Environmental Research and Consultancy Department

ERCD REPORT 0506

Precision of Aircraft Noise Measurements at the London Airports

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Summary

This report describes the key sources of uncertainty associated with the long-term measurement of noise from aircraft operations at the London airports and estimates their individual and combined magnitudes. The results of a controlled measurement study that was carried out to provide further information on the precision of aircraft noise measurements are also presented. The results indicate that measurement uncertainty is reduced when measuring aircraft noise levels in SEL rather than Lmax and provide additional confidence in the accuracy of the UK aircraft noise contour model ANCON, which has been validated extensively using measured SEL data.

November 2005

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Glossary of Terms

dBA	dBA is used to denote the levels of noise measured on an A-weighted decibel scale.
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
Leq	The equivalent continuous sound level, normally measured on an A-weighted decibel scale.
Lmax	The maximum sound pressure level of an aircraft noise event, normally measured on an A-weighted decibel scale.
NTK	Noise and Track Keeping monitoring system. The NTK system at the London airports associates radar data from air traffic control radar with flight information and related data from specially positioned noise monitors.
Reproducibility	The closeness of the agreement between measurements of the same property carried out under changed conditions of measurement.
SEL	The Sound Exposure Level generated by a single aircraft at the measurement point, normally measured on an A-weighted decibel scale. SEL has the same amount of acoustic energy as the original sound, but is normalised to a one second time interval.
Slant distance	The shortest distance between the noise monitor and the aircraft flight path.
Uncertainty	A parameter associated with the result of a measurement, which characterises the dispersion of the values that could reasonably be attributed to the quantity being measured**.**

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1 Introduction

1.1 The Environmental Research and Consultancy Department (ERCD) of the CAA provides a range of research and advisory services in the field of aviation and the environment. Much of this work involves the collection and analysis of large amounts of aircraft noise data from the Noise and Track Keeping systems (NTK) installed at Heathrow, Gatwick and Stansted airports. Like any other measured quantity, aircraft noise measurements are subject to some uncertainty, which can influence the 'quality' of the final measured result.

1.2 At the time of writing, a Working Group (WG52) of the ISO Acoustics Technical Committee ISO/TC 43 is in the process of drafting a new international standard on the reliable measurement of aircraft noise in the vicinity of airports[1]. One of the requirements of the new ISO standard (as currently drafted) will be that the uncertainty of measurement data from a permanently installed sound monitoring system (e.g. an NTK system) should be reported.

1.3 In anticipation of the new ISO Standard, ERCD has produced this report, which identifies the key sources of uncertainty associated with the long-term measurement of noise from aircraft operations at the London airports. It is envisaged that this report will provide a practical and reliable basis for quantifying measurement uncertainties in future ERCD noise studies.

1.4 The uncertainty contributions for a typical ERCD noise study can be considered in two groups. The first group includes the components of uncertainty associated with the measurement of aircraft noise at a particular monitoring location. The second group includes the components of uncertainty associated with any subsequent data analysis that may be carried out.

1.5 Section 2 of this report provides a general introduction to the concept of measurement uncertainty. For further background reading on the subject, readers may also wish to consult the NPL Measurement Good Practice Guide No. 11 (Ref 1). Section 3 assesses the likely magnitudes of possible uncertainty components associated with the measurement of aircraft noise at the London airports. In Section 4, the uncertainties associated with post-measurement data processing are discussed. Section 5 then provides an estimate of the overall combined uncertainty for a typical ERCD noise study. The results of a practical reproducibility study, which was carried out at Heathrow airport to provide further information on the precision of aircraft noise measurements, are presented in Section 6. The conclusions of the study are presented in Section 7.

1.6 It is recommended that this report be read in conjunction with ERCD Report 0406 (Ref 2), which describes the best practice monitoring techniques used by ERCD when carrying out aircraft noise studies.

2 General Approach to Evaluating Uncertainty

2.1 Background

2.1.1 The overall accuracy of any type of measurement is limited by various sources of error or uncertainty. Components of uncertainty can essentially be classified as either *random* or *systematic* in nature. When making a series of repeated measurements, the effect of the former is to produce randomly different results each time, which are

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[1] The UK is represented in WG52 by ERCD. The proposed new international standard is intended to replace ISO 3891: 1978, Acoustics – *Procedure for Describing Aircraft Noise Heard on the Ground*.

all spread or scattered around an average (mean) value. In contrast, systematic components of uncertainty cause the measurement to be consistently above or below the true value. For example, when measuring the time with a watch that has been set 1 minute slow, there will be a systematic error (or bias) in all the measurements. In a well-designed measurement study, the systematic components of uncertainty should generally be smaller than the random components.

2.1.2 A measurement uncertainty may be regarded as a range or interval either side (i.e. plus or minus) of a measured value. When quoting the uncertainty of a measurement result, it is customary to also state the *level of confidence* associated with the result; that is, the likelihood or probability that the interval will include the 'true' value of the quantity being measured. Typically, measurement uncertainties are quoted with a statistical confidence level of 95 percent.

2.1.3 Possible sources of uncertainty for aircraft noise measurements include not only the noise instrumentation itself, but also variations in the noise source and propagation path, meteorological variations, the local environment at the measurement site, and also any variance due to data sampling - all of these individual uncertainty components can influence the quality of the final measured result.

2.2 Standard method for combining uncertainties

2.2.1 An internationally accepted procedure for combining and expressing measurement uncertainties is given in the ISO *Guide to the Expression of Uncertainty in Measurement* (Ref 3). By following the procedures and statistical methods given in the *Guide*, and also other recommended guidance (Refs 1, 4), a reasonable estimate of the overall combined uncertainty can be made. It should be recognised however that the *Guide* is just that – a guide, and that there is no fundamentally correct way of combining uncertainties (Ref 5).

2.2.2 The first step to calculating the overall uncertainty involves listing all the factors that may influence the final measured result and estimating the value of each component. The estimates may be based on published information, manufacturer's data, or results from previous studies.

2.2.3 Once identified, each of the uncertainty components must then be expressed in similar terms by converting them (if necessary) into *standard uncertainties*, which equate to a statistical confidence level of 68 percent and are equivalent in magnitude to one standard deviation.

2.2.4 A standard uncertainty is derived from the uncertainty of an input quantity by dividing by a number associated with the assumed probability distribution. For example, the standard uncertainty of a normally distributed input quantity (assuming a statistical confidence level of approximately 95 percent) is found by dividing the uncertainty value by 2. However, if for example the value of uncertainty is equally likely to fall between upper and lower limits, a uniform or rectangular distribution (with a divisor of $\sqrt{3}$) may be assumed instead.

2.2.5 In order to calculate the overall combined uncertainty, the simplest method would of course be to add up each of the individual standard uncertainty values. However, using this method would produce a somewhat improbable 'worst-case' estimate of the overall uncertainty. The *Guide* therefore recommends a more practical approach based on established statistical methods: provided that all the uncertainty components are independent of each other, then the *combined standard uncertainty* is estimated by calculating the square root of the sum of the squares. The combined standard uncertainty can then be scaled by a *coverage factor* of k=2 to produce an *expanded uncertainty* value at a level of confidence of approximately 95 percent.

2.2.6 An assessment of the likely magnitudes of possible uncertainty components associated with a typical noise monitoring study at the London airports is now provided in Sections 3 and 4.

3 Noise Measurement Uncertainties

3.1 Variation of the noise source

3.1.1 Most ERCD measurement studies involve the determination of average noise levels by aircraft type at particular monitor locations around an airport. Typically, the aircraft type groupings are based on specific airframe and engine combinations (e.g. Boeing 767-300 with PW4060 engines), and can often include the same aircraft type from a number of different airline operators, each flying to/from a number of different airports.

