| Security class | Document ID | Issue no. | Issue date | Page |
|---|---|---|---|---|
| Restricted | PAN069-1 | 2 | 18/05/2008 | 1 of 22 |

| Project | | Document Title |
|---|---|---|
| AN069 | Initial study on aircraft cruise noise levels | D1. Final report |

**Summary**

This document describes the work carried out in an initial study on aircraft cruise noise levels in order to support possible future rulemaking for new developments like supersonic business jets and aircraft with open rotors.

Research has been performed on readily available information on this subject. Ways of communicating the information are considered. Options for further research are proposed for those areas where gaps or major uncertainties have been identified.

**Document revisions**

| Issue | Date | Affected pages | Modifications |
|---|---|---|---|
| 1 | 05/05/2008 | All | First issue |
| 2 | 16/05/2008 | 7, 13, 19-22 | Incorporation of comments from EASA on issue 1 |

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**Approval status**

| Prepared by<br>Project team | Approved by<br>Head Engineering & Design | Verified by<br>Responsible Airworthiness |
|---|---|---|
| Nico van Oosten | Nico van Oosten | N/A |

# Table of Contents

# 1 Introduction

Two developments in aviation industry will shortly have reached a phase where actual rulemaking work will have to commence. These developments are the preliminary studies on supersonic business jets and the revived interest in so called 'open rotor' engines. They have a common factor in that they will potentially create non negligible noise levels on the ground, not only when flying in the terminal area around airports but also while the aircraft are cruising in the airways. If aircraft with such technology would be numerous this would essentially mean that aircraft noise would be audible literally everywhere. The political discussion and the impact assessment will therefore require factual data on existing so called background noise levels (L99, L95) and on actual noise levels of 'classical' aircraft in cruise in Europe and elsewhere. Such data will make it possible to put the noise levels of these new technologies in perspective with existing situation.

Anotec Consulting SL was contracted by EASA to perform an initial study on existing noise levels caused by aircraft climbing to cruise level (so after having left the immediate vicinity of the airport), when flying horizontally in cruise mode and during the initial approach (descending form cruise to the airport circuit pattern.). This is a preliminary study on the available knowledge in this field, identifying gaps and uncertainties, making suggestions on the best way to communicate and report such information and suggesting possible further work to fill gaps of knowledge and reduce uncertainty.

The findings of this initial study are presented in the present document.

# 2 Data collection

The objective of the first phase of the project was to collect readily available relevant information on existing aircraft cruise noise levels by means of an internet search, review of literature and exploration of alternative sources of information.

Two periods in time were identified as potential sources of information, coinciding with major development efforts of new aircraft/engine concepts. The first block corresponds to the development of the so-called 'propfan' in the late 80's and early 90's of the past century. The second block is more recent and coincides with the renewed interest in now called 'open rotor' systems and the supersonic business jet (SSBJ).

In addition to these blocks the impact of sonic booms has been subject of investigation during decades, although in this context no relevant information was found within the scope of the present study.

Also long range propagation has been studied over decades, especially in relationship with wind turbines. In general these studies investigate sound propagation at very low elevation angles, not relevant for the present study.

Already in the very beginning of this phase it became clear that not much information appeared to be available on the subject of the present study.

## 2.1 Review of information related to the development of the propfan

In the 80's of the last century several models of advanced turboprops ('propfan', 'UDF') were developed and flight tested. This type of powerplant generates distinct tones at low frequency and relatively high noise level. Concerns about the impact of noise generated in the cruise phase were confirmed by measurements.

Significant research was done in this period, mainly in the US. A dedicated 'en route noise symposium' was organised by FAA and NASA. This is the main source of information found on this subject and in the following a review is given on the relevant papers presented at this event.

In [1] a definition is proposed for the term 'en route'. It is suggested that this term should include those flight phases above around 3000 ft (i.e. from initial climb upto and including ILS intercept).

[2] gives an overview of the flight tests performed with the Propfan Test Assessment (PTA) aircraft. Noise of overflights was recorded for a range of aircraft speeds and altitudes. One of the main results of interest for the present study is the scatter encountered. Whilst repeatability on a single test day was good, significant scatter (upto 12 dB) was found in the results from different test days. Since the source noise was found to be very repeatable (based on chase plane measurements), it was concluded that propagation through the atmosphere was responsible for this variability.

In [3] part of the scatter observed in [2] was found to be attributable to differences in atmospheric absorption. LAmax for the PTA at cruise altitude was found to be in the range of 55 to 60 dB(A).

In Germany a small test program was conducted in 1989 in order to determine the noise levels from two conventional turboprop aircraft in cruise, to serve as a reference for the establishment of acceptability criteria. In [4] it is stated that noise levels from new powerplants as received on the ground should not exceed those from the considered turboprops (Fokker 50 and Metro III). Interesting is figure 10 of this document, where cruise noise levels are given for several aircraft types (general aviation, turbofans, turboprops and UDF). It should be noted that this figure originates from a manufacturers' presentation, without further traceability.

