Noise source mapping for trucks, Part 2: Experimental results

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The elliptical array whose development and *insitu* calibration has been discussed in Part I was deployed roadside a test track for measurement of passby truck noise. This paper is a discussion of the capability of that array to localize the sound sources on the truck and to quantify the source levels thus allowing rank-ordering of the sources. The paper discusses an effort to benchmark the array-based measurements against intensity measurements on an idling stationary truck and the use of the array's output to define clearly the vertical distribution of sources at frequencies in excess of about 250 Hz at vehicle speeds up to 80 km/h (50 mph).

1 Introduction

In the previous paper [1] the elliptical array development and its basic beam forming calibration was shown to permit vertical discrimination beam width (-6dB) of less than 3.6m for frequencies above 250 Hz. Earlier developmental work [2] defined the measurement technique that is required to develop a spatio-temporal definition of truck sound at passby speeds up to 80 km/h (50mph). The distribution of source levels in vertical and cross-range dimensions are projected onto a plane parallel to the side of the truck at its closest tire track, i.e. 6 m downrange from the array's center. The first focus in this work was the on the improved vertical and horizontal discrimination of the array as provided by its design which was tailored for passby use. The second focus of this work is the determination of absolute-value source levels, rather than levels that are relative to the overall passby sound level. The array was deployed road-side at a test track for measuring the sound emitted from trucks during passby. Measurements were made on various truck models (all by International ®) in various operating states with and without trailers. The extensive spherical-source calibrations [1] confirmed the array's basic beam forming at both on-normal and steering angles (to 45^o); they also disclosed the magnitudes of ground reflection paths for localized sources at different elevations. In all cases, the array output was computationally inverted to produce two-dimensional spatial maps of source levels in the side profile of the truck. In the cases of stationary trucks, the source maps were correlated with simultaneously-obtained intensity maps. Comparisons verified that the array-based source maps for the trucks ranked sound sources of disparate levels in the same order as did the sound power levels deduced from the sound intensity data. Acoustic source maps obtained during truck passbys were then used to provide time-histories and spatial distributions of sources and source paths from the engine, muffler, tires, and certain body components.

2 On-Truck Calibrations and Illustrations of Source Dis*crimination*

The initial phase of measurement of the array's calibration in which a single spherical source was used [1] was followed by a second measurement with the same source now mounted on a truck bed. This measurement provided a second calibration check combined with verification of its ability to discriminate among sources. Fig. 1 shows a series of source distributions for Truck 4400 idling stationary with the spherical source installed on its bed. The source is clearly identified at the five indicated frequencies, the captions for which provide equivalent weighted 1/3 octave band levels of sound pressure re 20 μPa at each indicated frequency. These levels were calculated from the processed 1 Hz spectrum levels, say $G_{pp}(f)$, using the formula

$$L_s(f) = 10\log[G_{pp}(f)] + 10\log(0.233f) - 20\log(p_o) \quad [1]$$

where p_o is 20 μPa and 0.233f is the classical one-third-octave band frequency bandwidth. This was done to provide levels which could be compared to classically-processed 1/3 octave band levels which were also collected during the passbys. The actual measurement bandwidth was about 47 Hz. Although not clear at 231 Hz