3.1.2 For any particular flight, there are many (often interdependent) factors that can influence the noise level recorded at a particular track distance from the airport, including:

- the airline operating procedure (engine power settings, flap settings, cutback height on take-off, etc),
- the aircraft take-off/landing weight (which can determine engine power settings, flap settings, etc),
- the atmospheric conditions (e.g. air temperature and headwind, which can affect both aircraft and engine performance[2]), and
- the aircraft position relative to the noise monitor (i.e. its slant distance from the noise monitor).

3.1.3 The effect of the factors listed above on the variation of the noise ‘source’ being measured can usually be accounted for by adopting a suitable sampling strategy, i.e. their effects can normally be ‘averaged out’ over a period of time by analysing a large enough quantity of data. Therefore, for the purposes of this analysis, the uncertainty due to the variation of the noise source is considered to be practically negligible for a typical long-term noise study with large sample sizes, with any small element of uncertainty assumed to be already included in the uncertainty of the sampling distribution (see Section 4.3).

3.2 Effects of weather on noise propagation

3.2.1 Sound levels are affected by meteorological conditions particularly when the noise propagation distance is large. When measuring aircraft noise, it is generally at greater distances from the airport (i.e. when aircraft are typically much higher above the noise monitors) that the influence of the weather will be greatest. Atmospheric variations in temperature and relative humidity will produce different rates of sound absorption and hence result in different measured noise levels for the same source emission. Wind speed and direction can also affect the noise propagation path quite significantly due to refraction/turbulence effects, which will affect the noise on the ground.

3.2.2 As explained in ERCD Report 0406 (Ref 2), measurements acquired in wind speeds greater than 10 kts, excessively absorptive atmospheric conditions, or during periods of precipitation are normally rejected for ERCD noise studies. Thus, the overall influence of the weather is minimised when long-term average sound levels are

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[2] These effects are quite separate to the effects of weather on noise propagation (see Section 3.2).

determined over a range of (relatively stable) meteorological conditions. Furthermore, the results of previous studies have generally found a weak relationship between aircraft noise levels and meteorological conditions (e.g. Ref 6). Nonetheless, the possible effects of weather should not be totally ignored. Therefore, as a first order approximation (based on previous monitoring experience), an uncertainty value of ±0.5 dBA has been estimated to account for any underlying weather effects on noise propagation.

3.3 Effect of microphone height on measured noise levels

3.3.1 For most of ERCD's attended measurement exercises, microphones are placed at a height of 4 m above the ground surface to reduce the likelihood of interference from ground reflections. If it is required for a particular noise study, or if it is impractical to measure at 4 m, measurements are recorded (over soft ground) at a standard microphone height of 1.2 m[3]. By comparison, the NTK microphones are mounted either 6 m or 3.5 m (for fixed and mobile sites respectively) above the ground surface, both to minimise the risks of vandalism and also to reduce interference from ground reflections.

3.3.2 It is considered unlikely that the differences between these microphone heights would cause any significant mismatch between the recorded noise levels - provided of course that monitors are sited in non-obstructed areas with relatively soft or grassy ground cover. Previous checks carried out by ERCD have generally revealed no significant (or consistent) differences between pairs of measurements recorded at different heights above soft ground. Thus, aircraft noise measurements are recorded at the different microphone heights without the need for adjustments. However, for the purposes of this analysis, an uncertainty value of ±0.5 dBA has been estimated to account for any possible effect on measured noise levels. Again, this estimate is based on previous monitoring experience (e.g. Ref 7).

3.4 Noise instrumentation

3.4.1 The ERCD and NTK sound level meters are Type 1 precision instruments that conform to the appropriate IEC 60651 and IEC 60804 international standards (Refs 8, 9)[4]. The sound calibrators that are used to verify the accuracy of the sound level meters before and after each series of noise measurements all conform to the Class 1 requirements of IEC 60942 (Ref 10)[5].

3.4.2 The IEC standards specify the performance requirements of the noise instrumentation in a number of areas. In order to ensure that the noise instrumentation continues to operate in conformance to the manufacturing standards, all items are removed from service and calibrated by an approved calibration agency once a year. This calibration is traceable to UK National Standards. The UK's National Physical Laboratory has indicated that the standard uncertainty for a Type 1 sound level meter is ±0.4 dBA (Ref 11).

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[3] The international aircraft noise certification standards (ICAO Annex 16, Vol. 1) specify a microphone height of 1.2 m.

[4] In May 2002, IEC 60651 and IEC 60804 were replaced by IEC 61672-1 (the current international standard for sound level meters), which specifies two performance categories, Class 1 and Class 2. The new Class 1 standard is broadly equivalent to the previous Type 1 grade of IEC 60651/60804.

[5] In January 2003 the latest edition of IEC 60942 was published. However, the ERCD and NTK sound calibrators were all manufactured to a previous edition of the standard.

3.5 Event detection and contamination

3.5.1 Noise events are 'detected' automatically by the NTK noise monitors by means of a user determined threshold trigger level[6]. At each location the threshold trigger level has to be set at a level high enough above the residual (background) noise level to ensure that extraneous noise events are not recorded. However, if the threshold is set too high, some of the low level aircraft noise events will not register, leading to bias in the sample. Thus, the threshold levels are carefully selected so that reliable measurements are recorded for the quietest aircraft types of interest.

3.5.2 Another important factor that can influence the accuracy of aircraft noise measurements is the level of residual noise, which should be as low as possible in order to minimise the influence of non-aircraft noise sources. So as not to overestimate any noise measurement, the residual noise level should ideally be at least 10 dBA below the maximum noise levels of the quietest aircraft types of interest.

3.5.3 The fixed monitor sites, and also the mobile locations selected by ERCD for noise monitoring, are carefully chosen so that the average residual noise levels are at least 10-15 dBA below the quietest aircraft events of interest. Therefore, the uncertainty due to the contamination of aircraft noise events by any residual noise is considered to be negligible for most ERCD studies.

3.5.4 However, it should be recognised that for some noise studies the influence of residual noise can become significant. For example, when measuring aircraft events at relatively great distances from the airport, beyond say 10-15 km from the runway ends (e.g. Ref 6), then the requirement for low residual noise levels becomes even more important. In such cases, the choice of measurement location usually becomes more limited. Therefore, it may be necessary to restrict the data analysis to the noisier aircraft types only for which a complete 'distribution' (see Section 4.3) of noise levels can be accurately measured.

4 Data Analysis Uncertainties

4.1 Correlation of noise events to aircraft operations

4.1.1 The 'noise-to-track' matching algorithm in the current NTK system relies on the time synchronisation between the noise monitors and the NATS radar data. For each recorded noise event, the NTK software determines whether an aircraft passed within a user-defined zone around the noise monitor at the time of Lmax. If an aircraft is found, then the software correlates the noise event with that particular flight.

4.1.2 Because of the current nature of operations at the London airports (i.e. the single runways at Gatwick and Stansted, and the segregated mode of operation at Heathrow), it is unlikely, for noise monitors near these airports, that another aircraft would be passing nearby a monitor at around the same time. Thus, the likelihood of the NTK system assigning an aircraft noise event to the wrong aircraft operation is very small.

4.1.3 Optimal configuration of the NTK noise monitors can reduce the likelihood of recording extraneous (non-aircraft) noise events, and so the chances of the NTK system incorrectly assigning non-aircraft events to aircraft operations is also quite small. Because of these factors, the uncertainty due to the correlation of noise events

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[6] Triggering occurs when the measured noise level exceeds the threshold level for longer than a predetermined minimum event duration - see ERCD Report 0406 (Ref 2). Depending on the monitor location, noise event threshold levels are typically selected between 55 dBA and 65 dBA.

to aircraft operations is considered to be negligible for most long-term ERCD noise studies.

