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IMAGINE
Improved Methods for the Assessment of the Generic Impact of Noise in the Environment

Default aircraft source description and methods to assess source data

Deliverable 10 of the IMAGINE project

Project Co-ordinator: DeltaRail bv

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EXECUTIVE SUMMARY

One task of WP4 in the IMAGINE project was to develop a new aircraft sound source description that fits the general concept of HARMONOISE and IMAGINE, where source emission and propagation are treated separately. This source description will be based on sound power spectra and directivity.

This document provides information on how to generate sound source data and how to store it in a database.

After the description of the concepts and elements involved in the modelling of sound power levels and directivity, some background information is provided on existing knowledge about source directivity. Then, in Chapter 4, the procedures to measure and process data for the source emission model are described. These procedures were applied in the test measurements of WP4 with a Cessna Citation II. The second best solution is to infer source emission data from existing NPD information. Those possibilities and limitations are shown in Chapter 5 and additional information and examples are listed in the Annexes A (longitudinal directivity), B (hints on spectra) and C (examples). Finally, Chapter 6 addresses the concept of how to store, exchange and use source data, proposing data tables and a data base structure.

A key element for accurate aircraft noise predictions is the availability of reliable sound emission data. Establishing a comprehensive database was beyond the scope of the present work, but it is obvious that in the long term, provisions have to be made to launch new measurements, collect existing data and establish the dialogue with industries and users.

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1 Introduction

Different types of aircraft noise models currently exist, which differ in their level of complexity in modelling aspects of sound emission and propagation.

The modelling principle of integrated (segmentation-based) models like INM [1] , which is also fully described in ECAC Doc.29 [2], combines source characteristics and propagation in the well known Noise-Power-Distance (NPD) data. These provide immission levels at specific distances perpendicularly beneath the flight path. Source longitudinal directivity effects are implicitly included in the SEL-NPD data by the sound integration over the whole flight event. For receivers at lateral locations, a lateral directivity (installation effect) is added as a generalised term [3]. For the calculation, longitudinal directivity is explicitly accounted for in INM (as well as in DOC.29) by two formulae: first, at the start-of-take off on the runway, the sound radiated in areas behind the aircraft is estimated with an angular dependent function, and second the "Noise Fraction algorithm" (used in the segmentation process) relies on an assumption that sound is emitted with a dipole characteristic.

Another modelling approach is simulation. Simulation models developed during the 90's have proven to have advantages in complex situations. In these models, the sound source and the propagation model may be treated separately. In addition, the sound source directivity is also present. Directivity is defined as a function of emission angles in a sphere (or at least in the lower hemisphere) of sound.

The idea behind the IMAGINE model is to treat the sound source and the propagation models separately. As described in the document "*Modelling principles and layout*" [4] , to increase the accuracy and versatility of aircraft sound calculations, a more complex description of aircraft sound source is needed than the ones used mostly today. The sound radiation characteristics of an aircraft vary both in frequency and level during a flight. Therefore the IMAGINE model will be based on 3D directivities for the sound source.

Sound power and spectral directivity of an aircraft depend basically on the power plant and the airframe noise. As regards the propulsion system, the noise generating mechanism involved in jet, turbofan or propeller systems each have a distinct frequency dependent directivity. For jet, the spectral characteristic of jet mixing noise is the source that dominates the noise at full engine power. For lower power conditions on this type of engine it is necessary to count on the tonal and broadband components of the compressor and the turbine. In the case of turbofan, fan noise dominates all conditions, although jet noise is still important at high powers and the combustion system may also be relevant [5] . In general we can say that in a flyover time history, fan and compressor noise dominates forward of the aircraft, whereas aft the jet noise dominates over the rest of the noise sources. All the noise sources have different spectral characteristics.

Similar analysis can be made with propeller driven aircraft. The noise produced by the propulsion systems fall into the tonal and broadband categories. Tones are produced by the cyclic motion of the propeller blade. The energy contained in the discrete frequency components may be much higher than the broadband noise caused by fluctuations and turbulences of air around the blades and the rest of the engine structure.

The type of propulsion system is one of the main factors. Jet noise (or turbofan) is one of the main causes of noise pollution in the communities around airports; however the non-propulsive noise or airframe noise plays also a significant role, especially during approach and landing.

With clean configuration, the airframe noise is mainly produced by the main wing structure and is mostly broadband in nature. The airframe noise increases during the approach phase of operation due to the turbulences induced by fuselage, tail plane, wings, flaps and landing gear. They combine together and exceed the level of the engines running at low power. The overall airframe noise can increase on the landing approach by about 10 dB [5]. In airframe noise, the landing gear noise is the most important; it is broadly spherical in directivity and has spectral characteristics slightly higher in frequency than those for clean airframe. In general, the airframe noise produced depends on the dimensions of the aircraft and the speed of the airflow over the structure.

Another factor to take into account in aircraft noise are the installation effects. Various reflective, refractive or shielding effects can arise as a result of the position of the intake and the exhaust system with respect to major airframe structures. In underwing mounted positions, the noise radiated upwards from the power plant can clearly be reflected down from the under surface of the wing. The spectral character and variation of the noise with speed depend also on the particular design of every aircraft.

All the factors described above contribute to the overall directional characteristics of aircraft sound emission and the corresponding flight parameters (in terms of engine power settings, aerodynamic configuration and speed) must be potentially present in the database structure proposed by IMAGINE.

The assessment of uncertainties of aircraft noise calculations is an ongoing research topic [6]. It reveals that the precise characterisation of source emission levels is one of the most important factors influencing the resulting aircraft noise contours. Producing accurate airport noise contours with the Hamonoise / Imagine Engineering model requires the availability of the above-mentioned noise source data for the most representative aircraft types operating at European airports, and for each, for a sufficient number of operational conditions.

This report describes properties of the source and methods to estimate emission levels. The next step will be to build up a comprehensive database and maintain it, which is costly and will require international collaboration.

2 IMAGINE aircraft sound source description

In this chapter the requirements and limiting circumstances for the IMAGINE source database are discussed.

2.1 The concept of IMAGINE

The approach of IMAGINE is to separate the source description from propagation:

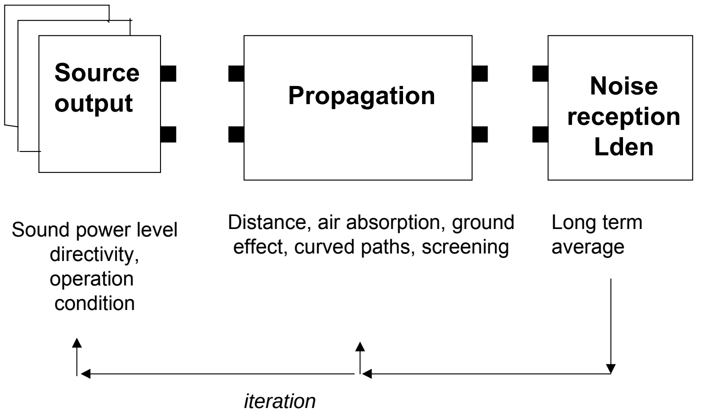


Figure 2-1: Separation of source, propagation and reception

The different aspects of source description are discussed in Chapter 2 of the Imagine document “Modelling principles and lay-out” [4].

To summarise:

- The aircraft is treated as a point source positioned consecutively at discrete points along the flight path
- The sound emission characteristics represent free field conditions
- The aircraft is in motion (“in-flight” conditions, not data from test stands)
- Levels are only specified in the outside of the immediate vicinity of the source (i.e. in the far field), that is there is no distinction between different sound source components of the aircraft (e.g. location of individual engines or different sources like fan inlet, fan exhaust, jet exhaust etc)
- Doppler effects are included in the source description as part of the apparent directivity

In general, source descriptions are deduced from fly-bys of the aircraft, either in the context of certification or from other well controlled measurements.

2.2 Definitions

Aircraft type: it describes the commercial name of the plane. Example: Boeing 737300

Engine type: The engine type used with a specific aircraft. Some aircraft models may be equipped with various engine types, differing in sound emission.

L_w: sound power level [dB] (overall level or level or per 1/3 octave band)

$L_{w,dir}(\theta, \varphi)$: Sound power level including level adjustment for the direction defined by θ and φ

L_{ASmax}: The maximum value during an aircraft flyover of the instantaneous, A- and "SLOW" weighted sound pressure level.

Longitudinal angle Theta θ: see Figure 2-2

Lateral angle Phi φ: see Figure 2-2

Elevation angle β: see Figure 2-2

Thrust: numerical value that represents the propulsive force produced by the engine. It is usually expressed as corrected net thrust per engine, the net thrust being the component of engine gross thrust that is available for propulsion (see also below)

Corrected net thrust per engine, **F_n/δ** : net thrust per engine divided by the ratio of the ambient air pressure at aircraft altitude to the International Standard Atmosphere (ISA) air pressure at mean sea level, expressed in Newton (N) or pounds (lb)

Aircraft Speed: numerical value indicating the speed of the aircraft along the flight path in m/s or knots (kt, international nautical miles per hour = 1,852 km/h)

Calibrated Airspeed (CAS): The indicated airspeed of an aircraft (as read from a standard airspeed indicator), corrected for position and instrument error. Calibrated airspeed is equal to true airspeed in standard atmosphere at sea level.

True Airspeed (TAS): The speed of an aircraft relative to the undisturbed air mass.

Ground speed: Speed of the aircraft relative to ground, e.g. as measured by the airport radar system. Equals TAS plus the corresponding component of the wind speed vector.

Flaps Identifier: represent the flaps configuration in terms of the number of degrees that the flaps are extended.

Landing gear: it represents the landing gear position (up or down)

Operation: Arrival (approach and landing) or departure

2.3 Co-ordinate systems

There are two co-ordinate systems:

- The emission co-ordinates fixed to the aircraft
- The immission co-ordinates fixed to ground.

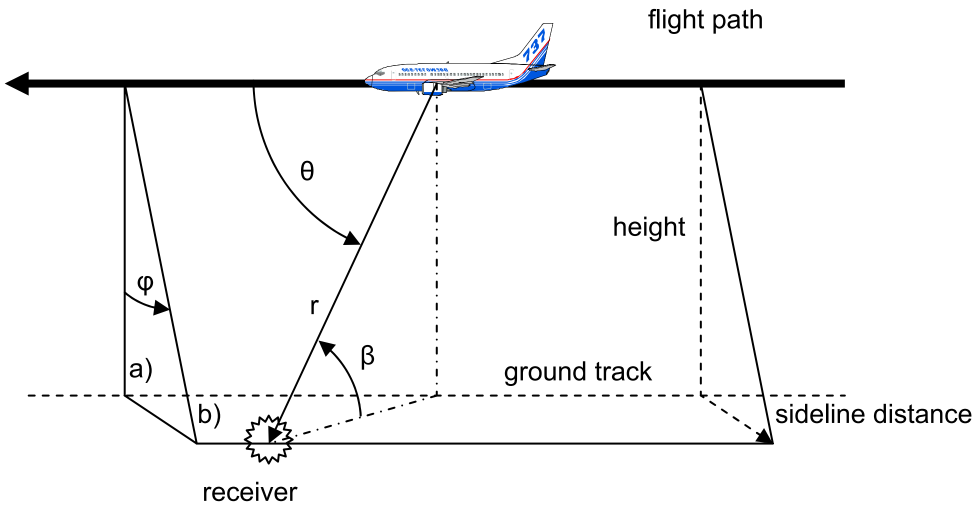


Figure 2-2 Aircraft sound emission co-ordinates theta (θ) and phi (φ), and the ground referenced quantities: distance to the receiver r and elevation angle beta (β) of sound incidence

2.3.1 Aircraft co-ordinates

The spherical angles theta (θ) and phi (φ) are defined in relation to the aircraft. The origin is at the centre of gravity of the aircraft.