[5] presents the results of these flight tests. It should be noted that this test is the only one identified which gives measured noise levels for conventional aircraft in cruise. In a later section these results will be used for some further analysis. It was found that the measured LAmax is in the order of 50 dB(A), the propeller BPF being fully responsible for this result. At one point a 7 dB(A) higher noise level is found, attributed to atmospheric disturbances. Another significant observation was the presence of noise beats due to the different rotational speeds of the two propellers, causing periodic fluctuations of up to 5 dB.

Sound propagation specific for en route noise is dealt with in [6]. It is suggested that the difference in acoustic impedance between cruise altitude and ground level will result in an overall 4 dB reduction of sound pressure level. Atmospheric absorption as defined by SAE ARP866A is found not to be usable for this application since it does not take into account the change in atmospheric pressure, nor does it cover the extremely wide range of humidity contents involved. It is found that the refraction due to the non-uniform atmosphere (wind and temperature gradients) will affect the sound ray paths such that only the sound radiated within ±55º from the vertical will eventually reach the ground. Small variations in these gradients might cause large variations in the noise levels received in the area of lower elevation angles.

In [7] the issue of defining an adequate metric for en route noise is addressed, from the 'wilderness' perspective. Although this issue is beyond the scope of the present study, it highlights the importance of some aspects which are to be addressed when defining further research options later on. The use of parameters which account for (very) low background noise levels, detectability, 'time above' and very fast or very slow onset rates is mentioned.

In [8] additional aspects like sleep disturbance and the importance of single event levels are addressed. Even in those areas where average day levels are well below legal limits adverse effects may be expected due to the high single event levels.

Also [9], [10] and [11] deal with the issue of annoyance from en route noise and the aspects involved, including the need for a representative metric.

Long range propagation of low frequency wind turbine noise is dealt with in [12] and [14]. Both studies find that a non-uniform atmosphere (especially temperature inversion) has a significant effect on propagation at low elevation angles, resulting in a cylindrical, rather than a spherical spreading. Although this effect should be taken into account when addressing sideline noise, for en route noise it is considered of less importance.

[13] addresses vertical propagation, based on the PTA tests. The day-to-day variability in received noise levels is discussed.

In [15] en route noise for a DC-9 aircraft is predicted and compared with measurements. At the time of the symposium this aircraft was representative for the existing fleet of conventional aircraft. The prediction took into account that above an altitude of 20.000 ft the exhaust jet becomes supersonic, thus introducing shock cell noise. An LAmax level of 54 dB(A) was found for a typical cruise altitude of 30.000 ft. A comparison was made with measured data, described in [16].

[16] appears to be an interesting document, describing measurements of en-route noise for several aircraft types. An intensive search was made to obtain this document, however without success. Even through personal contacts with FOI (the successor organisation of FFA) this report could not be retrieved

in the time available for the present study. Figure 1 of [15] suggests that a significant scatter of around 10 dB(A) was found for the DC9.

## 2.2 Review of information related to recent developments

Due to the high fuel cost and the increased concerns about gaseous emissions a renewed interest in open rotor systems has emerged, especially in Europe. Various new research projects have been started (DREAM, Clean Sky JTI), in which this concept will be further developed and validated. However, these projects are in their initial phase and no relevant information was yet released in the public domain.

Since some years several manufacturers have proposed new aircraft designs that promise to increase transportation speeds. In particular, the business jet market appears to present a business case for an exclusive Supersonic Business Jet (SSBJ). In Europe the HISAC project deals with this subject, with special attention to environmental issues, especially sonic boom impact. In this project few findings have been released in the public domain, obviously for competitive reasons. The only public document identified as potentially interesting deals with a review of sonic boom impacts [19]. An estimate is made for the population affected by sonic booms generated in cruise flight, which is then compared with population affected by noise from subsonic aircraft in the vicinity of airports. Based on this comparison an indication is given of an acceptable boom level. Surprisingly no attention is paid to the fact that the majority of the population affected by sonic booms is probably not living close to an airport. Since the noise of the SSBJ during take-off and landing will (by design) be comparable with that of conventional aircraft, this means that the number of people affected by noise from the SSBJ will in fact be doubled. As with all other documentation found on this subject (e.g. [20]), no reference is made to cruise noise levels of conventional aircraft. From the available information on HISAC no evidence could be found that indicates research on aircraft noise levels in cruise is being performed in this project. An attempt was made to contact with the project coordinator to request further information, but no response was obtained.

## 2.3 Review of additional sources of information

The review of readily available information as described in the former sections revealed that not much information is available on actual aircraft noise levels in cruise. It was therefore decided to explore an alternative route to obtain some further data.

The INM airport noise model [18] contains an NPD database for a wide variety of aircraft types and operating conditions. Distances for which noise levels are provided range from 200 ft to 25000 ft. It is recognised that the noise levels for the upper distance range are obtained from a significant extrapolation of data measured at low altitude (typically 1000 ft), applying corrections for spherical spreading, atmospheric absorption and duration. In this process the effect of atmospheric and operational conditions on e.g. noise generation is not taken into account. Nevertheless, a comparison of the NPD data with the measured data presented earlier is considered useful, since it will give an indication of the applicability of this methodology in the context of the present study, in order to extend the data beyond the currently available dataset.