4.2 Radar accuracy and data processing

4.2.1 Even if noise monitors are positioned exactly along nominal departure routes or final approach paths, aircraft will rarely fly directly overhead, and a lateral scatter of flight tracks is observed in practice. All other things being equal, the measured noise levels will all vary slightly due to their different slant distances. To account for the lateral scattering of flight tracks, adjustments can be made to the measured levels so that they correspond instead to the *heights* of the aircraft above the ground (at a given track distance from the airport). These adjustments are usually made by ERCD in accordance with industry supplied (but locally validated) Noise-Power-Distance (NPD) relationships (Ref 12).

4.2.2 Although the NPD data are normally derived from the noise certification process, not all airframe/engine combinations are available. In such cases, it is necessary to use substitute aircraft based on the best available match of the existing NPD data, which could be a potential source of uncertainty for some aircraft types. In addition, the NPD noise attenuation rates (as a function of distance) are based on a specific set of atmospheric conditions, whereas noise measurements collected for ERCD studies usually cover a range of atmospheric conditions. However, because the slant distance corrections made by ERCD are usually quite small, it is not expected that any uncertainty due to the NPD data would affect significantly the overall accuracy of the measurements.

4.2.3 There are also further uncertainties associated with the NATS radar data in the NTK system, which are required to position the aircraft relative to the noise monitors on the ground. It follows that any inaccuracies in the flight path information will also affect any slant distance corrections that are applied to the noise data. However, the results of a recent study indicated that the NTK data are of sufficient accuracy for the type of studies undertaken by ERCD (Ref 13), and since much of ERCD’s work is based on large samples of data (rather than individual flights), the effect of any possible inaccuracy in the NTK radar data is normally mitigated. In addition, the relatively short cycle time of the main NATS radar head at each airport (nominally a four second rotation period) means that aircraft flight paths in the NTK system can be resolved to a greater accuracy than systems based on longer cycle times, such as six or eight seconds.

4.3 Sampling distribution

4.3.1 As explained above, most ERCD measurement studies involve the determination of average noise levels by aircraft type at specific monitor locations. Generally speaking, the bigger the sample size, the better the estimate of the true mean value of the ‘population’ for each aircraft type.

4.3.2 Conventional statistical theory used to analyse the data is based on the properties of the so-called Normal (or Gaussian) distribution. This is a familiar bell-shaped curve, the shape of which can be precisely defined in terms of its mean and standard deviation. The distributions of aircraft noise levels, like those of many physical variables, are usually found to be close to Normal[7].

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[7] The term 'Normal' here does not imply that this is a usual or expected distribution. In fact, a perfectly Normal distribution is unusual in practice but most distributions approximate to this shape.

4.3.3 It should be noted that the standard deviation is a measure of the scatter or dispersion of a set of values from an estimated mean value; it is not the uncertainty associated with the mean value. This is evident, for example, when taking more and more noise measurements of the same aircraft type, since the standard deviation will not usually change apart from small fluctuations. In order to estimate how precisely the true (population) mean is estimated by the sample mean, the *standard deviation of the sampling distribution* must be determined instead.

4.3.4 The standard deviation of the sampling distribution, often called the *standard error* of the mean, is calculated by dividing the standard deviation by the square root of the number of measurements. Analysis of NTK data at a range of distances from the airports indicates that the standard deviation of measured noise levels for any particular aircraft type is typically less than 3 dBA. Therefore, for a random sample of say 50[8] noise measurements, the standard error will usually be less than 0.5 dBA.

5 Calculating the Combined Uncertainty

5.1 As explained in Section 2, a practical approach to estimating the combined uncertainty of the individual uncertainty components is to calculate the root sum of the squares. Firstly however, it is necessary to convert each component into a standard uncertainty by dividing by a number associated with the assumed probability distribution. The table below lists the standard uncertainties and assumed probability distributions for each of the relevant uncertainty components.

The combined uncertainty for a typical long-term study

Para Ref.	Source of Uncertainty	Value (± dBA)	Assumed Probability Distribution	Divisor	Standard uncertainty (dBA)
3.1	Variation of the noise source	negligible	-	-	-
3.2	Effects of weather on noise propagation	0.5	Normal (95 percent)	2	0.25
3.3	Effect of microphone height on measured noise levels	0.5	Normal (95 percent)	2	0.25
3.4	Noise instrumentation	0.4	Normal (68 percent)	1	0.4
3.5	Event detection and contamination	negligible	-	-	-
4.1	Correlation of noise events to aircraft operations	negligible	-	-	-
4.2	Radar accuracy and data processing	negligible	-	-	-
4.3	Sampling distribution	0.5	Normal (68 percent)	1	0.5
Combined Standard Uncertainty (root sum of squares)					**0.73**
Expanded Uncertainty (95 percent confidence level, k=2)					**1.46**

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[8] A sample size of more than about 30 to 50 cases is normally considered to be large in statistical terms.

5.2 In the above example, the final value of expanded uncertainty is approximately ±1.5 dBA, with a confidence level of 95 percent. In order to determine whether this value is a reasonable estimate of the overall uncertainty for a typical long-term noise study, a controlled measurement exercise was undertaken by ERCD. The results of the study, which was carried out at Heathrow airport, are reported in the following section.

6 Reproducibility Study

6.1 Methodology

6.1.1 The assessment of measurement uncertainty provided in Section 5 estimated that the expanded uncertainty for a typical airport monitoring study was ±1.5 dBA. A controlled measurement exercise was therefore set up at Heathrow airport to provide further information on the precision, or 'reproducibility', of measurements - that is, the closeness of the agreement between measurements of the *same* property carried out under *changed* conditions of measurement.

6.1.2 The reproducibility study, which took place over a period of six consecutive weeks during March and April 2005, involved the simultaneous measurement of aircraft noise levels at the same monitoring location using three NTK noise monitors – i.e. the *changed* conditions of measurement were the different noise monitors.

6.1.3 Heathrow was selected as the airport for the measurement exercise principally because of its proximity to the offices of the NTK field service engineers – in the unlikely event of a hardware failure, the monitor 'down-time' would be considerably less than at Gatwick or Stansted. To make best use of existing resources, it was decided to deploy two mobile NTK monitors alongside one of the existing fixed NTK noise monitoring terminals (the fixed sites are used principally to detect departure noise limit infringements).

6.1.4 Of the ten current fixed sites around Heathrow, site 'B' in Poyle was selected as the best monitoring site for this study because of the comparatively open surrounding terrain, which gave the greater potential for the placement of multiple noise monitors - see **Figure 1**. Site B is located approximately 6 km from the start-of-roll position on runway 27R. In addition, site B is conveniently located under the 09L approach path (approximately 2.5 km from the landing threshold) and so allows data to be collected for arrivals when the airport is operating in an easterly mode.

6.1.5 The two mobile monitors (referred to as site '23' and site '24' in the NTK system) were positioned approximately 5 m apart from each other and from the existing fixed monitor. It should be recognised that even a relatively small change in microphone position such as 5 m can have an effect on noise measurements. However, this amount of separation was considered to be a reasonable compromise between (i) positioning the monitors as near as possible to each other and (ii) minimising any possible reflection and/or shielding effects caused by the monitors themselves. To ensure consistency between the measurement results, the two mobile monitors were set up with the same carefully selected event detection parameters as the fixed monitor[9].