Theta, the longitudinal angle, is defined from the axis of flight to the vector pointing towards the receiver. It varies from 0° (aircraft approaching) to 180° (aircraft leaving the observer).

The lateral angle phi is defined between the following two planes: plane a) is defined by the axis of flight and the vector pointing out of the bottom of the aircraft, perpendicular to the wing-plane. In the earth-bound co-ordinate system, this plane a) is vertical for level flights, but for curved flights it is inclined by the bank angle of the aircraft. The plane b) is defined by the axis of flight and the vector from the aircraft to the receiver. Phi is zero directly underneath the aircraft and it increases to ± 90° if the receiver is in the wing-plane. Looking in the direction of the velocity vector of the aircraft, phi is positive to the left side. As fixed wing jet airplanes are assumed to have symmetrical lateral sound emission, the sign of phi is irrelevant for jets. For curved flights, the bank angle of the aircraft has to be accounted for to determine the lateral angle phi which points towards the receiver.

Note that some documents e.g. SAE AIR 5662 [3] and DOC.29, 3rd edition [2] use for the origin of phi the wing plane and call phi "depression angle". This ranges from 0° (wing plane) to 90° (bottom) to 180° (wing plane). The difference between the two systems is simply a shift in the number by 90 degrees.

2.3.2 Ground co-ordinates

The parameters in ground co-ordinates are the distance r, the elevation angle β and the corresponding height of the aircraft.

2.4 Relation between sound power, sound level and directivity

In this paragraph, the relations between different source descriptors are discussed.

According to ISO 9613-2 (1996) *Attenuation of sound during propagation outdoors - Part 2: General method of calculation* [7], the general form for the sound pressure level at the receiver is:

$$L_p (f,\theta,\varphi,r) = L_w (f) + D_c(f, \theta, \varphi) - C - A(f,r) \quad \text{(Equation 2-1)}$$

For IMAGINE, this equation will be used for 1/3 octave band quantities.

with:

$L_p(f,\theta,\varphi,r)$	Sound pressure level at the receiver for frequency band f
L_w (f)	Sound power level of the point source for frequency band f
$D_c(f, \theta, \varphi)$	Directivity correction for frequency band f Note: D_c(f) describes the angle dependent variation in sound emission. It is NOT the correction factor for a source placed on reflecting ground or in a corner of a room.
C	This constant relates the sound power level L_w (re 1pW) from an omni directional point sound source to the sound pressure level L_p (re 20 μPa) at a reference distance d_0 of 1 m:

$$L_p (1m) = L_w – C \quad \text{(Equation 2-2)}$$

$$C = 10 \lg [(4 \pi d_0^2 p_0^2) / (\rho c S_0)] \approx 11 \text{ dB} \quad \text{(Equation 2-3)}$$

with

ρc	Impedance of the air (≈ 408 Ns/m^3, depends on temp and pressure)
d_0	reference distance (= 1 m)
p_0	reference sound pressure (= 20 μPA)
S_0	reference surface (= 1 m^2)

A(f,r)	The attenuation in the frequency band f from the point sound source (sound pressure level at 1 m) to the receiver at distance r. It includes the effects of geometrical divergence, atmospheric absorption, ground effect, shielding and miscellaneous other effects related to sound propagation.

For IMAGINE, the intermediate term $\mathbf{L_{w,dir}}$ called ***sound power including directivity*** will be used as the interface to the propagation module. It is derived from equation 2-1 and when applied for all 1/3 octave frequencies, it is the source sound power spectrum for a specified direction of emission and for defined operational conditions of the source:

$$\mathbf{L_{w,dir} = L_w + D_c} \quad \text{(Equation 2-4)}$$

2.5 The structure of the source module

The source module for IMAGINE has the following input parameters to generate the requested output of the sound power spectrum:

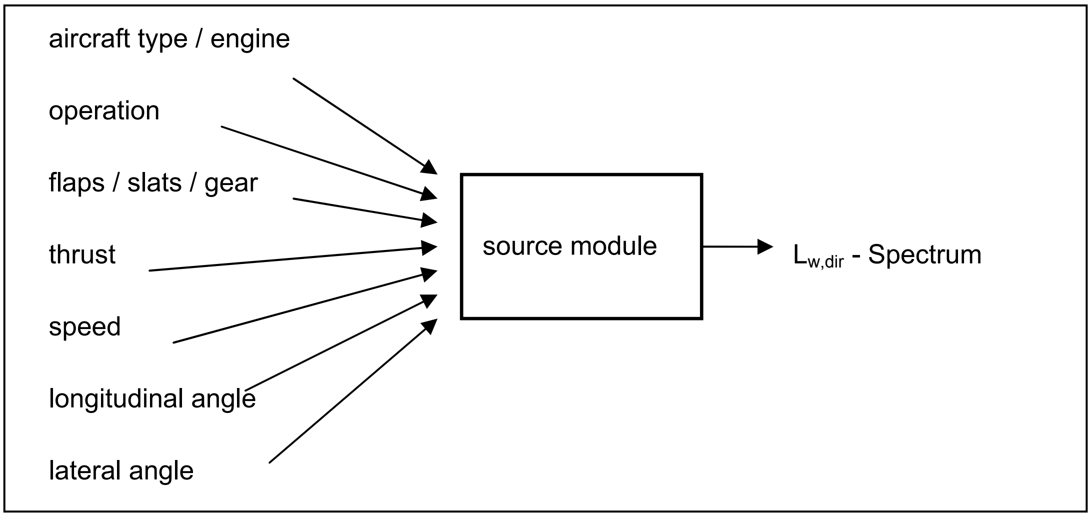


Figure 2-3 Possible input parameters for defining a specific source spectrum

The sound emission of the aircraft is described by the **sound power spectrum $L_{w,dir}$** which results from the combination of the following input parameters:

- aircraft type, including specification of the engine types
- operation (departure or arrival)
- especially for approach, the position of flap, slats and gear, which have an influence on airframe noise
- noise-related engine power parameter (thrust or equivalent)
- speed (optional parameter, which influences the airframe noise)
- longitudinal angle θ: angle between the longitudinal axis of the aircraft and the direction towards the receiver
- lateral angle φ: angle between the vertical plane (perpendicular to the wing plane) and the direction towards the receiver.

Notes:

- There are typical combinations of input parameters for the most common flight operations (example: full landing configuration with gear down is normally associated with a low - final - approach speed)
- There may not be available data to characterise all operational states of the aircraft.
- The form of the database will be look-up tables.
- The list of input parameters may not be complete.
- Ground operations like taxiing and operations at the terminal are not covered by WP4, but in principle they can also be calculated, provided the appropriate source data are available
- For immission calculations, only a few typical combinations of speed, thrust, flaps and gear are needed, e.g. for departure sound emission is dominated by the engine operation.
- Intermediate thrust levels may be interpolated as for NPD data.

Importance of the various parameters

Aircraft type / engine	The correct source description for the acoustically dominant aircraft types with their correct engine type is crucial. Acoustically dominant means that an aircraft type is either louder than average aircraft operating at a specific airport or that the number of movement reaches a high percentage of total movements on a specific landing or departure route. Usually there are about 20 acoustically important aircraft types with their associated engine type. The same aircraft type may be operated with various engine types, which may influence directly the source emission levels by up to 3 dB. Thus, correct engine type is crucial for those aircraft which contribute most to overall noise levels. Acoustically non dominant aircraft may be grouped together or substituted (For details see e.g. DOC. 29, Vol 1, Chapter 6.4) [2]
Operation	Distinction between approach and departure is essential
Flaps / slats / gear	For immission calculations, the typical configuration for approach and departure is sufficient: gear out for landing and gear in for departure. For research on low noise flight procedures those details may become important.
Thrust	For departure, engine noise is dominant and sound emission is directly related to the power settings (thrust) For landing, engine power may vary considerably over short periods to correct for speed and gliding angle, but in general thrust is at a low level, such that aerodynamic noise also becomes important (see speed)
Speed	Speed has a high impact on aerodynamic noise, which may become an important factor for landing operations with low engine power. Large variations of speed have some influence on engine noise. For immission calculations the typical speeds for landing and departure may suffice. Note: Here the aspect of source emission is addressed. Speed also has an influence on how long an aircraft produces high sound levels at the receiver, which will be accounted for in the calculation of the SEL of a fly-by.
Longitudinal angle	Longitudinal directivity is discussed in Chapter 3 and Appendix A
Lateral angle	There is few data on source emission in function of the lateral angle. Research at Empa seems to indicate for some of the aircraft with wing mounted engines an increase of 1 to 2 decibels around 30° [21]. SAE proposes somewhat lower effects (see Chapter 3.4)

3 Components to build up source data

In this chapter, existing knowledge, requirements and limitations on directivity and spectral information are discussed.

3.1 Introduction to directivity

So far, there is little information available about the complete, spectral directivity of the various aircraft types. (Except for the aircraft Cessna Citation II (C550) measured by IMAGINE WP4).

3.1.1 Qualitative description of directivity

In general sound emission may vary in any direction. To simplify the description, a distinction can be made between:

- **longitudinal** directivity, and
- **lateral** directivity

For departure, the **longitudinal** directivity of jet aircraft depends mainly on the directional sources of the engines, like fan and jet noise, each with its specific spectrum. For old engines (with a low bypass ratio) and especially for military jets, there is a distinct level increase due to the jet noise at angles of θ in the range of 120 to 130°. For modern engines, the longitudinal directivity is much less dominant. In any case, the sound emission decreases at the back of the aircraft (θ > 150 °). The longitudinal directivity of propeller aircraft show a moderate increase around theta = 85°. Examples are given in Annex A.

For departure, the **lateral** directivity depends on the geometric position of the engine. Usually, the distinction is made between fuselage mounted and wing mounted engines. Effects of shielding by the fuselage, reflections on the wings and refraction in the turbulent air behind the wing may produce a level increase at φ = 20 .. 30° of 1 to 2 decibels, while such an increase is not seen for fuselage mounted engines.

For landing approach with essential contributions from airframe noise no information on lateral directivity is known to the authors. It can be noted that the ECAC Document 29 methodology and INM apply the same lateral directivity to both approach and departure procedures.

3.1.2 Available information on directivity

Well controlled measurements of aircraft flyovers with specific placement of many lateral microphones would provide the required information. This is described in Chapter 4. But such measurements are expensive.

Existing information is as follows:

- If manufacturers do have information, it is generally not available for public use.
- INM uses a mathematical *longitudinal* directivity of $\sin^2$ in the algorithm of noise fraction (90-degree dipole).

- Empa has information mainly on *longitudinal* directivity from own measurements, which is used in their aircraft noise simulation program Flula [8]. Some Empa knowledge is shown in section 3.3.
- Empa has re-examined existing measurements and extracted information on *lateral* directivity for a few aircraft types [9].
- SAE – A21 has initiated several measurements to quantify the *lateral* directivity. The results are condensed in three general lateral directivity functions for
    - fuselage mounted jets,
    - wing mounted jets and
    - propeller engines.

  This is published in DOC.29, 3rd edition (2005) [2] and in SAE AIR 5662 [3] (see Section 3.4)
- NPD data provide emission levels for flyover conditions (lateral angle φ = 0°)

In the absence of measured data, it is recommended to use as default values the longitudinal directivities proposed in Chapter 3.3. and the SAE lateral directivity (see Chapter 3.4).

