Construction Noise Database (Phase 3)

Evaluation of Established Measurement Protocol

Report for DEFRA by

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3 Introduction

This report presents the results of an analytical and experimental investigation of the accuracy of sound power levels of large machines as determined from sound pressure level measurements taken according to the established measurement procedure used in the recent revision of BS 5228. The methodology of the established measurement protocol is to record sound pressure levels at a single distance that is considered large compared with the source dimensions and with the wavelength of sound. These measurements include the estimation of 1/1 octave band and A-weighted sound pressure levels. For plant performing normal stationary activities these are derived from L_{eq} recordings, while for dynamic plant these are derived from L_{max} recordings made during drive-by. The procedure includes a normalisation to a 10m distance, based on the assumption that the sound power propagates hemispherically from a point source located at the geometrical centre of the plant. For large noisy sources these far field measurements are usually the only practicable method when assessing in situ.

Propagation of noise in the open atmosphere is a complicated statistical problem, since the atmosphere is in constant fluctuation by its nature. Density in temperature, wind and humidity are never uniform in a given volume of air under observation, nor are they constant in time. Sound waves travelling through the atmosphere are affected by these non-uniformities. However the effects of these factors on sound propagation are not large unless the transmission path is very long, of the order of hundreds of meters. Usually it can be approximated that the air is an ideal, homogenous and loss free medium. Further it can be assumed that all sources are composed of numerous point sources, and that each elemental point source radiates noise energy incoherently in all directions, neglecting the nature of wave motion. These assumptions are reasonable and very useful for engineering noise prediction and control.

The principal objectives of source output quantification are as follows:

i. comparison of sound powers of machines and plant for the purpose of user selection
ii. source labelling
iii. predicting the sound pressure field and associated adverse effects, such as hearing hazard or environmental impact
iv. to check conformance with regulatory or legal requirements
v. to identify source mechanisms or diagnostics

In this study we are concerned primarily with objective iii, but the methods of quantification of sound power derived for the other objectives have equal applicability.

Sound power quantification methods fall into two categories, direct and indirect. In direct quantification, the power is inferred directly from measurements of the radiated sound power in conjunction with an assumed field model. In indirect quantification, it is determined either by comparison with a calibrated source, the substitution method, or from measurements of the vibration velocity of a radiating surface. For manufacturers and users to be confident in test results, and for the purpose of satisfying legal requirements, internationally agreed standardised test methods have been developed by the International Organisation for Standardisation (ISO). In Europe the CEN standards closely follow most ISO standards.

Since the sound pressure level generated by a source varies with distance, direction and environmental conditions, and the presence of other extraneous sources adds to the sound produced by a source under test to an unpredictable degree, these methods usually require the isolation of the source in an acoustical controlled environment. ISO 3745 (3744) requires an anechoic or semi anechoic test environment. The measurement surface is described around the source and divided into a number of segments. The sound pressure is sampled at one point in each segment. It is implicitly assumed that the intensity vector lies normal to the measurement surface. ISO 3741 (3742-1/2) requires a reverberant environment where the source sound power is equal to the estimated rate of energy dissipation by the walls, determined either from an array of fixed microphones distributed over the room volume, or from a mechanised continuous transverse of the volume. The other ISO 374- standards are variants on these methods with empirically derived factors to correct for non-ideal conditions.

Noise fall-off with distance has been the subject of earlier work. The fundamental work of Maekawa (1970) shows the noise reduction along the symmetry axis perpendicular to a circular and rectangular plane noise source. He also analysed the noise reduction with distance of plane sound sources composed of small surface elements with different radiation characteristics. Rathe (1969) derived the sound level along the line perpendicular to the centre of a rectangular plane noise source. He found the transition distances from plane source to line source, and from line source to point source behaviour of the rectangular noise source assuming omni-directional radiation characteristics. This work was expanded upon by Ellis (1970) concerning receiving points on and outside the boundary of the rectangular sound source. Janacek (1989) analysed analytical propagation models of plane sound sources, and together with a numerical integration, derived the intensity for a plane sound source and compared the results with measurement. The prediction of ground effects caused by sound radiated from a finite panel was investigated by Li (1989) using a numerical model. The model assumed omni-directional sound radiation of a panel over an impedance plane, and the sum pressure caused by each element was computed using a point source ground model above an impedance boundary. The sound pressure of the panel was evaluated using numerical integration. The effect of source directivity regarding the ground effects was analysed by Hohenwater (1990), who reasserted the finding of Rathe that fall-off with distance perpendicular to a noise radiating surface is like a point source or line source, depending on the geometric dimensions of the rectangular noise source and the receiver distance.

This topic has also been well researched by authors developing the ISO procedures for determination of sound power level. Holmer (1977) for example performed an investigation to place error bounds on several proposed measurement procedures, chiefly through the comparison with sound power levels determined from far field measurements. The data analysis centred on the comparison of sound power levels estimated from measured sound pressure levels on two measurement surfaces, one far field at 7-m radius and a near field at

1m from the surface of the machine. Empirical estimates of precision and accuracy were derived for each of several proposed ISO procedures for determination of sound power level. The near field measurements were found to produce an overestimate of the far field power level with the magnitude of the overestimate depending on the measurement surface shape.

A recent resurgence in interest has resulted from outdoor Noise Directive 2000/14/EC concerning the labelling of machines with guaranteed sound power levels. A report by Jonasson (1999) addressed the determination of emission sound pressure level and sound power level in situ. An assessment of reproducibility uncertainties for use in international standards on the determination of power was performed by NPL (2000). An analytical study of the uncertainties for A weighted sound power level determination using sound pressure measurements due to end the number of microphones, to the angle error and to the impedance error for the ISO 3740 series of standards has recently been examined by Loyau (2006). Carletti (2006) recently presented an inter-laboratory test for the assessment of reproducibility uncertainties of earth-moving machines. The findings of the above theoretical work are applied in the following analytical study of the established measurement protocol. Much of the research that formed the foundation of the ISO procedures for determination of sound power is applied in our experimental study.

4 Analytical study

4.1 The point sound source hypothesis

The measurement hypothesis is that the plant sound power can be accurately characterised by a single positioned measurement made over sufficient duration. Further it is asserted that this sound power can be normalised to a distance of 10m using point source propagation over a hard plane. This is equivalent to assuming that at the receiving position the plant acts as a point source propagating over an acoustically hard plane.

We first consider that a piece of large plant can be considered as a collection of point sources. A real sound source has its own dimensions, but can be treated as a point source from a receiving point sufficiently distant from the source. The wave front diverges from a point source and radiates sound energy spherically. Sound intensity decreases inversely with the square of distance, and this relationship is the well-known inverse square law. When a sound source is directional the inverse square law is also valid for any one direction.

Rathe (1969) showed that for the following geometry of a finite plane source dimensions b>c that characteristic ranges can be distinguished.

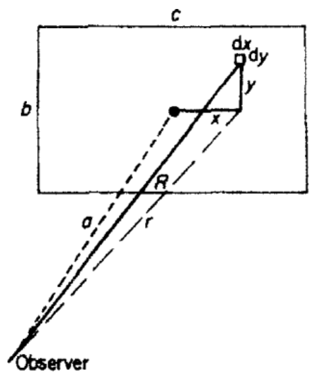

Figure 1: Finite plane source of dimensions b >c from Rathe (1969)

Here the sound source is a rectangular area of dimensions b and c, and the observer is situated at a distance a on the vertical axis of symmetry of the source. Three characteristic ranges can be distinguished. The first is near the source where a<<b and a<<c.

The sound pressure equation reduces to:

$$(p_{\text{r.m.s.}})^2_{\text{total}} = \frac{Wz_0}{\pi bc} \cdot \frac{\pi}{2} \cdot \frac{\pi}{2} = \frac{Wz_0 \pi}{4bc}.$$

with W the total power of the source, and z_0 the characteristic impedance of the medium. This expression has no dependence on a and so the sound pressure remains constant near the source. This is typical for a plane source.

The second range is defined by a>>b and a<<c. Then

$$(p_{\mathrm{r.m.s.}})^2_{\mathrm{total}} = \frac{Wz_0}{\pi bc} \cdot \frac{\pi}{2} \cdot \frac{b}{2a} = \frac{Wz_0}{4ac}$$

which corresponds to a line source.
The third range is given by a>>b and a>>c. when

$$(p_{\mathrm{r.m.s.}})^2_{\mathrm{total}} = \frac{Wz_0}{\pi bc} \cdot \frac{b}{2a} \cdot \frac{c}{2a} = \frac{Wz_0}{4\pi a^2}$$

for an attenuation equivalent to that of a point source.

4.2 Transition points and characteristic ranges

The sound pressure level as a function of distance is represented in the figure below.

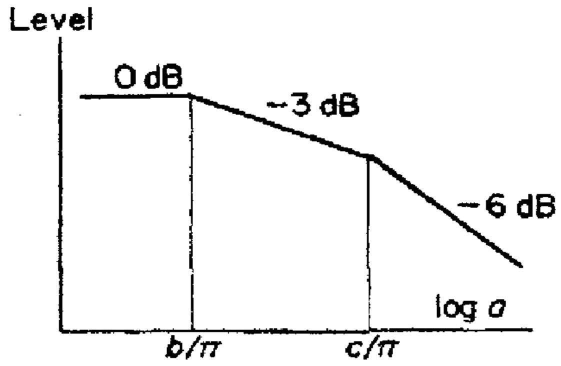

Figure 2: Sound pressure level attenuation with distance for a finite plane source from Rathe (1969)

These characteristic ranges are distances described by the transition points at which the source is perceived as a plane source, a line source, and a point source. The transition points are:

i. $a=b/\pi$ from plane source to line source
ii. $a=c/\pi$ from line source to point source.

Considering the plant to be composed of finite plane sources as viewed from the SLM position, the significant composite sources and their approximate dimensions in the plane of the vertical are as in the following example:

Component	Height b(m)	Length c(m)
Engine	2	2
Exhaust	0.5	0.2
Bucket	1	1
Wheel chains	2	2

Table 1: Face Shovel component sources and dimensions

Then the above components approximate to line and point sources at distances given in the following table.

Component	Line (m)	Point (m)
Engine	0.6	0.6
Exhaust	0.06	0.15
Bucket	0.3	0.3
Wheel chains	0.6	0.6

Table 2: Transition distances for Face Shovel component sources

These values show that the Face Shovel can be considered as a collection of point sources from a source to receiver distance greater than 0.6m.

4.3 Errors due to components within the main source plane

Since we considered the vehicle and operations to act as a single point source at a given distance, it is therefore necessary to estimate the error due to the difference in distance for each source to receiver. We first consider a source located in the plane of the vehicle at a distance x from the main source position as illustrated below.

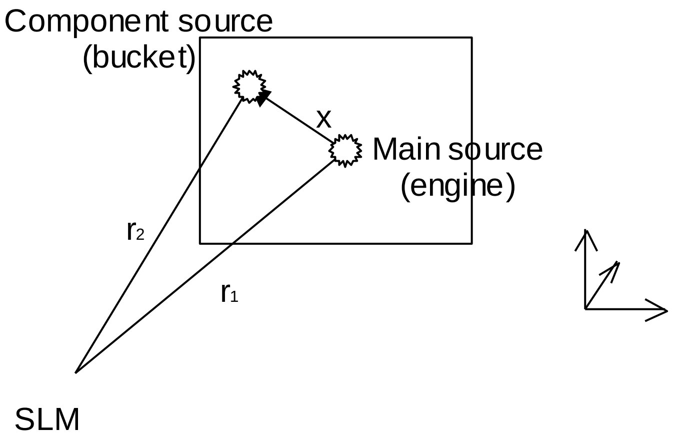

Figure 3: Plant considered as a main point source and component point source located at a distance x away in the same vertical plane.

We measure L_p and calculate

$$L_{w1} = L_p + 20\log_{10} r_1 + 8 \quad (1)$$

The actual component sound power level L_{w0} though is

$$L_{w0} = L_p + 20\log_{10} r_2 + 8 \quad (2)$$

If the error in component source estimation is

$$\delta L_w = \mathrm{L}_{w0} - \mathrm{L}_{w1} \quad (3)$$

then

$$\delta L_w = 20\log_{10} \frac{r_2}{r_1} \quad (4)$$

Let the perpendicular distance of the SLM from the main source on the machine be r_1 and the distance in the plane from the main source to the secondary source be χ . Then

$$\delta L_w = 20\log_{10}\frac{\sqrt{x^2+r_1^2}}{r_1} \quad (5)$$

$$\delta L_w = 10\log_{10}\frac{r_1^2+x^2}{r_1^2} \quad (6)$$

So as $\log_{10}\frac{x^2}{r_1^2} \Rightarrow 0$, $\delta L_w \Rightarrow 0$.

Rearranging we can obtain an expression for the ratio of component source distance x to main source to receiver distance r_1 as a function of maximum permissible error in sound power level estimate.

$$\frac{x}{r_1} = \sqrt{10^{\frac{\delta L_w}{10}} - 1} \quad (7)$$

Taking a sound level meter at a main source to receiver distance of 10m then the maximum error in sound power level estimation for various component source distances from the main source can be calculated as shown in table below, and is shown graphically in figure 4.

Max δL_w (dB)	**Ratio $\frac{x}{r_1}$**	**Max x (m) for $r_1 = 10m$**
1	0.5	5
0.5	0.35	3.5
0.1	0.15	1.5

Table 3: Limits on component source displacement for given uncertainty for SLM to main source distance r_1=10m

The influence of this error in component level on the L_{Aeq} at 10m is numerically smaller than the values shown in the table. This is because the component sound power level is a smaller value than the main source and so when combined by decibel arithmetic the error has numerically less contribution. Taking a 1dB error in component source sound power for example, 90 + 87 =91.76dB, while 90 + 86 = 91.45dB, so 1dB error in component source sound power level becomes ~0.3B in L_{Aeq} at 10m.

4.4 Positioning errors within the main source plane

The expression derived above can be used to estimate the uncertainties in sound power level due to errors in locating the source within the main source plane. The figure below shows the error in sound power level against the uncertainty in horizontal source position estimate for the SLM at 10m perpendicular distance.

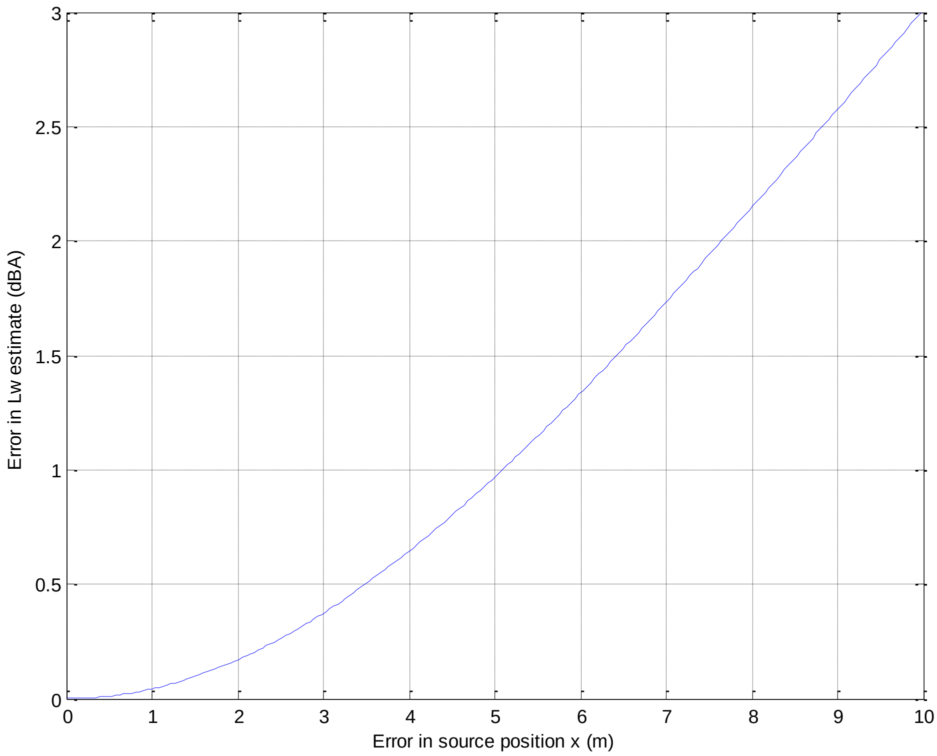

Figure 4: Variation in error in Lw measured by SLM at 10m perpendicular source-receiver distance with uncertainty in source position x in the plane of the vehicle

For $\delta L_w \leq 1dB$ then sources can be up to 5m from the assumed main source position in the vehicle plane for a SLM measurement distance of 10m.

4.5 Errors due to length of perpendicular to source plane

Now we consider an error y in the length of the perpendicular to the source.

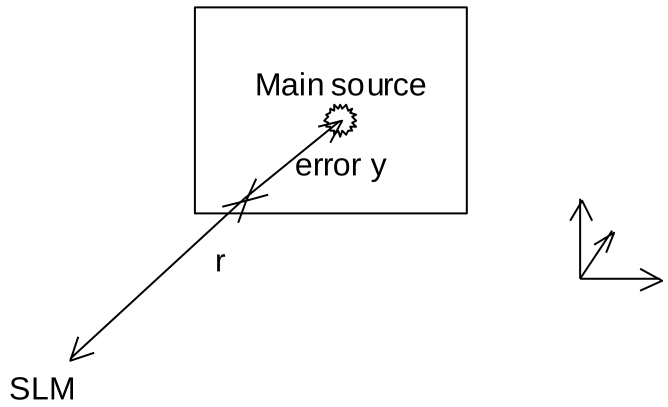

Figure 5: Plant considered as a point source located at a distance r from the SLM but with an error y in perpendicular distance.

As above we measure L_p and calculate

$$L_{w1} = L_p + 20\log_{10} r + 8 \tag{8}$$

Actually

$$L_{w0} = L_p + 20\log_{10}(r + y) + 8 \tag{9}$$

Therefore

$$\delta L_w = 20\log_{10}\frac{r+y}{r} \tag{10}$$

Rearranging

$$\frac{y}{r} = 10^{\frac{\delta L_w}{20}} - 1 \tag{11}$$

Taking a sound level meter at an assumed source to receiver distance of 10m then the maximum error in sound power level estimation for errors in the perpendicular source distance can be calculated as shown in table below.

Max δL_w (dB)	**Ratio $\frac{y}{r}$**	**Max y (m) for $r = 10m$**
1	0.12	1.2
0.5	0.06	0.6
0.1	0.01	0.1

Table 4: Limits on uncertainty in perpendicular source to receiver distance for given error in sound power level estimate for SLM at 10m

The Lw uncertainty estimates from measurements by a SLM at 10m distance for various errors in perpendicular source-receiver distance are illustrated in the figure below.

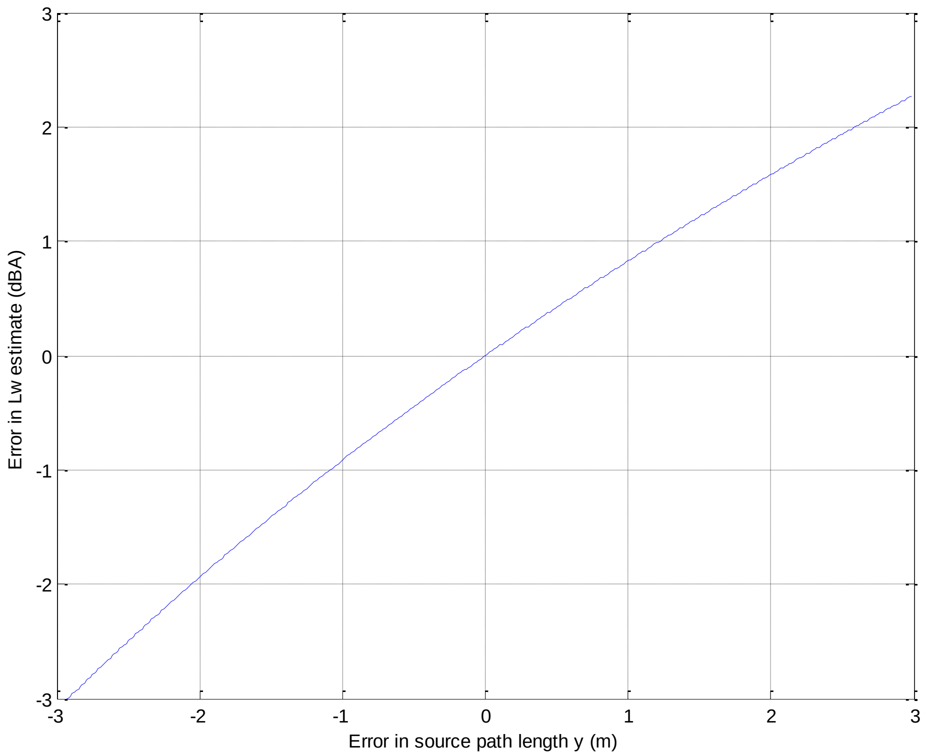

Figure 6: Variation in error in Lw measured by SLM at 10m perpendicular source-receiver distance with error y in perpendicular source-receiver distance

4.6 Errors in normalisation to 10m due to source-receiver uncertainties

The above results show that the measurement is far more sensitive to errors in main source to receiver perpendicular distance than to source displacement within the plane of the main source. This is likely to have significance when the setting up of recording instruments at a distance of 10m is found to be impossible for reasons of safety or restricted access. On these occasions noise measurements are taken at some convenient position and the measured sound level subsequently adjusted to that for a distance of 10m assuming point source propagation over a hard plane.

From equation (10), the sound power level calculated from the sound pressure assuming a 10% error in distance estimate is given by:

$$\delta L_w = 20\log_{10}\frac{r \pm \frac{r}{10}}{r} \qquad (12)$$

$$\delta L_w = 20\log_{10}\frac{10 \pm 1}{10} \qquad (13)$$

Equally the uncertainty in the sound pressure level assuming a 10% distance estimate calculated from the sound power level is given by:

$$\delta L_p = 20\log_{10}\frac{10 \pm 1}{10} \qquad (14)$$

Consequently the uncertainty in the sound pressure level normalised to 10m from a sound pressure level measured at 20m assuming a 10% error in distance is given by:

$$2 \times 20\log_{10}\frac{10-1}{10} \leq \delta L_{p10} \leq 2 \times 20\log_{10}\frac{10+1}{10} \qquad (15)$$

$$-1.83 \leq \delta L_{p10} \leq 1.66dB \qquad (16)$$

4.7 Effects of vector wind at short ranges

Experiments were performed to determine the likely uncertainty in the measured sound pressure level from the SLM at 10m due to variations in the wind vector. A high-power omni-directional electro-acoustic source with centre height 2m was used to provide a sound power of 130dB. Acoustical monitoring units with a microphone height of 1.5m were installed with reference positions near the source. Each station was used as a stand-alone data logger and audio recorder logging L_{eq}, L_{fast} and 1/3 octave band spectra each second. The source emitted pink noise in five-minute sections separated by one-minute sections of silence to enable background levels to be monitored. Automatic weather stations were used to simultaneously collect detailed meteorological information. The measurements detailed here were performed over flat grassland. The correlation of the L_{Aeq} with vector wind speed is illustrated below for a receiver distance 10m. The dotted line shows the sound pressure level using predicted using the CONCAWE calculation method. The data show a slight correlation with wind vector, with a downwind enhancement of ~1.5dB clearly evident and some indications of an upwind shadow.