### 2.3.1 Comparison of measured and predicted noise levels

As a first step NPD data was gathered for the only two aircraft for which measured en-route noise levels have been found (Fokker 50 and Metro III, see section 2.1). Since the INM 7.0 database does not contain data for these aircraft types, the proposed substitutions have been used (DHC8-300 and DHC6, respectively). The powersetting used was the lowest one available for departure. The NPD database does not state directly the power setting at cruise, so an estimate was made Since measured data is only given as LAmax, the comparison shall be based on this metric. However, since LAmax is not readily available for the DCH8-300, an estimate is made based on SEL. From the NPD database it can be concluded that for a wide variety of aircraft types the following relationship between both metrics exists:

$$SEL \cong LAmax + 9.3 \log D - 20 \quad \text{with D the distance in ft.}$$

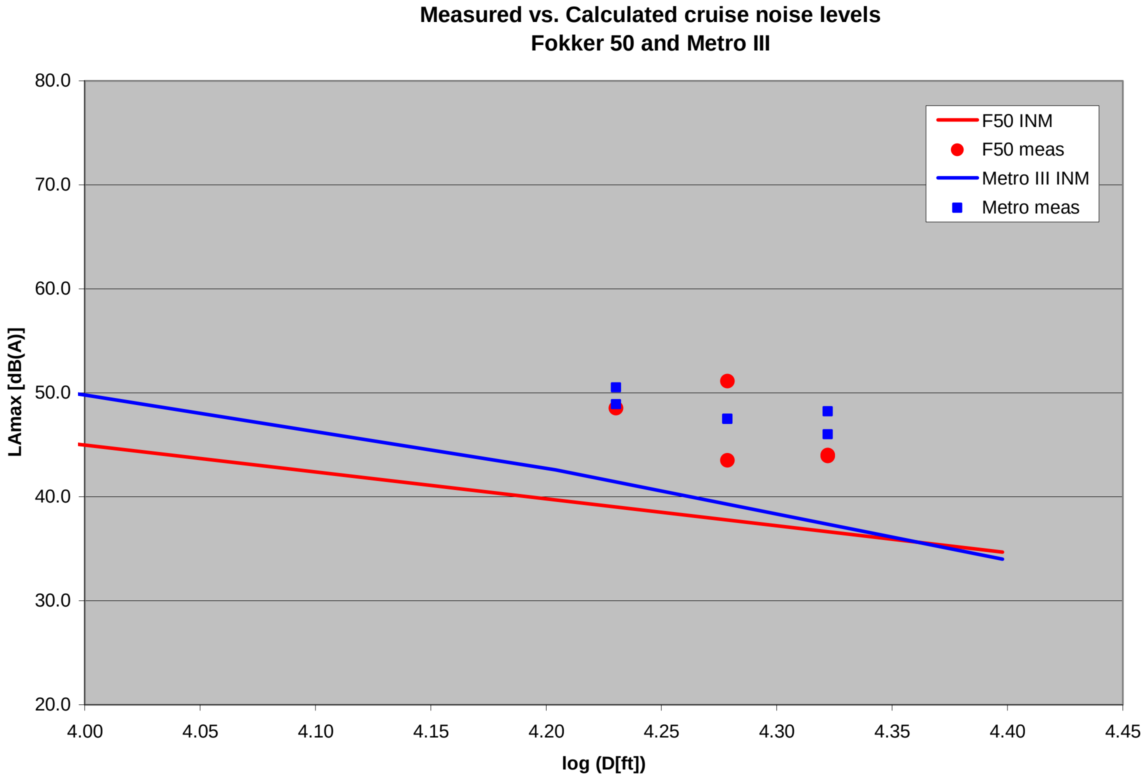
The resulting noise levels are given in the following table.

| Distance (ft) | LAmax at cruise power | |
|---|---|---|
| | Fokker 50 | Metro III |
| 200 | 83.2 | 95.6 |
| 400 | 76.8 | 89.5 |
| 630 | 72.5 | 85.3 |
| 1000 | 68.0 | 81.0 |
| 2000 | 61.6 | 74.3 |
| 4000 | 54.6 | 67.0 |
| 6300 | 49.9 | 61.6 |
| 10000 | 45.0 | 55.6 |
| 16000 | 39.7 | 49.0 |
| 25000 | 34.7 | 41.4 |

The results from the measurements, which were performed at 3 flight levels, are [5]:

| Distance (ft) | LAmax at cruise power | |
|---|---|---|
| | Fokker 50 | Metro III |
| 17000 | - | 48.9 |
| 17000 | 48.5 | 50.5 |
| 19000 | 51.1 | 47.5 |
| 19000 | 43.5 | 47.5 |
| 21000 | 43.9 | 48.2 |
| 21000 | 44.0 | 46.0 |

In the following graph both datasets are shown.