3.1.3 Symmetries for lateral directivity

While helicopters need a full directivity description due to their asymmetric sound emission, the situation may be simplified for fixed wing jet aircraft, assuming:

- **lateral symmetry**: seen in the axis of flight, the sound emission to the right is the same than to the left: φ = ± φ
- **up/down symmetry**: usually, sound emission is only relevant into the lower hemisphere. For computational reasons, it might be sometimes necessary to extend sound emissions to the upper hemisphere. Basically unknown, one might assume for the purpose of not violating fitting algorithms, that the sound emission is mirrored at the wing plane:

$$\varphi > 90° \qquad \varphi = 180° - \varphi$$
$$\varphi < -90° \qquad \varphi = 180° + \varphi$$

Thus, the database needs only information for the lateral angles 0 ≤ φ ≤ 90°

Note 1:
Propeller driven aircraft may show asymmetric lateral sound emission, depending on the direction of rotation of the propellers.

Note 2:
Some models use a database with **rotational** symmetry in respect to the axis of flight, i.e. there is no explicit dependence on φ. Provided the levels were estimated using input information from various lateral angles, this represents an average situation, taking into account globally the lateral effects.

3.2 Properties of longitudinal directivity

3.2.1 Angular properties

Directivity information extracted from measurements may look like the following figure:

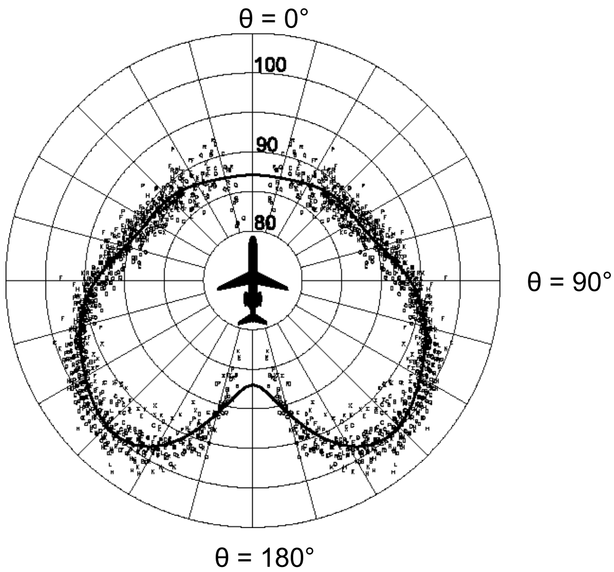


Figure 3-1: Example of longitudinal directivity. A-weighted levels from 14 measurements (taken at various lateral angles) for take-off of DC9-30. The plot shows the measured sound levels reduced to r = 305 m as a function of the emission angle θ. The fitted curve is used in FLULA [8].

3.2.2 Angular reliability of the levels:

At flyover (θ around 90°) the measured levels are high and distances are short. Thus the directivity indication around θ = 90° ± 30° is expected to be reliable. However, for θ close to 0° (aircraft far away, approaching) and for θ close to 180° (aircraft far away, leaving) distances are long and propagation is close to ground (at low elevation angles). Thus, directivity indications for angles θ < 20° and θ > 160° become less reliable.

3.2.3 Angular resolution of measurements:

If the aircraft is far away (approaching or leaving), it is seen for long times at nearly the same angles. Thus there will be many measurements available to estimate directivity for θ < 50° and θ > 130°. This is different around the point of closest approach. Around this point, angles change rather quickly. For example, for an aircraft flying at 100 m/s at an altitude of 300 m, if the aircraft is directly above the observer at t_0 (θ = 90°), the angle increases by 18° in only one second, the value at t_0 + 1 sec being θ = (90° + arctg (100/300)) = 108°. As a consequence, directivity information extracted from fly-over measurements have less accurate angular resolution around θ = 90°.

Note: In figure 3-1 care was taken to select per angular sector the same amount of measurement points to get equal weights for the fitting algorithm.

3.2.4 Angular sensitivity:

Which angular range of the longitudinal directivity is most important for accurate calculation of the SEL of a level flight? The following simplified example will be used to demonstrate the tendencies.
The flight event may be calculated using for the aircraft a point source, placed consecutively at discrete locations along the flight path. This is equivalent to an incoherent line source. If propagation is reduced to include only spherical attenuation, and if the source is assumed to be omni directional (no directivity), it can be shown, that every segment of the flight path which is seen under the same emission angle, contributes the same amount of intensity (For far distances the levels are lower, but the time duration increases). Hence, all angles of the longitudinal directivity would be equally important for an omni directional source and no air absorption. With air absorption, the contributions of emission angles θ close to 0° and to 180° will decrease.

3.2.5 Weighting of the directivity by spherical attenuation:

Directivity is described as a source property. What is the influence of directivity at a receiver location? For a straight flight, let us assume an omni directional source and look only at spherical attenuation.

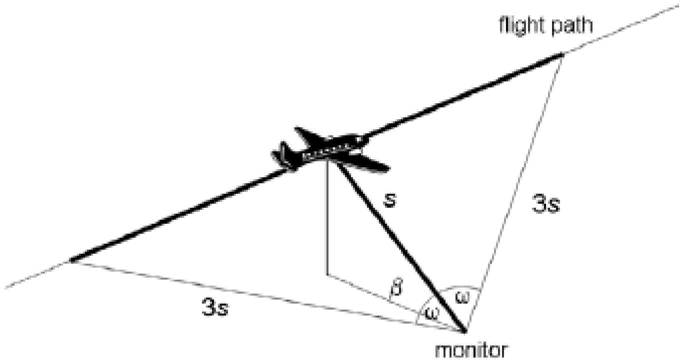


Figure 3-2: Maximum length of flight path for levels above L_{ASmax} -10 dB

If the shortest distance from the flight path to the receiver is s, then spherical attenuation from points located at three times s will be 10 dB higher than for the shortest distance. The corresponding angle ω is arccos (s/3s) = 70°. The general expression for this additional spherical attenuation due to longer sound paths is 20 lg (sin θ). It is shown in Figure 3-3.

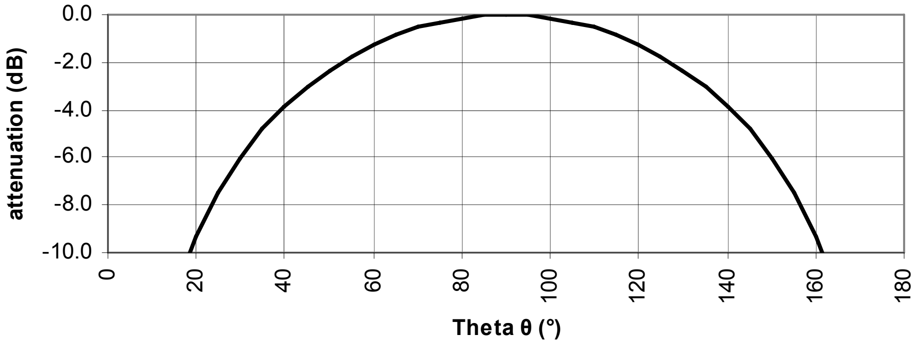


Figure 3-3 Spherical attenuation relative to shortest distance for a level flight [= 20 lg (sinθ)]

From Figure 3-3 the following conclusions may be drawn:

- Source emission is attenuated by less than 3 dB in the range of **θ = 90° ± 45°**.
- Source emission is attenuated by 10 dB at θ = 90° ± 70°. Therefore, source information is in general only of interest in the range of theta from 20° to 160°. As directivity effects may increase the level at low thetas, the range of interest is extended down to 10°.

If we consider instead of theta the opening angle at the receiver for that part of the flight path where the level is above "L_{ASmax}-10 dB", this angle is for spherical attenuation alone 140° (± 70°). In real situations including directivity and air absorption the angle is between 90° to 100° (propeller engines) and for jets between 100° and 110°. It differs between landing and departure.

So far, the influence on the SEL evaluated in the range "L_{ASmax}-10 dB" was discussed. Calculation with Flula (including air absorption) show, that the SEL calculated for a complete flyover is typically 0.5 dB higher than the SEL calculated only for the "10 dB down" fraction.

3.3 Classes of longitudinal directivity for departures

Longitudinal directivity is influenced by the type of fan, engine, bypass-ratio and jet characteristics. Empa has information on directivity based on "in-flight" measurements in the vicinity of the runways. Grouping similar shapes to typical classes, the 6 shapes described in Annex A were evaluated:

d1 to d4:	generalised longitudinal directivity for various generations of jet engines
d prop:	generalised longitudinal directivity for propeller driven aircraft
d m:	generalised longitudinal directivity for military aircraft

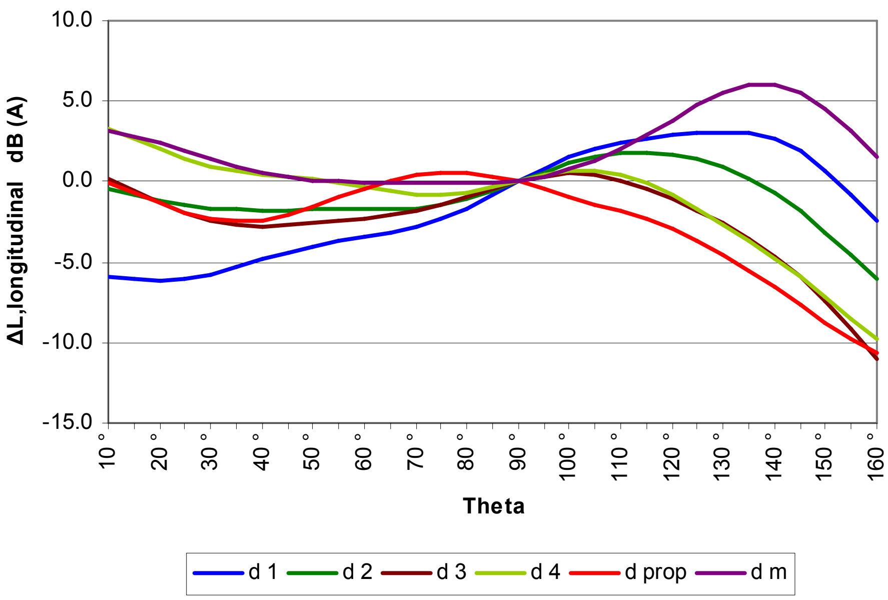


Figure 3-4: Six classes of longitudinal directivity for departures. Details see Annex A

For landings, similar classes could be evaluated.

3.4 Lateral directivity according to SAE

The SAE AIR 5662 [3] defines a generic lateral directivity, which is called "engine installation effect". (The same functions are also published in Doc.29, 3rd edition, Vol.2 [2]). These recommendations are based on recent measurements [10], [11], [12].