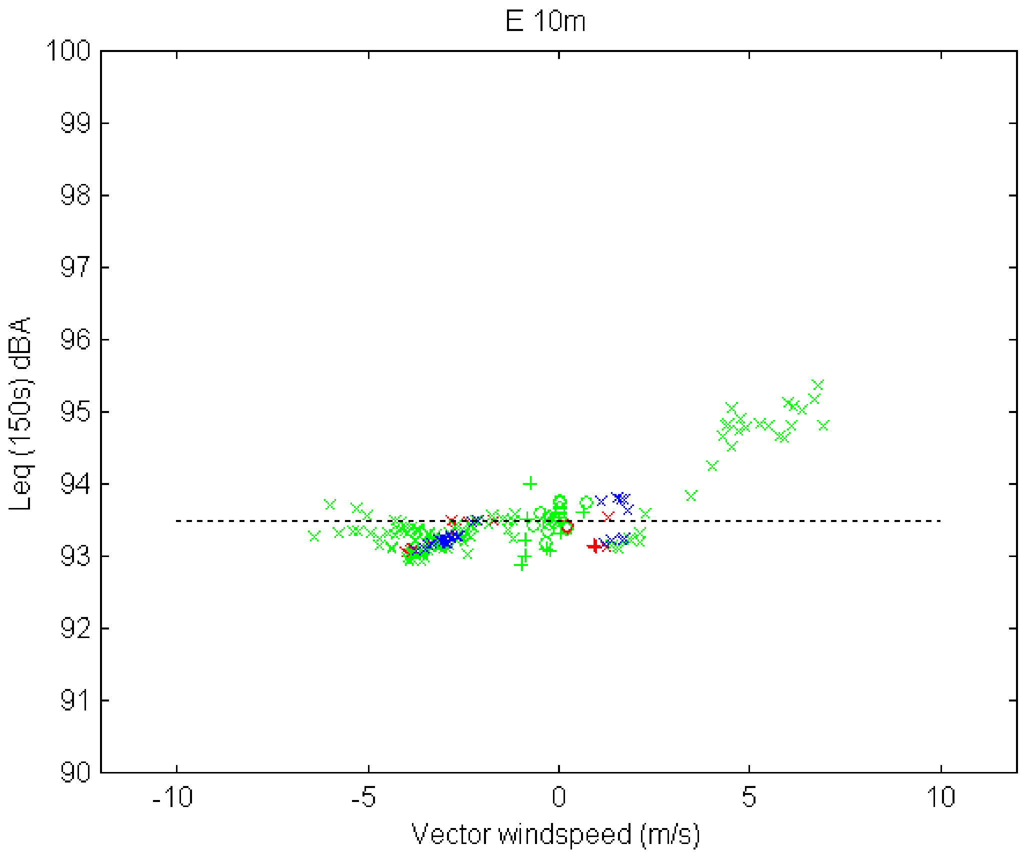

Figure 7: Effect of vector wind on measured L_{Aeq} (150s) at 10m over grass

4.7.1 Effect of the ground wave propagation approximation

It is assumed within the method that sound falls off at 6dB per distance doubling. This is the normal description of propagation from point source over a hard surface. This propagation model is used initially in the calculation of the sound power of the source when the single SLM is used to measure at a distance other than 10m. The propagation model is used again in the normalisation of the sound power measurement to the standardised distance of 10m. Consequently the choice of propagation model is significant and deserves closer inspection.

A more accurate description would take into account spherical propagation over an impedance plane, including a description of the ground wave. The figure below illustrates the predicted sound pressure spectrum for a monitor at a receiver height of 1.5m and distance 10m from a point source of height 2m. Three models had been used for the prediction of sound pressure. The first is the 6dB per distance doubling for hemispherical propagation from point source implicit in the established protocol. The second is a plane wave model over an impedance plane, while the third is a spherical wave model over an impedance plane giving account of the ground wave.

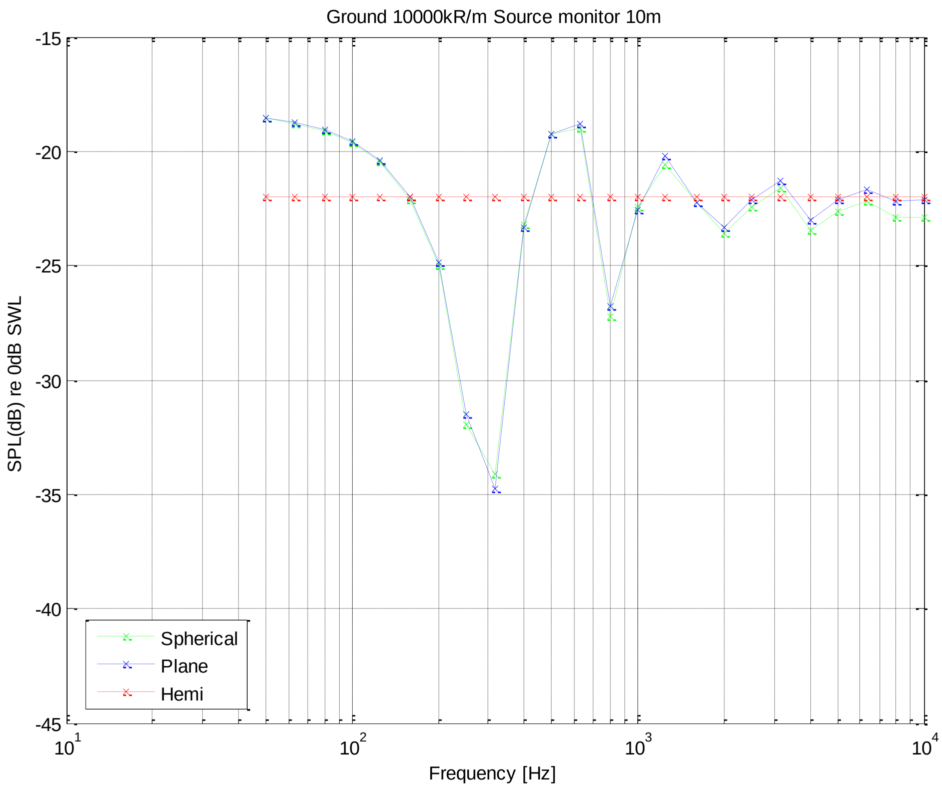

Figure 8: Predicted spectrum at 1.5m receiver height of distance 10m from a 2m-height point source. Three propagation models are: spherical wave model over a hard impedance plane giving account of the ground wave, plane wave propagation over an impedance plane, and 6dB per distance doubling for hemispherical propagation from point source.

The spherical and plane wave models show little difference for this very hard surface. However the results show the effect of the interference between the direct and ground reflected source to receiver waves in the form of the ~12dB dip at ~300Hz. In a real propagating atmosphere turbulence would reduce the depth of this dip considerably.

An equivalent comparison is performed below for a monitor at 20m distance. As expected due to the decrease in the path length difference between direct and reflected wave the frequency of the first interference dip has increased to ~500Hz.

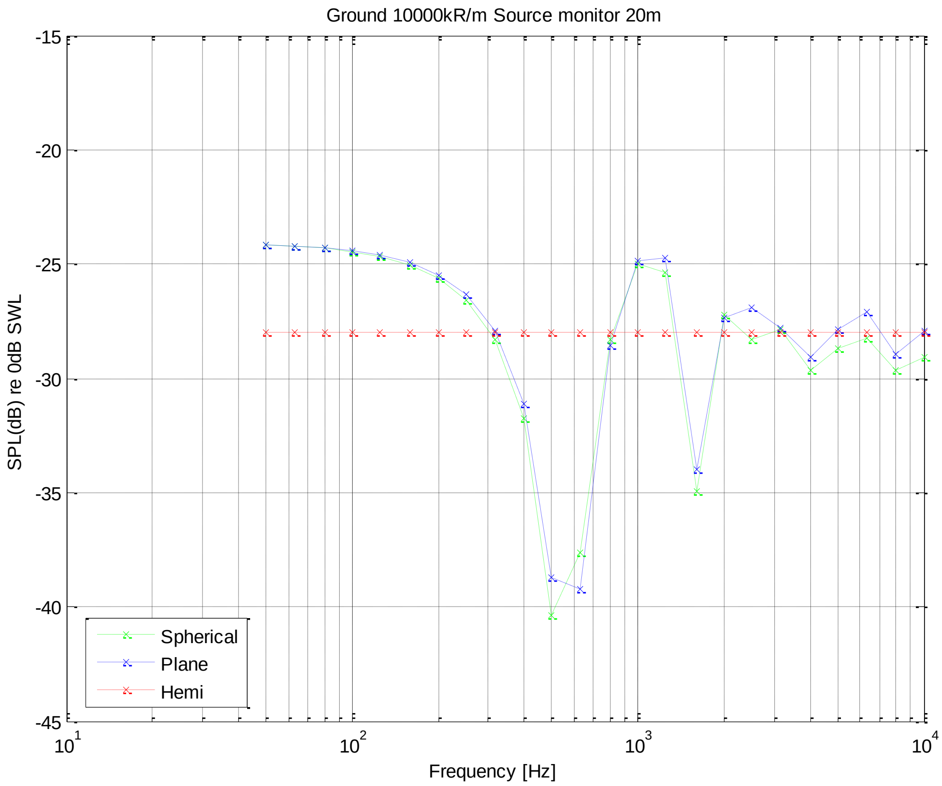

Figure 9: Predicted spectrum at 1.5m receiver height of distance 20m from a 2m-height point source over a hard impedance plane.

The figure below illustrates predictions performed for reasonably soft grassland. Again the interference dip is seen to occur at ~300Hz for the spherical and plane wave models, but the finite impedance of the surface is seen to have an effect in the ground wave resulting in significant differences between the two spectra.

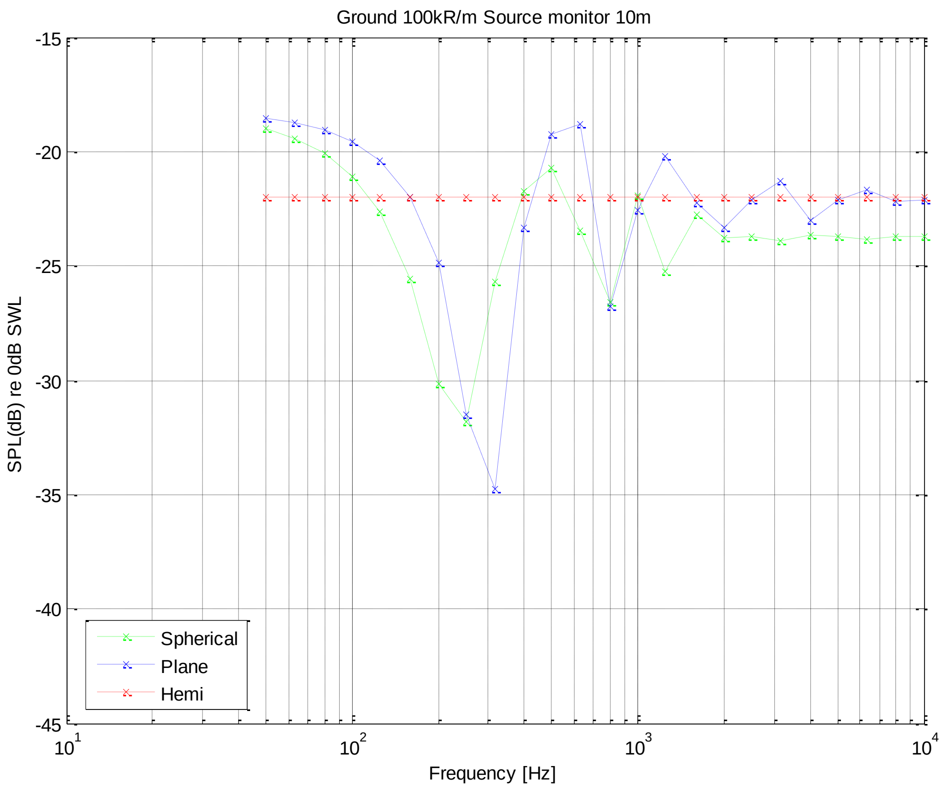

Figure 10: Predicted spectrum at 1.5m receiver height of distance 10m from a 2m-height point source over a soft impedance plane.

The differences between the plane wave and spherical wave models are seen more clearly in the following figure showing predictions for a receiver at 20m distance. Here the ground wave interactions are seen to significantly move the position of the interference dips.

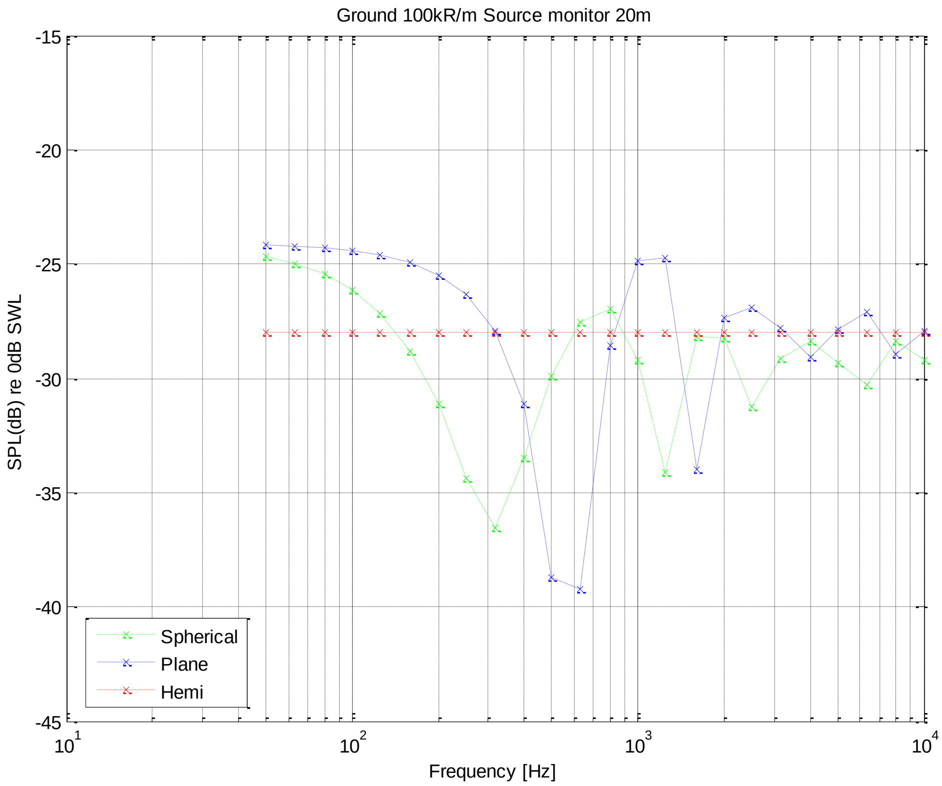

Figure 11: Predicted spectrum at 1.5m receiver height of distance 10m from a 2m-height point source over a soft impedance plane.

The computational requirements for the calculations applying the spherical wave model at multiple frequencies for a combination into 1/3-octave values is considerable and unworkable under practical circumstances. However, as mentioned above the depth of these interference dips in a real atmosphere would be significantly reduced due to the effects of turbulence. Moreover when summed to produce an overall A-weighted sound pressure level the significance of the dips and peaks will be further reduced. Nevertheless the interference dip is a real phenomenon that is observed in the measurements using a single SLM at a 10-metre distance. These observations are discussed further in the experimental study below.

5 Experimental study

5.1 Objectives

The objectives of the experimental study were:

i. To determine the uncertainties associated with the established protocol for measurements of sound power when normalised to 10m.
ii. To accurately measure the sound power emitted by a piece of stationary quarry plant using multiple microphones.
iii. To accurately measure the sound power emitted by a piece of mobile quarry plant using multiple microphones.
iv. To simultaneously measure the sound pressure levels at 10m or equivalent using a single SLM.

5.2 Overview of experiments

Consequently three experiments were performed as part of this study. These were:

i. Stationary test, comprising three consecutive measurements of a piece of plant using multiple microphones and simultaneously the SLM at 10m.
ii. Distance tests, comprising two separate measurements of the fall-off of sound pressure level with distance from a piece of plant.
iii. Dynamic tests, comprising three independent drive-by measurements using multiple microphones and simultaneously the SLM at 10m.

The methods and procedures of the acoustical measurements were performed in accordance with the British Standard 7445. 01dB Symphonie systems were used to log all data. In addition a 01dB SIP95 sound level meter was used to log data at the nominal single position of 10m. Due to the need for a drive-by no cables were allowed to cross through the measurement area, and all systems were battery operated. The measurements took place at a limestone quarry in North Wales. The date of measurements was 28th February 2006, determined by the period of the project and availability of suitable plant. The Salford team consisting of David Waddington and Gary Phillips, and were met by Paul Bassett of Hepworth Acoustics. The measurement area surrounded a quarry road. The north side of the area was an open hemispherical section approximately 50m in diameter backed by quarry face of approximately 30m height. The south side of the area was partially enclosed by a 1.5m earth barrier. Behind the earth barrier was an open area bounded by earth mounds of approximately 10m height, and 30m sheer drop into the main working face of the quarry. The surface of the measurement area was compacted limestone hard core. The surface conditions were very wet, such that the quarry road was virtually completely waterlogged. The wind was easterly with wind speeds typically less than 2m/s with occasional gusts of up to 5m/s. Light snow showers occurred regularly through the day interspersed with the occasional sunny spell. The low winds, stable temperatures and acoustically hard surface proved ideal measuring conditions.

The following parameters were logged by each Symphonie. This produced a record of each operation with time synchronisation between analysers.

i. Short time 1s L_{eq} giving one third octave bands from 20Hz to 20kHz
ii. Short time 1s L_{Aeq} to be used for time history

Measurement data are presented to one decimal place and consequently some rounding errors are evident in the tables below. Audio recordings were also made but not used in the following analyses.

Filename	Description	Time	Vehicle
Stationary			
stationary1	Comparing sound power measurements from a single SLM at 10m and from 6 mics on a hemisphere	14h20m05 – 14h21m59	Face Shovel (wheeled loader)
stationary2	Comparing sound power measurements from a single SLM at 10m and from 6 mics on a hemisphere	14h22m00 – 14h23m59	Face Shovel (wheeled loader)
stationary3	Comparing sound power measurements from a single SLM at 10m and from 6 mics on a hemisphere	14h24m00 – 14h25m59	Face Shovel (wheeled loader)
Dynamic			
dynamic1	Drive-by of front loader	14h37m08 – 14h38m25	Front Loader
dynamic2	Drive-by of dumper truck	14h29m15 – 14h30m30	Rigid Dumper Truck
dynamic3	Drive-by of dumper truck	14h45m29 – 14h47m45	Rigid Dumper Truck
Distance			
distance1	Fall-off with distance from rear of front loader whilst idling. Distances 10, 20, 30, 40 & 50m.	15h04m16 – 15h07m15	Face Shovel (wheeled loader)
distance2	Fall-off with distance from side of front loader performing repeated cycle of simulated operations. Distances 10, 20, 30, 40, 50 &	15h09m28 – 15h12m32	Face Shovel (wheeled loader)

	60m.		

Table 5: Summarising measurements used in the following analyses

5.3 Microphone positions and the measurement hemisphere

Measurements were performed on an item of stationary plant positioned in the centre of a hemisphere of six microphones. The microphones were positioned as detailed in ISO 6393:1998 - Measurement of exterior noise emitted by earth-moving machinery – Stationary test conditions, p6. The positions are dependent upon the basic length L of the machine. The relevant distances are summarized in the table below. All construction machinery measured had a basic length in excess of four metres and so the radius of the hemisphere was 16m.

Length L (m)	**Radius R (m)**
L<1.5	4
1.5<L<4	10
L>4	16

Table 6: Dimensions of hemispherical measurement surface relative to the basic length of the machine

Mic no	**x (m)**	**y (m)**	**z (m)**
1	2.80	2.80	1.50
2	-2.80	2.80	1.50
3	-2.80	-2.80	1.50
4	2.80	-2.80	1.50
5	-1.08	2.60	2.84
6	-1.08	-2.60	2.84

Table 7: Dimensions of hemispherical measurement surface for basic length of the machine L<1.5m

Mic no	**x (m)**	**y (m)**	**z (m)**
1	7.00	7.00	1.50
2	-7.00	7.00	1.50
3	-7.00	-7.00	1.50
4	7.00	-7.00	1.50
5	-2.70	6.50	7.10
6	-2.70	-6.50	7.10

Table 8: Dimensions of measurement surface for basic length of the machine 1.5<L<4m

Mic no	x (m)	y (m)	z (m)
1	11.20	11.20	1.50
2	-11.20	11.20	1.50
3	-11.20	-11.20	1.50
4	11.20	-11.20	1.50
5	-4.32	10.40	11.36
6	-4.32	-10.40	11.36

Table 9: Dimensions of measurement surface for basic length of the machine L<4m

Distances and heights were measured with a tape measure. Allowing for slight variations in the terrain, tension of the tape measure and reading error, the uncertainty in the distances and heights was estimated as ±0.1m with a 95% level of confidence. Due to the earth barrier on the southeast side of the area, microphone number 1 was repositioned directly south as shown in the diagram below.

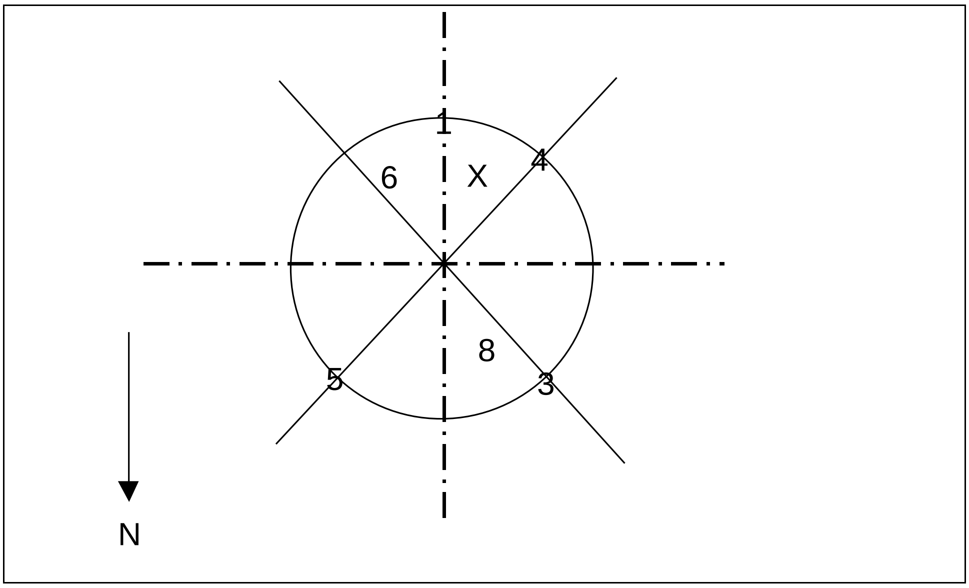

Figure 12: Schematic of microphone positions. Numbers indicate microphone number. X marks the SLM.