It can be seen that measured noise levels are 5 to 10 dB(A) higher than those derived from INM. Possible explanations for the observed differences are:

- The uncertainties in the INM datasets for both aircraft (substitutions, LAmax estimate for F50, wrong selection of powersetting)
- The effect of altitude and aircraft speed on noise generation, which is not accounted for in the INM database
- Propagation effects, especially atmospheric absorption, since the measured values are not corrected to reference conditions

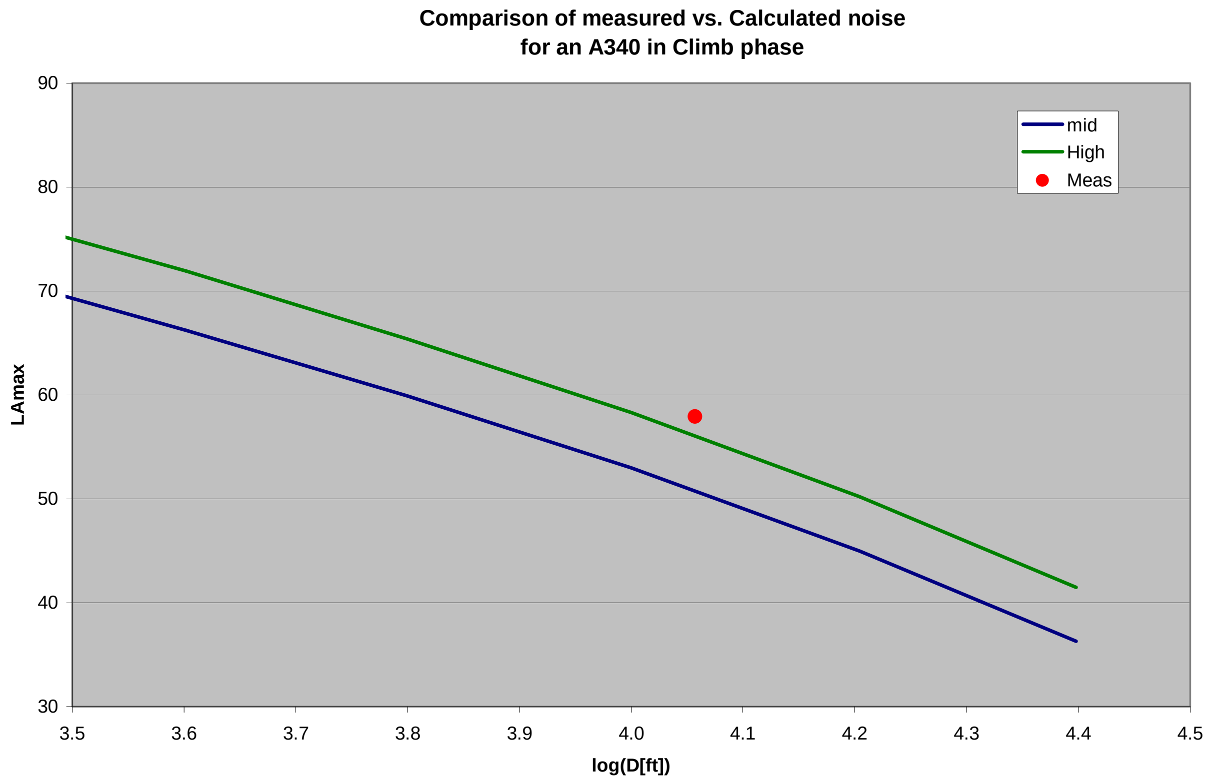
As mentioned before, the above dataset was the only one found in the literature. In order to enhance somewhat this information, Anotec took the opportunity during a recent flight test campaign in Germany to do some additional noise recordings of aircraft in the climb phase with the already deployed measurement system. The tests were performed at Manching, situated at 40 km north of München airport. Several aircraft overflights were recorded, although due to time constraints only one could be further analysed for the purpose of the present study. An Airbus A340 was recorded when it was overflying the test site. The following parameters were assumed in the calculation of the overhead height at the test site:

- distance flown since TO: 40 km + 20% due to the runway orientation rel. the test site
- average climb rate 2000 fpm
- average speed of 280 kts
- elevation of MUC rel. test site: +80 m

With these values the height above the microphone is estimated to be around 3470 m (11385 ft).

Measured LAmax was 57.9 dB(A) with a background noise level of 31.1 dB(A). Obviously the powersetting of the aircraft is unknown.

To be able to compare this data with INM, the noise levels have been derived for both mid and high powers. The following graph shows the comparison of measured data with the results from INM.




Also from this comparison it can be seen that the measured noise level is several dB(A) higher than the expected level based on INM data.