6.1.6 The monitor installed at site 23 was calibrated immediately before the commencement of the study. Similarly, the monitor installed at fixed site B was (recently) calibrated in November 2004. However, in order to provide for a representative range of calibration dates for the study, the noise monitor selected for

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[9] Each monitor was set up with a threshold trigger level of 65 dBA and a 10 second minimum event duration.

site 24 was at the end of its 12-month calibration period[10]. An on-site sound calibration 'check' was also performed on each unit using a hand-held sound calibrator at the start of the measurement period.

6.1.7 To limit the effects of weather for this study, noise measurements recorded in wind speeds greater than 10 kts (measured 10 m above the airfield) or during periods of precipitation were excluded from the analysis. This restriction meant that approximately 30 percent of the data were rejected.

6.2 Results

6.2.1 In total, valid noise event readings for 5,229 departures and 7,448 arrivals were recorded by all three noise monitors. For the purposes of this analysis, the measurement data were first arithmetically averaged to obtain the mean noise level by aircraft type for each monitor location. This process was carried out separately for arrivals and departures, in both Lmax and SEL noise metrics. The 95 percent confidence interval of the mean of each set of three averaged noise levels was then calculated. The results for 25 of the most common aircraft types that operated at Heathrow during the measurement study are summarised in the following table.

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[10] Although a regular calibration test ensures that the sound level meter continues to operate in conformance to the manufacturing standards, it should be remembered it is not an absolute guarantee that the meter will perform as intended for the following 12 months – merely, it is a statement of the instrumentation's performance at the time of the test. Regular on-site checks using traceable sound calibrators also add extra confidence to the validity of any noise measurements, but again it should be remembered that such checks are normally only carried out at a specific sound pressure level and frequency.

95 percent confidence interval by aircraft type
(based on the mean of each set of 3 averaged noise levels)

		Number of flights analysed		95 percent confidence interval (±dBA)			
				09L Arrivals		27R Departures	
Type	Engine	09L Arrivals	27R Departures	Lmax	SEL	Lmax	SEL
Airbus A319-111	CFM56-5B5/P	61	56	1.5	0.9	1.4	1.2
Airbus A319-131	V2522-A5	1053	810	1.3	0.6	1.0	1.0
Airbus A320-111	CFM56-5A1	126	107	1.5	0.8	1.4	1.3
Airbus A320-211	CFM56-5A1	283	189	1.5	0.8	1.2	1.0
Airbus A320-214	CFM56-5B4/2P	83	51	1.7	1.1	1.3	1.1
Airbus A320-214	CFM56-5B4/P	124	89	1.6	0.9	1.2	1.1
Airbus A320-232	V2527-A5	839	603	1.3	0.6	1.1	1.1
Airbus A321-112	CFM56-5B2/P	65	55	1.5	0.9	0.9	1.0
Airbus A321-211	CFM56-5B3/P	264	193	1.5	0.8	1.1	0.9
Airbus A321-231	V2533-A5	494	355	1.4	0.8	1.1	1.0
Airbus A330-243	Trent 772B-60	107	50	1.2	0.9	1.0	0.9
Airbus A340-313	CFM56-5C4	134	83	1.1	0.6	1.0	0.9
Airbus A340-642	Trent 556	68	44	0.7	0.5	1.2	1.0
Boeing 737-400	CFM56-3C1	82	51	1.6	1.1	1.1	0.9
Boeing 737-600	CFM56-7B20	63	48	1.8	1.1	1.4	1.3
Boeing 737-800	CFM56-7B26	81	55	1.8	1.0	1.0	1.0
Boeing 747-400	CF6-80C2B1F	154	93	0.7	0.4	1.0	0.9
Boeing 747-400	PW4056	152	99	0.5	0.4	0.9	0.9
Boeing 747-400	RB211-524G/H	495	351	0.1	0.2	0.9	0.9
Boeing 757-200	RB211-535E4	367	264	1.3	0.6	1.3	1.2
Boeing 767-300	RB211-524H	255	186	0.1	0.3	1.3	1.1
Boeing 777-200	GE90-90B	75	63	1.2	0.6	1.3	1.0
Boeing 777-200	PW4090	92	53	1.1	0.5	1.3	1.1
Boeing 777-200	Trent 892	182	130	0.9	0.5	1.6	1.2
Boeing 777-200	Trent 895	144	84	0.8	0.5	1.7	1.2
			Maximum value	1.8	1.1	1.7	1.3

6.2.2 The results show that in nearly all cases, the 95 percent confidence intervals - taken here to represent the reproducibility of the measurements - are no greater than the expanded uncertainty value of ±1.5 dBA estimated earlier for a typical long-term measurement study (see Section 5). The reproducibility results indicate that the estimate of expanded uncertainty is reasonable.

6.2.3 The results also indicate that the uncertainty associated with SEL noise measurements is generally smaller than for Lmax levels, for both arrivals and departures. For example, the 95 percent confidence intervals for the averaged SEL data are no greater than ±1.0 dBA in more than 70 percent of cases, compared to just 30 percent of cases for Lmax. This is as expected, since SEL is an integration over the entire aircraft noise event and therefore less susceptible to short-term perturbations in the noise propagation path. Because SEL is a ‘building block’ of Leq, the reproducibility results also provide additional confidence in the accuracy of the UK aircraft noise contour model ANCON, which has been validated extensively using measured NTK data (e.g. Ref 14).

6.2.4 A further analysis of the Heathrow data, with particular regard to the individual measured differences between each noise monitor, is provided in Appendix A.

7 Conclusions

7.1 The study has provided an insight into the various components of uncertainty associated with the long-term measurement of aircraft noise at the London airports. The study has also highlighted the importance of good measurement practice when carrying out noise monitoring, which can help to reduce measurement uncertainties.

7.2 The estimated value of expanded uncertainty for a typical noise study is ±1.5 dBA. This estimate was based on uncertainty contributions associated with the effects of the weather on noise propagation, the performance of the noise instrumentation, the different microphone heights on the measured levels, and also the sampling distribution of the measured data.

7.3 The results of a controlled measurement study, which was carried out to provide further information on the reproducibility of measurements, have confirmed the validity of the estimate of expanded uncertainty. The results also indicate that measurement uncertainty is reduced when measuring aircraft noise levels in SEL rather than Lmax and provide additional confidence in the accuracy of the UK aircraft noise contour model ANCON, which has been validated extensively using measured SEL data.