The photograph below shows the scene as viewed from the south of the hemisphere. A Rigid Bodied Dump Truck is positioned in the centre of hemisphere, the earth barrier is seen in the south west of the measurement area, and a selection of microphones and the SLM are labelled.

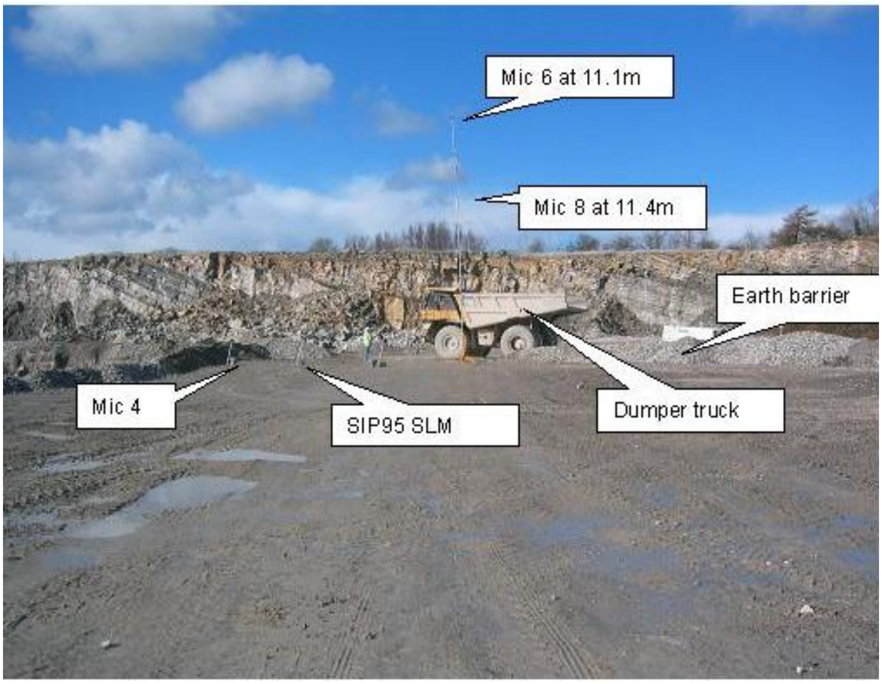

Figure 13: View of measurement area looking north. The dumper truck is standing at the centre of the measurement hemisphere.

5.4 Stationary tests

5.4.1 Description of stationary tests

Three stationary tests were performed on the 370kW 50t Face Shovel (wheeled loader). The face shovel simulated operations with forward driving, reverse driving with reversing warning alarm, and lifting and lowering of the bucket. A wide range of engine revs was used, and the noise sources included engine noise predominantly at the rear, tyre chains, and bucket noise. The variability of simulated operations increased with each test, with the third test including turning operations within the hemisphere.

Figure 14: The Face Shovel during the stationary test

Figure 15: The Face Shovel during the stationary test

5.4.2 Noise characteristics of stationary tests

The sonogram below shows the general characteristics of the noise generated by the Face Shovel during the first stationary test. This figure together with the three-dimensional plot present data averaged over the six microphones of the hemisphere. Virtually all the noise energy is contained below 2kHz and during intensive operations there is comparatively little variation with time.

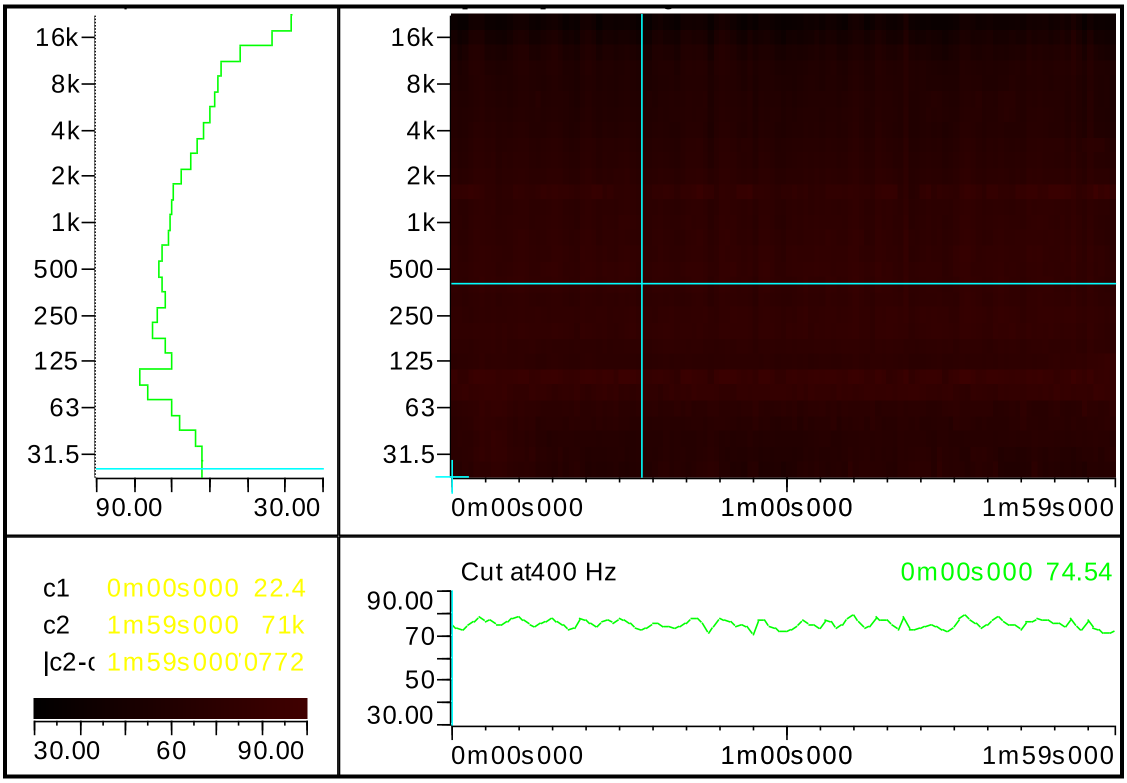

Figure 16: Sonogram of measurement stationary test 1

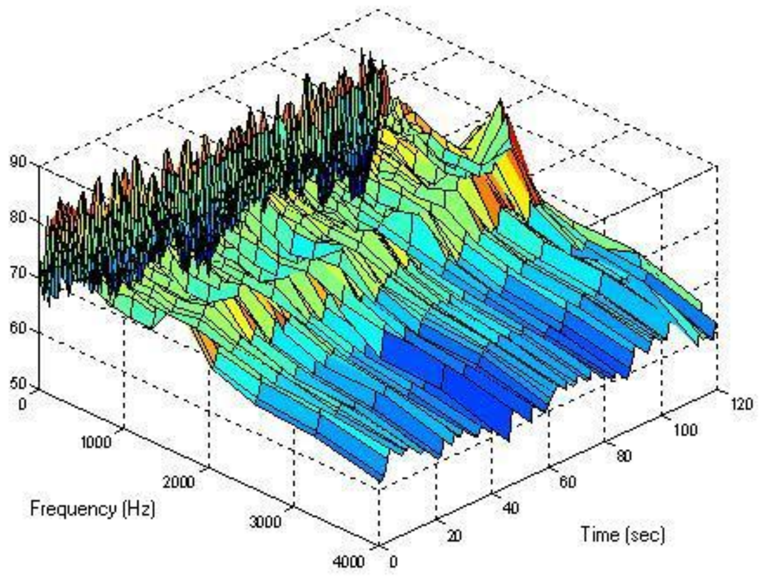

Figure 17: Time-varying mean spectrum over 6 mics on hemisphere of radius 16m for stationary test 1

5.4.3 Stationary test 1

5.4.3.1 Amplitude distribution

The comparison of the time-varying sound power levels calculated from measurements from the six microphones on the hemisphere and from the single SLM at 10m is shown in the plot below. The levels measured by the SLM at 10m show greater variation than the mean from six microphones on hemisphere.

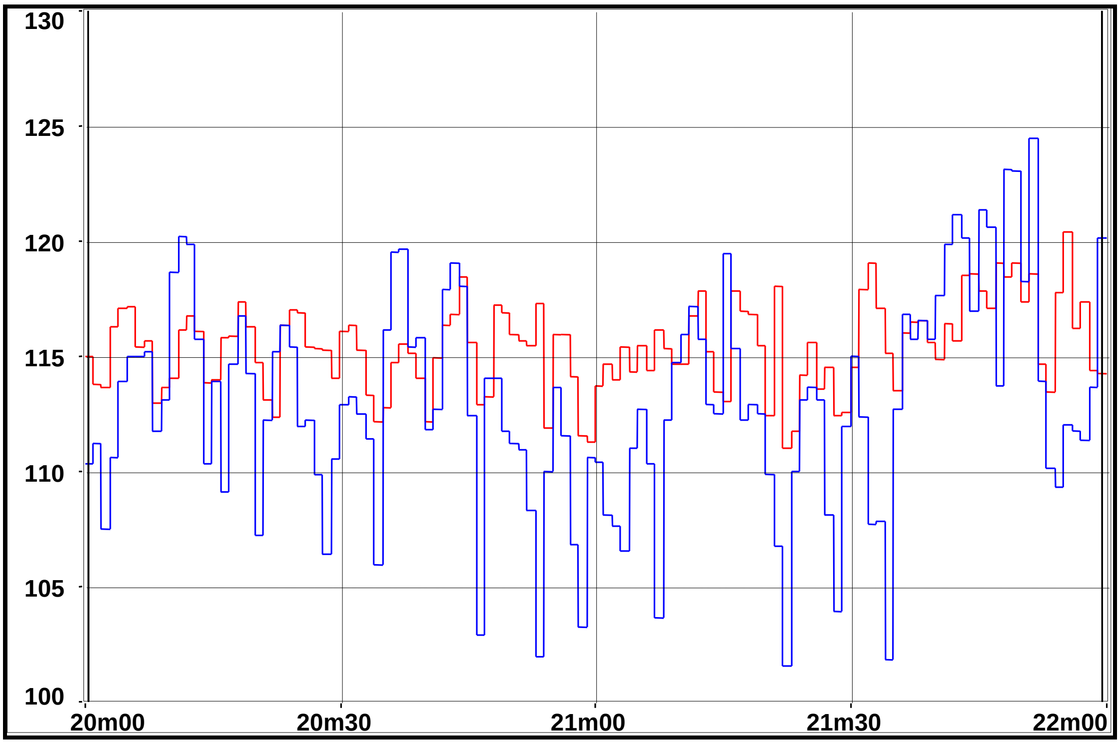

Figure 18: Comparing time-varying sound power levels calculated from measurements by single SLM at 10m (blue) and by 6 mics on hemisphere of radius 16m (red) for stationary test 1

This variation in calculated sound power level is illustrated by the amplitude distribution histograms shown below. These results show that although the overall levels show excellent agreement, the SLM measured levels vary more widely with time than those from the mean of the hemisphere. These data are summarised in the table below.

Measurement	Unit	**SWL**	$\mathbf{L_{min}}$	L_{max}	**StdDev**
SWL = hemisphere + 32dBA	dBA	115.8	111.0	120.4	1.8
SWL = SLM + 28dBA	dBA	115.4	101.5	124.4	4.6

Table 10: Summarising the one-second sound power level distributions as measured by the SLM and hemisphere during stationary test 1.

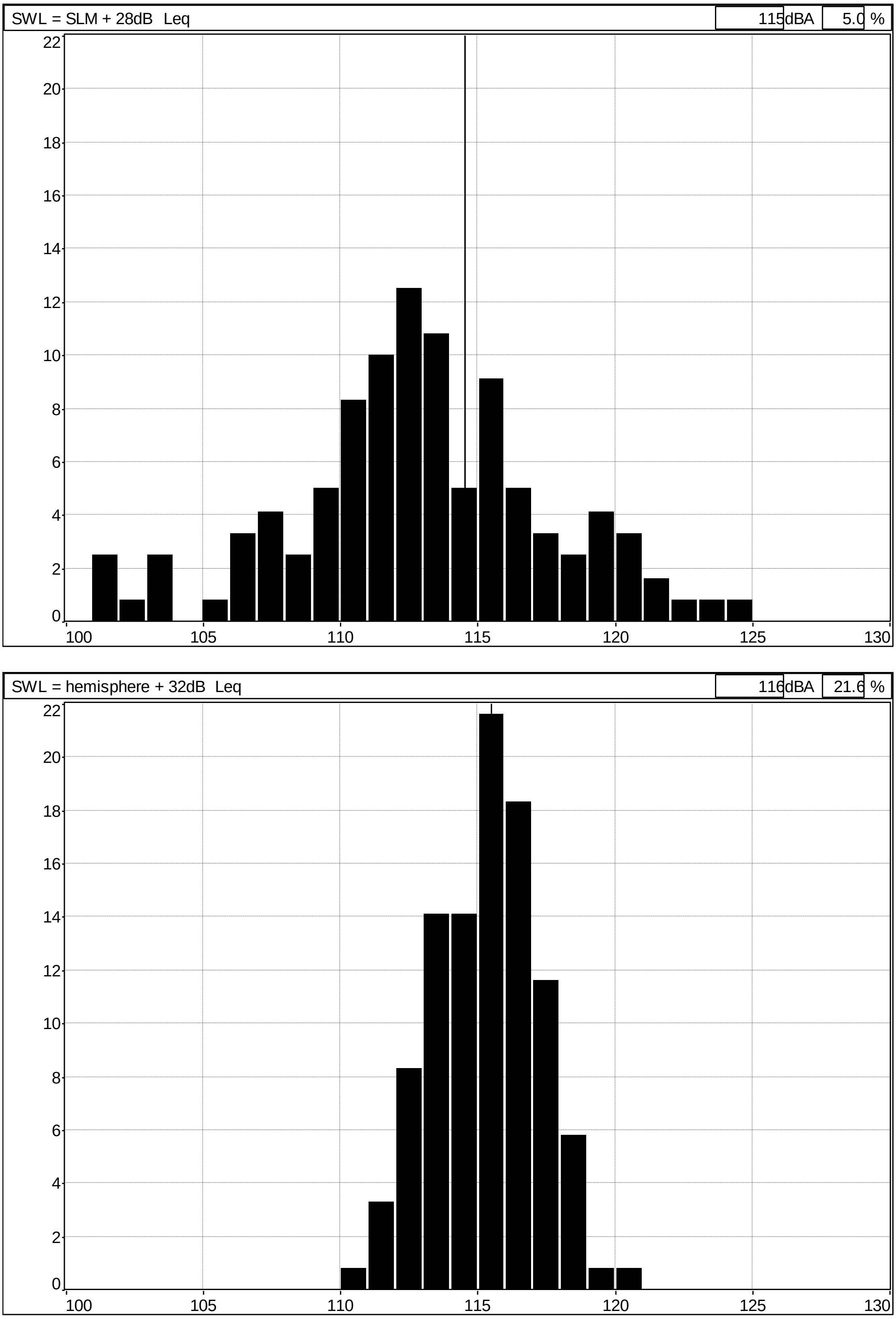

Figure 19: Histograms showing the amplitude distribution of one second sound power levels calculated from one second L_{Aeq} measurements at the SLM and from six microphones on the hemisphere.

5.4.3.2 Directionality

Directionality is illustrated by the plan view of the stationary test 1 measurement area shown in the polar plot below. LAw (2min) levels at each of the six microphones on the hemisphere and the average LAw (2min) level at the sound level meter at radial distance 10m perpendicular from the centre of the measurement area are compared. These results indicate that at 16m the Face Shovel is emitting sound reasonably equally over the hemisphere in the horizontal plane.

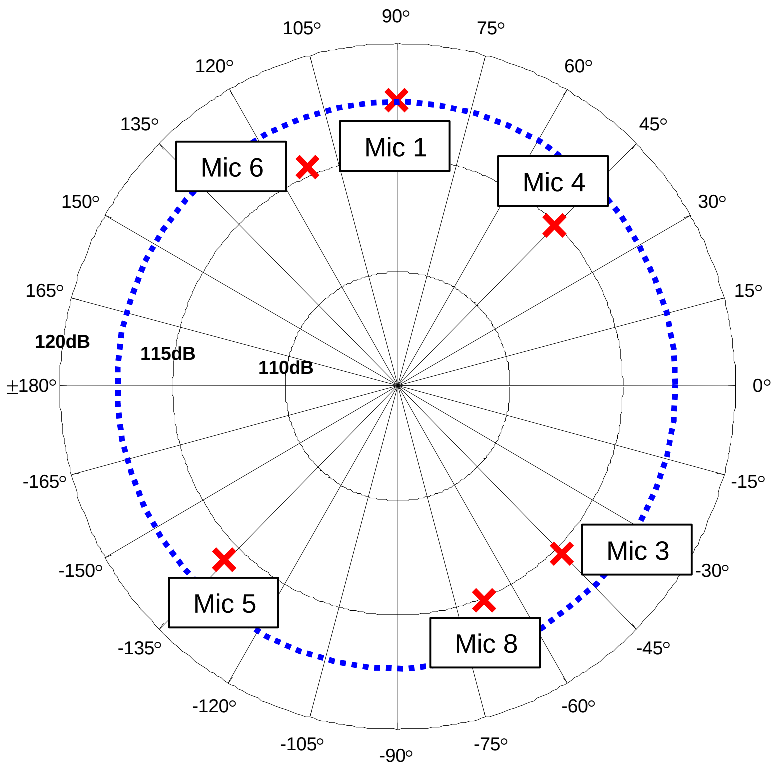

Figure 20: Polar plot illustrating plan view of stationary test 1 measurement area. Showing LAw (2min) levels at each of the six microphones on the hemisphere of radius 16m (red X) and the average LAw (2min) level at the sound level meter at radial distance 10m perpendicular from the centre of the measurement area (blue circle).

Directionality in the vertical plane is illustrated by the polar cross sectional view of stationary test 1 measurement looking south. LAw (2min) levels at microphones 3 and 5 at height 1.5m, 6 and 8 at height 11.4m on the hemisphere of radius 16m, and the average LAw (2min) level at the sound level meter at radial distance 10m perpendicular from the centre of the measurement area are shown. These results indicate that at 16m the Face Shovel is emitting sound equally over the hemisphere in the vertical plane.

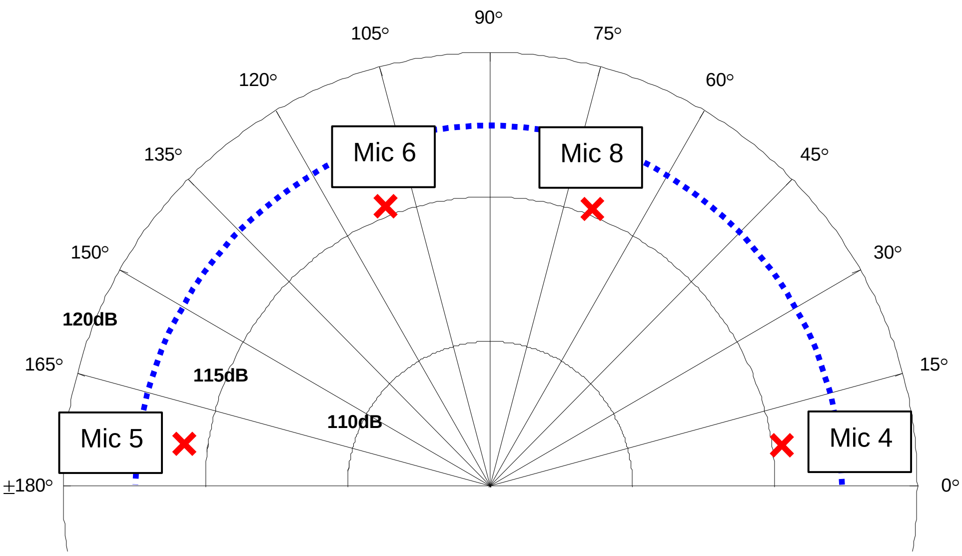

Figure 21: Polar plot illustrating cross sectional view of stationary test 1 measurement looking south. Showing LAw (2min) levels at microphones 3 and 5 at height 1.5m, 6 and 8 at height 11.4m on the hemisphere of radius 16m (red X) and the average LAw (2min) level at the sound level meter at radial distance 10m perpendicular from the centre of the measurement area (blue circle).

The directionality of the Face Shovel is illustrated in the frequency domain by the two plots below. In the first, the average sound power spectra over 2 min calculated from measurements by the 6 mics on hemisphere for stationary test 1 is compared with the overall average. The second plot shows the difference sound power spectra between the mean over hemisphere and each of the 6 mics. Also shown is the overall level difference obtained by a summation of all frequency differences. These results indicate that of the six microphones, the position providing poorest agreement with the mean over hemisphere is Mic 5, which is seen to detect a lower sound power at higher frequencies. This is perhaps an indication that a barrier effect due to the vehicle body was reducing some bucket noise at this location. The sound power spectrum measured by Mic 1 gives best agreement with the average over the hemisphere. Furthermore Mic 1 is the microphone positioned closest to the sound level meter, indicating that the positioning of the sound level meter was optimal for the measurement of the sound power spectrum.

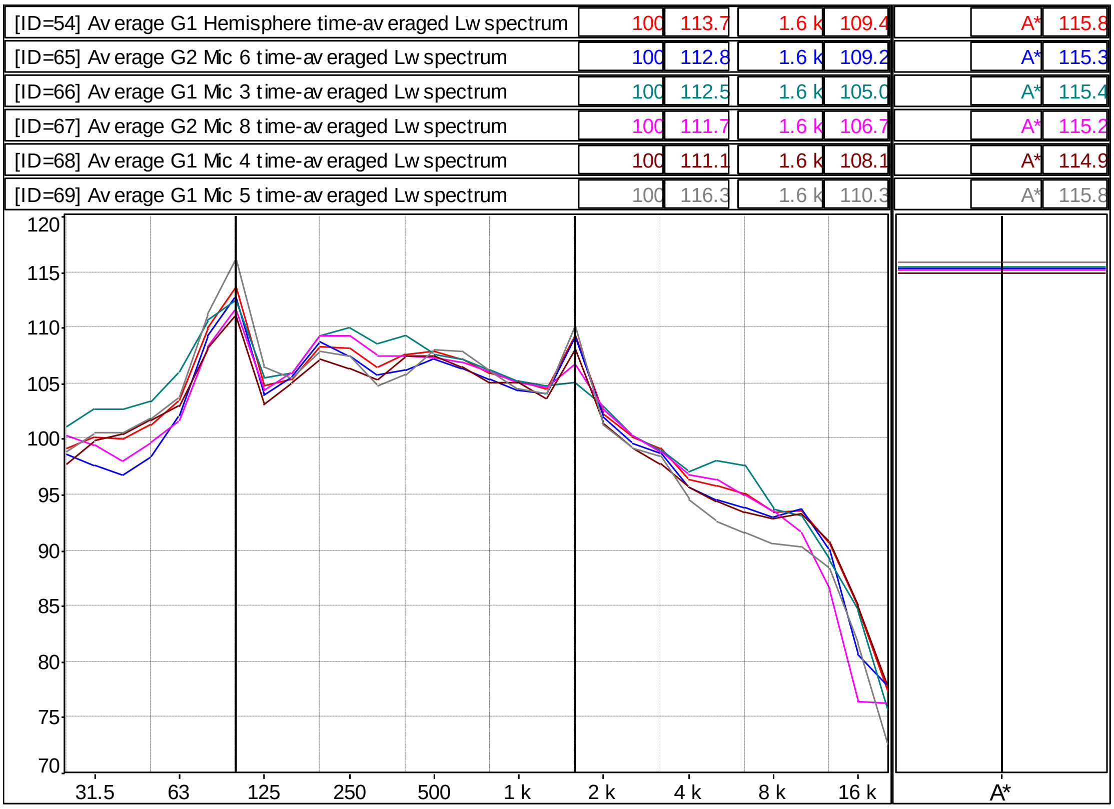

Figure 22: Average sound power spectra over 2 min calculated from measurements by 6 mics on hemisphere of radius 16m for stationary test 1. Compared with overall average.