There is a distinction between:

- fuselage mounted engines (lateral levels decrease due to fuselage shielding)
- wing mounted engines (lateral levels may increase due to reflections on the wing)
- propeller aircraft, which have constant levels

Using the definition of the lateral angle phi according to Section 2.3 (wing plane = ± 90°) the formulas are:

$$\Delta L_{lateral,fuselage} = 10\lg(0.1225\sin^2(\varphi)+\cos^2(\varphi))^{0.329} \quad \text{(equation 3-1)}$$

$$\Delta L_{lateral,wing} = 10\lg\left(\frac{0.0039\sin^2(\varphi)+\cos^2(\varphi))^{0.329}}{0.8786\sin^2(2\varphi)+\cos^2(2\varphi)}\right) \quad \text{(equation 3-2)}$$

$$\Delta L_{lateral,propeller} = 0\ \text{dB} \quad \text{(equation 3-3)}$$

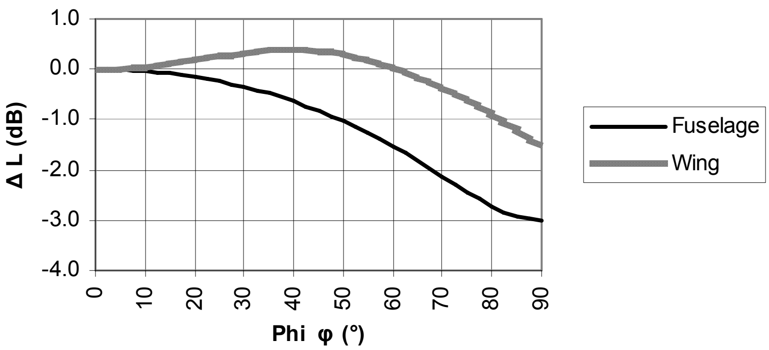


Figure 3-5 Installation effect for wing- and fuselage mounted engines

Phi φ (°)	Fuselage (dB)	Wing (dB)
0.0	0.0	0.0
10.0	0.0	0.1
20.0	-0.2	0.2
30.0	-0.4	0.3
40.0	-0.6	0.4
50.0	-1.0	0.3
60.0	-1.5	0.0
70.0	-2.1	-0.3
80.0	-2.7	-0.8
90.0	-3.0	-1.5

Table 3-1: lateral directivity (installation effect) according to SAE AIR 5662

3.5 Spectra

Certainly, the shape of the spectrum changes from fan inlet noise when measured in front of the aircraft approaching to jet noise when measured from locations behind the aircraft flying away, but often only one spectrum is available at $L_{ASmax.}$

3.5.1 Available information on spectra

The comments made in 3.1.2 for directivity concerning measurements and manufacturer data also apply for spectra.
INM provides spectral classes, which are typical spectral shapes to be used for several aircraft types. They are documented in detail in the report "Spectral classes for FAA's INM" [18] or in the ANP database [17].
Most of the original data for spectral classes with individual spectra were published in 1986 [13].
In the presentation at Internoise 2003, Volpe and FAA presented the approach to spectral classes and recommend accounting for spectral one-third octave band data in updated programs [14].

As an overview, Annex B shows examples of spectra measured by Empa.
The NPD curves may be analysed using the procedures of SAE 1845 to estimate a source spectrum. This will be described in detail in Chapter 5.

4 Source data from measurements

In this chapter the data reduction from measurements of fly-by situations to source data is described. The procedures described in this chapter were applied in the test measurements of IMAGINE, WP4.

4.1 Measurement requirements

For a test site and the measurement layout the following requirements apply:

- Flat terrain with no obstruction
- Installation of a number of microphones perpendicular to the axis of flight, one microphone at the centre, the others at suitable distances to cover various lateral angles.
  Note: Assuming lateral symmetry of sound emission for fixed wing jet aircraft (φ = ± φ), the microphone array may extend only to one side, but it is recommended to have at least one microphone on the other side.
- Microphones mounted on poles at least 5 m above soft ground, preferably 10 m.
  Note: Figure 5-2 illustrates the interference dip at 200 Hz for a microphone at 1.2 m above soft ground. For a microphone at 5 m, this effect is shifted to lower frequencies by 2 octaves or for 10 m by 3 octaves. In fact, microphones may be mounted at any height over any kind of surface if the propagation model used for data reduction is capable to handle those effects.

- Aircraft test flight path assumed to be a straight level flight at constant speed (in the 10dB-down measurement area)
- Availability of flight parameters: engine power setting, flap, slat and gear configuration
- Recording of exact position (and speed) of aircraft along the flight path[1] (on board GPS, if aircraft is accessible or if this data may be provided from Flight Deck Recordings (FDR); otherwise tracking radar or optical tracking)
- Precise and synchronized time stamps on all acoustic and flight path data
- Availability of temperature, wind and relative humidity information during measurements, if possible as a function of height.

There are tradeoffs between distance, angular increments, settling time of 1/3 octave band filters and the influence of background noise on measured aircraft sounds. The first step in data reduction is to generate 1/3 octave band spectra, usually in the form of linear averages over a time interval. A time increment of 0.5 seconds may be too long for sufficient angular resolution. For example, if the aircraft travels at 80 m/s and the minimum distance to the microphone is 100 m, the angle changes by 22° within 0.5 s for the longitudinal angle theta around 90°. For a minimum distance of 300 m and 0.5 s intervals, the angular increment around theta = 90° is about 8°[2]. When reducing the averaging time of the spectra to improve angular resolution, attention has to be given to the transient response of 1/3 octave filters for low frequencies. A compromise may be time intervals of 0.1 second. Increasing minimum distance to the flight path alleviates these timing problems, but longer distances mean lower sound levels (even accentuated for high

[1] Aircraft position may be obtained from a single measurement such as the minimum aircraft-to-microphone distance. This measured distance and corresponding time are used in conjunction with assumptions of straight flight path and constant speed to determine aircraft position at any time during the measurement period.

[2] These estimations do not include the sound propagation time effects.

frequencies) and increased influences from atmospheric effects (wind, turbulences). It is recommended to pursue an angular resolution better than 5º

4.2 Data reduction

4.2.1 Generation of data sets: spectrum and geometry

Let us consider a specific location on the flight path. For this point, the geometry has to be linked with the corresponding 1/3 octave spectrum. The relevant geometric values are: distance, emission angles theta and phi and at the receiver the immission angle beta (see Figure 2-2). The link with the spectrum is based on the time stamps. It is easier to start from a specific point (and time) on the flight path, add the time for sound propagation and then interpolate between the spectrum before and the one after sound arrival time. The other way around, i.e. starting with a spectrum at a specific time and calculating the corresponding source position is fully described in Appendix B of SAE AIR 1845: for each acoustic time stamp, the associated sound propagation time and sound-emission angle are calculated, using the average aircraft speed during the period of interest.

4.2.2 Reducing data to L_p (1m) by removing sound propagation

For each data set (spectrum and geometry) a calculation of propagation is made for each 1/3 octave band. Ideally, this calculation is as precise as ever possible, taking into account ground properties, microphone height and air absorption for temperature and humidity at the time of measurement. For aircraft certification, SAE ARP 866A [15] is used, but for environmental noise calculations the newer ISO standard 9613-1 [7] is recommended. Since the results of the latter are valid for pure tones, a correction for third octave bands should be applied (e.g. the correction specified in Harmonoise report D16, section 4.2.4).

This “propagation-spectrum” is subtracted from the measured spectrum to yield the free-field emission spectrum at a reference distance, for a specific combination of theta and phi.

Doppler Effect generates an increase / decrease as well in frequency as in sound level. In general, propagation models do not take into account this effect. Therefore, Doppler Effect is included implicitly in the source emission model. No error results if the source model is used to make calculations at similar speeds to those of the measurements. In consequence, for slow speeds on the runway the Doppler Effect is not exactly accounted for. To include the Doppler Effect physically correct depends on the degree of sophistication of the propagation models used for data reduction and later for noise calculations. So far, the extra effort was considered to be too high compared with the benefits.

Note:
Wyle has published similar procedures to generate from measurements the "sound hemispheres" i.e. the spectral source data to be used in NASA's "rotorcraft noise model (RNM)". They call it "Acoustic Repropagation Technique, ART" [16].

4.2.3 Data selection and inspection

Measured data will have to be averaged as described in the next section. Using aircraft positions with equal time increments, there will be a concentration of data at theta close to 0° and at theta close to 180°, but only few data around theta = 90°. Thus, aircraft positions may be selected to provide the equal amount of spectra per angular increment of theta, or data at far distances may be averaged to some degree.

An important issue is the quality of the measurements. For instance, for long distances the air absorption may be so high for high frequencies that the aircraft sound level would be well below the environmental noise level or the electronic noise. Removing propagation from the noise baseline of the measurement produces unrealistic high emission data. Provisions have to be made to exclude such data from processing. Further, all parts of the recordings affected by environmental noise have to be excluded from processing or corrected in a proper manner [16]. .

4.3 Averages over several flight events and interpolation

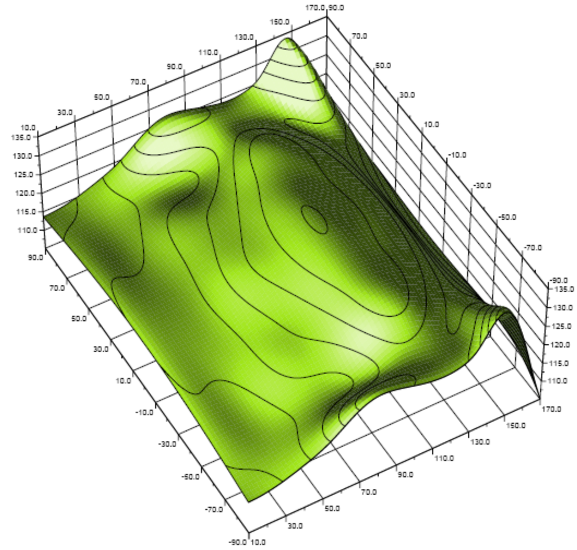
To end up with the sound emission data, two problems have to be solved for each 1/3 octave frequency:

- Emission data will be used to predict average aircraft noise e.g. for one year. Therefore, emission data shall reflect the average over several flights (with the same aircraft configuration, power and speed) and ideally the average over several aircraft of the same type. Hence, some kind of averaging of measured data is needed.
- Measured data exist only for discrete longitudinal and lateral angles. It does not cover all combinations. To complete the emission model, some kind of interpolation between angles is needed.

One way is to average measured data within angular sectors and then to interpolate missing values, e.g. by means of a Delaunay triangulation.

Another way is to make an optimised data fit using spherical harmonics and a least square criterion. The order of the spherical harmonics may vary according to available data and frequency. Experience at Empa showed good results with maximum order of 7. Care has to be taken that the fit does not produce uncontrolled data in undefined regions, e.g. in the upper hemisphere where no data exists. Therefore, data has to be mirrored prior to the fit into the upper hemisphere and - if data exists only for one side of the aircraft - it has to be mirrored also to the other side. (see section 3.1.3)

Once the coefficients of the spherical harmonics are estimated, the model can be used to calculate the sound emission level for any combination of theta and phi and results may be stored in a look-up table as proposed in Figure 6-1.



Example:
The figure to the right shows the three dimensional directivity of the IMAGINE test measurements of Cessna Citation II (Lp (1m)) fitted with spherical harmonics in every 1/3 octave band and converted for visualisation purpose to the A-weighted level.
Axis to the right: longitudinal angle theta from 10° to 170°,
Axis to the left: lateral angle phi from -90 ° to 0° to + 90°
Spacing of the niveau-lines: 2.5 dB.
The figure shows lower levels in front (Theta=10°) and a maximum for flyover (phi = 0°) around Theta =110°. This corresponds to the longitudinal directivity class d 1 in Annex A.

Comparison between the results of both methods as applied to the Imagine flight test results revealed that no significant difference was found in the predicted overall noise levels (SEL) [23]

4.4 Validation

After having estimated the average source spectra, the measured results shall be reproduced by a calculation with the aircraft noise model, using the flight path, speed, microphone location etc. of the measurement situations. Because the source spectra result from averaging several measurements, there might be deviations between measured and calculated levels. If deviations are systematic, the source spectra may be fine tuned by that level difference and the validation calculations repeated.

4.5 Uncertainty of source data

The averaging described in Chapter 4.3 provides an estimate of the standard deviation for the source data calculated from several flights. Depending on fluctuation in the measurement conditions (long distances, turbulence, low angles of incidence) but also depending on the variability of the source (individual noise characteristics of engine samples, slight variations in thrust settings) the number of measured flights may vary. For well controlled measurements, some 5 flights may be sufficient, while for measurements at an airport with less optimal controlled conditions, at least 10 and preferably 20 to 30 flights are recommended. Special attention has to be given to the precise measurement of the distance between aircraft and measurement location so as not to introduce a substantial uncertainty due to distance variations. Exact aircraft identification for averaging only one aircraft type/engine combination is required. Under the conditions mentioned, an expanded uncertainty (two times the standard deviation for 95% confidence interval) of about three decibels may be achieved. The issue of uncertainty is treated in the thesis of G. Thomann [6].