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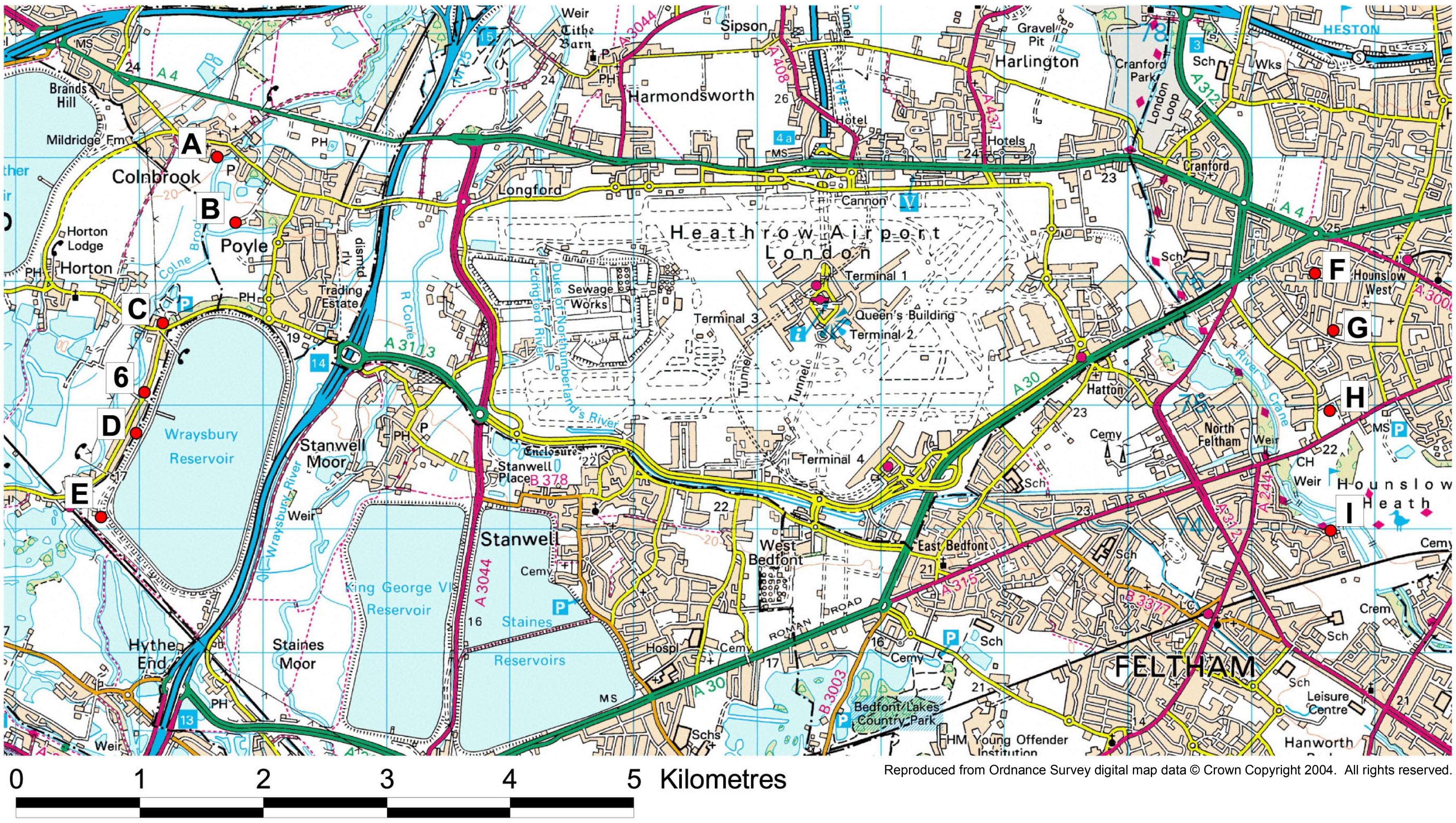
Figure 1 Fixed Noise Monitor Locations at Heathrow



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Appendix A Additional analysis of Heathrow measurement data

A1 **Average noise level differences between monitors**

A1.1 To provide a general indication of the variability of the different noise monitors selected for the Heathrow reproducibility study (see Section 6 of the main report), the average *differences* between the individual noise levels recorded at each pair of noise monitors are compared in the table below.

Summary of average noise level differences (between each pair of noise monitors)

Noise monitor comparison	Metric (dBA)	09L Arrivals (N=7,448) Mean Difference	09L Arrivals (N=7,448) Std Dev	27R Departures (N=5,229) Mean Difference	27R Departures (N=5,229) Std Dev
Site B *minus* Site 23	Lmax	-0.8	0.5	0.1	1.1
	SEL	-0.3	0.3	-0.1	0.6
Site B *minus* Site 24	Lmax	-0.8	0.6	-0.7	1.0
	SEL	-0.5	0.4	-0.8	0.6
Site 23 *minus* Site 24	Lmax	0.0	0.5	-0.8	0.8
	SEL	-0.2	0.3	-0.6	0.5

A1.2 The results indicate that, on average, there is a relatively good correlation between the measurements from each noise monitor. In all cases, the mean noise level differences are no greater than ±0.8 dBA. Such small differences are unlikely to affect significantly the conclusions of any long-term measurement study.

A1.3 It is interesting to note also that the arrival noise levels recorded at site B are, on average, slightly quieter than at either mobile site, indicating a possible ground reflection effect due to the different microphone heights and/or different monitor locations. The results for departures on the other hand show no such (consistent) bias in the measurements, possibly due to the significantly different source-to-receiver geometries for arriving and departing aircraft at this general location. However, without further detailed investigation it is not possible to say with any certainty what the cause of the differences might be.

A1.4 As mentioned in Section 6, the monitor installed at site 23 was calibrated immediately before the commencement of the study. In contrast, the monitor installed at site 24 was at the end of its 12-month calibration period. The above comparison between the noise levels recorded at the two mobile sites reveals no significant bias one way or the other, which indicates that instrument drift between calibration dates is not likely to have been a factor for this study.

A1.5 The results also show that the variability (i.e. standard deviation) of the measured differences is slightly greater for departures than for arrivals in all cases. Again, this is as expected, since the noise propagation distances were significantly greater for departures than for arrivals[1].

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[1] The average heights of arriving and departing aircraft above the noise monitors were approximately 150 m (500 ft) and 600 m (2000 ft) respectively.

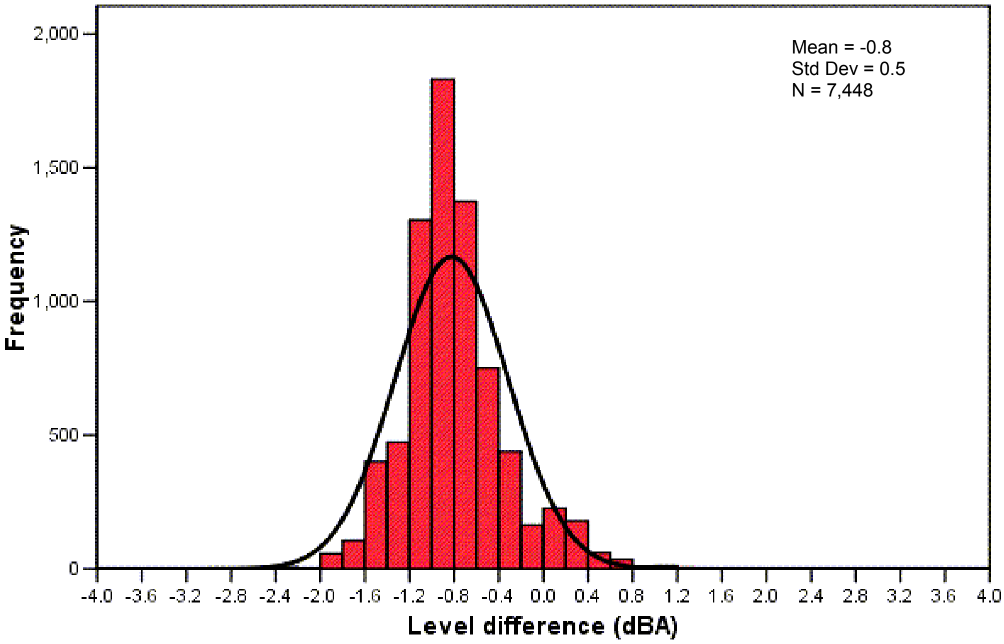
A2 Distribution of noise level differences

A2.1 **Figures A1 to A3** present the distributions of the measured Lmax noise level differences between each pair of monitoring sites. These figures are ‘histograms’, which classify the noise level differences in 0.2 dBA bands. Superimposed on each histogram is the equivalent Normal distribution; i.e. the one having the same mean and standard deviation as the data. **Figures A4 to A6** present the equivalent SEL data for each pair of noise monitors.