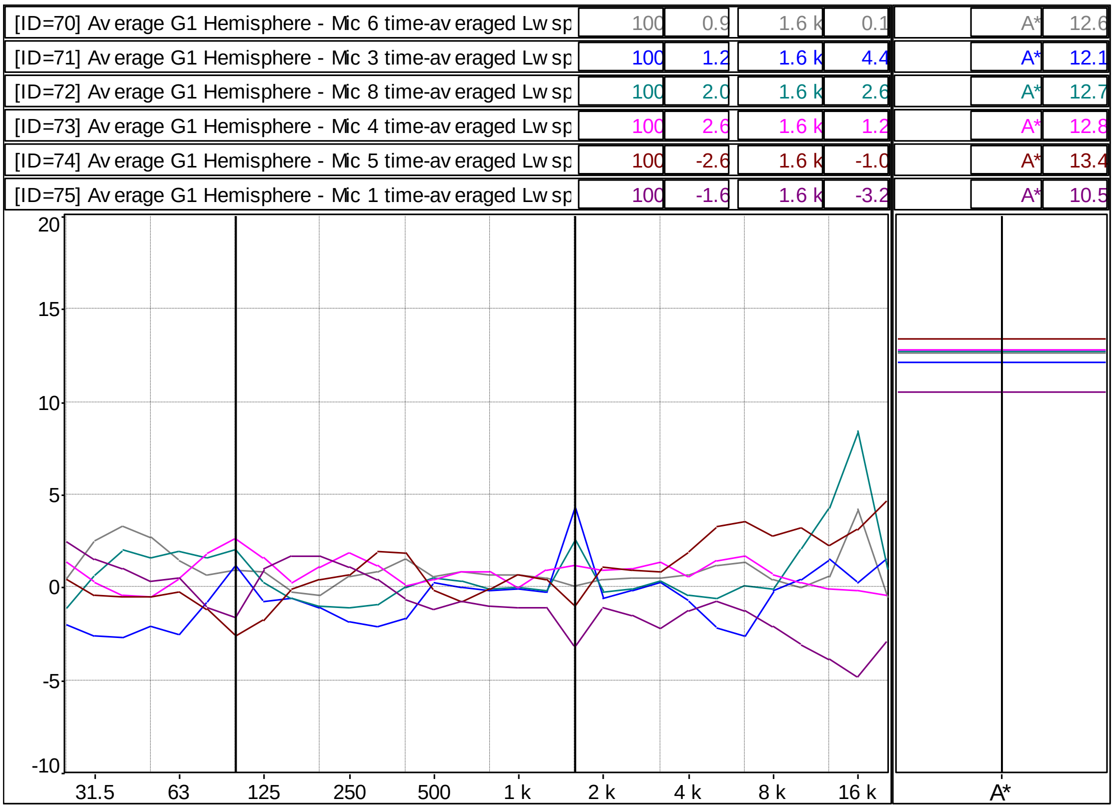

Figure 23: Difference in sound power spectra between mean over hemisphere and each of 6 mics.

When viewed in the form of a polar plot illustrating the plan view of stationary test 1 measurement area, showing Lw (2min) 1/1 octave spectra levels at each of the four 1.5m microphones on the hemisphere, the figure below is seen. These results indicate that the vehicle is reasonably omni-directional at most frequencies, although some directionality is seen at 125Hz (red) and at 8kHz (green) at the rear of the vehicle.

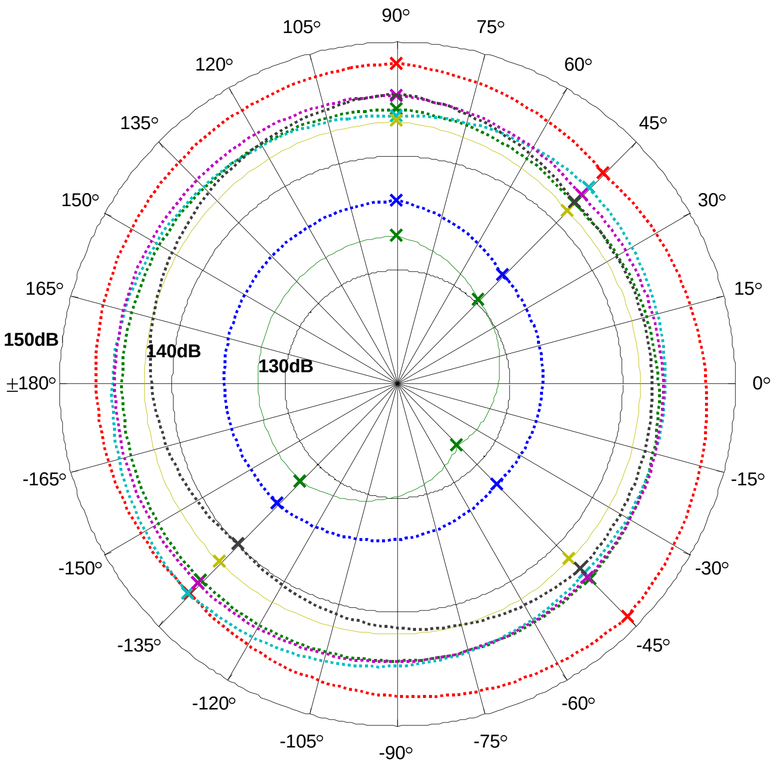

Figure 24: Polar plot illustrating plan view of stationary test 1 measurement area. Showing Lw (2min) 1/1 octave spectra levels at each of the four 1.5m microphones on the hemisphere of radius 16m.

Similarly the figure below shows the polar plot illustrating the cross sectional view of stationary test 1 measurement looking south. Showing Lw (2min) 1/1 octave spectra levels at four microphones on the hemisphere, these results indicate that at 16m the Face Shovel is emitting sound equally over the hemisphere in the vertical plane at most frequencies. However a 3dB increase is seen at the rear of the vehicle at 125Hz (red).

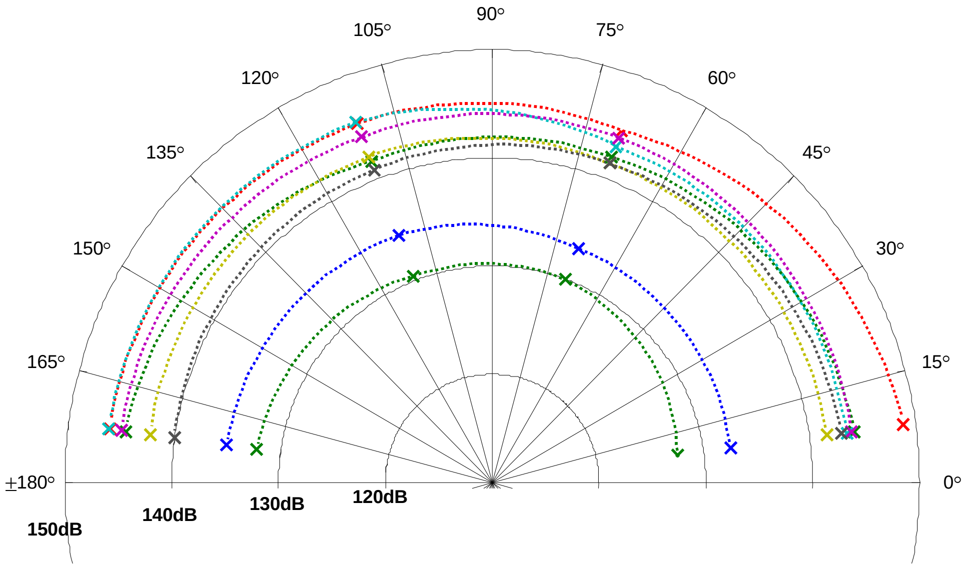

Figure 25: Polar plot illustrating cross sectional view of stationary test 1 measurement looking south. Showing Lw (2min) 1/1 octave spectra levels at four microphones on the hemisphere of radius 16m.

5.4.3.3 Comparison of hemisphere and SLM measurements

The 1/3 octave sound power spectra calculated from measurements by the single SLM at 10m and by 6 mics on hemisphere for stationary test 1 are shown in the figure below. Also seen is the calculated overall L_{AW} level. The difference between the two spectra is within ~2dB at most frequencies as illustrated in the figure below, although following the A weighting the overall levels agrees within ~0.3dB.

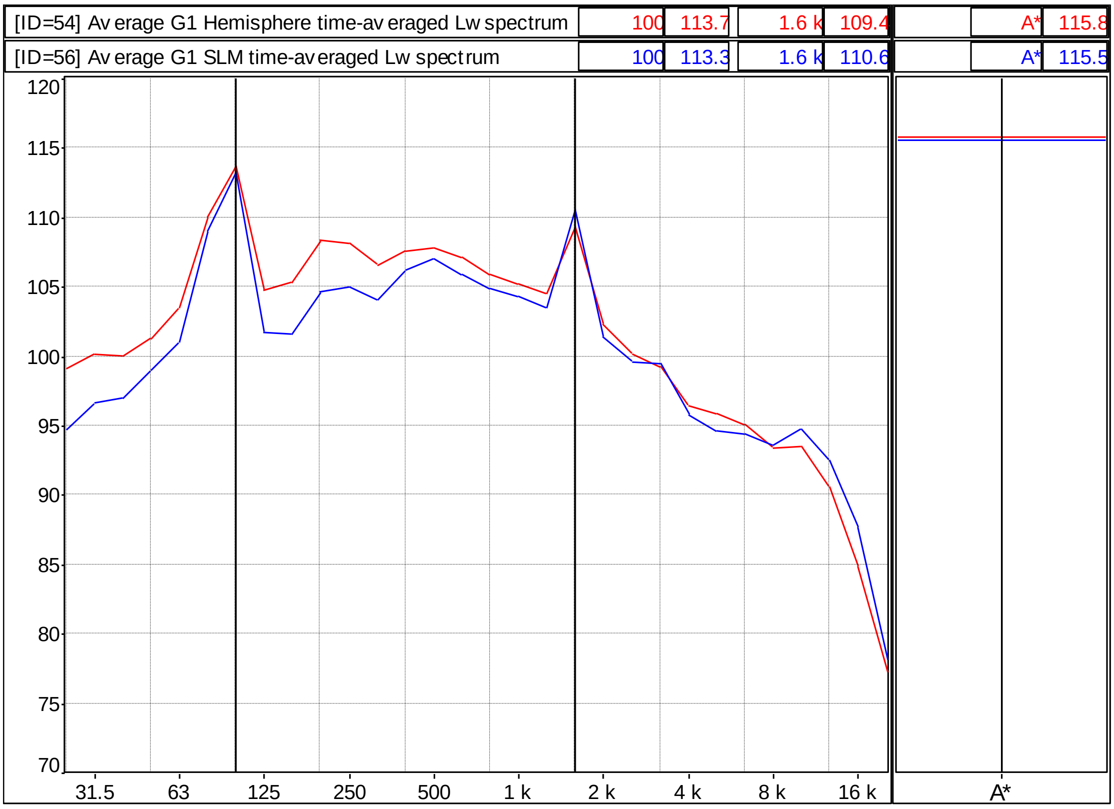

Figure 26: Comparing average sound power spectra calculated from measurements by single SLM at 10m and by 6 mics on hemisphere of radius 16m for stationary test 1

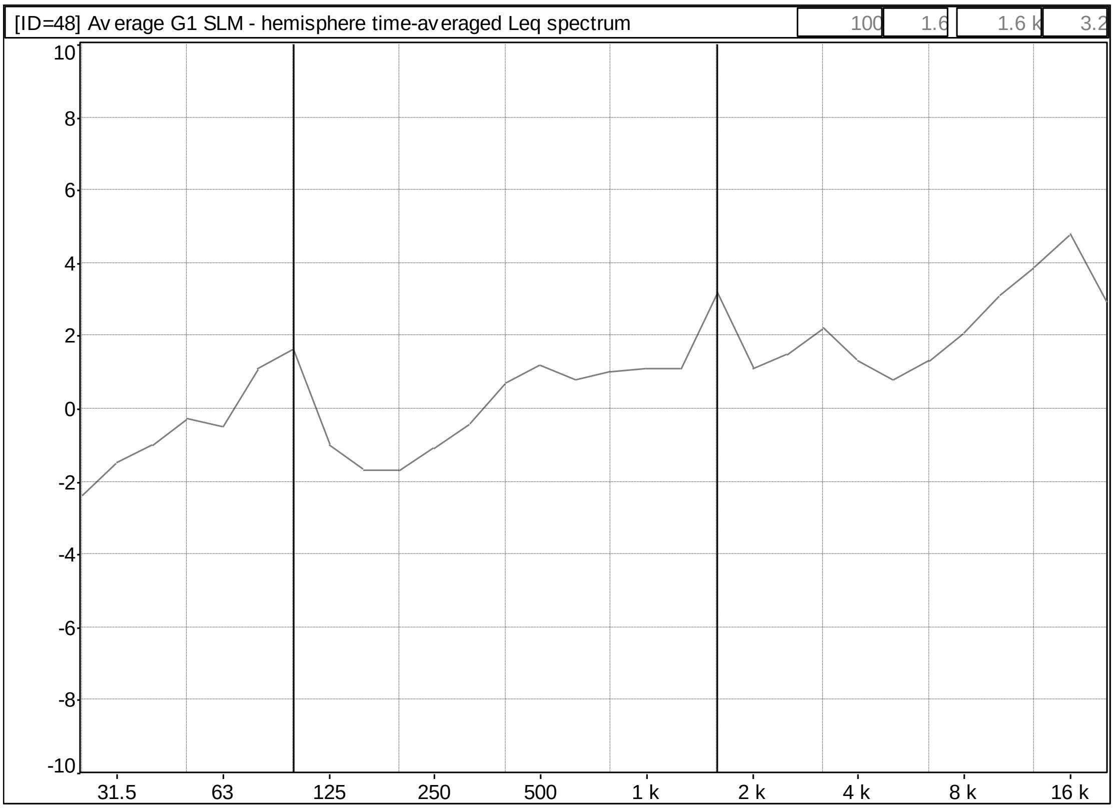

Figure 27: Difference between average sound power spectra calculated from measurements by single SLM at 10m and by mean of 6 mics on hemisphere of radius 16m for stationary test 1

A further comparison is made comparing 1/1 octave band spl spectra at 10m from measurements by the single SLM at 10m and those calculated from the measurements at the 6 mics on hemisphere in the figures below. The normalisation from 16m to 10m was performed using the point source over a hard plane method.

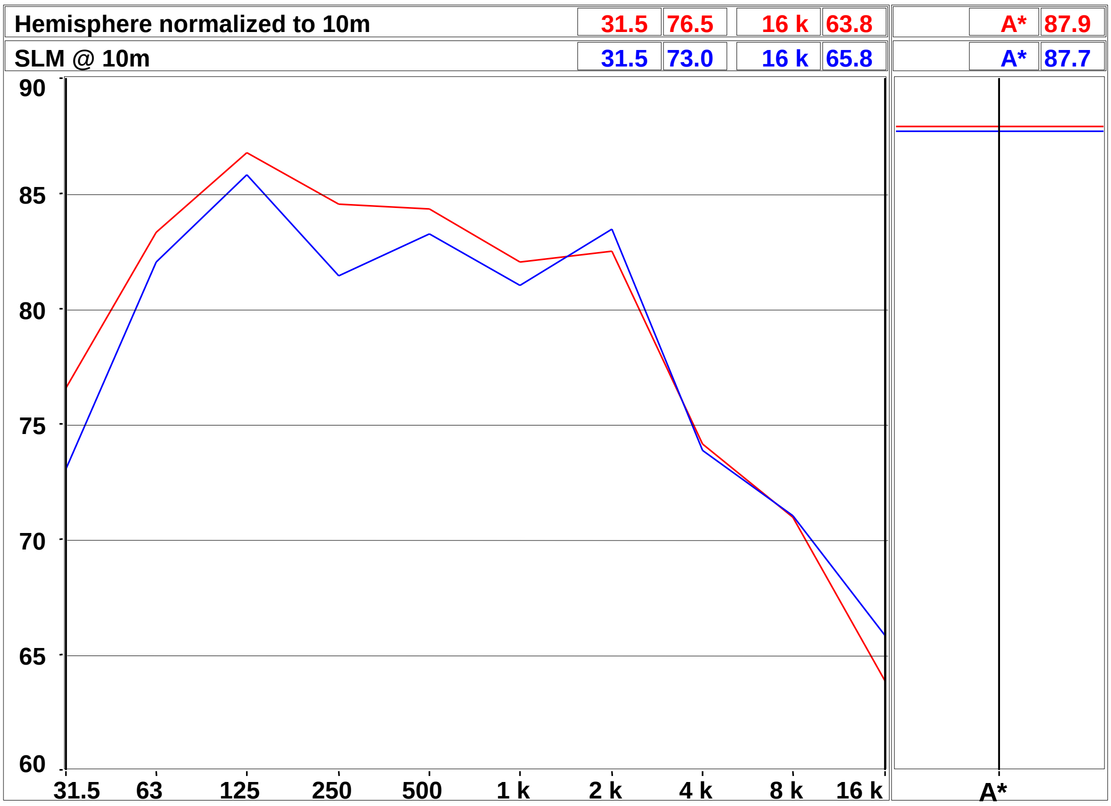

Figure 28: Comparing 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 1

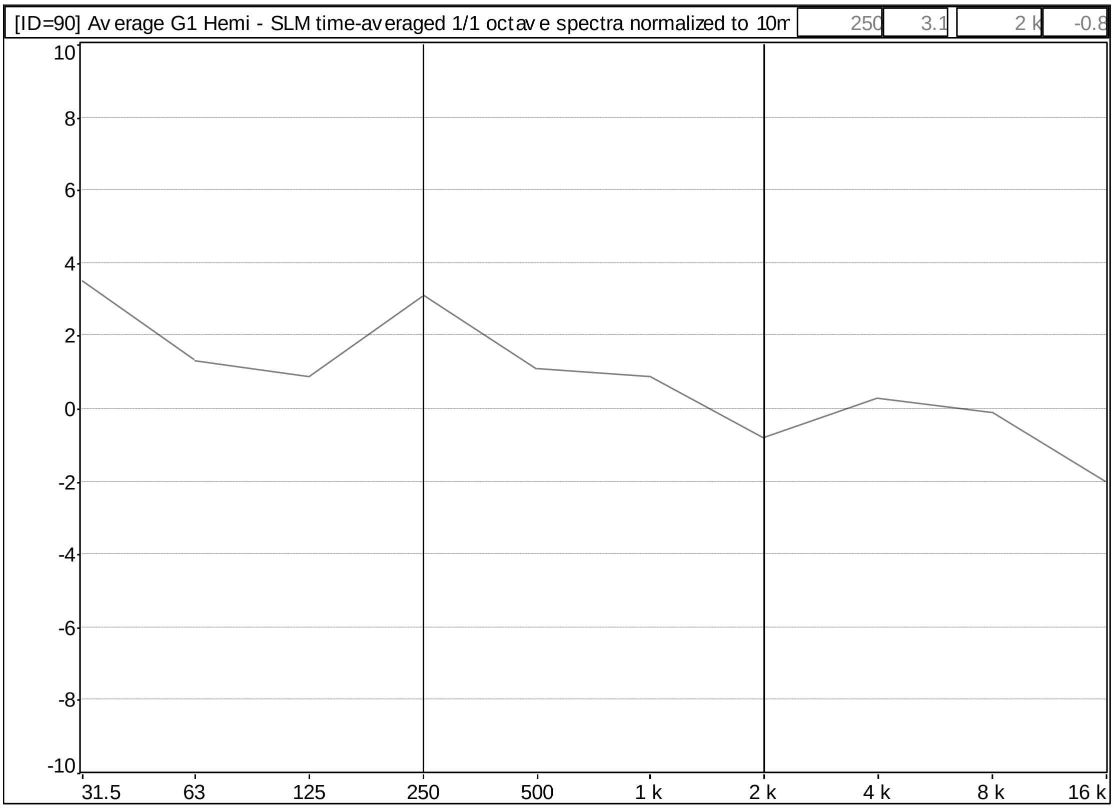

Figure 29: Difference between 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 1

Frequency (Hz)	63	125	250	500	1 k	2 k	4 k	8 k	10m Normalised L_{Aeq} (dB)
Hemi	83.3	86.7	84.5	84.3	82.0	82.5	74.1	70.9	87.9
SLM	82.0	85.8	81.4	83.2	81.0	83.4	73.8	71.0	87.7
Hemi-SLM	1.3	0.9	3.1	1.1	1.0	-0.9	0.3	-0.1	0.2

Table 11: Comparing 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 1.

These results demonstrate the effect of directionality upon the measured sound pressure level spectrum using a single SLM. Levels at most frequencies are within 1 dB except in the 250Hz band where a difference of 3dB is seen, thought to be due to the first interference dip at the SLM and engine noise. The calculation of the first interference dip between the sound level meter and at microphones on the hemisphere is summarised in the table below. During the measurements the SLM was positioned at a range of 10m and height of 1.5m. Four of the microphones on the hemisphere were positioned at a height of 1.5m and at a range of 16m, while two of the microphones were positioned at a height of 11.4m and a range of 16m.

	SLM @ 10m range & 1.5m height	**Hemi @16m range & 1.5m height**	**Hemi @16m range & 11.4m height**
Direct path length (m)	10.6	16.4	17.2
Reflected path length (m)	11.9	17.3	22.9
Path difference (m)	1.3	0.9	5.7
f=c/path difference (Hz)	258	385	60

Table 12: Calculation of first interference dip at the sound level meter and at microphones on the hemisphere.

5.4.4 Stationary test 2

During stationary test 2 the Face Shovel performed slightly more variable operations than those in stationary test 1. This is evident in the plot below comparing sound power level as calculated from the measurements by the SLM at 10m and the hemisphere.

