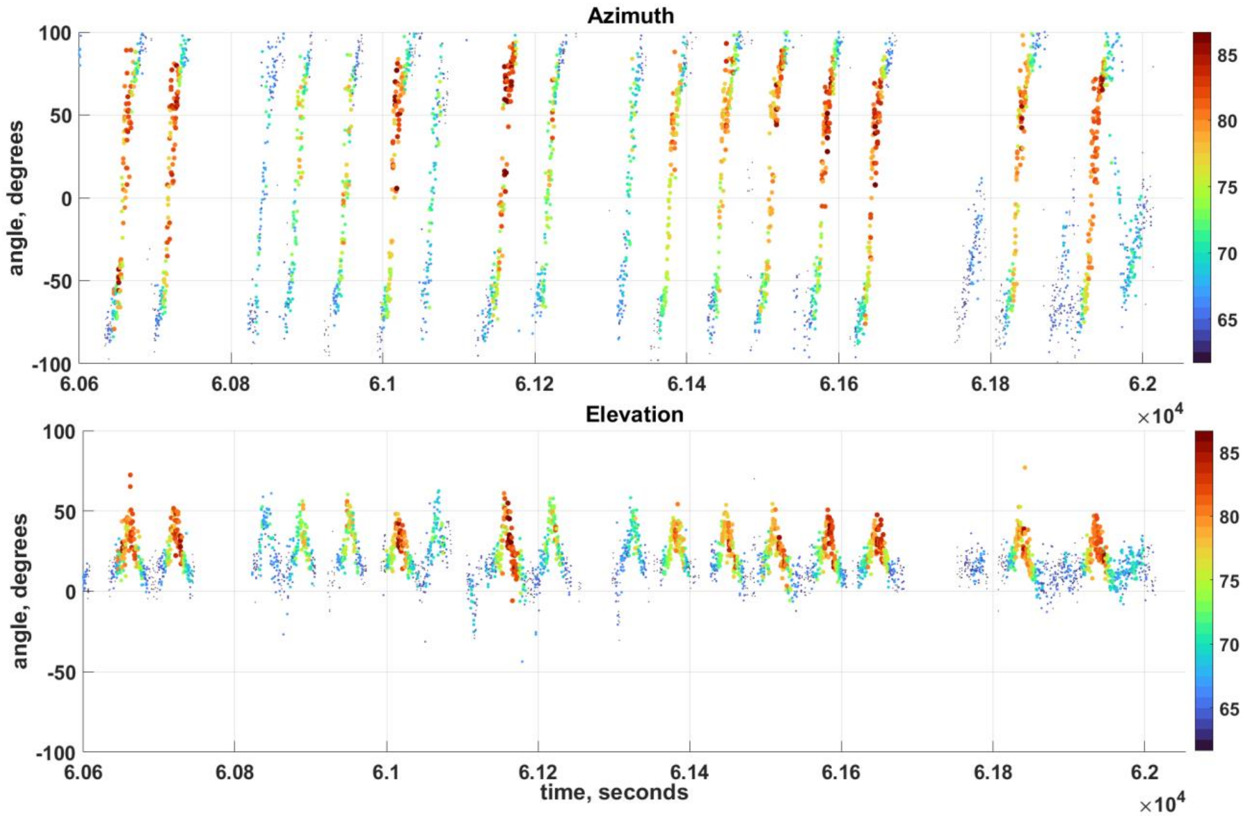

Figure 4. Bearing output for a series of jet fly-by over downtown Seattle, WA.

While the bearing estimates are reasonable, we must now compute the contribution of the jet noise signature to the overall SLM measurement, $L_{A,eq,T}$. This allows the SLM to segment its Class 1 standardized measurements by event, using the simultaneously computed ARES-100 results to spatially filter the equivalent noise values. Depending on the monitoring scenario, the SLM can set the values in ARES-100 according to Table 1, or use the defaults.