### 2.3.2 Estimate of en-route noise levels for various aircraft groups

Although the result obtained in the former section does not appear very encouraging, it is considered that application of INM to other aircraft types might be feasible under certain conditions, under which the above uncertainties might be somewhat reduced:

- select only models for which data are available (no substitutions, data available for LAmax)
- NPD data available for a powersetting representative for cruise

The following aircraft types have been selected as representative for a certain aircraft group:

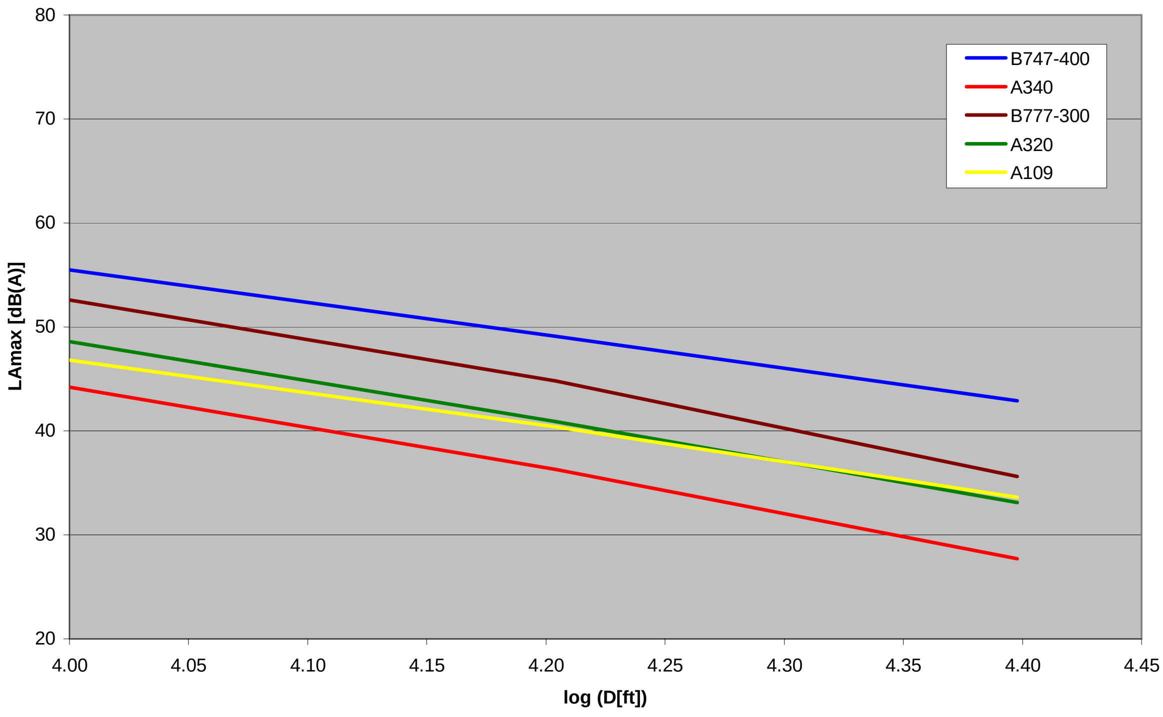
| Type | Model |
|---|---|
| Long range quad | ✈ B747-400 / A340 |
| Long range twin | ✈ B777-300 |
| Single aisle twin | ✈ A320 |
| Rotorcraft | ✈ A109 |

No attempt has been made to model General Aviation due to the high variability in flight procedures.

The corresponding datasets based on INM are:

| Distance (ft) | LAmax at cruise power | | | | |
|---|---|---|---|---|---|
| | B747-400 | A340 | B777 | A320 | A109 |
| 200 | 101.9 | 98.9 | 100.4 | 100.3 | 92.0 |
| 400 | 94.4 | 89.4 | 93.4 | 92.0 | 85.5 |
| 630 | 89.3 | 82.8 | 88.5 | 86.2 | 81.1 |
| 1000 | 83.9 | 76.4 | 83.3 | 80.3 | 76.5 |
| 2000 | 75.7 | 67.3 | 74.9 | 71.1 | 68.8 |
| 4000 | 67.7 | 57.8 | 65.7 | 61.7 | 60.1 |
| 6300 | 61.9 | 51.3 | 59.4 | 55.4 | 53.8 |
| 10000 | 55.5 | 44.2 | 52.6 | 48.6 | 46.8 |
| 16000 | 49.1 | 36.3 | 44.8 | 40.9 | 40.4 |
| 25000 | 42.9 | 27.7 | 35.6 | 33.1 | 33.6 |

**Calculated noise levels**
**for different aircraft types**




Based on these data an estimate can be made of the en-route noise levels to be expected for the different aircraft types, by interpolation in the NPD curves at the relevant cruise altitude.

In addition to the levels derived here, Figure 10 of [4] also states a range of noise levels for some aircraft types. It should be noted that this information is not traceable, and in any case reflects the state-of-the-art of 20 years ago, with noise levels significantly higher than those of current technology aircraft.

| Type | Typical cruise alt | LAmax en-route* | LAmax en-route** |
|---|---|---|---|
| Long range quad | 30-40 kft | 21 – 40 | 35 – 53 |
| Long range twin | 30-40 kft | 29 – 31 | |
| Single aisle twin | 27-35 kft | 28 – 33 | |
| Turboprop | 15-23 kft | 36 – 40 | 40 – 60 |
| Rotorcraft | 5-15 kft | 40 – 58 | - |

*based on INM data
** based on figure 10 of [4]

As mentioned above, these levels should only be considered a first estimate, since various potentially important effects are not taken into account:

- The effect of altitude on noise generation.
  At high altitudes ambient pressure and temperature are considerably different from the test conditions for which the NPD was derived, thus affecting noise generation at the source. The engine exhaust conditions might become supercritical and new noise sources might be introduced (e.g. shock cell noise).
- The effect of speed on noise generation.
  The NPD data has been derived for low speed conditions. At high forward speed relative jet velocity will change and subsequently also jet noise. Convective amplification will increase the received noise in the forward arc, whereas in the rearward arc noise will be reduced. At high aircraft speeds this effect might significantly alter the shape of the time history [17]
- The effect of ambient conditions (pressure, temperature and humidity) on atmospheric absorption
  The NPD has been derived by correcting to a constant atmosphere, but for higher altitudes this is not a valid assumption
- The effect of ambient conditions on acoustic impedance
  The NPD has been derived without taking into account the different acoustic impedance existing at high altitude
- The effect of ambient conditions (wind and temperature gradients) on acoustic propagation
  Measurements on the propfan showed a significant day-to-day scatter, attributed to propagation effects. Certainly at lateral positions refraction effects might become significant.

Although not sufficient information is available to substantiate the influence of the abovementioned effects, the (few) results from the comparison with measurements indicate that an error of 5 to 10 dB(A) may be expected.

These results indicate that en-route noise from various aircraft types can be expected to be audible, especially in areas with low background noise.

## 2.4 Summary of data collection

Reviewing the information gathered above, it can be concluded that:

- Very few measurement data are available for conventional aircraft in the cruise phase
- Significant scatter is found in measurement results, mostly attributed to atmospheric propagation effects
- Noise from conventional aircraft in the cruise phase is expected to be detectable, especially in areas with low background noise
- Existing noise metrics do not seem to adequately describe annoyance of en route noise
- Prediction of en route noise based on data obtained at low altitudes should be performed with caution

# 3 Gaps and Uncertainties

Based on the information obtained in the former section several gaps and uncertainties can be identified in the existing knowledge on aircraft en route noise levels.

## 3.1 Lack of a comprehensive database of measurements on noise of current technology aircraft in climb, cruise and descent

Some test campaigns on en route noise were organised in the mid 80's of the past century in support of the development work carried out for the propfan. Although the resulting datasets contributed to a better understanding of various aspects of en route noise, the aircraft types measured are not representative for the current aircraft fleet and corresponding state of the art of powerplant technology. The results of these tests can therefore not be used as a reference for any potential future legislation on new aircraft or powerplant concepts. No measured data was identified on en route noise of current aircraft.

## 3.2 Lack of understanding and quantification of the scatter found in measured noise levels

In the available datasets a significant scatter, in the order of 5 to 10 dB(A), can be observed in the measured noise levels. In general this scatter is attributed to propagation effects.

If measured data were to be used to establish limits in a future legislation, a quantification of this scatter is required, since it is likely that the same variability will also be present in the noise levels of future designs.

If a methodology to correct from measured to reference conditions would be implemented in a future certification scheme, a better understanding of propagation effects and corresponding correction procedures would be required.

At present insufficient data is available to support both issues.

## 3.3 Uncertainty in the extrapolation of data acquired at low heights to cruise altitude

The only known extensive datasets of aircraft noise are those used for airport noise modelling, such as the NPD database of INM. These data are mainly derived from noise certification measurements, usually performed at low altitudes and low aircraft speeds. Use of these data for prediction of noise from an aircraft flying at high speed at high altitudes, representative for cruise is not straight forward, as observed in section 2.3. For example, the effect of height and speed on noise generation mechanisms is not accounted for and correction procedures for propagation effects like atmospheric absorption might not be valid for cruise conditions. The results obtained for en route noise with models like INM will therefore have a significant uncertainty and should therefore be used very cautiously.

## 3.4 Lack of knowledge on annoyance related to low noise levels in low noise environments and a corresponding suitable metric

Although annoyance related to en route noise and the definition of a suitable metric are beyond the scope of the present study, it is considered useful to mention the lack of knowledge in this field, since it might be possible to support this issue with data originating from the work proposed under future research in section 5.