5 Source data from reverse engineering using NPD data

In this chapter methods are presented to estimate source data based on NPD data and using additional knowledge.

5.1 What are NPD tables?

INM [1] (Integrated Noise Model) uses Noise Power Distance (NPD) data, available in a database for a large series of aircraft models and variants. These data can be directly retrieved from the Aircraft Noise and Performance (ANP) database [17]. NPDs are usually based on certification measurements and produced by the manufacturers, following documented data specifications. It is the worldwide best known comprehensive database.

NPDs provide, for different power settings, noise event levels at ten specific propagation distances, ranging from 200ft to 25'000 ft. The noise levels are given for various single event noise metrics, including L_{Amax} and SEL.

By definition, NPDs provide overall noise levels perceived underneath a notionally infinite straight flight path, flown at constant speed. The different other flight parameters characterizing the noise source state (power settings and aircraft configuration in particular), are also assumed constant along this infinite flight path. Each of the ten distance values at which the noise levels are provided represent the shortest distance between the ground receiver and the flight path.

NPDs are normalized to standard reference conditions (standard atmosphere, microphone at 1.2 m above soft ground). For exposure-based metrics like SEL, NPDs include the duration effect associated with a reference speed of 160kt (83.3 m/s).

The noise-related parameter in the NPD relations is the engine power setting (usually the corrected net thrust per engine), as the noise perceived on the ground is to a large extent - especially for departure operations - 'driven' by this parameter. It serves as a simple surrogate for the state of the aircraft and reflects the changes in the noise source as the aircraft/engine state changes. However, NPD data are distinguished by operating mode (approach or departure) as, due to airframe effects, noise depends on the flight configuration as well as power setting during approach operations. Approach NPDs are therefore provided for lower (approach-specific) power settings, and for a specific – single – approach configuration, which is close to the final landing configuration (full flaps, gear down). The power settings span normal operating values, both for approach and departures, in order to avoid the need for large modelling extrapolations.

Additionally, each of the listed aircraft/engine combinations is associated with a spectral class for landing and for departure. The spectrum indicates an average value at LAmax for all aircraft included in one spectral class. It includes the SAE 1845 air absorption for 305 m (1000 ft) and is normalised to 70 dB at 1 kHz. Details are found in [18] and the spectra are available in the ANP database.

For the purpose of IMAGINE, the A-weighted SEL values are of interest. As these indicate only the resulting – integrated - A-level of the fly-over operation, all details on spectrum and on longitudinal information are lost. Further, as the levels are provided for locations directly underneath the aircraft, there is no information on lateral directivity.

The propagation model used to generate NPDs only takes into account spherical spreading ($20lg(d/d_0)$) and air absorption. For older NPDs the values listed in SAE 1845 are used, for newer NPDs the air absorption for 25°C / 70% relative humidity according to SAE 866A [15] is used, which is identical to the values used for certification according to ICAO Annex 16, Table A1-7 [19]. All values are indicated in Table 5-1.

5.2 The concept of reverse engineering

The goal is to estimate the spherical sound power spectrum $L_{w,dir}$ according to Chapter 2. The steps are as follows:

a) SAE 1845 [20] defines how to generate NPDs. Knowing the propagation conditions used to generate the NPDs, it is possible - at least partially - to estimate from the SEL-NPD the A-weighted source spectrum (Lp at 1 m) which produced the NPD levels at the 10 distances. In the most interesting frequency range from 63 Hz to 5000 Hz there are 20 1/3-octave values. All of them cannot be estimated directly. However, knowing the general shape from the spectrum of the corresponding spectral class, and using the fact, that for long distances the air absorption eliminates high frequencies, one can first estimate the low frequency components with the longest distances and then estimate higher frequencies using the closer distances.

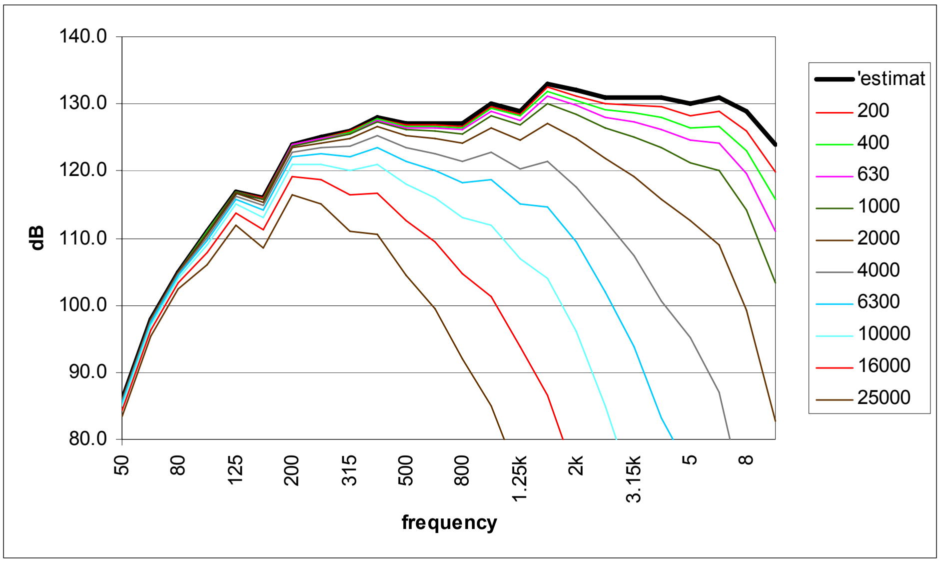


Figure 5-1 Example of A - weighted source spectrum ("estimat" = $L_{pA}(1m)$) with added air absorption for various distances (in feet)

b) Using a simple Excel program for aircraft noise simulation, the level-time history of a flyover is calculated. (To limit the number of calculations, the program may use variable length segments that are seen from the receiver under constant angle increments of e.g. 2.5°, starting from a longitudinal angle of 10° up to 160°). For the source the estimated spectrum of step a) is used and a longitudinal directivity is added. For the longitudinal directivity one of the appropriate classes listed in Annex A may be used. For propagation the NPD-conditions are used (see 5.1 and Table 5-1).

c) In an iterative loop the source spectrum is optimised to produce the best fit for the SEL values for all 10 distances of the NPD.
d) After having found the optimal spectrum, it is converted to a linear spectrum by removing the A-weighting.
e) To convert to free field conditions, the ground interference is subtracted from the source spectrum.
f) The spectrum of L_p(1m) is converted to sound power $L_{w,dir}$, adding 11 dB.
g) The number N of engines is accounted for by adding 10* lg (N) to the result.

The resulting source spectrum reflects average sound emission close to L_{ASmax}. Neither the variations from fan-noise (approach) to jet-noise (leave) nor the Doppler shift are accounted for. By lack of information it is assumed that the spectrum at L_{ASmax} applies for all longitudinal directions. This is definitively wrong, but as the most important contribution to the resulting L_{AE}-level is in general produced by the levels around L_{ASmax} this simplification is tolerable. Additionally, the estimated source spectrum can be seen as a scaled (or calibrated) spectrum which, combined with a longitudinal directivity class (also averaged), enables reproduction of the SEL values for the ten NPD distances under the same propagation conditions. In particular, this should ensure that the Harmonoise/Imagine models can produce noise contours equivalent to INM-like models under the same standard conditions.

As a best available approximation, the estimated source spectrum is used for all angles of theta, but the level of longitudinal directivity is added for the appropriate direction.

For the lateral variation the concept of SAE AIR 5662 [3] may be used as a default (see Section 3.4). For a few aircraft types, Empa has published some indications on lateral behaviour in [21].

5.3 Constants used in reversed engineering

The adapted model of Harmonoise was used to estimate the effects of ground interference of a microphone at 1.2 m.

The calculation of ground effects is based on the Delanay & Bazley impedance model. It was calculated with the Harmonoise demo software incorporating the PointToPoint.DLL version 2.015.

Parameters were:
Source height: 300m, Receiver height: 1.2m, Ground impedance: 200 kRayls, Homogeneous atmosphere (no gradients, no turbulence). To account for various angles of incidence (close to vertical), the ground effects calculated for 70°, 80° and 90° (horizontal distances of 111, 54 and 1 m) were averaged arithmetically, which alters the curve only slightly compared to 90° incidence. The altitude of the source has very little influence: 30, 100, 300 and 1000 m show the same frequency curve and amplitudes within a fraction of a decibel. The calculation is for a point source. Results differ only slightly for a line source.

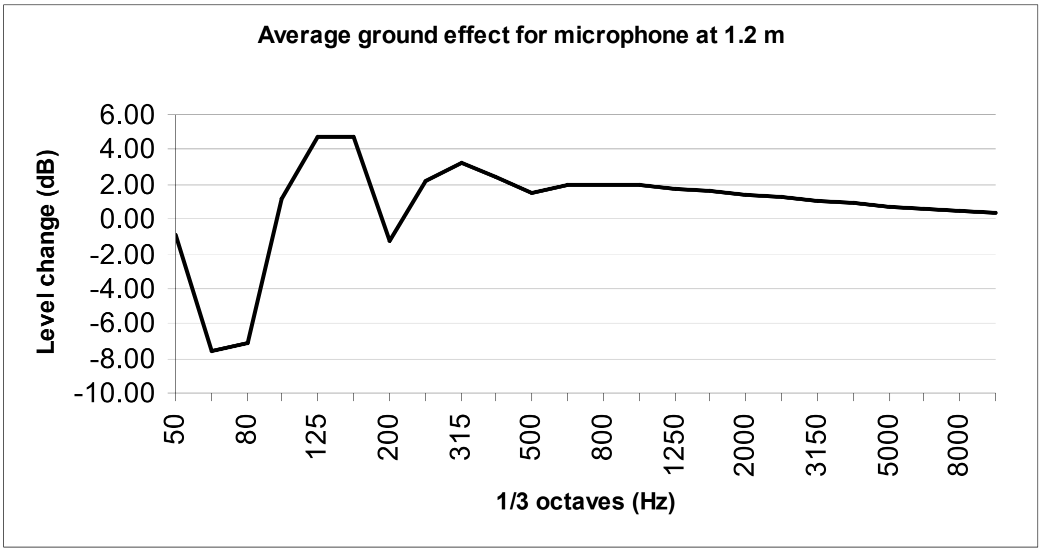


Figure 5-2 Ground effect of Table 5-1 (Parameters are described in the text)

A general overview of the influence of microphone height was published in [22].

Table 5-1 lists the values graphically shown in Figure 5-2, as well as air absorption and the A-weighting.