A2.2 In each figure, the upper half (i) gives the distribution of the measured differences for arrivals, and the lower half (ii) for departures. In most cases, it can be seen that the distributions resemble the theoretical Normal distributions quite closely. The histograms also illustrate the differences between random and systematic errors. In this instance, the effect of random errors (such as the effects of weather on the noise propagation path) is to produce a spread of measurements centred on 0 dBA. Systematic errors on the other hand (such as calibration errors, or ground reflection effects, etc.) cause a shift in the distribution away from the centre value.

Figure A1

(i) Arrival Lmax noise level differences: SiteB *minus* Site23



(ii) Departure Lmax noise level differences: SiteB *minus* Site23

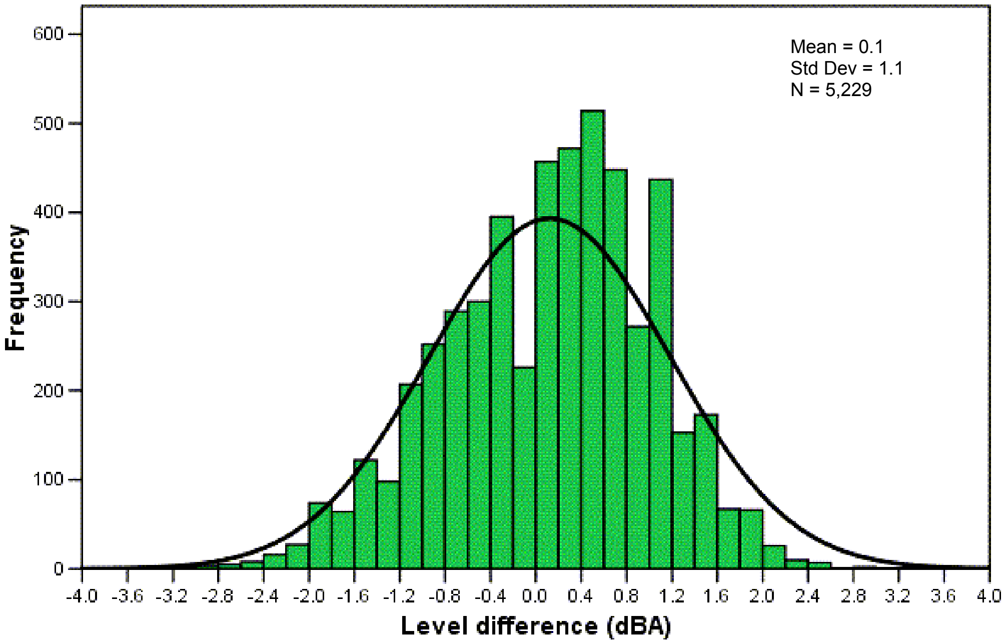
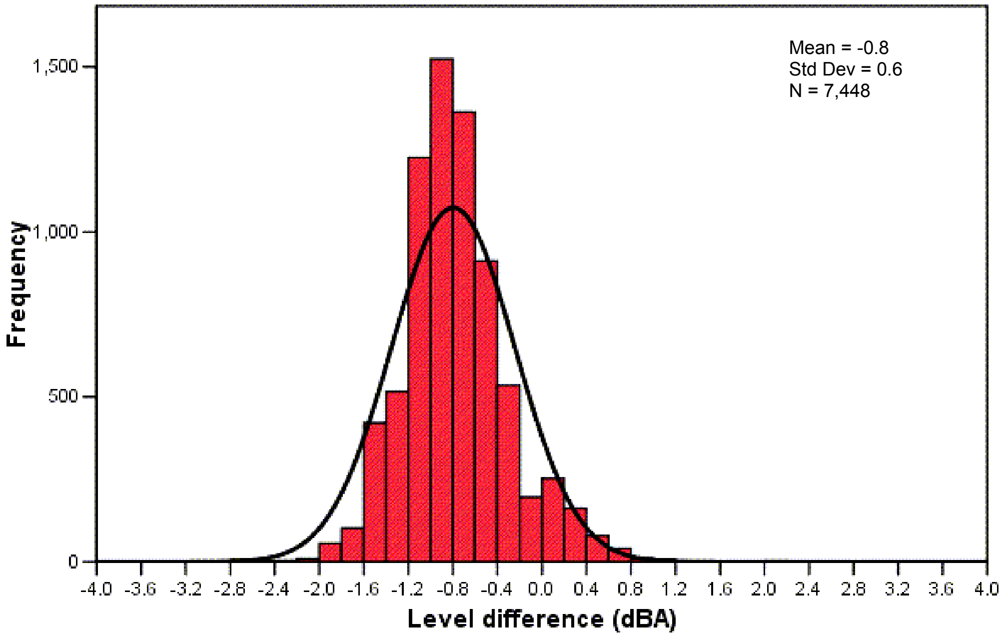


Figure A2

(i) Arrival Lmax noise level differences: SiteB *minus* Site24



(ii) Departure Lmax noise level differences: SiteB *minus* Site24

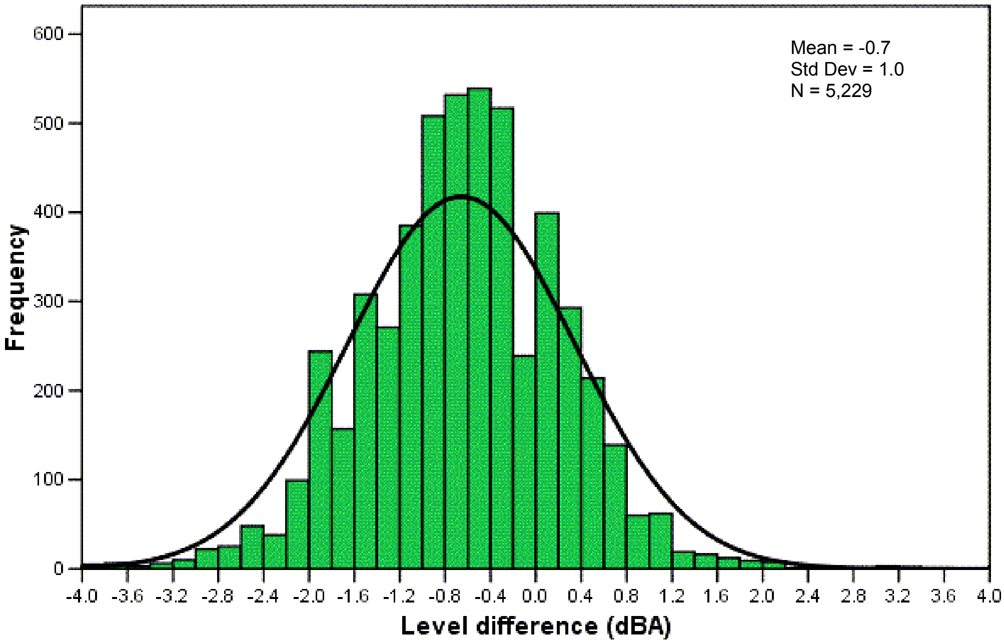
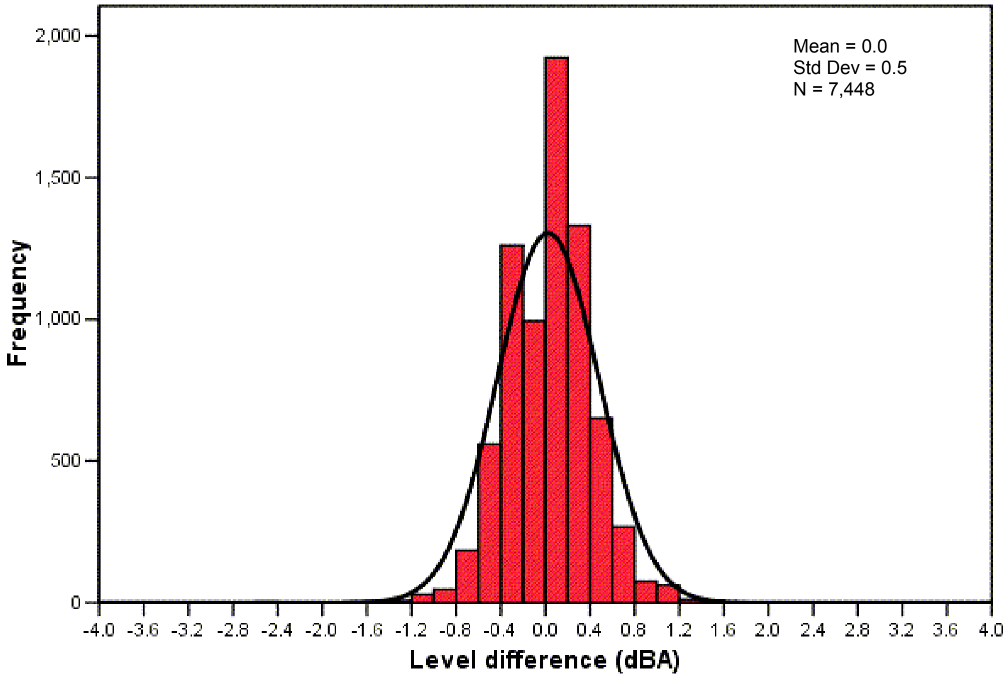