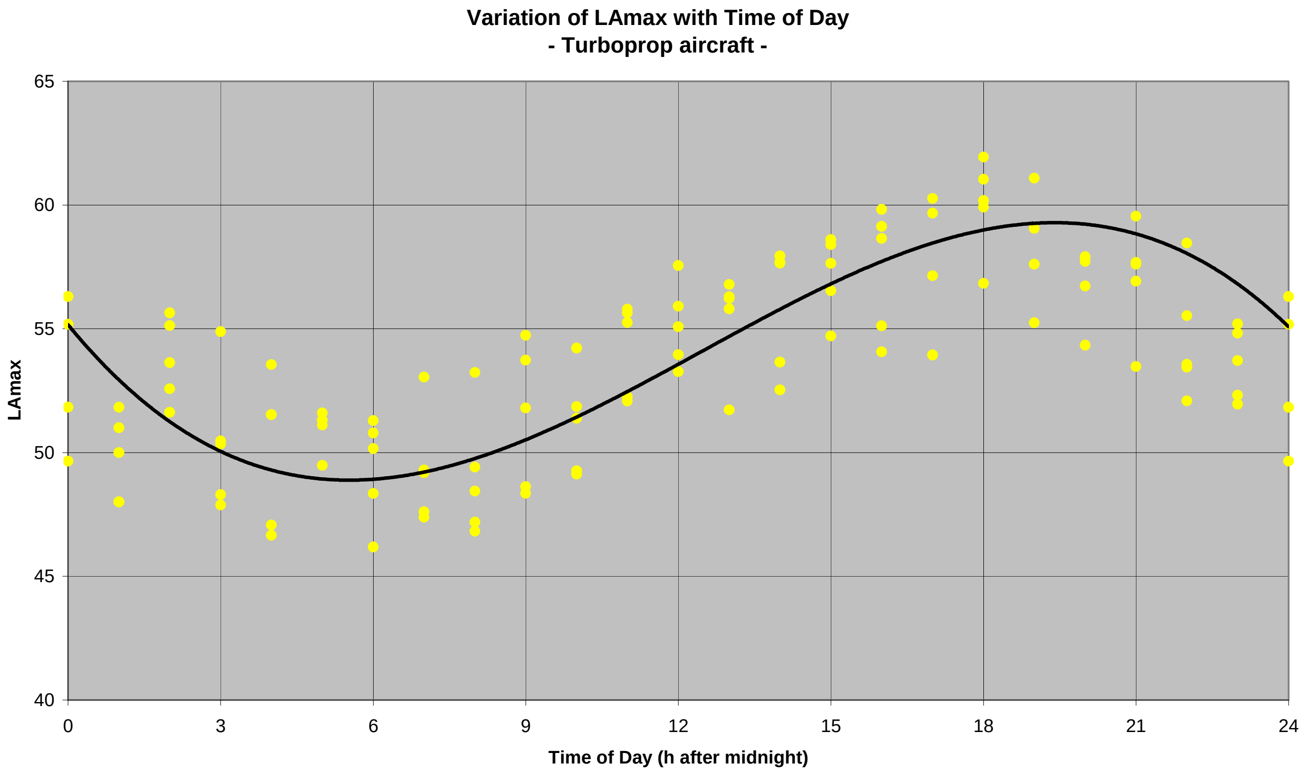
# 4 Data presentation

Once data will be available on en route noise, it should be made easily accessible and understandable in the political discussion on this subject. The objective of this section is to recommend a preferred way to present the data. However, since at present no such data is available, it is difficult to propose a definite format. The following presentation scheme should therefore be considered an initial guideline, to be revised once data becomes available.

The same data can be presented in many ways, depending of the objective and the corresponding aspects to be considered. Hereafter some relevant relationships are presented. It should be noted that the data presented does not represent actual measured or predicted values.

Variation of noise over time of day

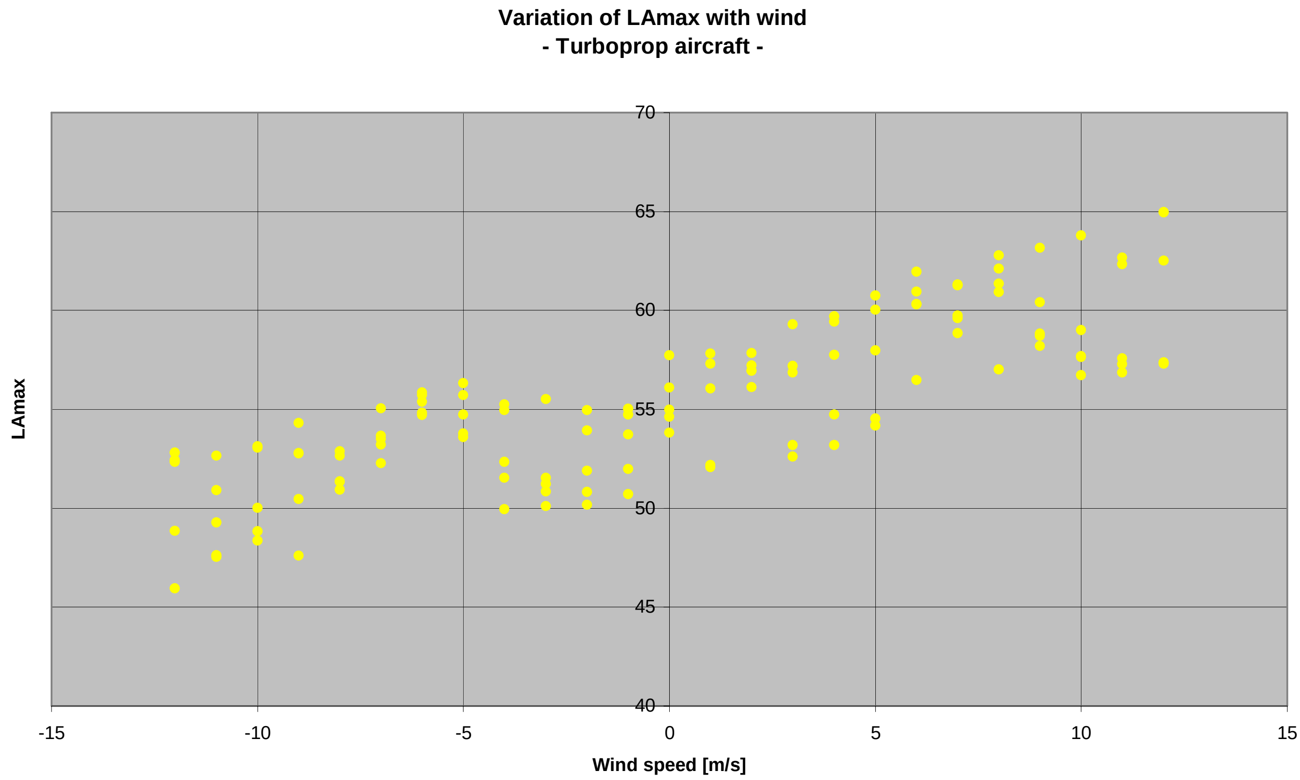
The time of day at which a noise event occurs is an important parameter when assessing noise impact and annoyance. However, this aspect is considered to be beyond the scope of this study. An effect which might alter the noise level received depending on the time of day is in fact related to atmospheric conditions. At night a temperature inversion may occur which has a significant effect on noise propagation. A possible way of presenting this is depicted in the following graph. It should be noted that this graph should be elaborated for each aircraft type (turbofans, turboprops, etc).