Table 1. ARES-100 parameters set by the SLM

Parameter	Range	Default	Description
Event SPL(A) threshold (dB)	30 – 120	30	Overall A-weighted SPL must be > this dB level to send results to the connected SLM (30 ≈all results)
Histogram angular precision (°)	1 – 10	1	Degrees per elevation or azimuth interval
Maximum sorted histogram peaks	1 – 360	5	Maximum number of peak bins to send in message
Event time window (20 ms periods)	1 – 500	50 (1 sec)	Time window in units of the number of histogram update period (equal to the overlapped FFT time, normally 20 ms)
Peak delta (dB)	0 – 40	40	Additional sources are detected if histogram peaks are less than this number of dB down from max (default=40 is ≈ all peaks)

With respect to the multiple source detection capability of ARES-100, as long as there is sufficient angular, frequency, and/or time separation between acoustic events, the system can detect more than one dominant source. Note (such as for the jet fly-bys) that if the angular precision of the histogram is small (e.g., set to the default 1°), then the multiple detected sources could pertain to the same event due to scatter in the detected angles. This is not really a problem, since this can be used as an estimate of confidence in the angle result. So, the number of sources is often set to a higher number than the actual expected simultaneous noise events.

Let us look in detail at the detection process for the left-most flyby shown in Fig. 4, for which the expanded spectrograms are shown in Figs. 5-6. For this example, there is essentially only one source, the jet.

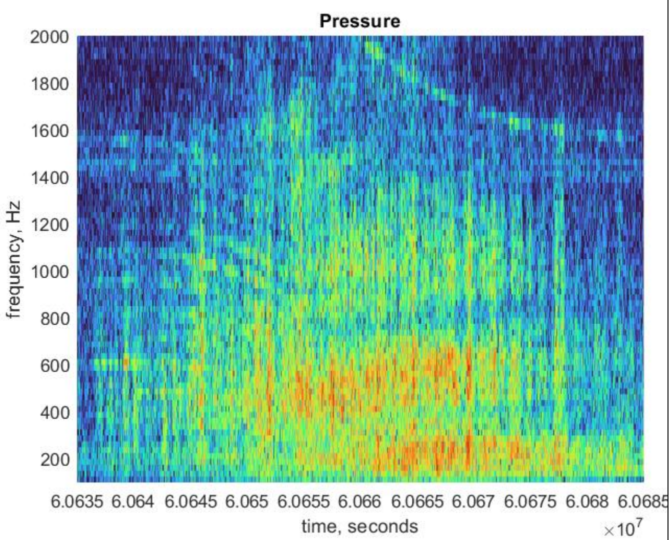

Figure 5. Expanded spectrogram for the left-most fly-by in Fig. 4 (pressure).

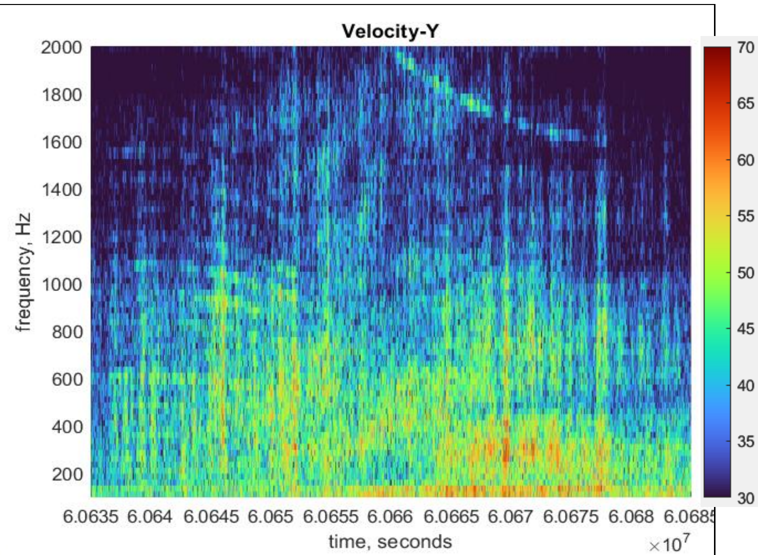

Figure 6. Expanded spectrogram for the left-most fly-by in Fig. 4 (velocity-Y).

The next six plots will show how the number of maximum sorted histogram peaks can be used for spatial filtering of the SLM $L_{A,eq,T}$ value, and to deduce the effective $L_{A,eq,T}$ for detected sources. The event time window is fixed at 1 second for all plots, in accordance with the slowly changing fly-by and to allow some data smoothing. The event SPL(A) threshold, histogram angular precision, and peak delta are set at default values per Table 1 (30 dBA, 1°, and 40 dB respectively). The "NumPeaks" parameter for Figures 7-12 is set according to Table 2.