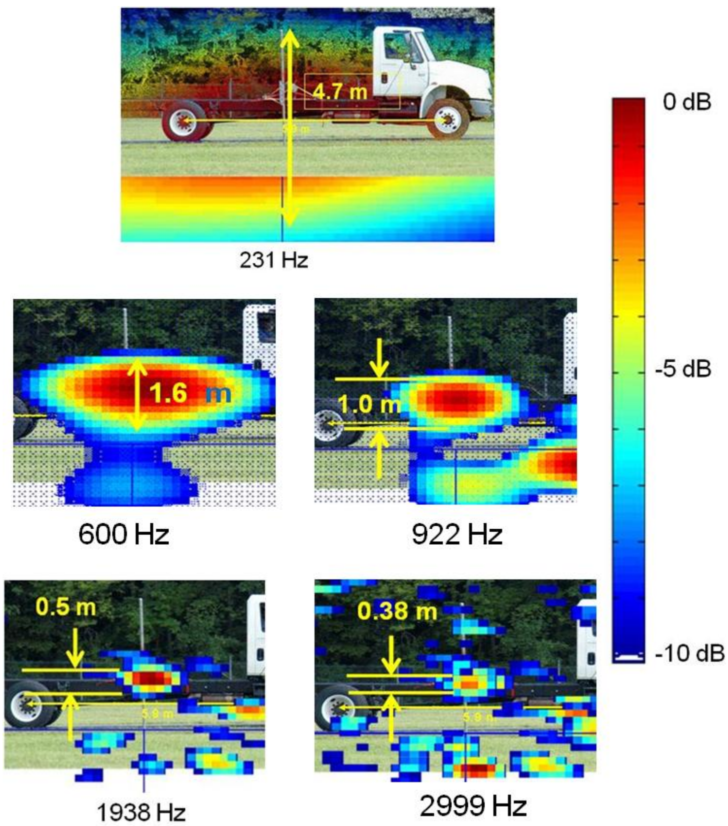


Fig. 1 Measured vertical aperture beam widths from examples of source distribution maps for the spherical source attached to a Truck model 4400 bed. The 10 dB colorbar range applies to all maps.

due to obscuring by the direct path, the ground reflection is cleanly resolved at higher frequencies as are sound sources from the truck which will be discussed in the next section. The 0 dB level of the colorbar is referenced to the maximum in each map. At 600 Hz, 922 Hz, and 1938 Hz the images are clear except for the ground reflections; this is consistent with the source-alone as discussed in [1]. At 2999 Hz, however the expected side lobes contaminate the source map as expected from the calculated beam response. The comparisons of calculated and measured beam widths are shown in Fig. 2 for both the source-only and source-on-truck measurements. Agreement with the expected beam widths is excellent and demonstrates the expected

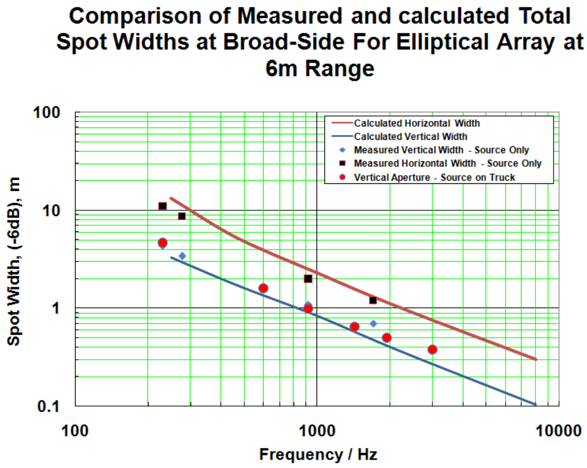


Fig. 2 Calculated and measured-*insitu* beamwidths of the large-aperture elliptic array.

performance advantage of the larger vertical aperture of the elliptical array from 250-2000 Hz.

3 Description of the range geometry

The range geometry, Figure 3, used for these measurements generally followed that used in earlier work [2] with improvements in the timing of the truck position relative to the center of the array in order to reduce positioning error. The positions of the photocells and array relative to the test track are illustrated. In the case shown, the length of the truck as it intermittently cuts the photocell beam is shown by the total length of its signal. The front bumper is taken here as the reference point on the truck so that the maximum sound occurs slightly (typically ~0.15 sec) later than the bumper passage. The data processing, including the range correction for equalizing the passby levels and the Doppler shift for frequency correction, is described in ref. [2] and requires time-accurate truck coordinates. Improvements of that processing to the beam former algorithm made for these measurements produce better resolution of the ground reflection as it relates to the more refined vertical discrimination.

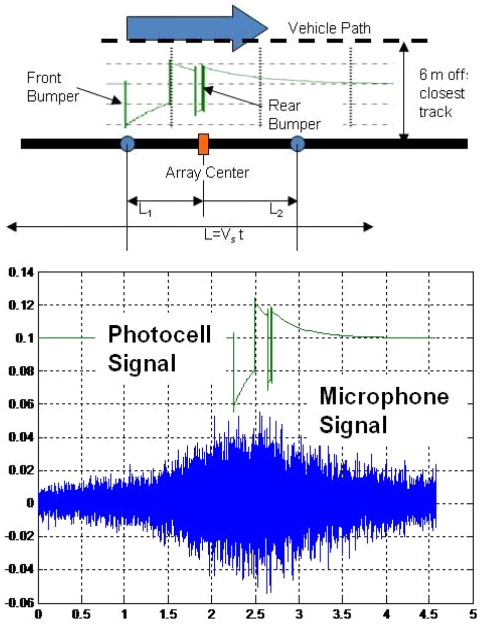


Fig. 3 Example of a passby signal record with the range geometry.