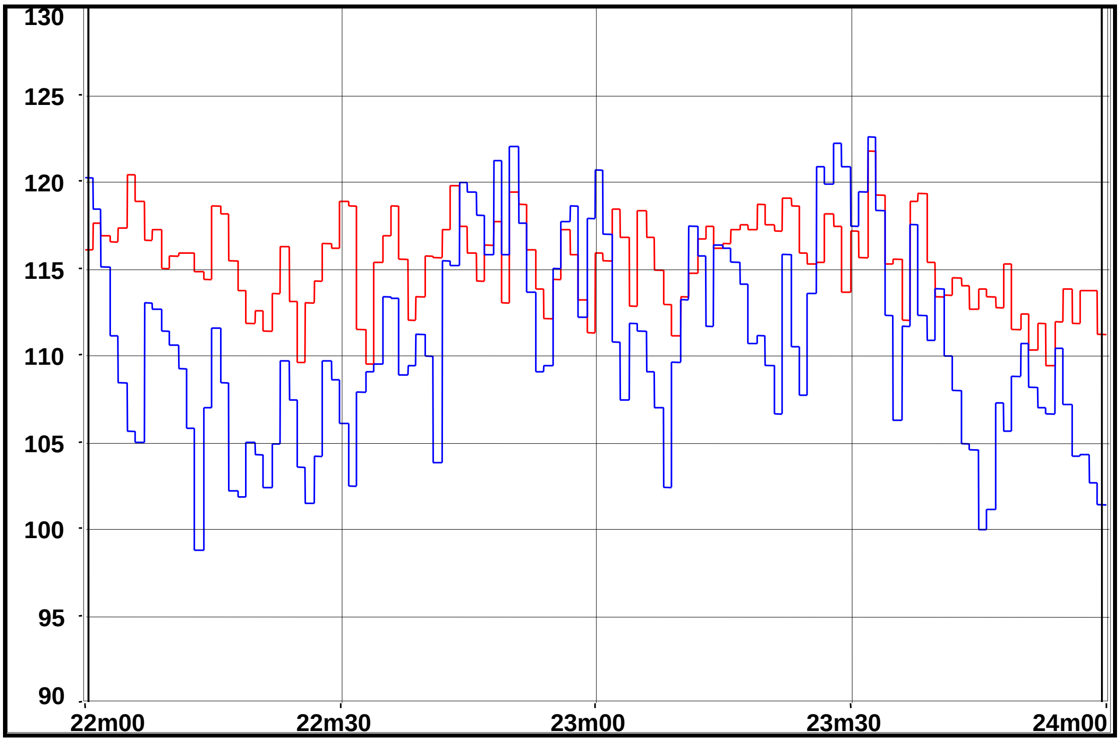

Figure 30: Comparing time-varying sound power levels calculated from measurements by single SLM at 10m (blue) and by 6 mics on hemisphere of radius 16m (red) for stationary test 2

This variation in calculated sound power level is illustrated by the amplitude distribution histograms shown below. These results show that although the overall levels show excellent agreement, the SLM measured levels vary more widely than those from the mean of the hemisphere. These data are summarised in the table below.

Measurement	Unit	**SWL**	**L_{min}**	L_{max}	**StdDev**
SWL = hemisphere + 32dBA	dBA	116.0	109.3	121.7	2.5
SWL = SLM + 28dBA	dBA	114.3	98.7	122.5	5.6

Table 13: Summarising the one second sound power level distributions as measured by the SLM and hemisphere during stationary test 2

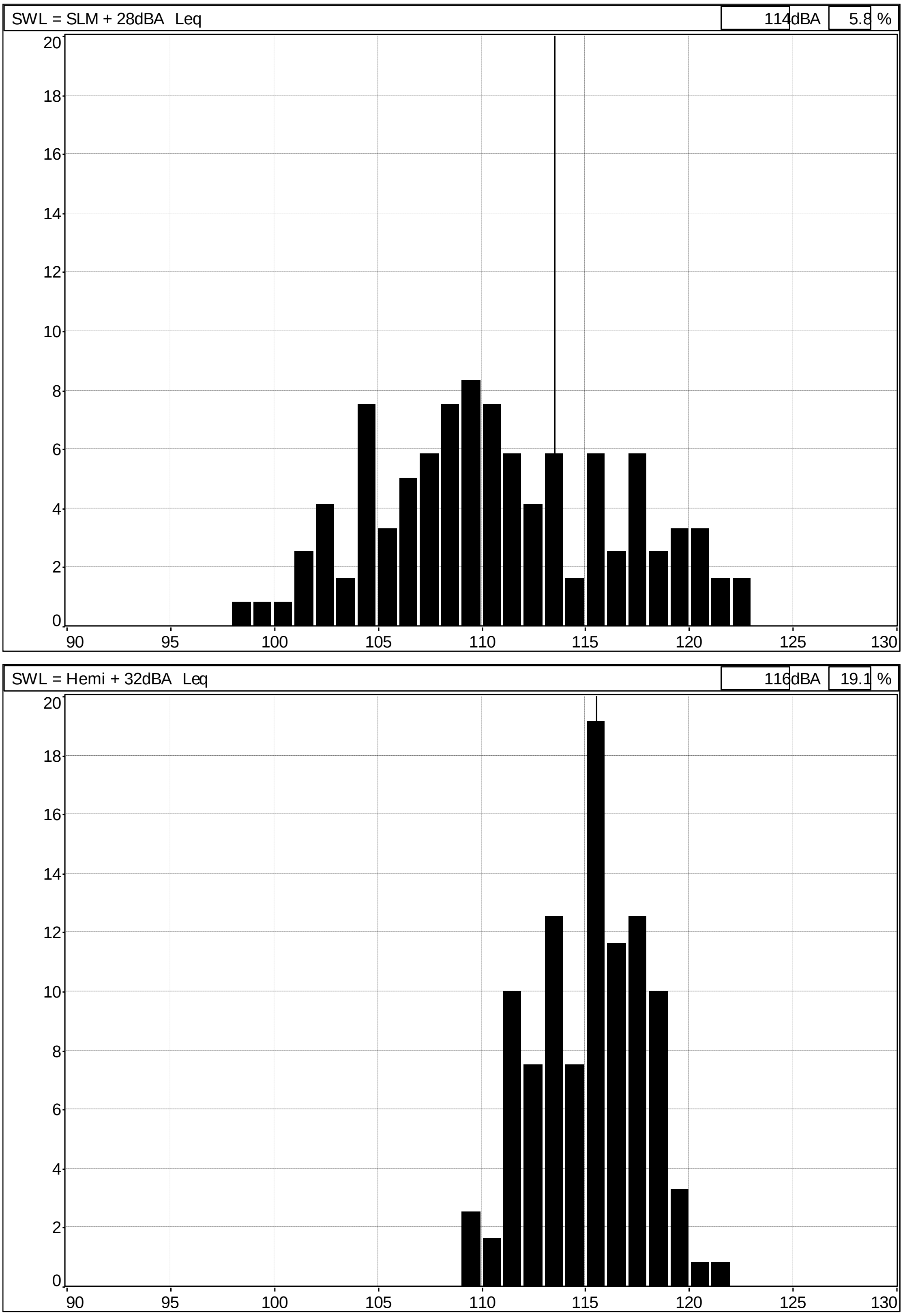

Figure 31: Histograms showing the amplitude distribution of one second sound power levels calculated from one second L_{Aeq} measurements at the SLM and from six microphones on the hemisphere for Stationary Test 2.

The 1/3-octave sound power spectra calculated from measurements by the single SLM at 10m and by 6 mics on hemisphere for stationary test 2 are shown in the figure below. Also seen is the calculated overall L_{AW} level. The difference between the two spectra is again within ~2dB at most frequencies as illustrated in the figure below, and the A-weighted overall levels agrees within ~1.0dB.

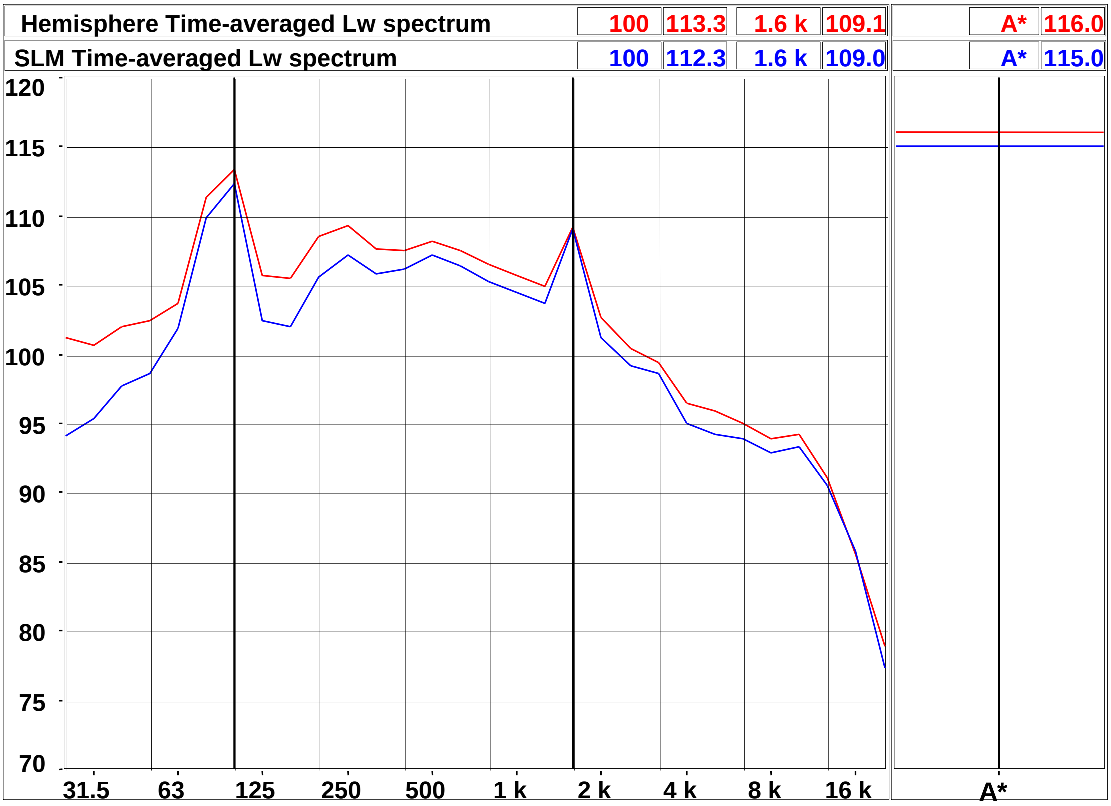

Figure 32: Comparing average sound power spectra calculated from measurements by single SLM at 10m and by 6 mics on hemisphere of radius 16m for stationary test 2

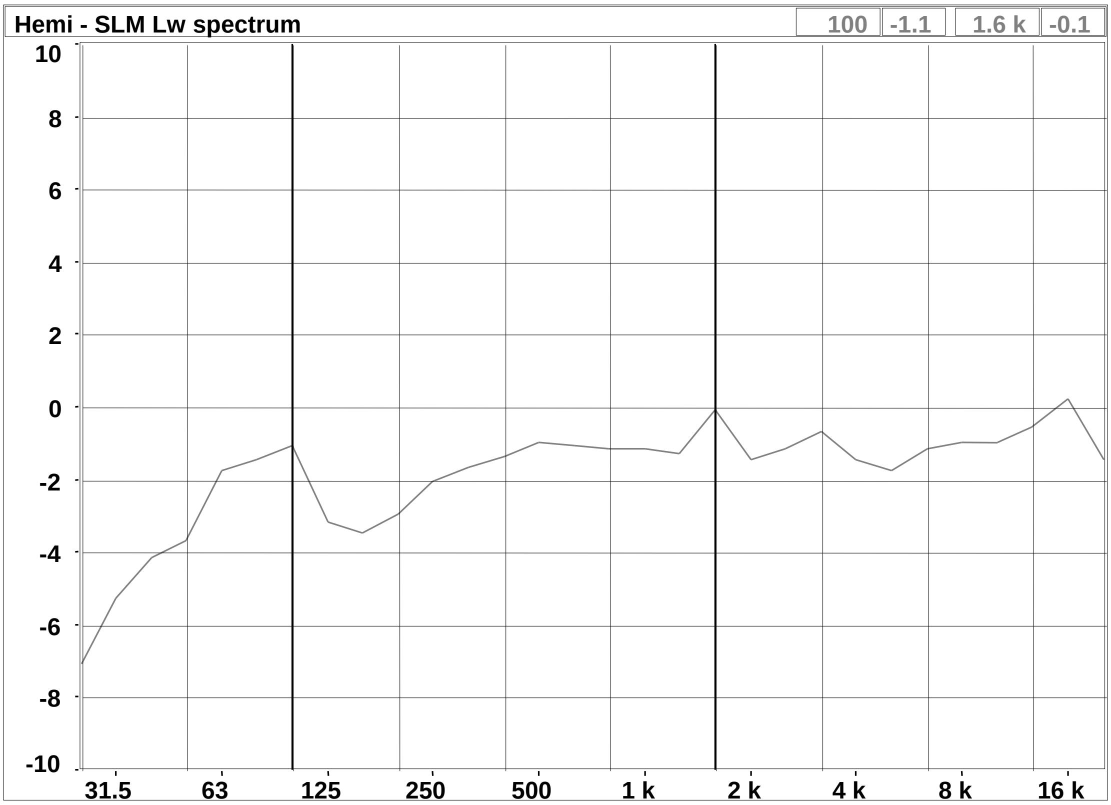

Figure 33: Difference between average sound power spectra calculated from measurements by single SLM at 10m and by mean of 6 mics on hemisphere of radius 16m for stationary test 2

A further comparison is made comparing 1/1 octave band spl spectra at 10m from measurements by the single SLM at 10m and those calculated from the measurements at the 6 mics on hemisphere in the figures below. The normalisation from 16m to 10m was again performed using the point source over a hard plane method.

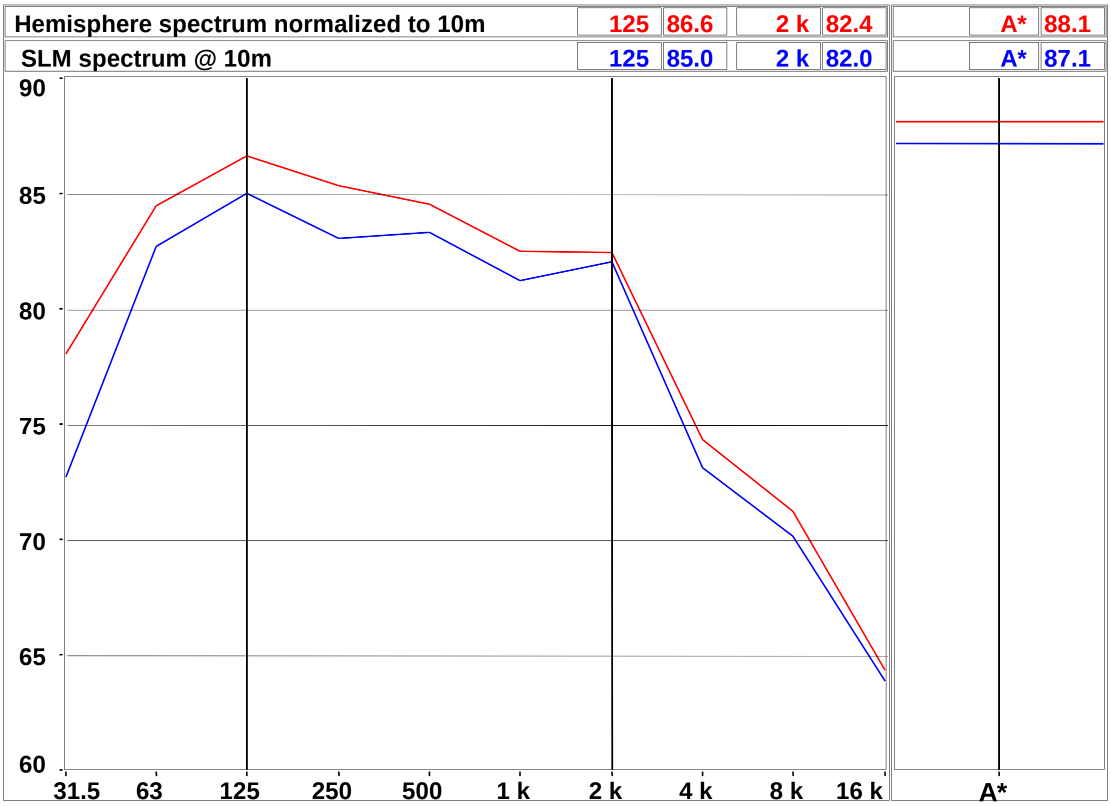

Figure 34: Comparing 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 2

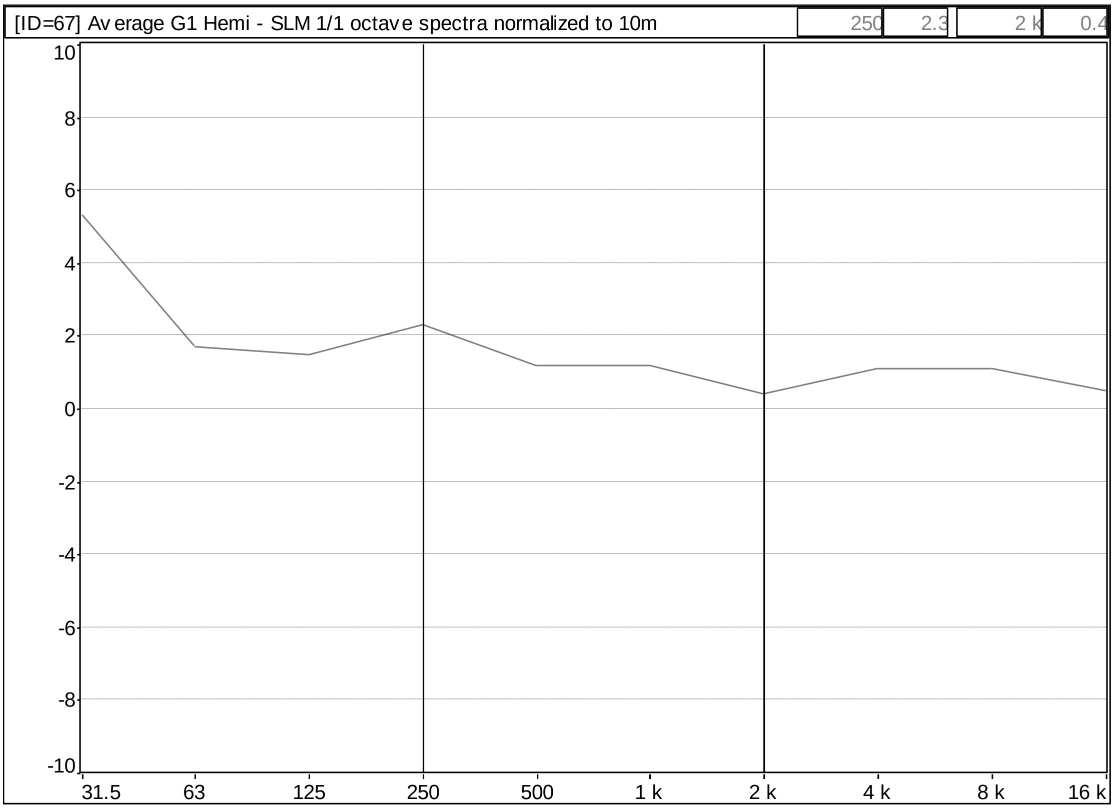

Figure 35: Difference between 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 2

These results again demonstrate the effect of directionality upon the measured sound pressure level spectrum using a single SLM. Levels at most frequencies are within ~1.5 dB except in the 250Hz band where a difference of 2.3dB is seen, thought to be due to the first interference dip at the SLM and engine noise. Despite the more variable sound pressure levels due to the differing activities of the Face Shovel overall agreement between the SLM measured L_{Aeq} at 10m and the hemisphere L_{Aeq} measurements normalised at 10m agree within 1.0dB.

Frequency (Hz)	**63**	**125**	**250**	**500**	**1 k**	**2 k**	**4 k**	**8 k**	**10m Normalised L_{Aeq} (dB)**
Hemi	84.4	86.6	85.3	84.5	82.5	82.4	74.3	71.2	88.1
SLM	82.7	85	83	83.3	81.2	82	73.1	70.1	87.1
Hemi-SLM	1.7	1.5	2.3	1.2	1.2	0.4	1.1	1.1	0.4

Table 14: Comparing 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 2.

5.4.5 Stationary test 3

During stationary test 3 the Face Shovel performed the most variable operations, including a turn within the hemisphere. This is illustrated in the plot below comparing sound power level as calculated from the measurements by the SLM at 10m and the hemisphere.

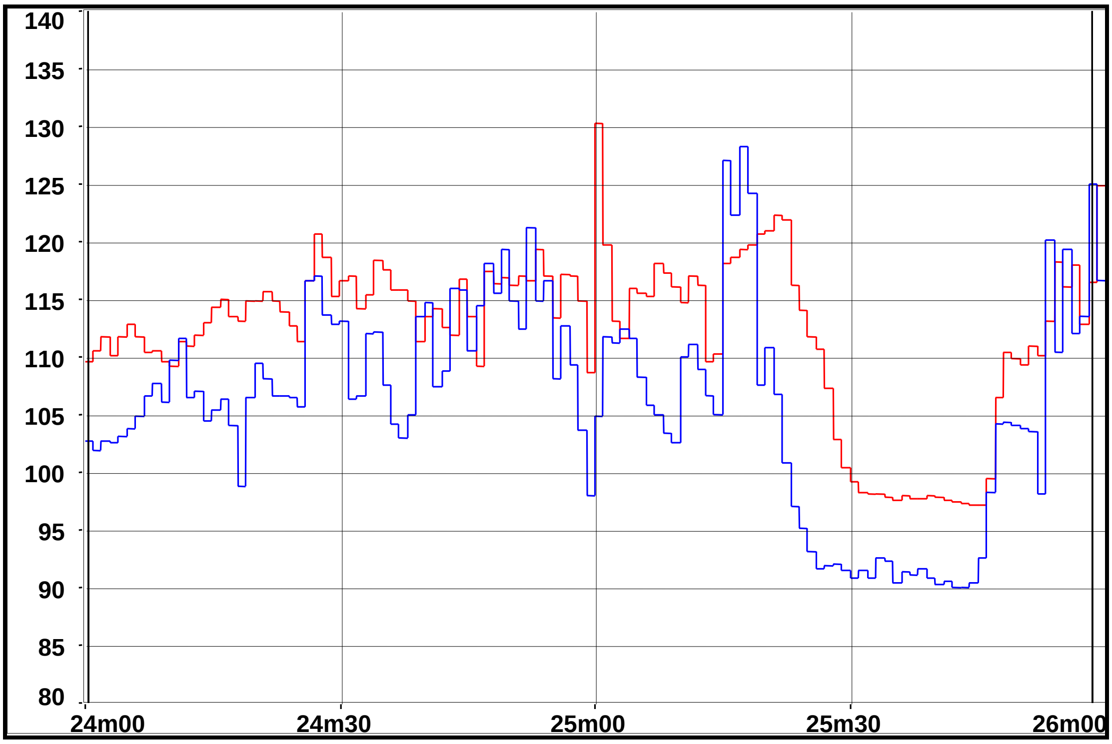

Figure 36: Comparing time-varying sound power levels calculated from measurements by single SLM at 10m (blue) and by 6 mics on hemisphere of radius 16m (red) for stationary test 3

The location of the vehicle within the hemisphere varied significantly during this test, on one occasion approaching the eastern boundary. The SLM measured levels are subsequently seen to vary more widely than those from the mean of the hemisphere due to greater variation in the mean path difference from source to receiver. The variation in calculated sound power level is further illustrated by the amplitude distribution histograms shown below. These results show that while the SLM measured levels and vary significantly from those of the mean of the hemisphere, the overall levels show excellent agreement. These data are summarised in the table below.