Table 2. Settings for Figs. 7-12.

Figure	Num Peaks
7	360
8	50
9	20
10	10
11	5
12	1

When NumPeaks is 360 (i.e., all histogram bins are output to the SLM), essentially all the acoustic energy in the full 3D space is lumped into the reported acoustic pressure. When NumPeaks is 1, only the maximum histogram bin in terms of measured active intensity is output. In a free field, the sound pressure level will approximately equal the sound intensity level (also in dB). Pressure is scaled in dB re: 20 μPa, and intensity in dB re: 1 pW. Thus, the reported pressure level can be taken as the portion of the overall $L_{A,eq,T}$ attributable to the selected number of peaks in the histogram, sorted by maximum intensity. Let's see how this works for the jet fly-by example.

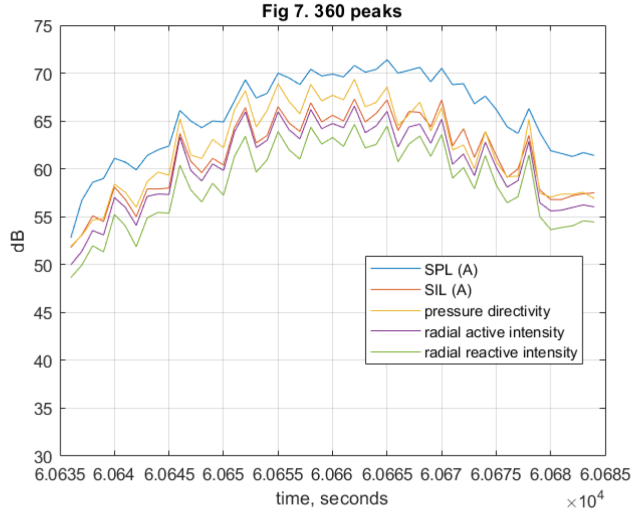

Fig 7. 360 peaks

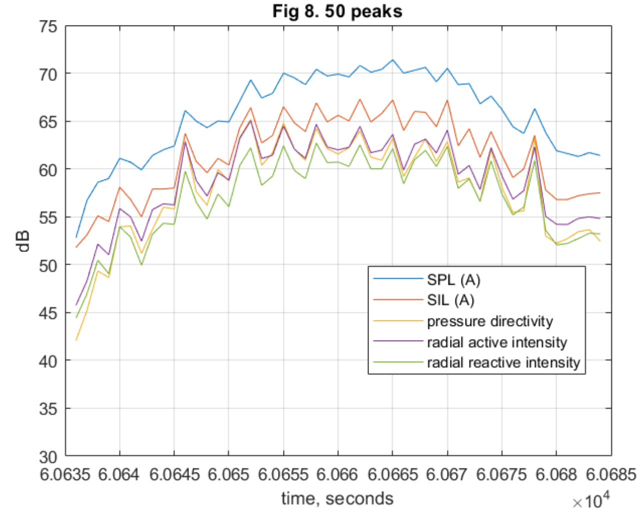

Fig 8. 50 peaks

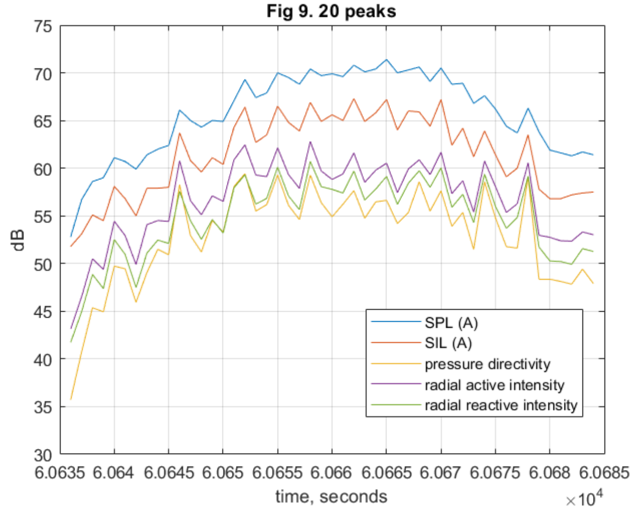

Fig 9. 20 peaks

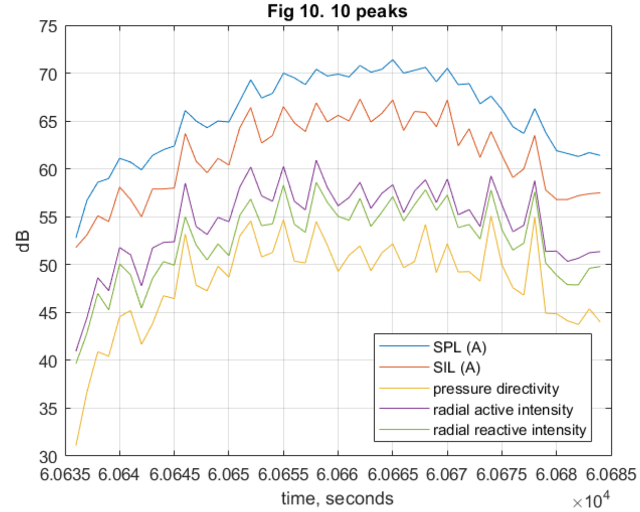

Fig 10. 10 peaks

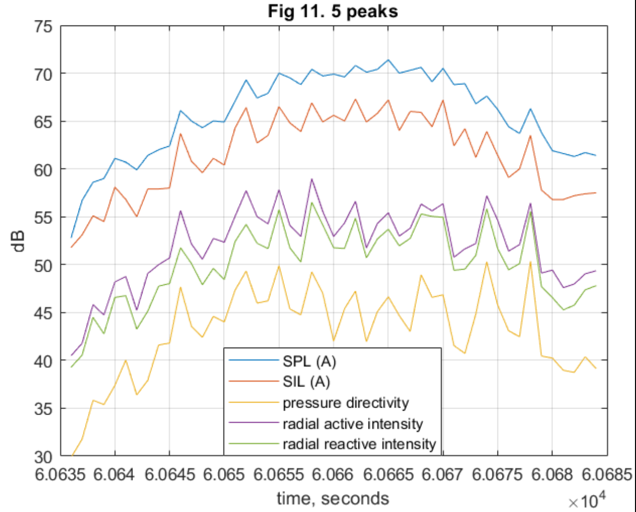

Fig 11. 5 peaks

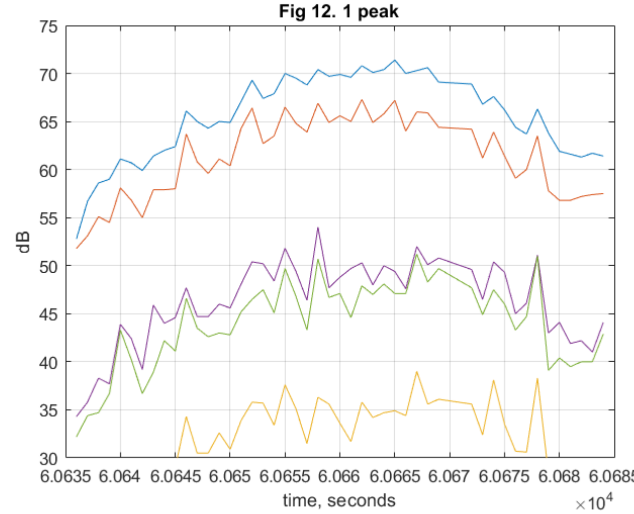

Fig 12. 1 peak

From the spectrogram (Figs. 5 and 6), it is clear that although there are many frequencies in the jet signature, but only one actual source position. Theoretically, multiple spectral bins should map to only one angular histogram bin, but low SNR will spread this power over several depending on the setting of histogram angular precision.

The family of plots Figs. 7-12 can be interpreted in the following way. During each 1 second event window across the whole fly-by duration of about 50 seconds, the A-weighted SPL will be independent of the Table 2 settings. It can be seen that this (blue) trace is identical in all four plots. Similarly, the overall sound intensity level at the sensor (SIL, red trace) will also be constant, since it is the sum across all angular histogram bins. The "pressure directivity" represents the summed pressure for the selected "NumPeaks" in the histogram, representing varying azimuthal subspaces encompassing the bins with maximum power. In Fig. 7, all 360 histogram angular bins are summed and thus the pressure directivity is almost the same as SPL. It differs only in that lowest signal level bins are excluded per the PeakDelta setting in Table 1. As "NumPeaks" is reduced in Figs. 7-12, the pressure directivity falls linearly, as do both the active and reactive radial intensity. This behavior is expected since there is really just one dominant wideband source in the entire 3D space surrounding the sensor. As we reduce the number of maximum outputs from the histogram, the sum of those outputs (per time step) will become gradually smaller.