Frequency Hz	Ground effect dB	A-weighting dB	Air absorption SAE 866A 25°C/70%rH dB/1000m	Air absorption SAE 1845 Table B1 dB/1000m
50	-0.96	-30.2	0.33	0.33
63	-7.64	-26.2	0.33	0.33
80	-7.15	-22.5	0.33	0.33
100	1.13	-19.1	0.66	0.66
125	4.73	-16.1	0.66	0.66
160	4.70	-13.4	0.98	0.98
200	-1.22	-10.9	0.98	1.31
250	2.17	-8.6	1.31	1.31
315	3.18	-6.6	1.97	1.97
400	2.45	-4.8	2.30	2.29
500	1.51	-3.2	2.95	2.95
630	2.02	-1.9	3.61	3.61
800	1.99	-0.8	4.59	4.59
1000	1.92	0	5.91	5.90
1250	1.77	0.6	7.22	7.54
1600	1.60	1.0	9.51	9.83
2000	1.44	1.2	11.81	13.11
2500	1.27	1.3	15.09	17.05
3150	1.09	1.2	19.36	22.95
4000	0.91	1.0	24.93	31.15
5000	0.74	0.5	28.54	36.07
6300	0.58	-0.1	36.09	52.45
8000	0.44	-1.1	48.88	72.13
10000	0.33	-2.5	67.59	98.36

Table 5-1 Ground effect, A-weighting and air absorption used in reverse engineering

5.4 Thrust and speed interpolations

If the calculation needs a source spectrum for a specific value of corrected net thrust, the interpolation between source spectra levels for listed thrust levels is made linearly, analogous to calculations with NPDs. (See e.g. DOC. 29, Vol. 2 [2]). The same kind of linear interpolation is performed for a specific speed value, using the spectra associated with the two bounding tabulated speed values.

5.5 Worked example

Annex C shows some worked examples

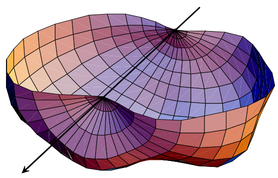
6 Sound source database

6.1 Data tables

In Section 2.4 the relation between sound power, directivity and sound levels at reference distance were discussed. The source description is based on sound power, including directional information: $L_{w,dir}$. The various factors influencing sound emission were listed in Section 2.4. Each hemisphere represents for an aircraft/engine combination a unique operating condition that depends on the factors mentioned. There is one table for each 1/3 octave frequency. This is a multi-dimensional database where a large matrix of sound hemispheres is therefore required to model an aircraft's sound emission.

The universal way to describe emission is to use tables for spectral sound power in the polar co-ordinates theta and phi. (Definition see Figure 2-2). Lateral symmetry can be assumed for fixed wing jet aircraft, i.e. phi has only to be listed in the range from 0° to 90°.

The polar co-ordinates theta and phi indicate locations on a sphere as shown in the figure to the right. When $L_{w,dir}(\theta,\varphi)$ is listed in a rectangular table, there exist combinations of θ and φ, which must have the same values. For instance, at θ = 0 ° and at θ = 180° all values of φ coincide in the same point (the poles of the sphere). This is indicated in Figure 6-1 by the grey fields. It is recommended, that those fields have the interpolated (or constant) value of neighbouring cells.



The resolution (or the amount of data) of the database will depend on the available data. A 5º resolution in both θ and φ is recommended. Based on the experience from the Imagine flight tests the benefits of a higher resolution (if any) do not justify the additional cost involved with the increased number of flights required.

Aircraft type:											Engine type:								
1/3 octave band frequency = f											Operation								
Corrected net thrust (CNT)= T											True air speed (TAS)= v								
Flaps / slats angle =											Landing Gear = up/down								
Sound power $L_{w,dir}$		**Longitudinal angle θ**																	
		0º	**10º**	**20º**	**30º**	**40º**	**50º**	**60º**	**70º**	**80º**	**90º**	**100º**	**110º**	**120º**	**130º**	**140º**	**150º**	**160º**	**170º**	**180º**
Lateral angle φ	**0º**																			
	10º	XX	XX	XX	XX												XX	XX	XX	XX
	20º	XX	XX	XX														XX	XX	XX
	30º	XX	XX		XX												XX		XX	XX
	40º	XX	XX	XX														XX	XX	XX
	50º	XX		XX	XX												XX	XX		XX
	60º	XX	XX																XX	XX
	70º	XX	XX	XX	XX												XX	XX	XX	XX
	80º	XX	XX	XX														XX	XX	XX
	90º	XX	XX	XX	XX												XX	XX	XX	XX

Figure 6-1 Proposed structure of data table

6.2 Proposed database structure

One of the possible options to build a multi-dimensional database is using the star schema model. It is one of the most common systems for data analysis. It permits the implementation of multi-dimensional views of data using a relational database. It also eases understanding. The star schema model is composed of a single “fact table” (Figure 6-2) which contains the final values of sound power. The values of $L_{w,dir}$ will depend on the values of the “dimension tables” (aircraft ID, thrust, speed, flaps positions, landing gear position, emission angles and frequency) which surround the fact table in a star schema model. The dimension tables are used to group data when performing data queries that will allow representative tables like those of the previous paragraph: i.e. directional levels of a certain combination of thrust, speed, flaps and landing gear position and frequency.

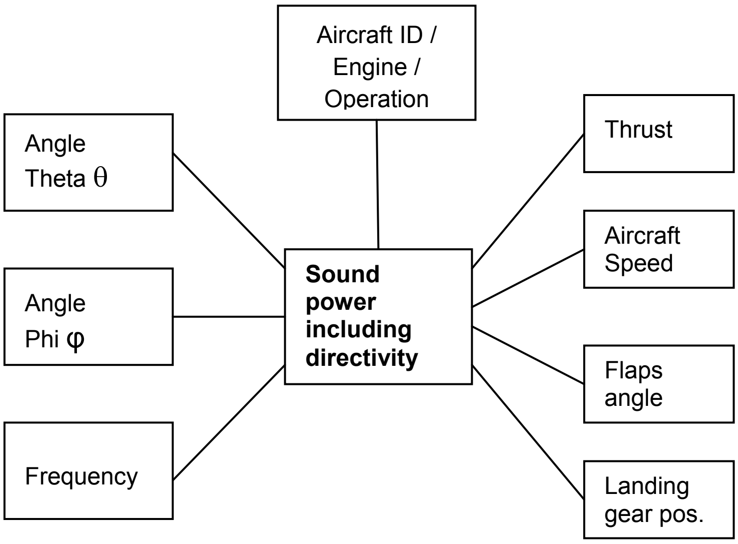


Figure 6-2: Star-scheme of a data base structure

The data base would consist in a single table. An example has been made with Access 2000

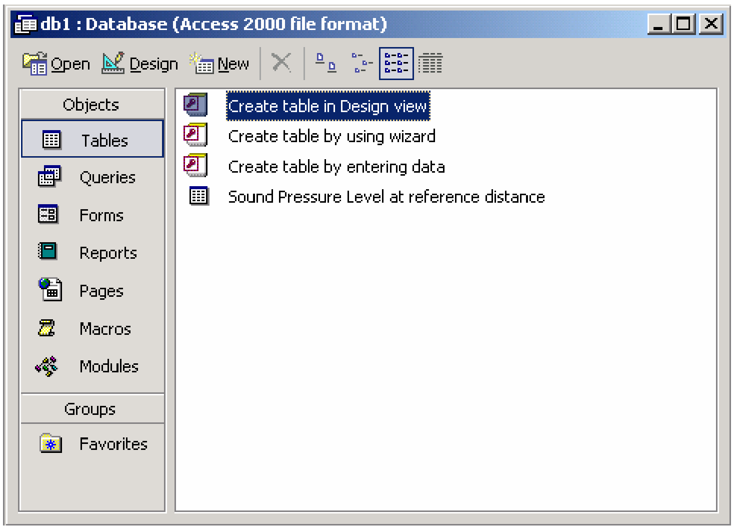


Figure 6-3 Example of Access Program

Microsoft Access - [Sound power and directivity pattern : Table]

ID	Aircraft ID	Thrust	Speed	Flaps	Landing gear	Frequency	Angle 1 (phi)	Angle 2 (theta)	Sound power	Directivity pattern
1	737800	6000	140	15	☑	125	90	90	150	-0.5
2	737800	6000	140	15	☑	125	90	100	150	-0.5
3	737800	6000	140	15	☑	125	90	110	150	-0.5
4	737800	6000	140	15	☑	125	90	120	150	-0.5
5	737800	6000	140	15	☑	125	90	130	150	-0.5
6	737800	6000	140	15	☑	125	90	140	150	-0.5
7	737800	6000	140	15	☑	125	90	150	150	-0.5
8	737800	6000	140	15	☑	125	90	160	150	-0.5
9	737800	6000	140	15	☑	125	90	170	150	-0.1
10	737800	6000	140	15	☑	125	90	180	150	0
11	737800	6000	140	15	☑	125	80	90	150	-0.6
12	737800	6000	140	15	☑	125	80	100	150	-0.5
13	737800	6000	140	15	☑	125	80	110	150	-0.5
14	737800	6000	140	15	☑	125	80	120	150	-0.4
15	737800	6000	140	15	☑	125	80	130	150	-0.5
16	737800	6000	140	15	☑	125	80	140	150	-0.6
17	737800	6000	140	15	☑	125	80	150	150	-0.6
18	737800	6000	140	15	☑	125	80	160	150	-0.5
19	737800	6000	140	15	☑	125	80	170	150	-0.5
20	737800	6000	140	15	☑	125	80	180	150	0
21	737800	6000	140	15	☑	125	70	90	150	
22	737800	6000	140	15	☑	125	70	100	150	
23	737800	6000	140	15	☑	125	70	110	150	
24	737800	6000	140	15	☑	125	70	120	150	
25	737800	6000	140	15	☑	125	70	130	150	
26	737800	6000	140	15	☑	125	70	140	150	
27	737800	6000	140	15	☑	125	70	150	150	
28	737800	6000	140	15	☑	125	70	160	150	
29	737800	6000	140	15	☑	125	70	170	150	

Record: 21 of 39

Figure 6-4 Example of a data sheet in the Access program

7 Conclusions

The precise characterisation of source emission levels is one of the most important factors influencing the aircraft noise contours. The present document shows how source data can be evaluated, and the test measurements of WP4 provide an example of how this can be made.

Unlike street traffic noise, where source data may be characterised by category (cars, trucks, ..), for aircraft noise the acoustic source description lists specific aircraft/engine combinations, which are related to specific manufacturers. Therefore, acoustic data is often considered to be sensitive data in competition.

Building up a database for spectral, directional sound source emission was beyond the scope of the present work. Probably this task will require international collaboration to set up the rules applicable to all, to collect data, to fund measurements and to present a platform for dialogue with manufacturers and users.

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Annex A: Classes of longitudinal directivity

Longitudinal directivities have been discussed in Chapter 3 and their use for reverse engineering was mentioned in Chapter 5. Based on "in-flight" measurements, Empa has established its own database for the aircraft noise simulation program Flula. The directivities used in Flula assume rotational symmetry and they provide the A-level for a specified distance. They represent typical departure procedures of initial climb, usually flown with flex-power for ATOW below 85% of MTOW.

The directivity functions presented here are the A-levels on a sphere around the aircraft at the constant distance of 305 m (including air absorption for 15°C/70% according to ISO 9613-1). The A-levels were calculated based on the source spectrum and spectral air absorption. They represent average values, measured during many flights of various aircraft samples. The curves are normalised to 0 dB at θ = 90°.

Figure A-1 gives an overview for the six classes for departures. Each curve is explained below. A class is calculated by a linear average of the individual directivity patterns of the aircraft types in the class. The Table A-1 at the end of this Annex lists the corresponding values.

The selection of individual jet aircraft into a specific group was made by visual judgement. Due to interaction of spectral shape of the source spectrum and of spectral air absorption, the resulting directivity in various distances may vary slightly. The figures at 305 m indicate realistic values.