Figure A3

(i) Arrival Lmax noise level differences: Site23 *minus* Site24



(ii) Departure Lmax noise level differences: Site23 *minus* Site24

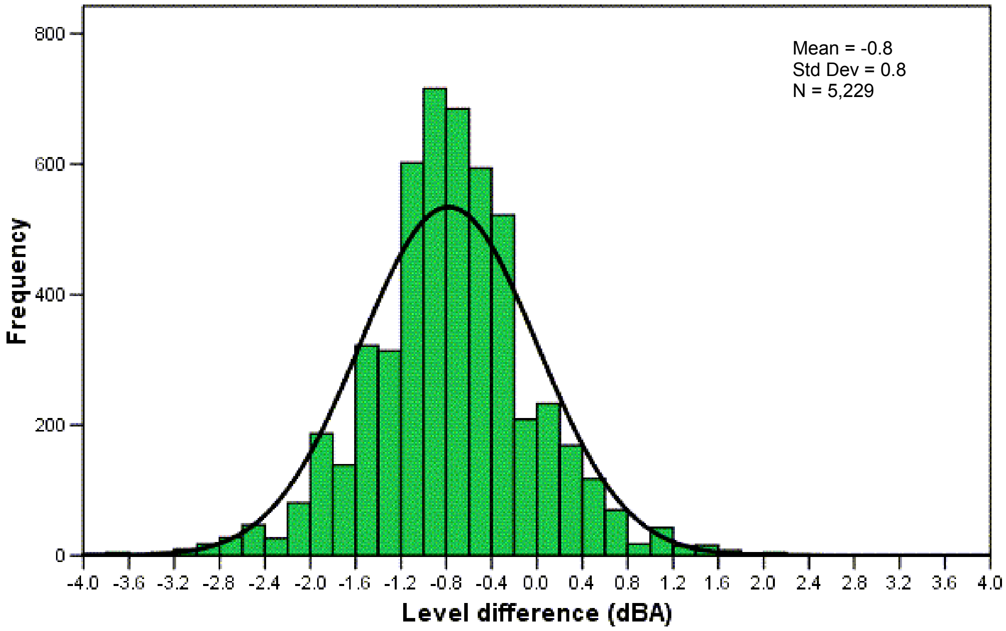
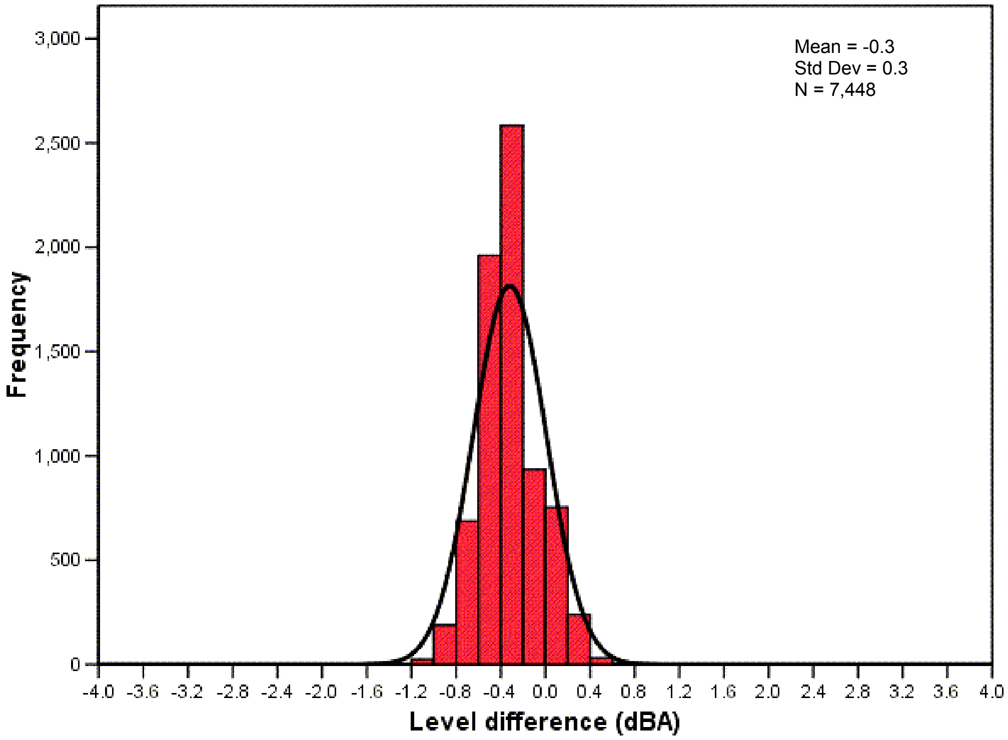