4 Benchmarking against sound intensity measurements

Figure 4 revisits the series of source distributions for Truck 4400 idling stationary with a 2000 rpm engine speed with the spherical source installed on its bed. Now we examine the overall detection of sources which now include those which are native to the truck's engine. The spherical source and its reflected path are separated from those of the truck at all frequencies shown. At 922 Hz, the engine noise propagation paths consist of a path under the cab as well as through the wheel well. The ground reflection path appears to persist at 1937 Hz. As discussions of these trucks continue, the reader will be presented with further evidence of ground-reflected engine noise as an important contributor to passby sound.

Further calibration of the array *insitu* included correlation with classical measurements of sound intensity which were made over the areas of the truck side-plane as indicated at the top of Figure 5. The intensities averaged over these areas were converted to sound power, the spectra of which are shown at the bottom of Figure 5. These sound power contributions provide a rank ordering of the overall sound; the rankings can also be ascertained from the array's source map images. These are tabulated in Table 1 and the rankings that are obtained by both methods agree well. The rankings include the direct path contributions to the roadside levels as well as much of the reflected path contributions since the intensity scans generally extended below the truck to the near the road surface. Although the data presented here showed excellent correlation between the two methods, when the truck sources were more

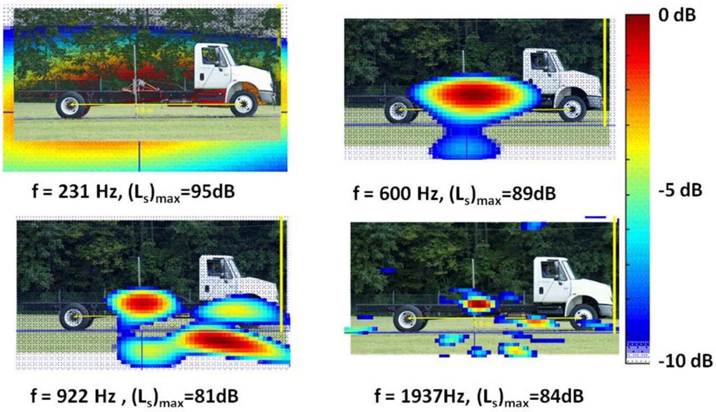


Fig. 4 Images for the source distribution of Truck 4400 stationary opposite the array with its engine at 2000rpm and with the energized spherical source installed. The color bar is calibrated to provide approximate equivalent 1/3 octave band levels the maximum values of which are shown on each picture.

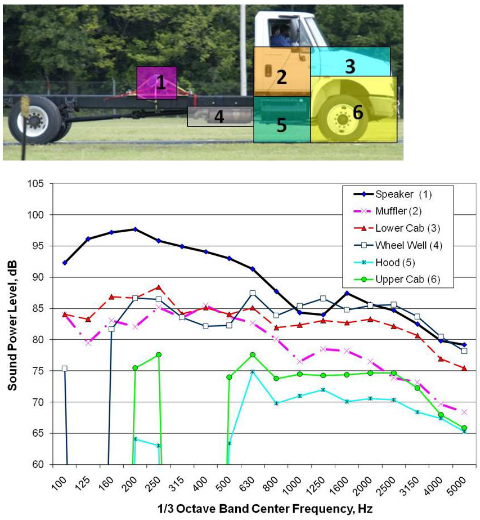


Fig. 5 Contributing sound power levels (dB re 10^{-12} W) in the indicated areas for Truck 4400 idling with loud speaker source and engine at 2000 RPM.