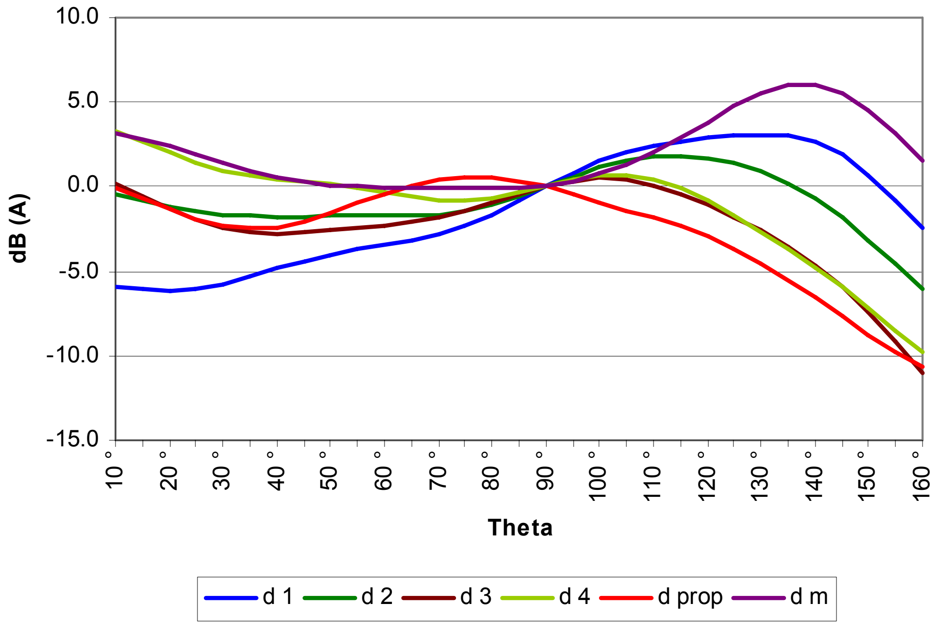


Figure A-1 Directivity functions for the A-level at constant distance of 305 m around the source

For landings, similar classes could be evaluated.

Class "Propeller-departure"

Figure A-2 shows a maximum in the directivity slightly before the point of closest approach (θ around 80°)

The following aircraft types were grouped into this class:

AT42	ATR42 (all series)
BA31	British Aerospace Bae-3102 Jetstream 31
BE20	Beech Super King Air 200
DC3	Douglas DC-3 Dakota
D328	Dornier Do-328, Fairchild Dornier 328
SB20	Saab 2000
SF34	Saab 340, SF340A/B

Class "Military-departure"

This class is presented here only for information to illustrate development of jet engines. Military jet engines have a very pronounced jet noise. Figure A-2 shows a pronounced level increase and a maximum for θ around 140°

The following aircraft types were grouped into this class:

F18	McDonnel Douglas F/A-18 Hornet
MIR	Dassault Mirage III, IIIRS
TIG	Northrop F-5E Tiger

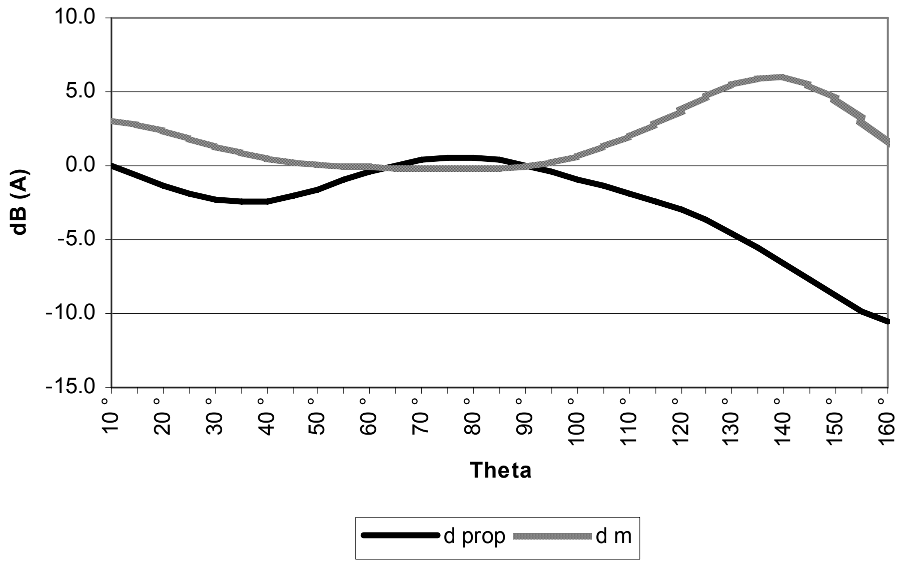


Figure A-2 Classes "Propeller" and "Military" for departure

Class "Jet 1-departure"

This class of older aircraft types has a pronounced jet noise component (maximum for θ around 140°), but low fan noise (for θ < 90°)

The following aircraft types were grouped into this class:

C550	Cessna 550 Citation II
C650	Cessna 560 Citation V
LR30	Learjet 30
LR50	Learjet 55
MD80	McDonnell Douglas MD-80/81/82
MD83	McDonnell Douglas MD-83 (DC-9-83)
MD87	McDonnell Douglas MD-87 (DC-9-87)

Class "Jet 2-departure "

This class has (compared to class 1) a less pronounced jet noise (for θ > 90°), but increased fan noise (for θ < 90°)

The following aircraft types were grouped into this class:

CL65	Canadair Regional Jet CRJ-200 (CL-65)
DA20	Dassault Falcon 20 Mystere
FK70	Fokker 70
HS257	Hawker Siddeley HS-125-700/800
RJ100	BAe Avro RJ-100 (146-RJ100)
TU54M	Tupolev Tu-154M

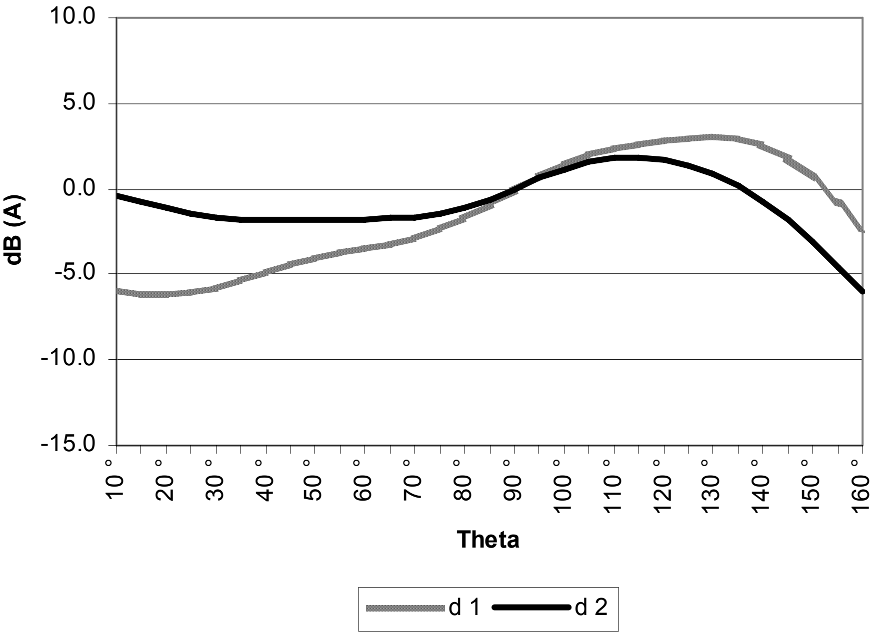


Figure A-3 Classes "Jets 1" and "Jets 2" for departure

Class "Jet 3-departure "

Due to new engine technology with high bypass ratio, the jet noise is reduced substantially. This class shows little fan noise (for θ < 90°).

The following aircraft types were grouped into this class:

B73S	Boeing 737-300
B73F	Boeing 737-400
B73V	Boeing 737-500
MD11	McDonnell Douglas MD-11 with PW 4462

Class "Jet 4-departure "

Many modern aircraft types are grouped in this class. They show little jet noise but some level increase due fan (and compressor) noise.

The following aircraft types were grouped into this class:

A3103	Airbus A310-300
A319	Airbus A319
A320	Airbus A320
A321	Airbus A321
A3302	Airbus A330-200
A340	Airbus A340-200/300
B7473	Boeing 747-300 with JT9D-7R4G2
B7474	Boeing 747-400 withPW4056
B7572	Boeing 757-200
B7672	Boeing 767-200
B7673	Boeing 767-300
DC10	McDonnell Douglas DC-10 with CF6-50

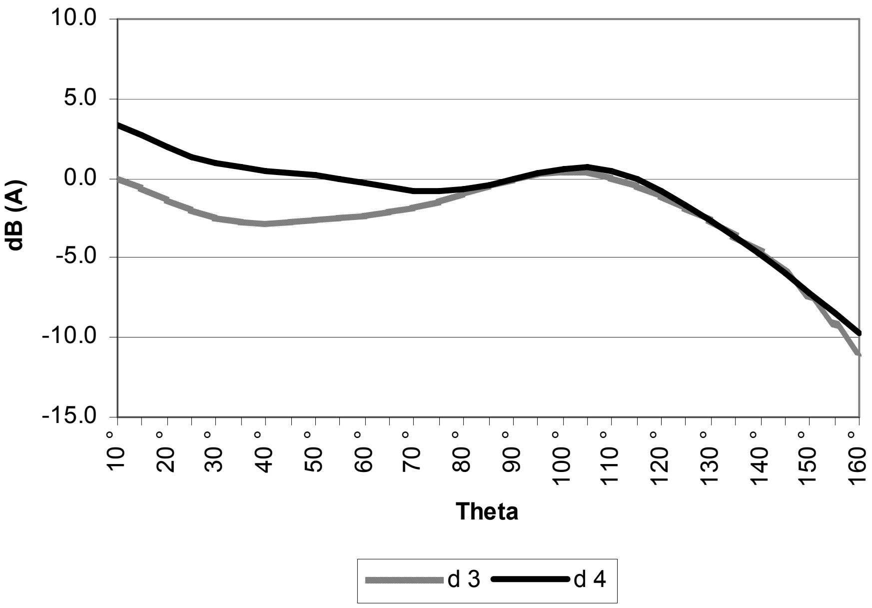


Figure A-4 Classes "Jets 3" and "Jets 4" for departure

Table of directivity functions for the six classes (departure)

The values are shown graphically in Figures A1 to A4.