Over the aforementioned serial interfaces, ARES-100 nodes output bearing results as JSON formatted strings after every event time window. Time is in POSIX milliseconds, with the measurement sync time representing the measurement start. The overall levels are "spl" in dBA re: 20 µPa, and "sil" in dBA re: 1 pW. Azimuth and Elevation for one or more detected sources are in degrees relative to accelerometer coordinates. "pres" is the pressure directivity, and "acti", "reac" are the active and reactive intensities. The output messages in Fig. 13 are for two successive 1-second outputs, with NumPeaks set to 5 and event time window set to 50 (1-sec). The balance of the parameters is the same as for Fig 11.


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```


Figure 13. JSON output for the fly-by represented Figure 10.

Multiple sources

It is interesting to apply this same analysis to noise monitoring scenarios in which there is more than one simultaneous source in the environment. This example is shown in Figure 14. The sensor is mounted on a building roof in an urban environment near other buildings. Two HVAC noise sources are observed at low signal levels throughout the measurement session. The azimuth and elevation of the two HVAC sources vary enough so that these sources are clearly separated in the data. In addition to the two HVAC noise sources, three louder noise events occur. A jet fly-by is present, though it is on the horizon with about zero degrees elevation. Also, later in the dataset a pair of distant train horn events occur, from a freight train track 3 km distant south of downtown Seattle, such that the elevation is also about zero degrees.

From Fig. 14, the jet flyby clearly dominates all chosen angular peaks from the histogram, such that the two HVAC sources don't appear in the azimuth or elevation plot. But 250 seconds later, a pair of low-level train horns occur, and the system has simultaneously detected that source as well as the two HVAC systems.