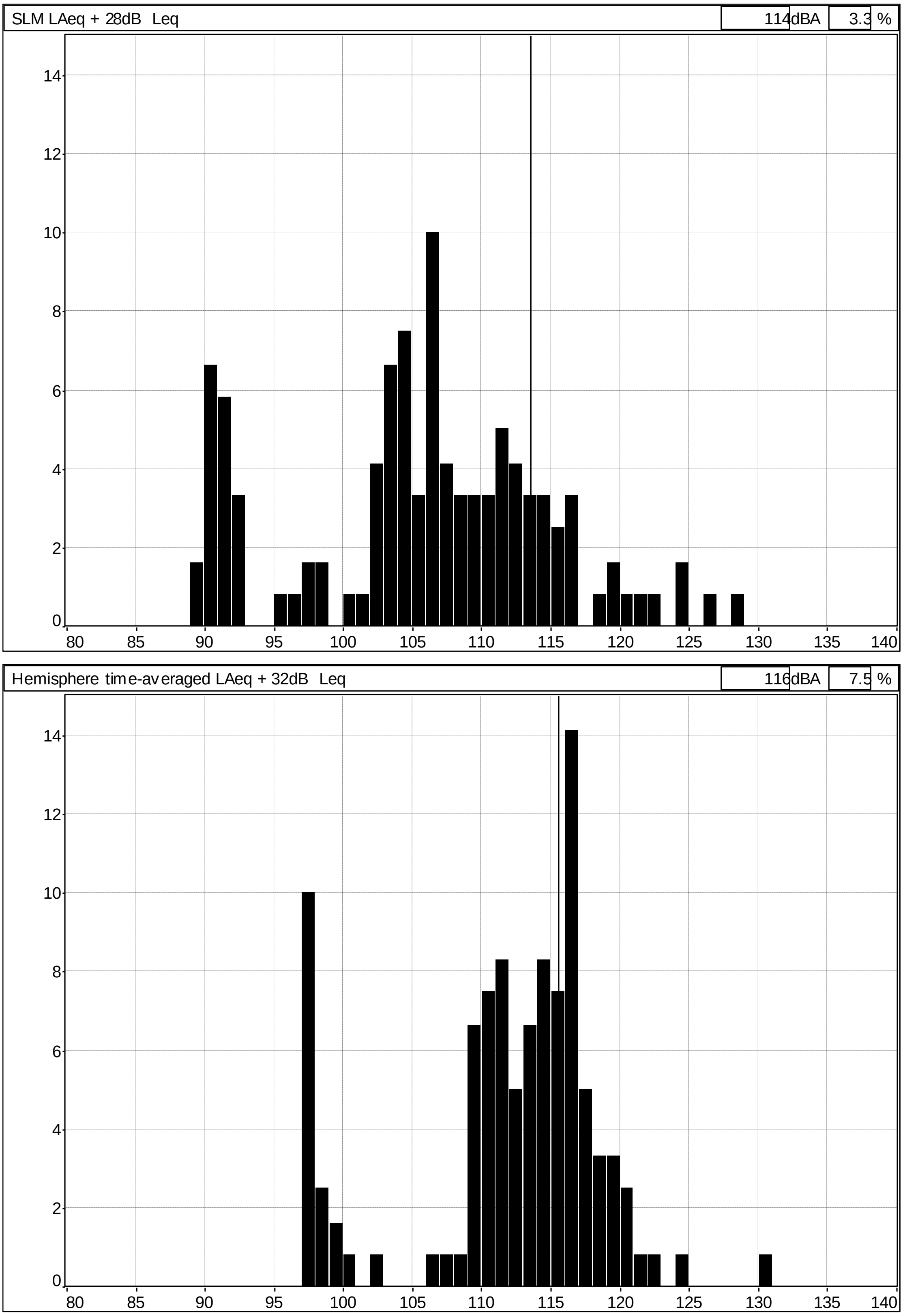

Figure 37: Histograms showing the amplitude distribution of one second sound power levels calculated from one second L_{Aeq} measurements at the SLM and from six microphones on the hemisphere for Stationary Test 3.

Measurement	Unit	**SWL**	L_{min}	L_{max}	**StdDev**
SWL = hemisphere + 32dBA	dBA	116.2	97.0	130.2	6.9
SWL = SLM + 28dBA	dBA	114.4	89.9	128.2	9.0

Table 15: Summarising the one second sound power level distributions as measured by the SLM and hemisphere during stationary test 3

The 1/3-octave sound power spectra calculated from measurements by the single SLM at 10m and by 6 mics on hemisphere for stationary test 3 are shown in the figure below. Also seen is the calculated overall L_{AW} level. The difference between the two spectra is greater than for stationary tests 1 and 2 and is within ~4dB at most frequencies as illustrated in the figure below. Nevertheless the A-weighted overall levels agree within ~2dB.

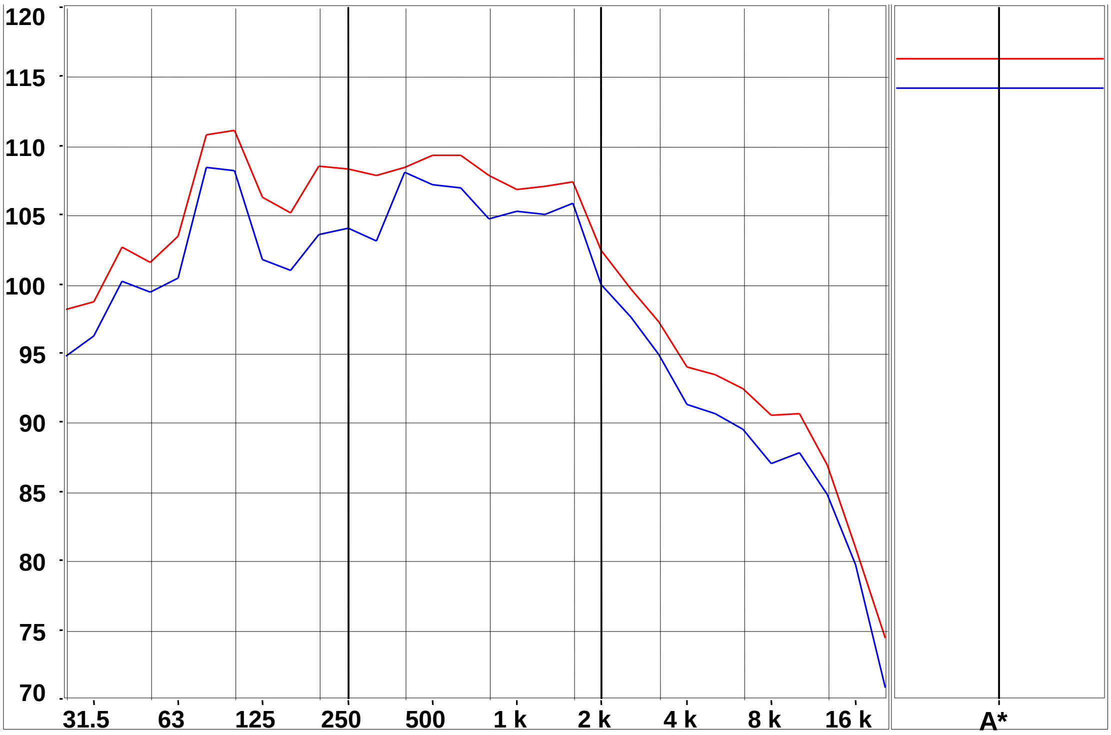

Figure 38: Comparing average sound power spectra calculated from measurements by single SLM at 10m (blue) and by 6 mics on hemisphere of radius 16m (red) for stationary test 3

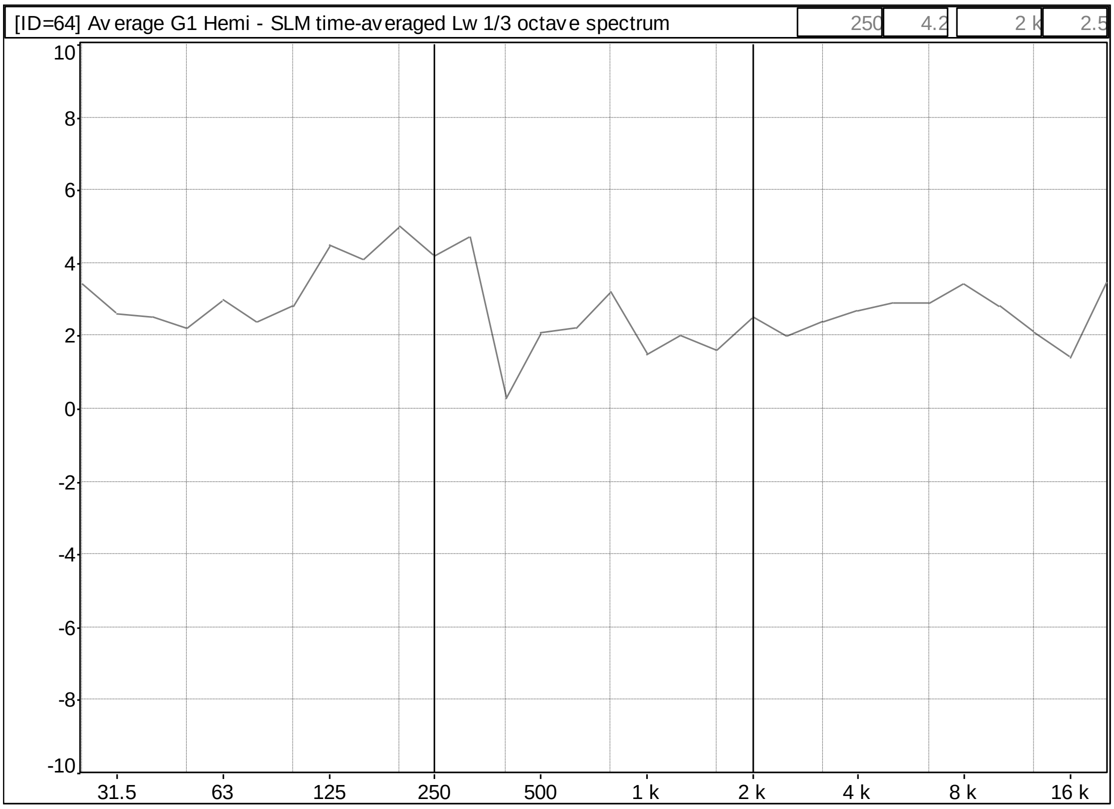

Figure 39: Difference between average sound power spectra calculated from measurements by single SLM at 10m and by mean of 6 mics on hemisphere of radius 16m for stationary test 3

The comparison of 1/1-octave band spl spectra at 10m from measurements by the single SLM at 10m and those calculated from the measurements at the 6 mics on hemisphere is shown in the figures below. The normalisation from 16m to 10m was again performed using the point source over a hard plane method.

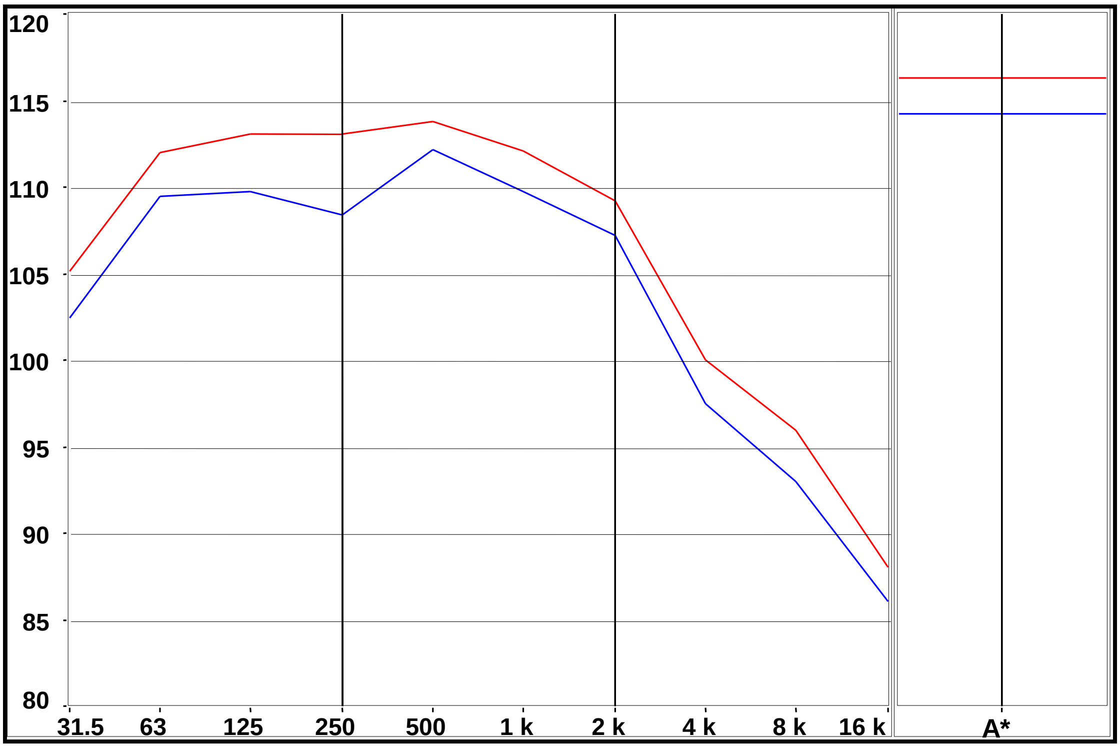

Figure 40: Comparing 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m (blue) and calculated from measurements at 6 mics on hemisphere of radius 16m (red) for stationary test 3

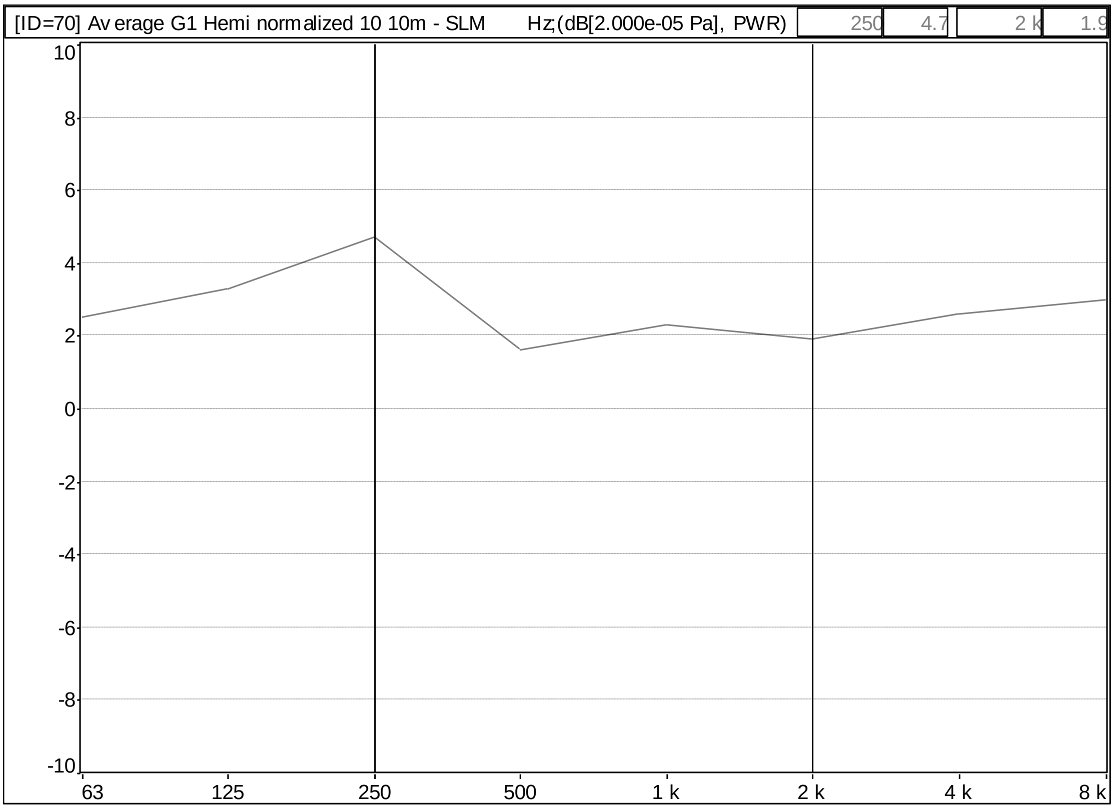

Figure 41: Difference between 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 3

These results demonstrate the effect of errors in the location of the source to receiver distance. Levels at most frequencies differ by a more than ~2 dB except in the 250Hz band where a difference of nearly 5dB is seen, thought to be due to engine noise and the first interference dip. Despite the more variable sound pressure levels due to the varying location of the Face Shovel, overall agreement between the SLM measured L_{Aeq} at 10m and the hemisphere L_{Aeq} measurements normalised at 10m is 2.1dB.

Frequency (Hz)	63	125	250	500	1 k	2 k	4 k	8 k	10m Normalised L_{Aeq} (dB)
Hemi	83.9	85.0	85.0	85.7	84.0	81.1	72.0	67.9	88.3
SLM	81.4	81.7	80.3	84.1	81.7	79.2	69.4	64.9	86.2
Hemi-SLM	2.5	3.3	4.7	1.6	2.3	1.9	2.6	3.0	2.1

Table 16: Comparing 1/1 octave band spl spectra at 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for stationary test 3.

5.5 Distance tests

5.5.1 Distance test 1

Tests were performed using the Face Shovel to investigate the variation in sound pressure level with distance from construction plant under operational conditions. For the first distance test sound pressure levels were measured on the SIP95 sound level meter at distances of 10, 20, 30, 40 and 50m from the rear of the constantly idling Face Shovel. Each measurement lasted approximately 15 seconds. Distances were measured by striding out and allowing for variability in terrain and human error uncertainties are estimated as ±10% with a 95% level of confidence. These measurements were repeated three times.

Figure 42: The Face Shovel during the first distance test

The variation in measured L_{Aeq} (15s) with distance from the rear of the Face Shovel whilst ticking over is shown in the figure below. Also shown are spherical propagation curves calculated from the measurements at 10m and 50m assuming the vehicle is acting as a point source. It is seen that sound pressure levels fall-off quicker with distance than might be expected from spherical propagation alone. These differences are perhaps due to near-field effects, atmospheric absorption, ground absorption, meteorological effects or directionality of the source, but are most likely due to the undulating topography resulting in a slight barrier effect.

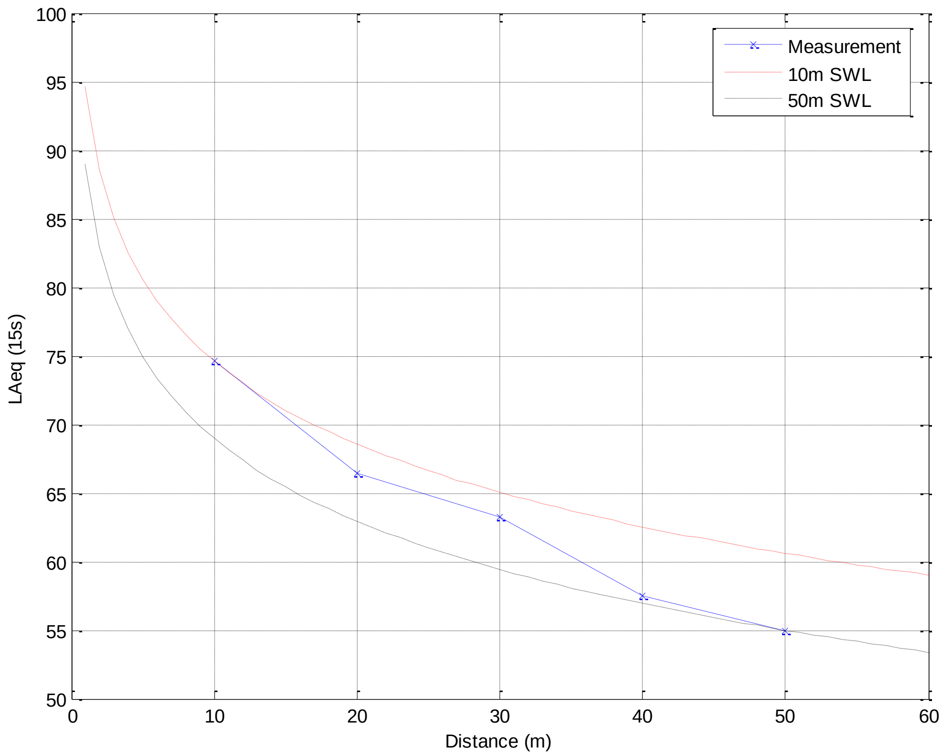

Figure 43: Showing the variation in measured L_{Aeq} (15s) with distance from the rear of the Face Shovel whilst ticking over. Also shown are spherical propagation curves calculated from the measurements at 10m and 50m assuming the vehicle is acting as a point source.

These data are presented in the figure below in the form of the variation in sound power level with distance calculated from the measurements of L_{Aeq} (15s). The sound power level is calculated assuming spherical propagation over a hard plane. It is seen in this case that the estimated sound power level is lower by approximately 2dBA per distance doubling, thought to be due to a slight barrier effect as mentioned above.

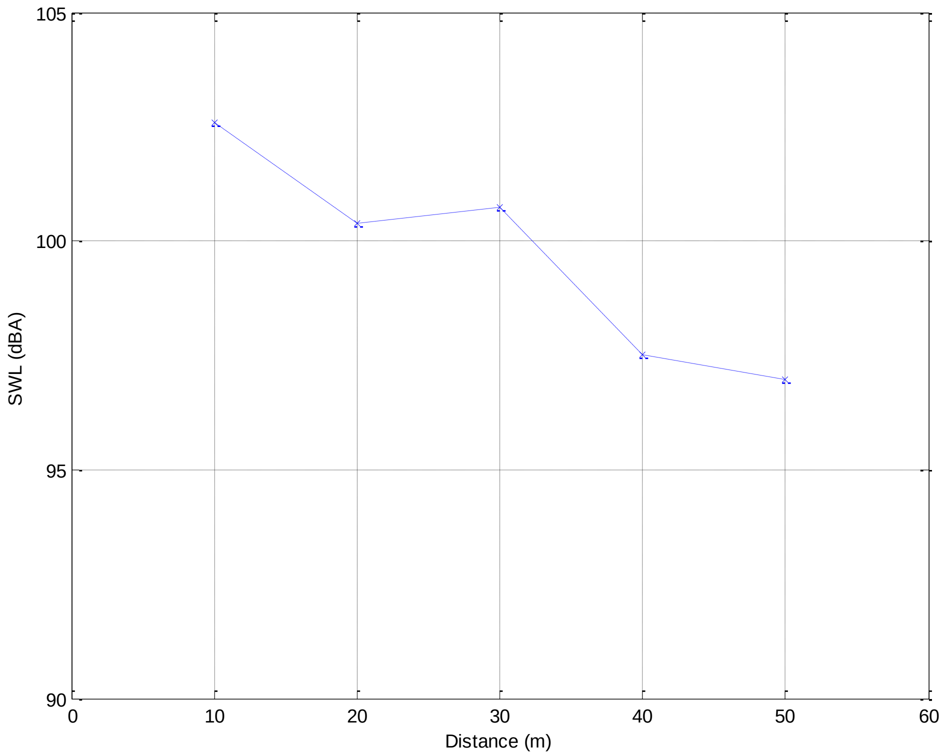

Figure 44: Showing the variation in sound power level with distance calculated from measurements of L_{Aeq} (15s) from the rear of the Face Shovel whilst ticking over. The sound power level is calculated assuming spherical propagation over a hard plane.