Truck 4400 with Speaker Source							
Frequency		Speaker Source level		Wheelwell		Lower cab	
Image	Sound Power	Image	Sound Power	Image	Sound Power	Image	Sound Power
231	250	95	96	< 86	87	< 86	86
600	630	89	91	< 80	87	< 80	85
922	1000	80	84	81	85	76	83
1430	1251 to 1600	79	85	77	85	76	83
1938	2000	84	85	77	85	82	83

Table 1 Comparison of rank ordering of sources obtained by sound intensity and array source maps.

spatially distributed, for example with multiple simultaneously-occurring sources and with the indicated multiple propagation paths beneath the truck and through the wheel well, the comparisons were more demanding. In those cases the delineation among sources was less clear.

5 Examples of the truck-noise source distributions during passby

Passby measurements were made on four trucks with and without trailers and over a range of operating conditions that included: passby speed (0, 56 km/h (35mph), and 80 km/h (50mph)), gear ratio, engine speed, acceleration and deceleration, coasting and idling, compression brake, various tire tread patterns and muffler condition. Overall, these data permit a significant parameterization of the sound from all the localized sources. Space permits discussions for two truck models only in addition to that discussed above. The source map images for the Truck 5900 stationary and during a 80 km/h mph passby are

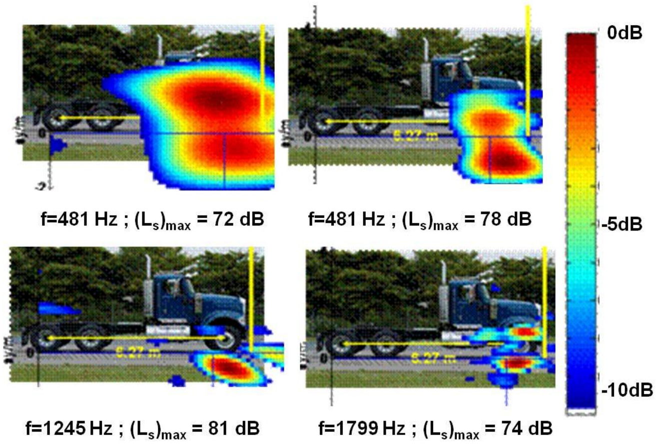


Fig. 6 Images for source distribution of Truck 5900 stationary opposite the array with engine at 1400rpm.

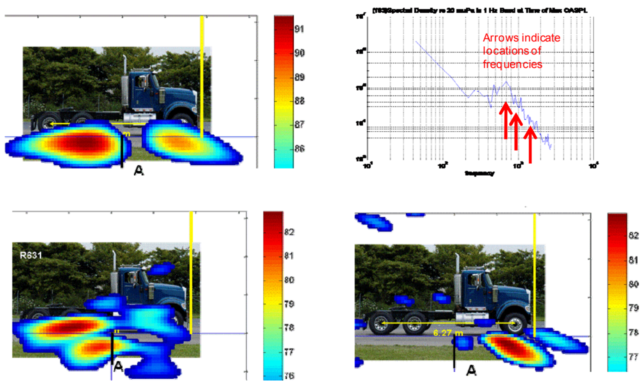


Fig. 7 Source distributions for Truck 5900 moving to the right at 80 km/h with engine at 1400 rpm at frequencies: (a) 695 Hz, (b) 868 Hz, and (c) 1346 Hz indicated in the truck noise spectrum (d). These frequencies are indicated in the spectrum.

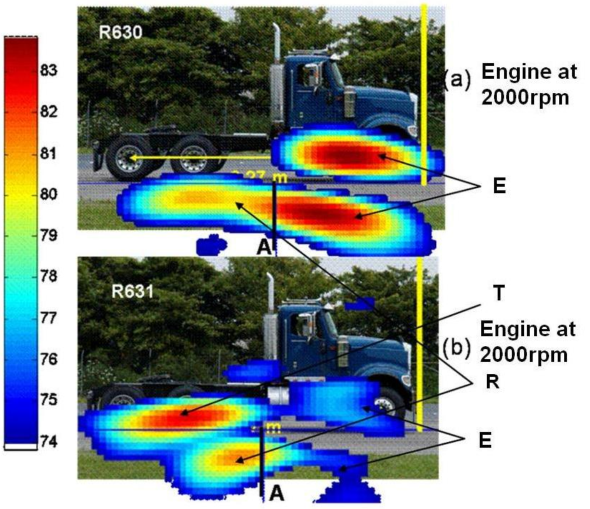
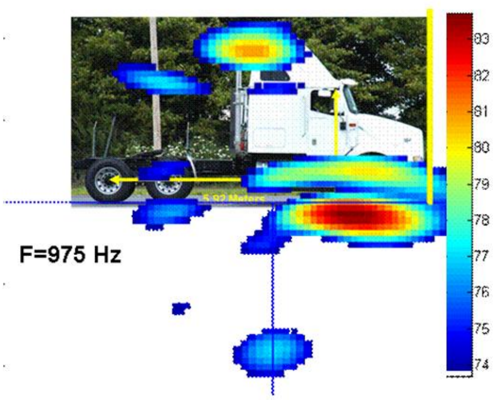