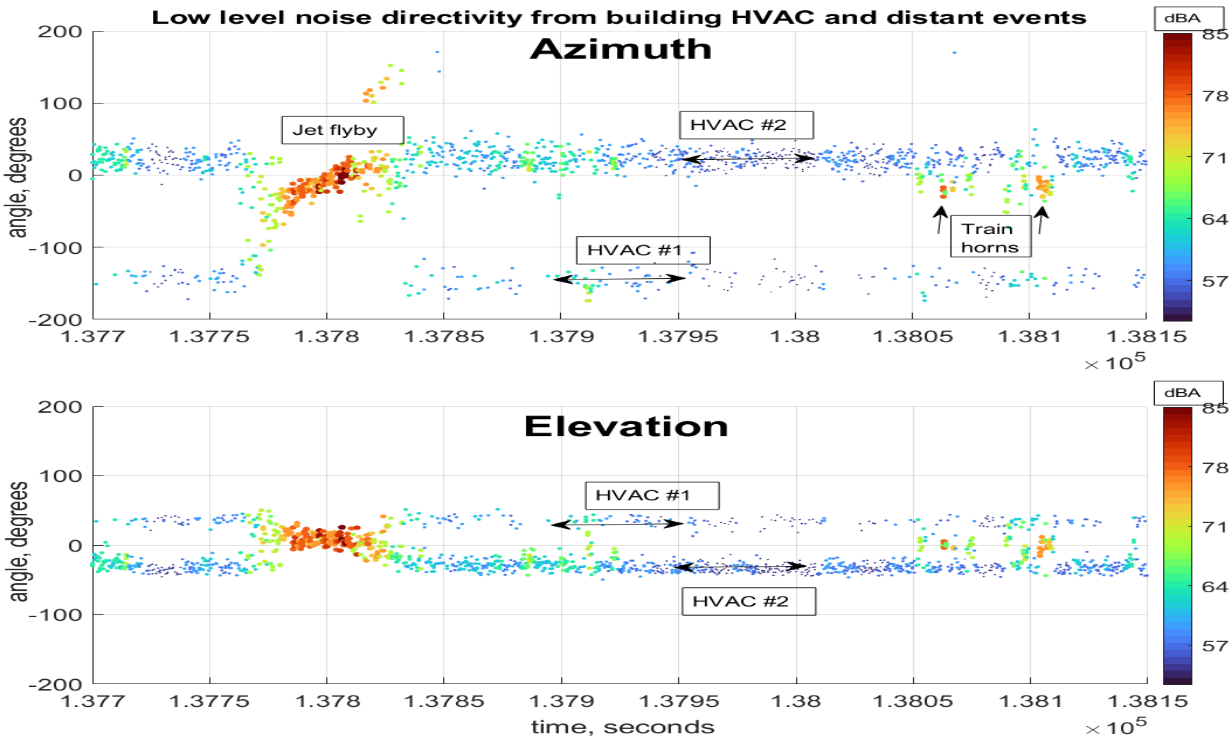

Figure 14. Estimated bearings when ARES-100 is placed on a building rooftop with HVAC interference from a taller adjacent building, as well as from the street.

While Fig. 14 seems to indicate that there are only two main train horn events, an expansion of the time axis around the event indicates that there are actually four short events in each. These are marked in the Figs. 15 and 16 spectrograms. The overall A-weighted SPL for these events is between 65 and 73 dB, though individual spectral components are much smaller (45 to 50 dB) as there are a number of harmonics generated by the horn.

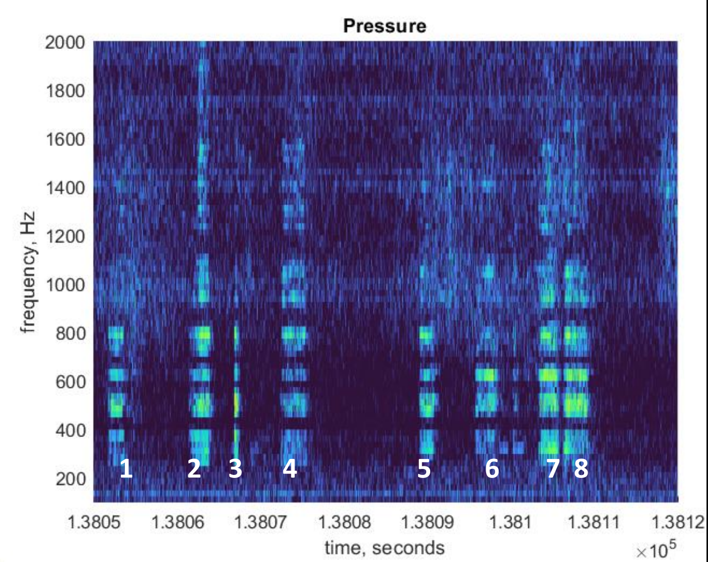

Figure 15. Pressure spectrogram for the train horn example.

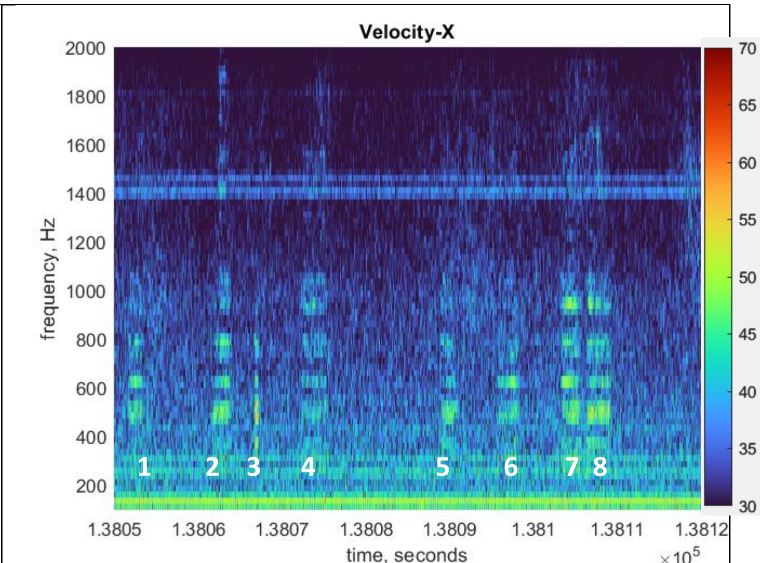

Figure 16. Velocity-X spectrogram for the train horn example.