5.5.2 Distance tests 2

For the second test sound pressure levels were measured on the SLM at distances of 10, 20, 30, 40, 50 and 60m from the side of the Face Shovel across the open space to the north. The Face Shovel stood in the centre of the measurement hemisphere and measurements were simultaneously made on the hemisphere and the SLM. During the measurements at each distance the vehicle performed a regular and consistent cycle of forward, lift, reverse and forward movements. Each cycle lasted approximately 15 seconds.

The figure below shows the variation in measured L_{Aeq} (30s) with distance. Also shown are spherical propagation curves calculated from the measurements at 10m and 50m assuming the vehicle is acting as a point source. It is seen that sound pressure levels fall-off slower with distance than might be expected from spherical propagation alone. These differences are perhaps due to near-field effects or directionality of the source, but are more likely due to variations in the sound power of the source.

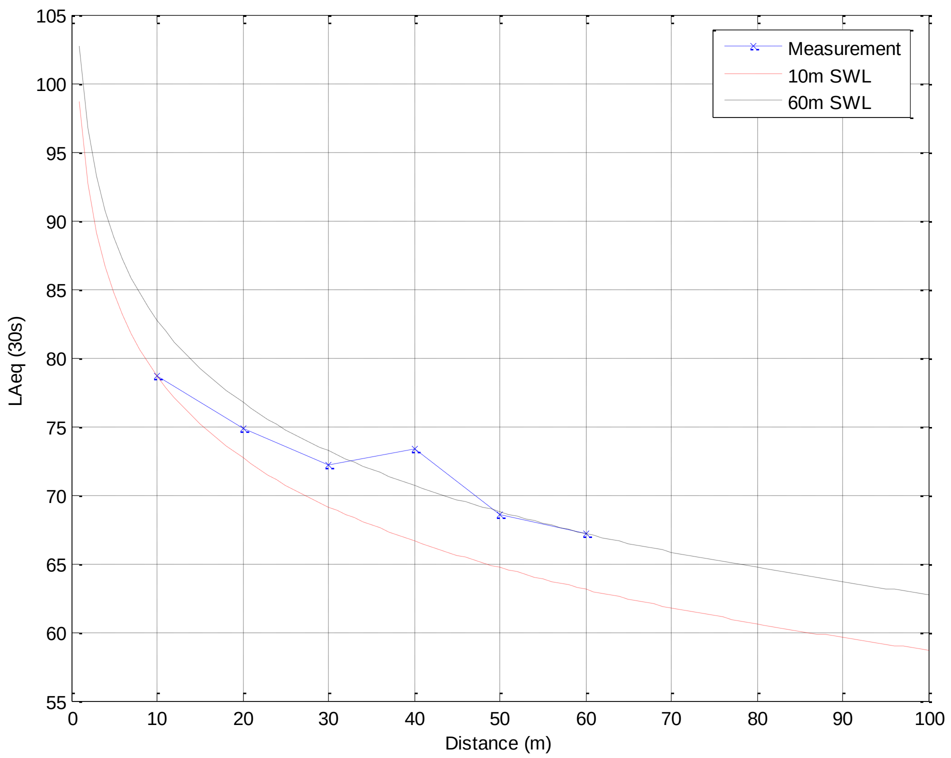

Figure 45: Showing the variation in measured L_{Aeq} (30s) with distance from the side of the Face Shovel performing repeated cycles of simulated operations. Also shown are spherical propagation curves calculated from the measurements at 10m and 50m assuming the vehicle is acting as a point source.

These data are presented in the figure below in the form of the variation in sound power level with distance calculated from the measurements of L_{Aeq} (30s). The sound power level is calculated assuming spherical propagation over a hard plane. It is seen in this case that the estimated sound power level increases at a rate of approximately 2dB per distance doubling.

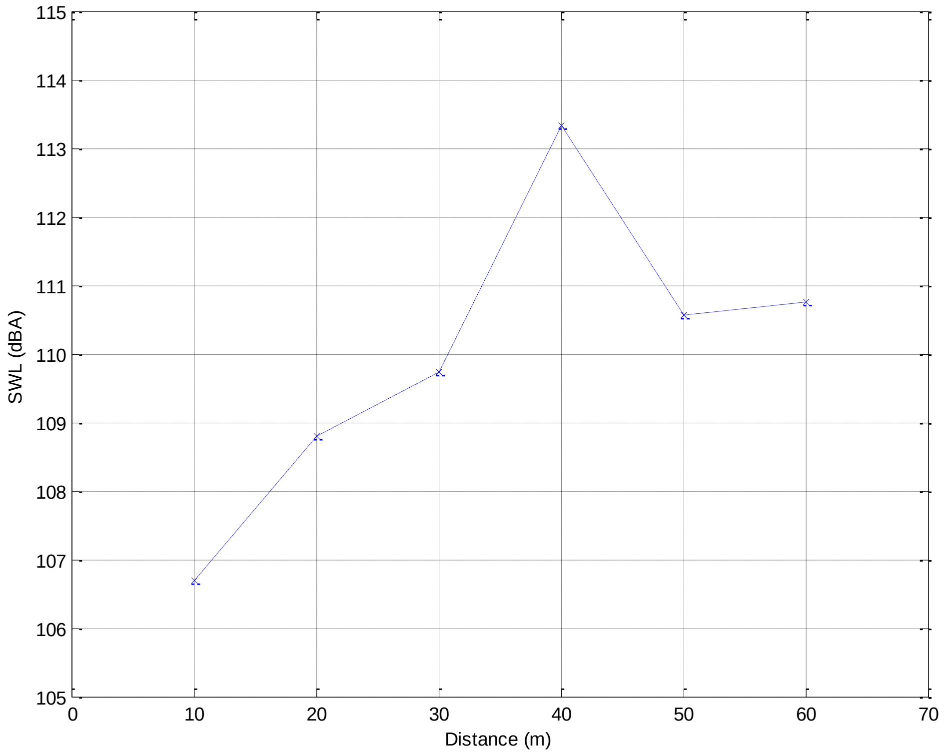

Figure 46: Showing the variation in sound power level with distance calculated from measurements of L_{Aeq} (30s) from the side of the Face Shovel performing repeated cycles of simulated operations. The sound power level is calculated assuming spherical propagation over a hard plane.

A comparison of the estimated sound power level as calculated from the SLM at varying distances and from the 6 mics on the hemisphere at 16m is shown in the figure below. Measurements were performed on all six microphones of the hemisphere, and the sound power level calculated assuming spherical propagation over a hard plane. Simultaneous SLM measurements of L_{Aeq} (30s) were performed at distances of 10, 20, 30, 40, 50, and 60m from the centre of the hemisphere. The sound power level was calculated from the SLM measurements assuming spherical propagation over a hard plane from a vehicle positioned at the centre of the hemisphere. The estimate of sound power level from the hemisphere exceeds that from the SLM by ~4dBA. At a range beyond 30m this difference is seen to vary, perhaps influenced by measurement error at 40m, meteorology, and topography.

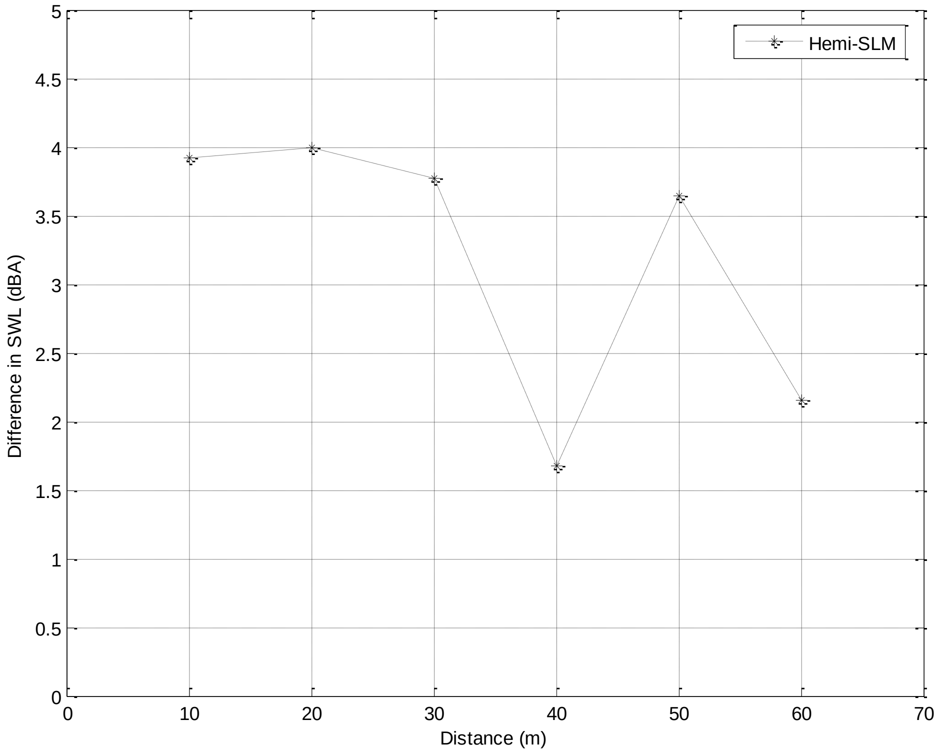

Figure 47: Showing the difference between hemisphere and sound level meter estimates of sound power level. The Face Shovel was performing repeated cycles of simulated operations located at and within three metres of the centre of the hemisphere.

5.6 Dynamic tests

Measurements were performed on mobile plant during drive-by. The six microphones were positioned on the hemisphere as detailed in ISO 6395:1998 – Airborne noise emitted by earth-moving machinery – Method of measurement of exterior noise in dynamic test conditions, p4-5. The positions are dependent upon the basic length L of the machine and are as summarized in the tables above. The single SLM was positioned at 10m from the centre line of passage of the vehicles. Numerous drive-by events were recorded since the measurement hemisphere was positioned over the quarry road. Drive-by events were recorded before and after the stationary and distance tests described above. Events selected for analysis were those for which the vehicle was considered to have passed along the centre of the hemisphere. These include measurements on a 544kW 60t Rigid Dumper Truck and on the Face Shovel (wheeled loader) used in the stationary tests.

5.6.1 Dynamic test 1

A time history comparing the sound power levels calculated from measurements by the single SLM at 10m and the mean of the 6 mics of the hemisphere for dynamic test 1 is shown in the figure below. Sound power levels were calculated from the SLM measurements of L_{Aeq} (1s) assuming a source-receiver distance of 10m. Similarly for the 6 mics on the hemisphere a radius of 16m was assumed. The cursors show the positions of the L_{Amax}(1s) for the SLM and the hemisphere, and it is seen that these occur at slightly different times .

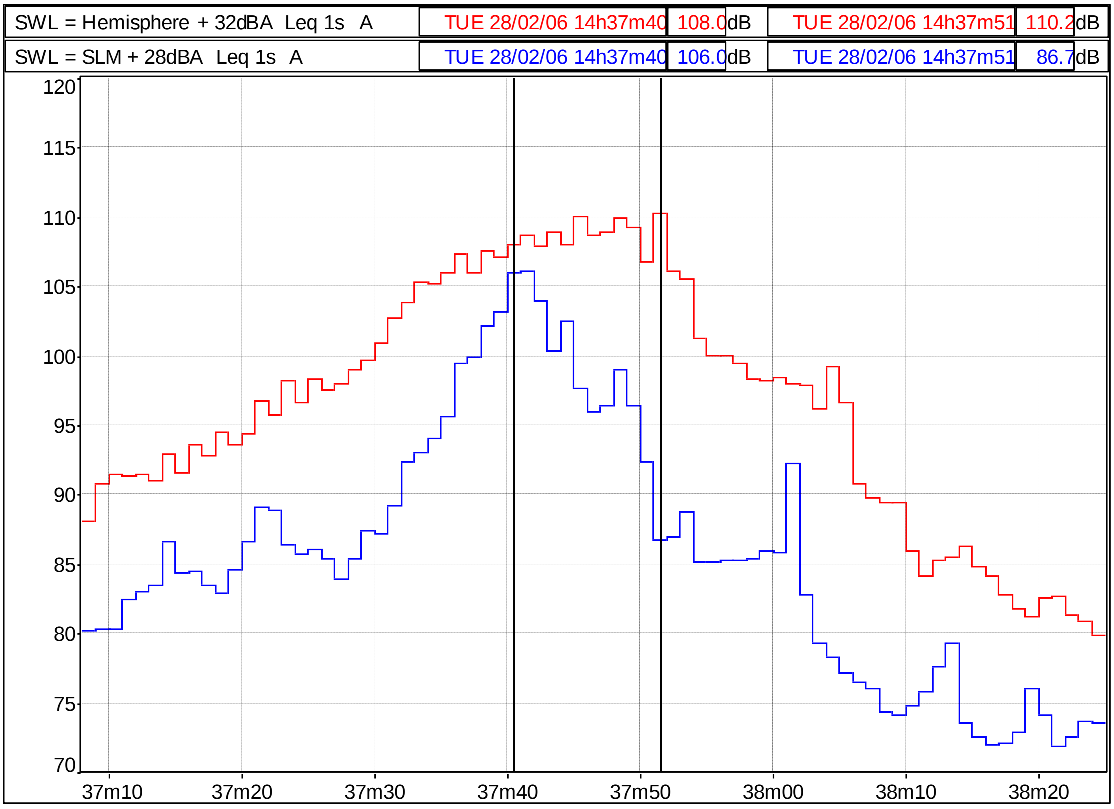

Figure 48: Comparing time-varying sound power levels calculated from measurements by SLM and the hemisphere for dynamic test 1.

A comparison of 1/1 octave max spectra is presented in the figure below, showing various hemisphere and SLM spectra.

i. In blue is seen the SLM Max spectrum.

ii. In green is the spectrum measured by the SLM at the time the SLM recorded its L_{Amax}, 14h37m40.

iii. In black is the spectrum measured by the hemisphere at the same time, 14h37m40.

iv. In red the hemisphere Max spectrum is calculated from the Max of all of the six microphones at each frequency.

It is seen that the spectrum measured in the hemisphere at the time the SLM recorded its Max shows far better agreement with the SLM Max spectrum than either the SLM at 14h37m40 or the hemisphere Max.

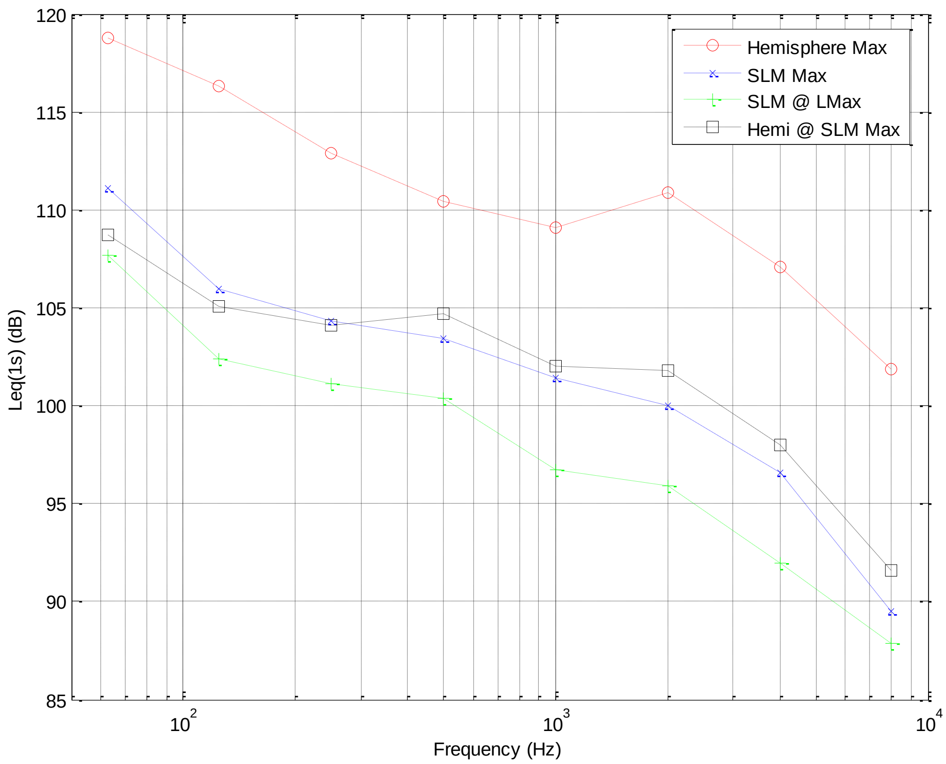

Figure 49: Comparing hemisphere and SLM spectra during dynamic test 1.

The values for the 1/1-octave spectra for the SLM L_{max} and the hemisphere at the time of the SLM L_{max} are shown in the table below, together with the L_{Aeq} normalised to 10m calculated from these data.

Frequency (Hz)	63	125	250	500	1 k	2 k	4 k	8 k	10m Normalised L_{Aeq} (dB)
Hemi	80.7	77.1	76.1	76.7	74.0	73.8	70.0	63.6	80.0
SLM	83.1	78.0	76.3	75.4	73.4	72.0	68.6	61.5	78.9
Hemi-SLM	-2.4	-0.9	-0.2	1.3	0.6	1.8	1.4	2.1	1.1

Table 17: Comparing 1/1 octave band Max spectra normalised to 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for dynamic test 1.

These results give support to the hypothesis that the SLM L_{max} measured at a perpendicular distance of 10m can be used to describe the sound power of a vehicle during a drive-by.

5.6.2 Dynamic test 2

The time-varying sound power levels calculated from measurements by the single SLM at 10m and the hemisphere for dynamic test 2 are shown in the figure below. The cursors show the positions of the L_{Amax} (1s) for the SLM and the hemisphere, and it is again seen that these occur at slightly different times.

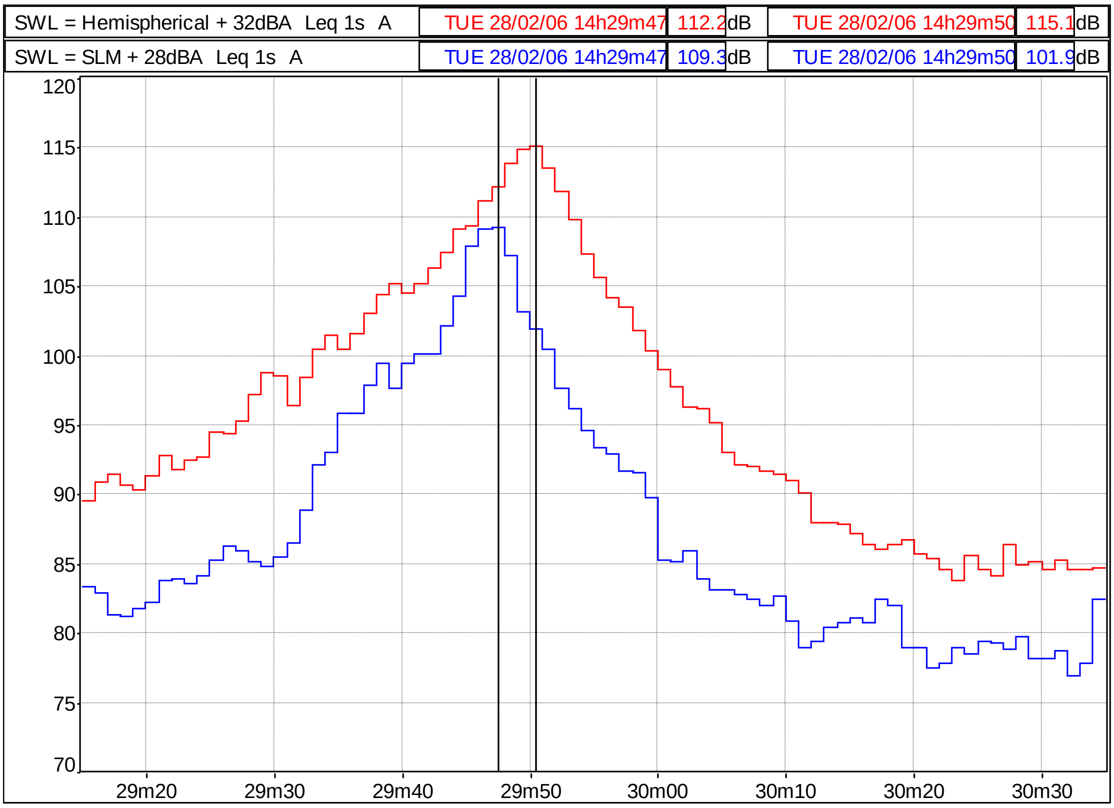

Figure 50: Comparing time-varying sound power levels calculated from measurements by SLM and the hemisphere for dynamic test 2. Sound power levels were calculated from the SLM assuming a source-receiver distance of 10m.

A comparison of 1/1 octave max spectra is presented in the figure below. Here the SLM Max spectrum is compared with the mean hemisphere spectrum at the time when the SLM recorded its L_{Amax}, 14h29m47. It is seen that the spectrum measured in the hemisphere at the time the SLM recorded its Max shows good agreement with the SLM Max.

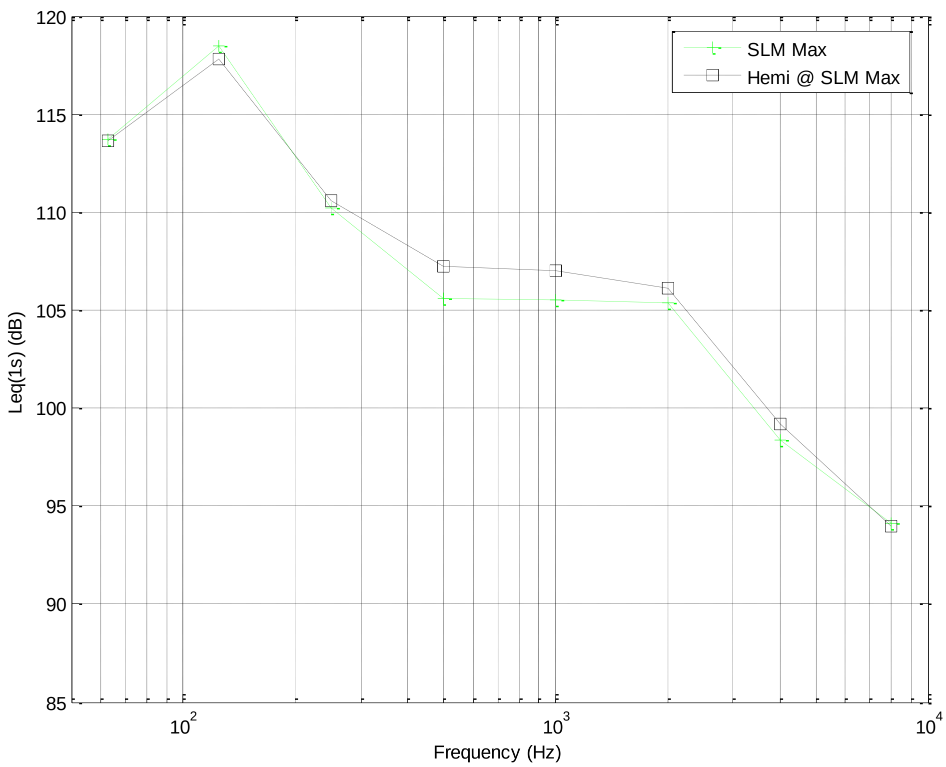

Figure 51: Comparing hemisphere and SLM spectra during dynamic test 2. The SLM Max spectrum is compared with hemisphere spectrum at the time when the SLM recorded its L_{Amax}, 14h29m47.