Theta	jets 1	jets 2	jets 3	jets 4	propeller	military
°	dB	dB	dB	dB	dB	dB
10	-5.9	-0.4	0.1	3.3	0.0	3.2
15	-6.1	-0.8	-0.6	2.7	-0.6	2.8
20	-6.1	-1.1	-1.3	2.0	-1.3	2.4
25	-6.0	-1.4	-1.9	1.4	-1.9	1.9
30	-5.7	-1.6	-2.4	0.9	-2.3	1.4
35	-5.3	-1.7	-2.7	0.7	-2.5	0.9
40	-4.8	-1.8	-2.8	0.5	-2.4	0.5
45	-4.4	-1.8	-2.7	0.3	-2.1	0.3
50	-4.0	-1.7	-2.6	0.2	-1.6	0.1
55	-3.7	-1.7	-2.5	-0.1	-1.0	0.0
60	-3.5	-1.8	-2.3	-0.3	-0.4	-0.1
65	-3.2	-1.7	-2.0	-0.6	0.1	-0.1
70	-2.8	-1.6	-1.8	-0.8	0.4	-0.1
75	-2.3	-1.4	-1.4	-0.8	0.6	-0.1
80	-1.7	-1.1	-0.9	-0.7	0.6	-0.1
85	-0.9	-0.6	-0.5	-0.4	0.4	-0.1
90	0.0	0.0	0.0	0.0	0.0	0.0
95	0.8	0.6	0.3	0.4	-0.4	0.3
100	1.5	1.1	0.5	0.6	-0.9	0.7
105	2.0	1.5	0.4	0.6	-1.4	1.3
110	2.4	1.8	0.1	0.4	-1.9	2.0
115	2.7	1.8	-0.4	-0.1	-2.4	2.9
120	2.9	1.7	-1.0	-0.8	-3.0	3.8
125	3.0	1.4	-1.8	-1.7	-3.7	4.7
130	3.1	0.9	-2.6	-2.7	-4.5	5.5
135	3.0	0.2	-3.5	-3.7	-5.5	6.0
140	2.6	-0.7	-4.6	-4.8	-6.6	6.0
145	1.9	-1.8	-5.9	-6.0	-7.7	5.5
150	0.7	-3.1	-7.4	-7.2	-8.8	4.5
155	-0.8	-4.6	-9.2	-8.5	-9.8	3.1
160	-2.4	-6.0	-11.0	-9.8	-10.6	1.5

Table A-1 Directivity classes for departure

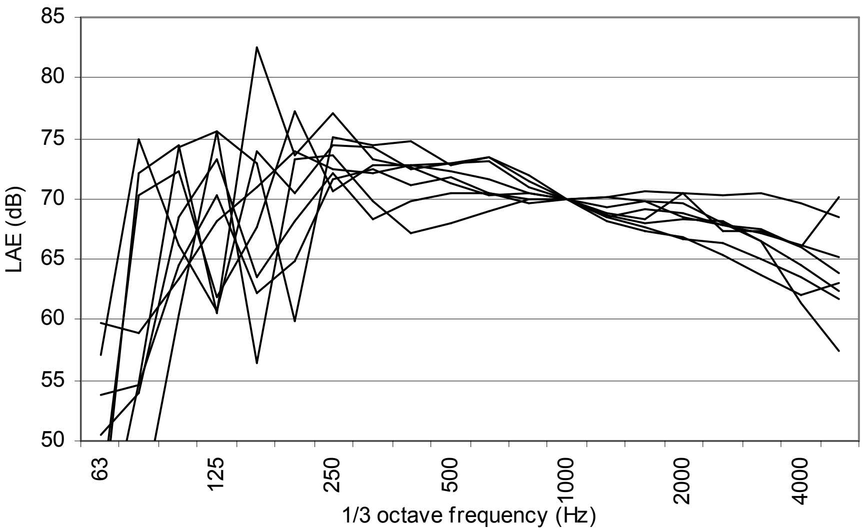
Annex B: Examples of spectra

This Annex presents spectra for departures as an aid for the reverse engineering described in Chapter 5.

The spectra were extracted at Empa from measurements of departing aircraft close to the runways. For each specific aircraft type the spectrum shown is an average of several individual flights of several microphone positions. Measured at 10 m above ground, spectra are normalised for a distance of 305 m and they include air absorption according to ISO 9613-1 (15°C/70%) for 305 m. They represent the L_{AE} values resulting from a complete flight event. They are A-weighted to show which frequency range contributes most to the overall L_{AE}. All spectra are normalised to 70 dB at 1000 Hz.

For better visibility, the jets were grouped into two figures by the arbitrarily criterion, if the level at 100 Hz was above 58 dB or not. The spectra shown are proprietary data of Empa. It is not intended to allow for individual identification, but to show general tendencies. The abbreviations of aircraft types are explained in Annex A.

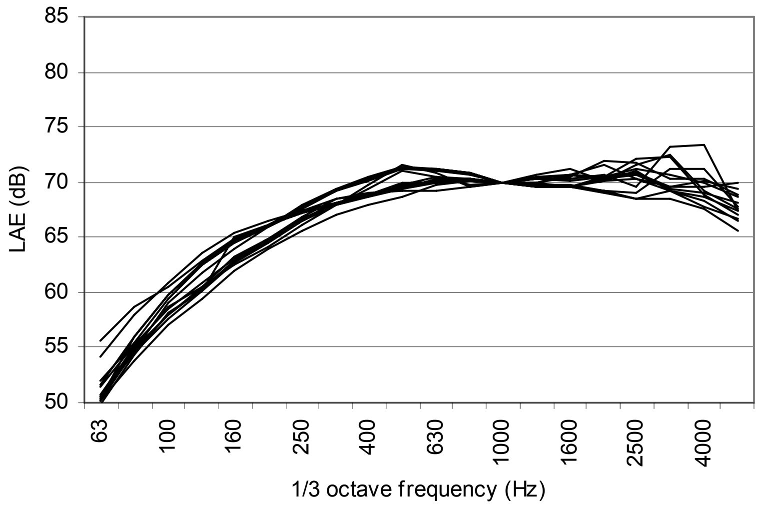
B1: A-weighted spectra for propeller driven aircraft



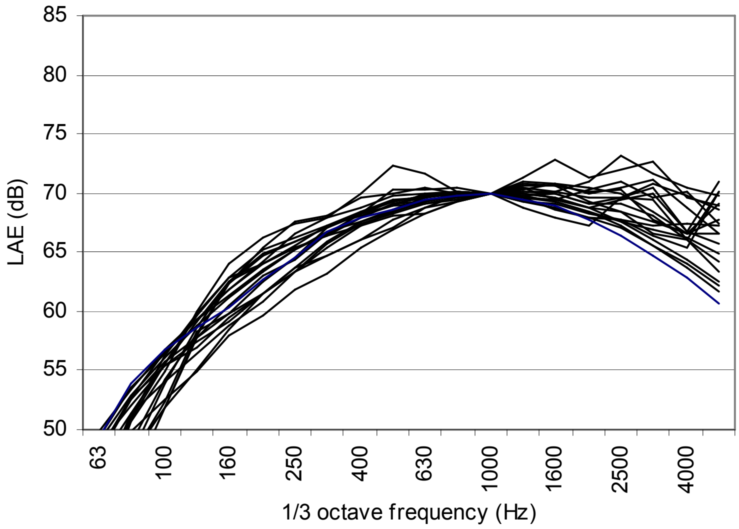
Propeller-driven aircraft: ATR42, BA31, BE20, DC3, DH8, FK50, SB2000, SF 340

For propeller driven aircraft the spectra show tonal components at low frequencies and increased levels below 1000 Hz

B2: A-weighted spectra for jets



jets with levels > 58 dB at 100 Hz: A320, A321, A310-300, B707F, B737(-300, -400, -500), B757-200, B767(-200, -300), DC10, RJ100, MD11.



jets with levels < 58 dB at 100 Hz: A319, A340, B737-200 advanced, B747(-300, -400), DA20, DA90, C550, C650, CL65, DC9(-30, -40), FK10, FK70, HS257, MD80, MD83, MD87, LR30, LR50

The typical dip at 125 .. 250 Hz from ground interference for microphones at 1.2 m found in the spectral class data of ANP [17] (and INM [11]) is not found here because the measurements were made at 10 m above ground (see Figures 5-1 and 5-2)

Annex C: Examples for reverse engineering

This Annex lists as examples four source spectra extracted from NPD data using procedures described in Chapter 5.

The examples are:

Aircraft	Engine	Index	Thrust
Airbus A 320	CFM 565	SEL	D, 21'000 lb
Airbus A 320	CFM 565	SEL	D, 16'500 lb
MD 83	2JT8D2	SEL	D, 19'000 lb
B 737-400	CFM 563	SEL	D, 21'180 lb

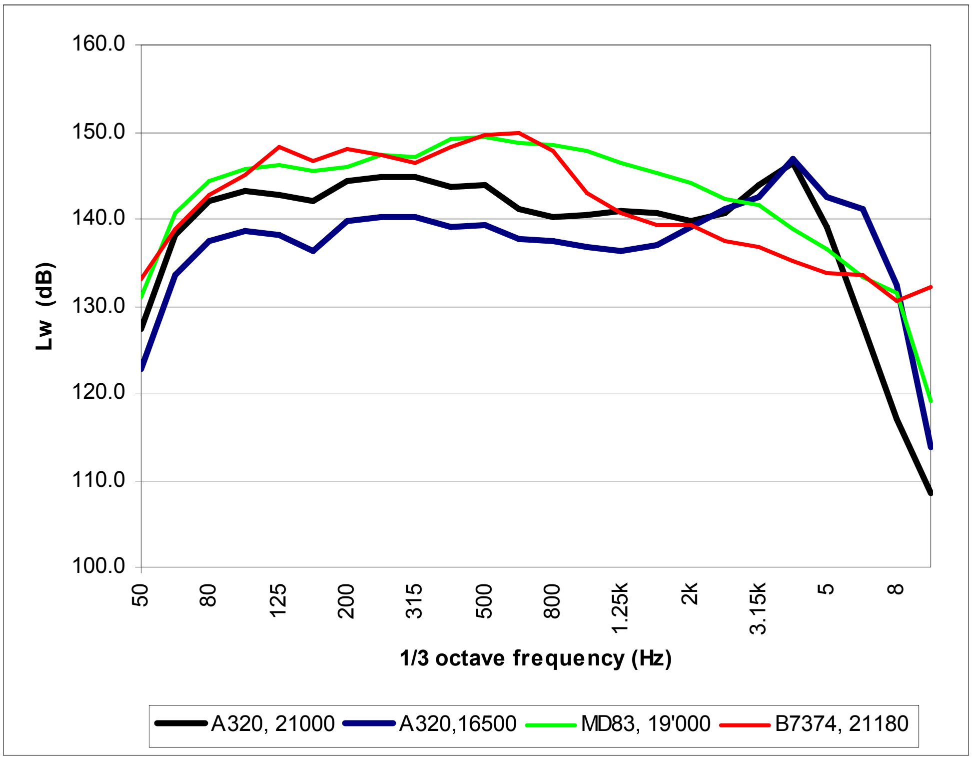


Figure C-1 Examples of sound power spectra (not A-weighted)

The values of Figure C-1 are indicated in Table C-2. They are estimations for $L_{w,dir}$ at theta =90° and phi = 0°. For other angles, the appropriate correction for longitudinal directivity (Table A-1) and for lateral directivity (Table 3-1) have to be added.

	A 320, 21000 lb	A 320, 16'500 lb	MD 83, 19'000 lb	B 737-400 21'180 lb
Frequency (Hz)	Lw,dir (dB)	Lw,dir (dB)	Lw,dir (dB)	Lw,dir (dB)
50	127.5	122.9	131.0	133.2
63	138.2	133.6	140.7	138.9
80	142.0	137.4	144.5	142.7
100	143.3	138.7	145.8	145.0
125	142.7	138.1	146.2	148.4
160	142.0	136.4	145.5	146.7
200	144.4	139.8	145.9	148.1
250	144.7	140.1	147.2	147.4
315	144.7	140.1	147.2	146.4
400	143.7	139.1	149.2	148.4
500	144.0	139.4	149.5	149.7
630	141.2	137.6	148.7	149.9
800	140.1	137.5	148.6	147.8
1k	140.4	136.8	147.9	143.1
1.25k	140.9	136.3	146.4	140.6
1.6k	140.7	137.1	145.2	139.4
2k	139.7	139.1	144.2	139.4
2.5k	140.7	141.1	142.2	137.4
3.15k	144.0	142.4	141.5	136.7
4	146.4	146.8	138.9	135.1
5	139.1	142.5	136.6	133.8
6.3	127.8	141.2	133.3	133.5
8	117.0	132.4	131.5	130.7
10k	108.5	113.9	119.0	132.2

Table C-2 L_w-spectra for four examples

The estimations of source spectra were made with the Excel program "NPD_retrofit_xxxx.xls" developed by Empa. The deviations between the original SEL-values of the NPD and the calculated SEL values using the estimated spectrum were for the 10 NPD-distances at the end of the iteration loops typically 0.0 to 0.1 dB, in the maximum for a specific distance 0.2 dB. There exist variations in the spectral shape, which all satisfy more or less stringent the required reproduction of the NPD SEL values. Those variations may reach several decibels in some 1/3 octave bands.