Since there are multiple sources, we set NumPeaks to 20 in hopes of capturing all sources simultaneously. However, from inspection of the plots in Figs. 17 and 18, the horn still dominates and the two HVAC sources are not detected when the horn is active. To increase the effectiveness of simultaneous source detection, choosing a wider angular precision on the histogram (> 1°) should help. Interestingly, away from the eight successive train horns, both HVAC systems are simultaneously detected, albeit with imprecise azimuth accuracy for the very low level (~40 dB) sources.

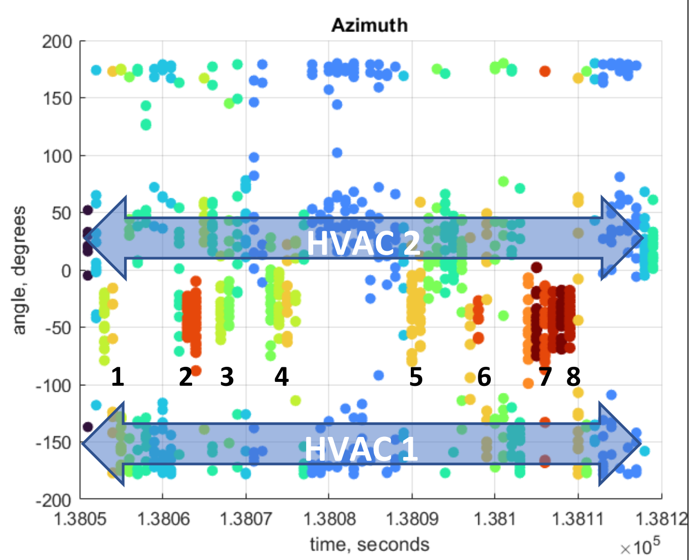

Figure 17. Detected azimuth for all sources (HVAC 1, HVAC2, and 8 successive horn blasts).

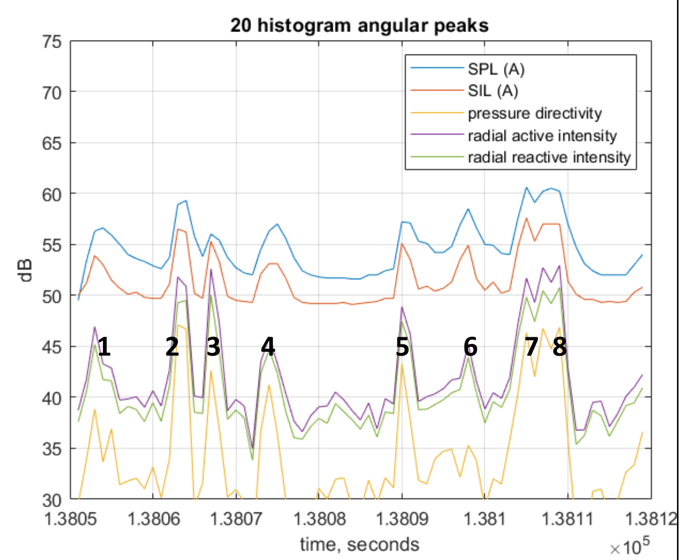

Figure 18. Measured SPL, SIL, pressure directivity, and radial intensity.

In Figure 18, notice that both the pressure directivity and the radial intensity can be used to discriminate the train horn sources from background noise. The quantities are confined to a subspace represented by the 20 maximum histogram bins, while the SPL and SIL measure the aggregate sound pressure and radial sound intensity from the entire 3D space.

Spatial Filtering Summary

For both the two above examples (jet fly-by and train horn noise), the dominant noise source was so distinct that other simultaneous sources were obscured. So, in these cases there isn't a need to prorate the $L_{A,eq,T}$ value by an amount proportional to the dominant source. Based on the estimated azimuth and elevation angles, the detected dominant source can be either removed or included in the reported $L_{A,eq,T}$. If the measured bearing is within the region being monitored, then the $L_{A,eq,T}$ integration continues, else that event is excluded from the integration period.

The pressure directivity is useful in determining how much of the acoustic energy is captured by the selected NumPeaks parameter, and the radial intensity can be used to discriminate sources from background noise. Both examples presented in this application note represent relatively low-level sources, and the performance of the system in higher level noise environments exceeds that presented here.

The JSON messages output by ARES-100 to the Sound Level Meter can thus be used to qualify individual events that occur during noise surveys. In addition, the same bearing data increases the dimensionality of noise signatures, improving the precision of downstream machine characterization of sound events.