Figure A4

(i) Arrival SEL noise level differences: SiteB *minus* Site23



(ii) Departure SEL noise level differences: SiteB *minus* Site23

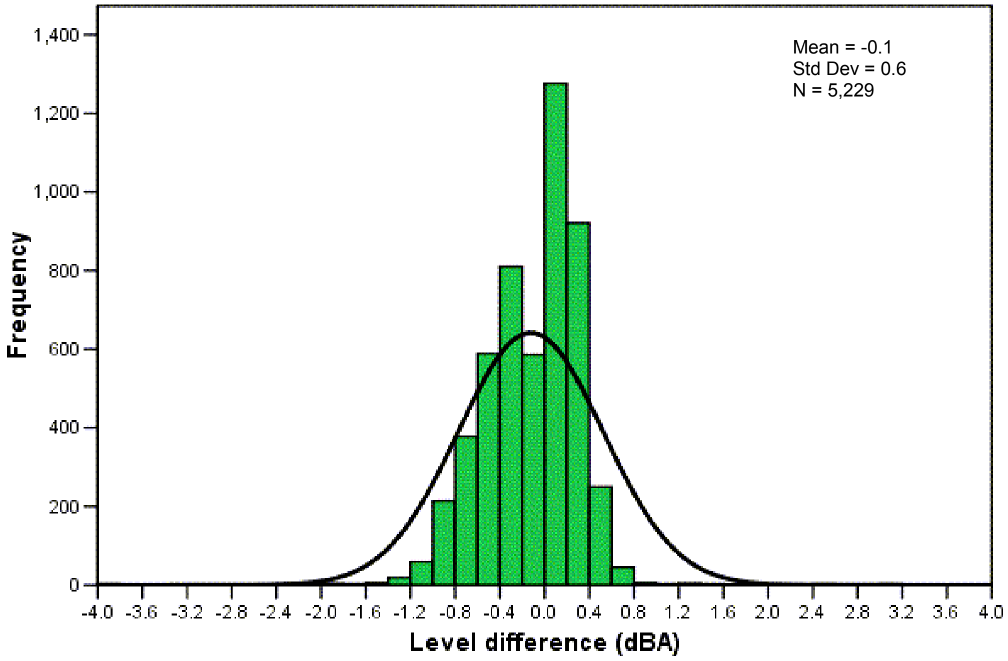
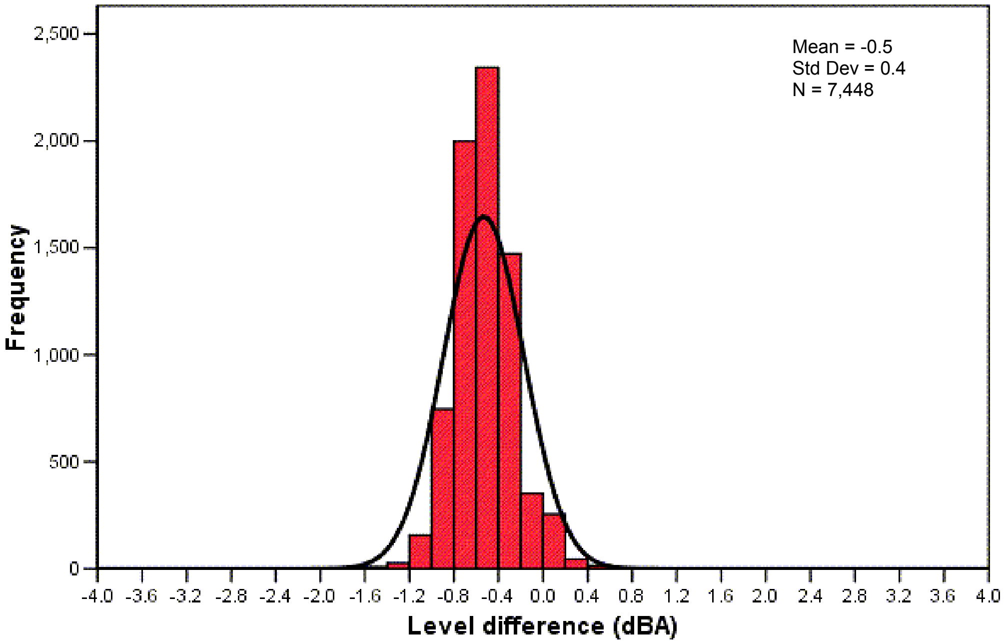


Figure A5

(i) Arrival SEL noise level differences: SiteB *minus* Site24



(ii) Departure SEL noise level differences: SiteB *minus* Site24

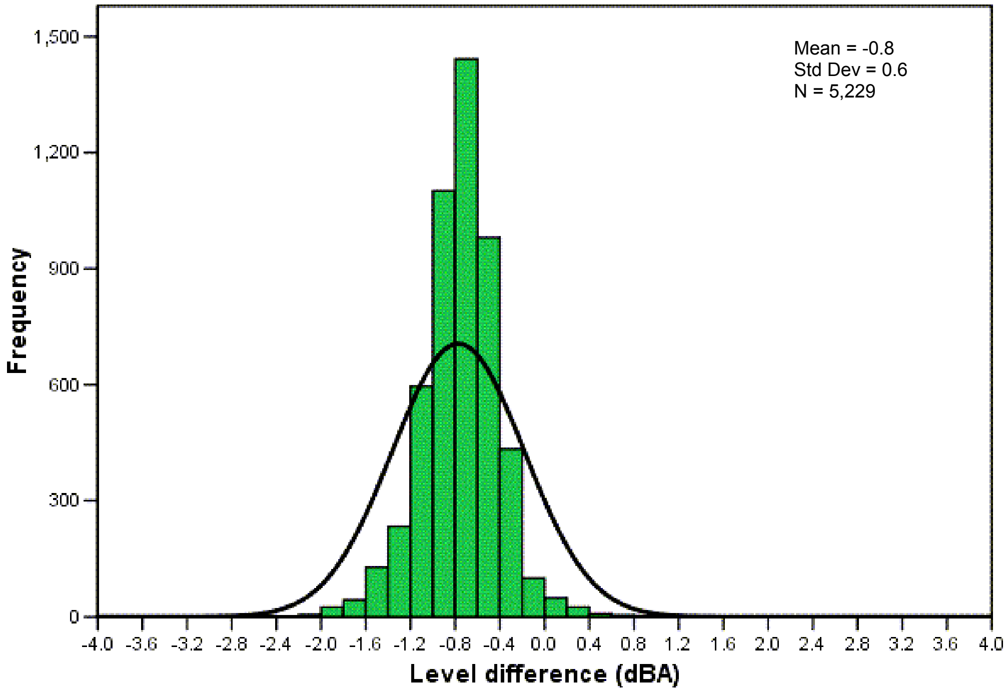
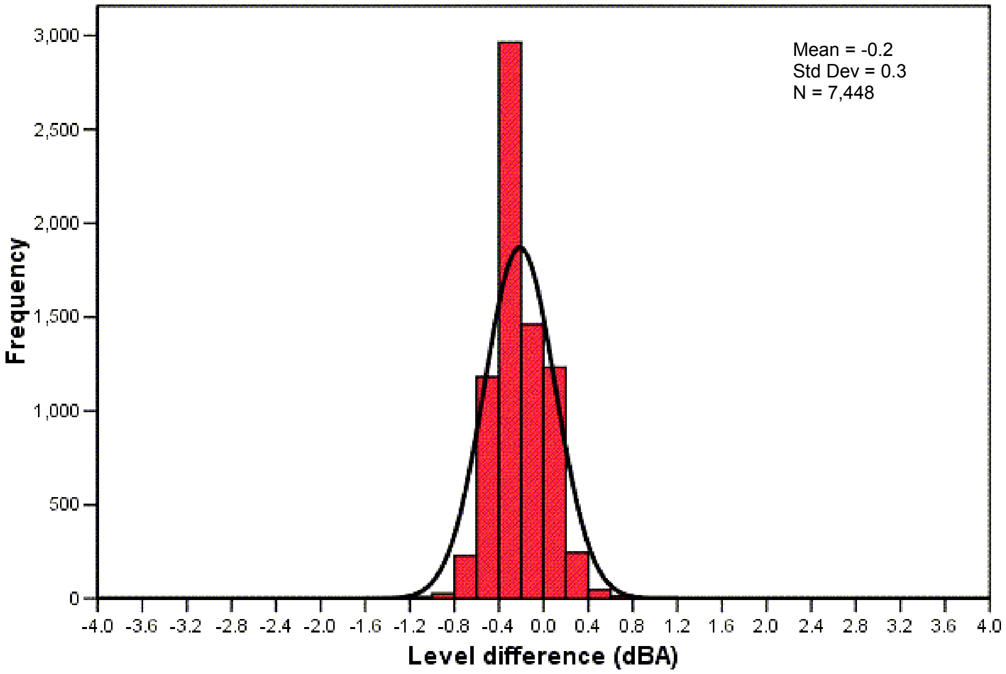


Figure A6

(i) Arrival SEL noise level differences: Site23 *minus* Site24



(ii) Departure SEL noise level differences: Site23 *minus* Site24