Fig. 8 Source distribution (at frequency of 868 Hz) of truck 5900 moving to the right at 80 km/h with engine at (a) 2000 rpm and (b) 1400 rpm. Engine noise contributions are identified as "E", tire noise as "T", and reflected-path tire or drive-train noise as "R".

a. with Muffler



b. NO Muffler

Fig. 9. Source distribution for Truck model 9200 traveling at 56 km/h with the engine speed 1900rpm: (a) with muffler and (b) without muffler. The colorbar applies to both illustrations to within 2 dB.

shown in Figures 6 and 7, respectively. The engine speed is 400rpm. We see excellent resolution for frequencies ncluding 481 Hz and the dominance of tire noise over the ngine noise for the passby case. Engine noise is still learly apparent and significant road reflection either lominates or contributes to the received levels. The engine ioise appears to dominate at 1346 Hz for this truck at this osition during passby. When the engine speed is increased o 2000 rpm the engine noise increases significantly (~6dB) is shown in Fig. 8. Note also that ground reflection ontributes to the tire noise. Other examples of the sound ource map images at various array steering angles provide lata at other aspect angles; these disclose the directivity atterns of the sources, see also [2].

The array was also capable of resolving the location of sound induced by the exhaust. Figure 9 shows image maps for a truck with the muffler removed compared with the same truck with the muffler installed. This enhancement in exhaust noise resulted in a source at the top of the stack and its reflection image well-beneath the road surface. The chosen frequency was one of a series of harmonics in the passby noise autospectrum. The truck's aerodynamic fairing was open at its rear so the exhaust noise was amplified by the cavity resonance of the fairing. This produced harmonics of a lateral resonance; the one selected for illustration here is the 5th harmonic. Note that the source location is shifted slightly forward of the stack suggesting that it is the resonating cavity, and not the stack itself, that is the source. Note also that the engine noise is transmitted by the road reflection that is the same level in both cases.

One of the most important uses of the array-based measurements is the definition of the vertical distribution of the sources. The images just examined can be 'rolled-up' into maps such as shown in Fig. 10, again for Truck 4400 which transported an actuated spherical source past the array. The time axis has been converted to bumper position

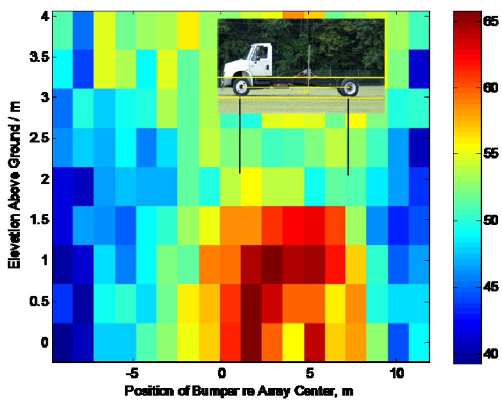


Fig. 10. Vertical scan at 937 Hz for Truck 4400 passing to the right with its engine at 2200 rpm, and the spherical source activated.

relative to the array center. Level is, again, the equivalent approximate one third octave band level; truck photo is scaled to the horizontal scale with its ~6 m wheel base indicated, but vertical axis of the acoustic scan is expanded with the 1m mark on the truck indicated with the line. Although the truck passes to the right, time scale increases to the left. Thus the photo is reversed left-to-right to account for the fact that t=0 corresponds to the bumper passing CPA, and at t=8 sec the rear of the truck passes. The spherical source on the truck bed is about 1 m above the road; this accounts for the horizontal stripe in the vertical distribution at that height. The source at about -2 m behind the bumper corresponds to the spot shown at 922 Hz in Fig. 4 due to the engine and its reflected path. The vertical scan shown here does not extend beneath the road surface. If it did, it would register that path as well.