The values for the 1/1-octave spectra for the SLM L_{max} and the hemisphere at the time of the SLM L_{max} are shown in the table below, together with the L_{Aeq} normalised to 10m calculated from these data.

Frequency (Hz)	**63**	**125**	**250**	**500**	**1 k**	**2 k**	**4 k**	**8 k**	**10m Normalised L_{Aeq} (dB)**
Hemi	85.6	89.8	82.6	79.2	79.0	78.1	71.2	66.0	84.4
SLM	85.7	90.5	82.2	77.6	77.5	77.4	70.4	66.1	83.5
Hemi-SLM	-0.1	-0.7	0.4	1.6	1.5	0.7	0.8	-0.1	0.9

Table 18: Comparing 1/1 octave band Max spectra normalized to 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for dynamic test 2.

These results further support to the hypothesis that the SLM L_{max} measured at a perpendicular distance of 10m can be used to describe the sound power of a vehicle during a drive-by.

5.6.3 Dynamic test 3

The time-varying sound power levels calculated from measurements by the single SLM at 10m and the hemisphere for dynamic test 3 are shown in the figure below. The cursors show the positions of the L_{Amax} (1s) for the SLM and the hemisphere, and it is seen that these occur at only slightly different times.

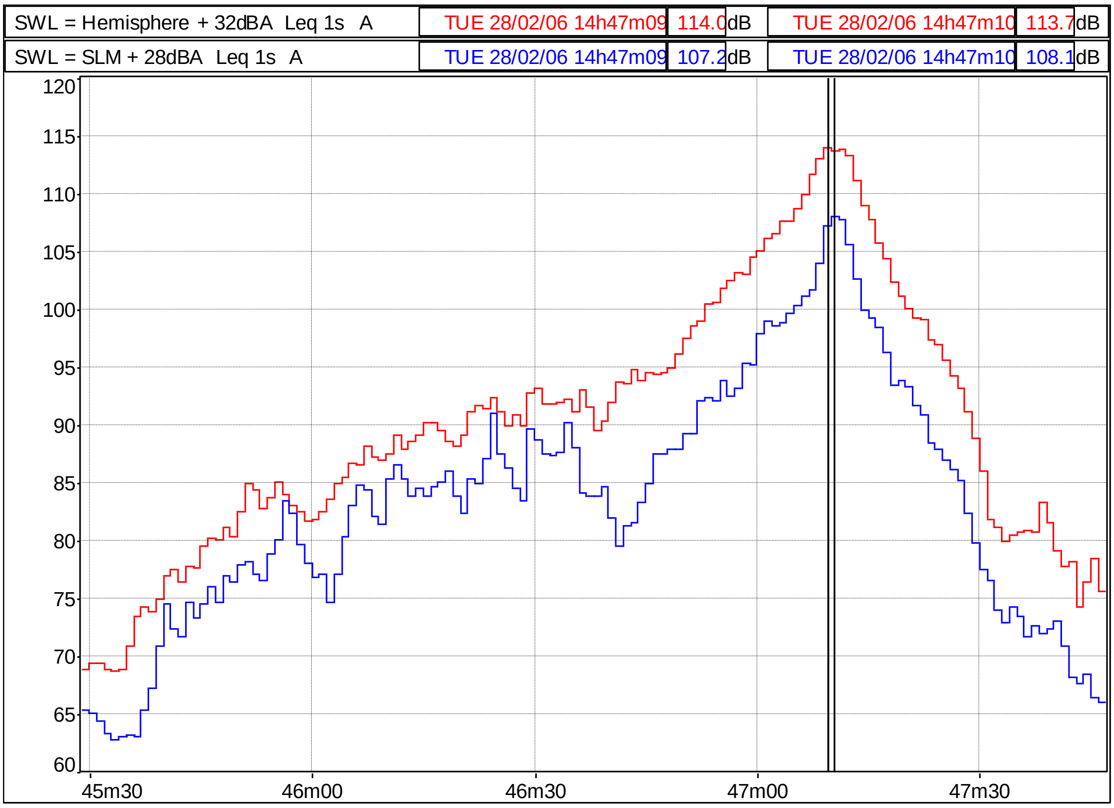

Figure 52: Comparing time-varying sound power levels calculated from measurements by SLM and the hemisphere for dynamic test 3. Sound power levels were calculated from the SLM assuming a source-receiver distance of 10m. Similarly for the 6 mics on hemisphere a radius of 16m was assumed. The cursors show the positions of the L_{Amax}(1s) for the SLM and the hemisphere.

The comparison of 1/1 octave max spectra is presented in the figure below. The SLM Max spectrum is compared with the mean hemisphere spectrum at the time when the SLM recorded its L_{Amax}, 14h47m10.

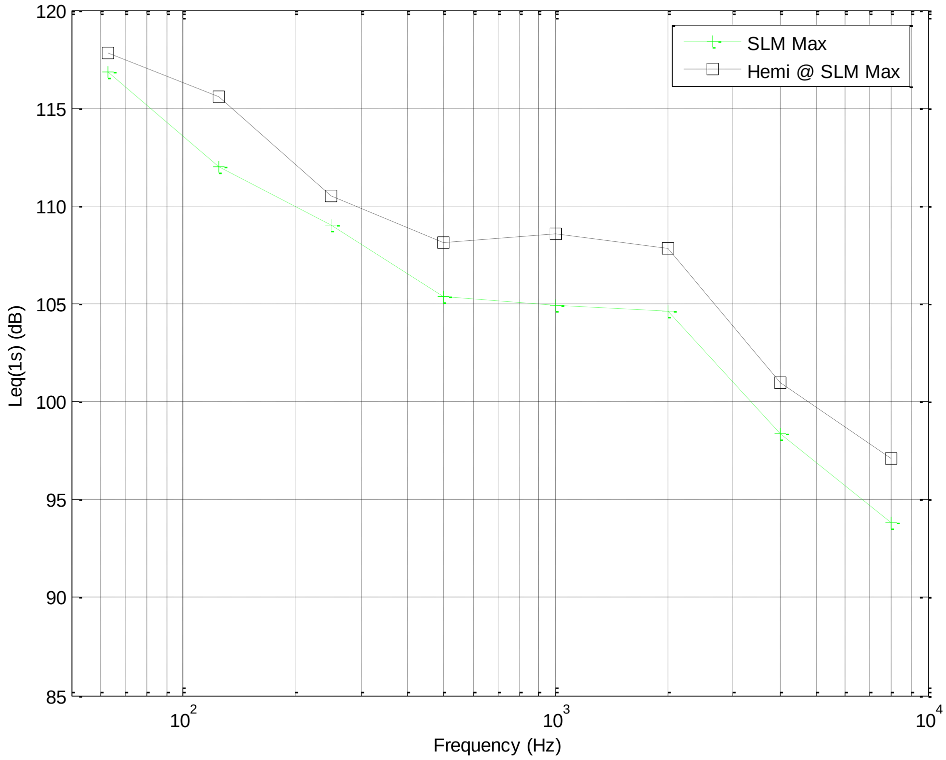

Figure 53: Comparing hemisphere and SLM spectra during dynamic test 3. The SLM Max spectrum is compared with hemisphere spectrum at the time when the SLM recorded its L_{Amax}, 14h47m10.

The values for the 1/1-octave spectra for the SLM L_{max} and the hemisphere at the time of the SLM L_{max} are shown in the table below, together with the L_{Aeq} normalised to 10m calculated from these data.

Frequency (Hz)	63	125	250	500	1 k	2 k	4 k	8 k	10m Normalised L_{Aeq} (dB)
Hemi	89.8	87.6	82.5	80.1	80.6	79.8	73.0	69.1	85.6
SLM	88.8	84.0	81.0	77.4	76.9	76.6	70.4	65.8	82.5
Hemi-SLM	1.0	3.6	1.5	2.7	3.7	3.2	2.6	3.3	3.1

Table 19: Comparing 1/1 octave band Max spectra normalized to 10m from measurements by single SLM at 10m and calculated from measurements at 6 mics on hemisphere of radius 16m for dynamic test 3.

These results show the SLM L_{max} at 10m to give an estimate of drive-by sound power level ~3dB lower in each 1/1 octave than the hemisphere.

5.7 Repeatability study from experimental measurements

An approach to providing a statement of uncertainty is to consider declaring values that are statistical maxima based upon sets of practical measurements likely to encompass typical statistical variations. Such statements are based on the values of standard deviations of reproducibility and repeatability of measurement situations. Reproducibility measurements are defined as those that encompass the same noise source measured using the same measurement procedure, by different operators using different equipment at different times, but not necessarily at different sites. Such reproducibility measurements are beyond the scope of this study. Repeatability measurements on the other hand cover the same noise source, measured using the same method, repeated at short intervals by the same operators using the same equipment, and at the same site. Such an analysis was performed for the stationary and dynamic tests detailed above.

Measurement repeatability is compared for the hemisphere and SLM at 10m methods in the figure below. These data are calculated from the Face Shovel stationary tests 1, and 2 and 3, and the Rigid Dumper Truck dynamic tests 2 and 3. Dynamic test 1 is excluded since it was performed on a different noise source, the Front Loader.

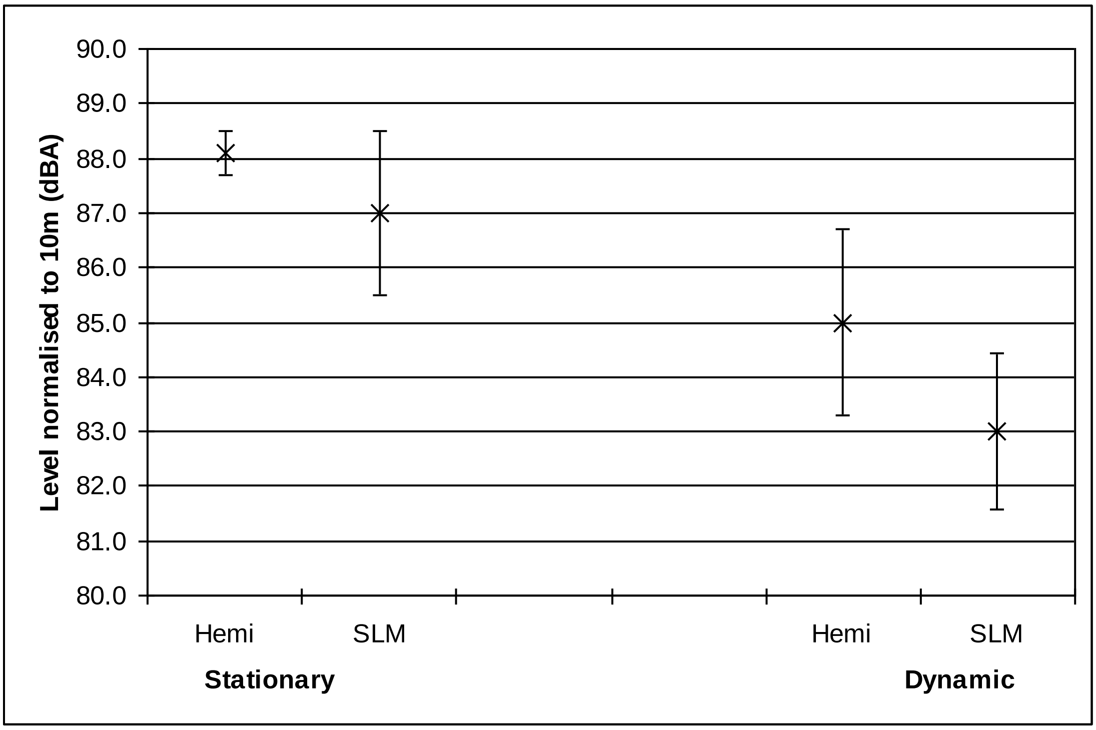

Figure 54: Measurement repeatability for the hemisphere and SLM methods. Showing the mean and two standard deviations for stationary tests 1, 2 and 3 (Face Shovel) and dynamic tests 2 and 3 (Rigid Dumper Truck).

The mean and two standard deviations of repeatability providing 95% confidence limits for the stationary tests and dynamic tests are summarised in the tables below.

	Hemi	**SLM**
Stationary 1	87.9	87.7
Stationary 2	88.1	87.1
Stationary 3	88.3	86.2
Mean	**88.1**	**87.0**
2 σ	**0.4**	**1.5**

Table 20: Stationary test repeatability for the hemisphere and SLM measurements. Showing the mean and two standard deviations providing 95% confidence limits

	Hemi	**SLM**
Dynamic 1	80	78.9
Dynamic 2	84.4	83.5
Dynamic 3	85.6	82.5
Mean (2&3)	**85.0**	**83.0**
2 σ (2&3)	**1.7**	**1.4**

Table 21: Dynamic test repeatability for the hemisphere and SLM measurements, using tests 2 and 3 (Rigid Dumper Truck) only. Showing the mean and two standard deviations providing 95% confidence limits

The figure below presents the 95% confidence levels for the hemisphere and SLM methods calculated from repeatability measurements for the stationary L_{Aeq} tests at the dynamic L_{max} tests.

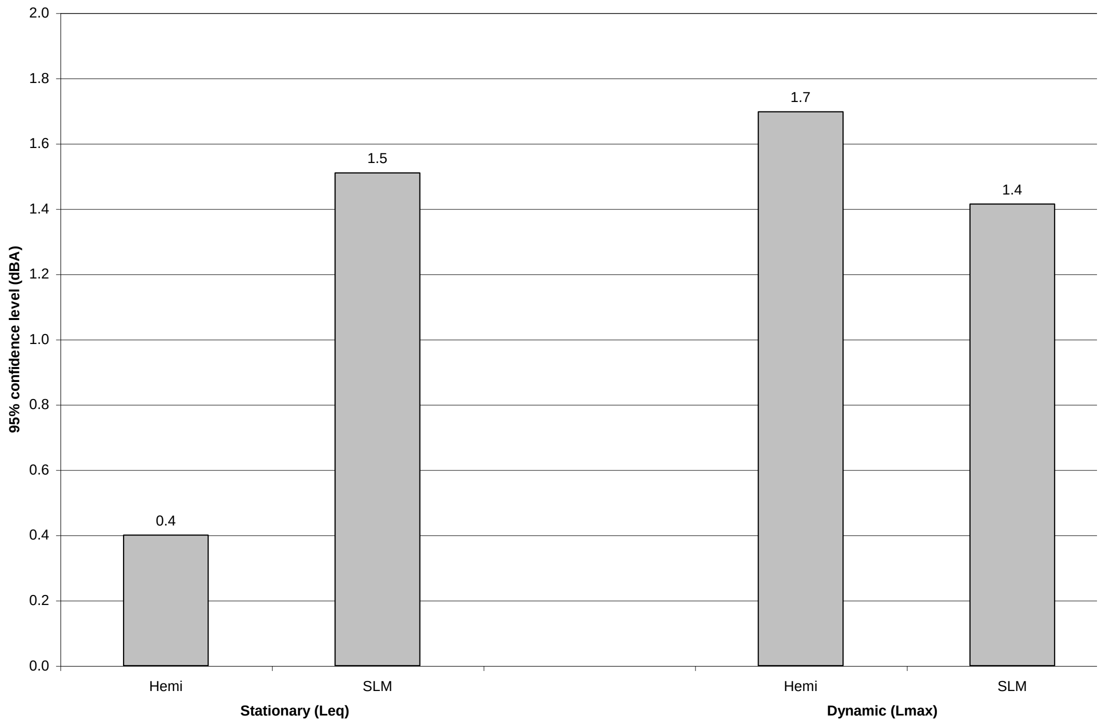

Figure 55: 95% confidence levels for the hemisphere and SLM methods calculated from repeatability measurements

For the stationary tests the repeatability using the 6 mic hemisphere method show a 95% confidence level of ± 0.4 dB. This indicates that the method was highly repeatable and a good measure for comparison of the SLM method. The 95% confidence level of ±1.5dB for the SLM method during the stationary tests seems a reasonable value given the variation in source position and consequently source-receiver path length. This variation is the most significant source of error as discussed above. For the dynamic tests the 95% confidence levels show that the hemisphere value of ±1.7dB slightly exceeds that for the SLM of ±1.4dB. The most likely explanation is path length. Since the measured level is L_{Amax}, the maximum spectrum recorded by the hemisphere will be as susceptible to path level errors as the SLM. The above results are drawn from only three stationary tests and two dynamic tests, and so should be taken as indicators of magnitude rather than as definitive values.

6 Discussion

6.1 Analytical error analysis

i. The method using the single SLM at 10m from the main perceived source on a construction plant for the determination of sound power is seen to be sensitive to errors in the main source to receiver distance.
ii. For a source to receiver distance error of 1m at a nominal 10m range the error in sound power level estimate is seen to be 0.8dB.
iii. For the same error from a component source, a displacement within the source plane (perpendicular to the line joining the source to the microphone) of 5m would be required.
iv. These results illustrate that attention to the main source to receiver path length is the best way to reduce errors in the sound power estimate.

6.2 Experimental study

6.2.1 Stationary tests

The results of the stationary tests indicate:

i. The SLM and hemisphere measured similar overall mean levels although the amplitude distribution is much greater with the SLM.
ii. The amplitude distribution is greater with the SLM than with the hemisphere due to directionality of the source, variations in vehicle orientation during the tests, and variation in path length due to vehicle movement during the tests.
iii. The vehicle was not strongly directional. The largest directionality was measured at 8 kHz although the emissions are low at this frequency. The more significant directionality in terms of environmental noise is seen at 125Hz at the rear of the machine and is less than 3 dB.
iv. In the 1/1-octave bands, the frequency showing the greatest difference in sound power estimation is 250Hz. Here the hemisphere is seen to measure around 3 dB greater than the SLM. This is thought to be due to the fixed path difference of the SLM compared with the two path lengths used in the hemisphere.
v. The single SLM method is more sensitive to correct source positioning than the six-microphone hemisphere method. This is demonstrated by stationary test 3 in particular.

6.2.2 Distance tests

The distance investigations indicate:

i. The point source hypothesis method for the measurement of sound power is sensitive to topography and meteorology.

ii. The largest distance suitable is 30m. Beyond this errors of around 3 dB were seen.

6.2.3 Dynamic tests

The dynamic tests indicate:

i. The spectrum measured at the time of the L_{Amax} is a good estimate of sound level.
ii. The L_{max} spectrum measured by the SLM shows good agreement with the L_{eq} spectrum measured by the hemisphere at the time of the L_{Amax}.
iii. These results indicate that the hypothesis that a passing vehicle acts as an omni-directional point source with a maximum sound pressure level at the closest transitional point is acceptable.

6.3 Repeatability tests

6.3.1 Six microphone hemisphere method

The measurements of repeatability for the stationary test using the hemisphere method show the 95% confidence level of ± 0.4 dB. Given the variable operations performed by Face Shovel during the three two-minute measurement periods, this repeatability is lower than might have been expected. However this gives substantiation to the principle that the sound power level of the piece of plant may be determined by measurements at a small number of selected locations.

6.3.2 SLM at 10 metre method

The 95% confidence level of ±1.5dB for the SLM method during the stationary tests seems a reasonable value given the variation in source position and consequently source-receiver path length. This variation is the most significant source of error. It is not surprising that the variation has greater effect on the single SLM method than on the six microphone hemisphere method, since for the latter as one path increases for any one microphone it decreases for another, so reducing the error in sound pressure measurement over the surface.

In contrast the 95% confidence levels for the dynamic tests show that the hemisphere level of ±1.7dB slightly exceeds that for the sound level meter of ±1.4dB. The most likely explanation is again path length. Since the measured level is L_{Amax}, the maximum spectrum recorded by the hemisphere will be as susceptible to path level errors as the SLM. On the other hand the agreement in repeatability between the stationary and dynamic SLM tests indicates that the path length estimates during both methods are of a similar magnitude.

The above results are drawn from only three stationary tests and two dynamic tests. Although they indicate that sound power levels from the stationary and dynamic plant do not vary widely, experience suggests that greater variability might be expected between drivers and depending on site conditions and operations. For the 95% confidence level of ± 1.5 dB for both the stationary and dynamic test derived from repeatability, the results indicate that the single SLM method at 10m is an accurate and reliable method for the characterisation of plant sound power on-site.

7 Conclusions

i. The results indicate that the single SLM method at 10m is a reasonably accurate and reliable method for the characterisation of plant sound power on-site for both stationary and dynamic activities.

ii. The largest cause of variation is the source to receiver path, and consequently the perpendicular source to receiver distance should be determined with the greatest possible precision.

7.1 Analytical study

i. Component sources on construction plant can be considered to act as point sources after only short distances. For the Face Shovel, the transition distance to point source from the main component source was ~0.6m.

ii. Even if the entire vehicle is a finite plane source, it can be considered to behave as a point source at distances greater than ~3m.

iii. Considering the construction plant to be a collection of component sources and measuring at a known distance from the main source, the error due to dislocation of the component sources in the vertical plane of the vehicle is shown to be small. For the Face Shovel of length 10m the error in sound power estimate for the bucket at the front of the vehicle when measured from the side is <1dB.

iv. The error in sound power estimation for the component sources has a smaller effect on the L_{Aeq} normalised to 10m since the level is less significant when compared with the contribution from the main source.

v. The single SLM method is sensitive to errors in estimation of the perpendicular source to receiver distance. For the Face Shovel a realistic error in distance of 1m results in an error in the sound power level of ~0.8dB.

7.2 Experimental study

7.2.1 Tests of stationary measurement accuracy

Stationary measurements of the noise levels from large quarry plant using a single SLM at 10m range provides an accurate characterisation of the L_{Aeq} and of the 1/1 octave spectrum. Levels are within ~1 dB at all frequencies, except at 250Hz where the level is underestimated by ~3dB due to the first interference dip determined by the SLM geometry.

7.2.2 Distance tests

During practical measurements on quarry plant of dimensions greater than four metres, the point source hypothesis was found to function acceptably under fairly calm wind and temperature conditions up to receiver distances of 30m. For ranges greater than 30m the method is sensitive to topography and meteorology.

7.2.3 Tests of dynamic measurement accuracy

For drive-by tests the hypothesis that a passing vehicle acts as a point omni-directional source with a maximum sound pressure level at the closest transitional point is acceptable. Further, the L_{Amax} and L_{max} spectrum provide good estimates of source level. Levels are within 2dB L_{Amax} and spectra levels are within 2dB at all frequencies.

7.2.4 Repeatability measurements

Measurements by the single SLM at 10m agreed with those of a six-microphone hemisphere, within 95% confidence limits. The repeatability was within ±1.5dB for both stationary and dynamic tests. The largest cause of variation is source to receiver path, as indicated by the smaller ±0.4dB 95% confidence limit of the hemisphere method for the stationary tests. These results indicate that the single SLM method at 10m is a reasonably accurate and reliable method for the characterisation of plant sound power on-site for both stationary and dynamic activities.

8 References

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