Fig. 11 shows the vertical distribution of sound sources "rolled-up" for Truck 5900, but now at 56 km/h. With the measured passby speed, the time record of the passby was again translated into distance for scaling to the photograph of the truck. The cab-only produces levels both at the engine and at the rear wheels. The addition of the trailer provides a repeated pattern at the cab locations and at the trailer's tires. Note that all the sound is concentrated to within 1.5 m of the road surface; inspection of the photograph of the trailer discloses (using the figure of a man as a reference) that these sources are all below the trailer's frame.

6 Conclusion

The measurements exemplified in this paper and the calibrations discussed in [1] demonstrate that the array and its post processing can provide absolute level comparisons of truck noise sources with adequate localization to pinpoint the source location with the sound-generating truck component. For this large-aperture elliptical array, with the 6 m passby range geometry, the spatial discrimination of sources on trucks was as expected for frequencies between 231 Hz and 2000 Hz with aperture limiting at low frequencies and grating lobes limiting above 2000 Hz. Engine noise appears to be a significant contributor to passby levels at frequencies in excess of about 1000 Hz and for the Truck 5900 increased nominally 7-8 dB for an engine speed increase of 1.4. A ground-reflected path for this noise is generally dominant over an expected flanking path through the wheel well. For well-operating mufflers in normal steady-velocity conditions exhaust noise does not appear to be dominant. Tire noise is important at all speeds and ground reflection is an important contributing feature of the noise measured at road side. Comparison with sound intensity measurements confirmed the ability of the array and the post processing algorithm to rank order the sound sources.

Acknowledgments

This project is funded by the National Cooperative Highway Research Program of the Transportation Research Board of the National Academies, USA. Specific thanks are also due to Mr. Les Grundman and Mr. Lee Schroeder of the International Truck and Engine Co. for support during the test track measurement program and to Mr. Damien Bell of Wyle Labs. and to Mr. Clayton Anderson of I&R for their assistance in the measurements.

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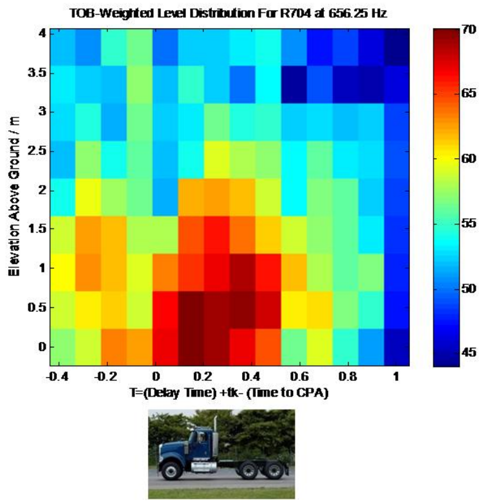
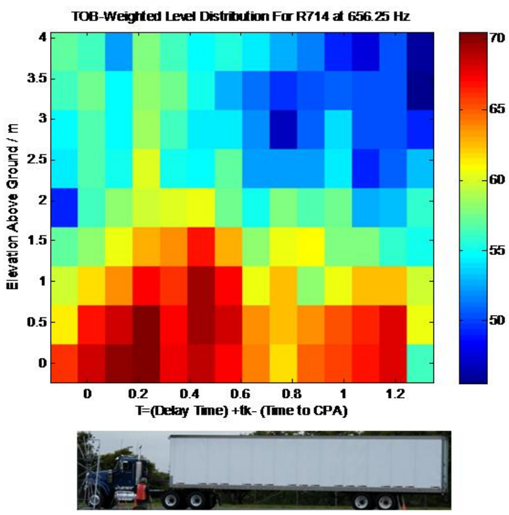


a) Truck cab only



b) Cab and trailer

Fig. 11 Vertical distributions of source levels for a truck passing at 80 km/h, 1400 rpm engine speed in 7th Gear with and without trailer.