| Security class | Document ID | Issue no. | Issue date | Page |
|---|---|---|---|---|
| Restricted | PAN069-1 | 2 | 18/05/2008 | 14 of 22 |

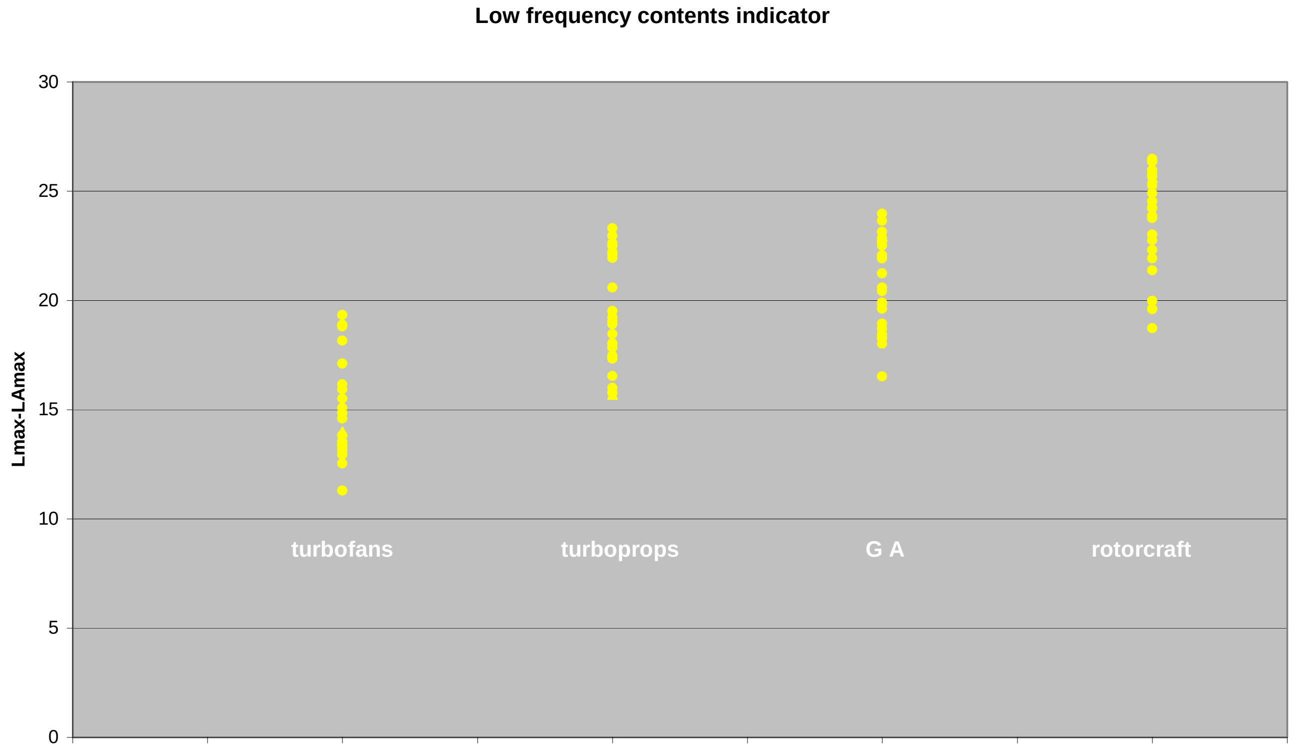
Variation of noise with atmospheric conditions

Atmospheric conditions like wind and temperature gradients might significantly alter noise propagation. The following graph is proposed to cover this aspect. A graph should be elaborated for each aircraft type considered.



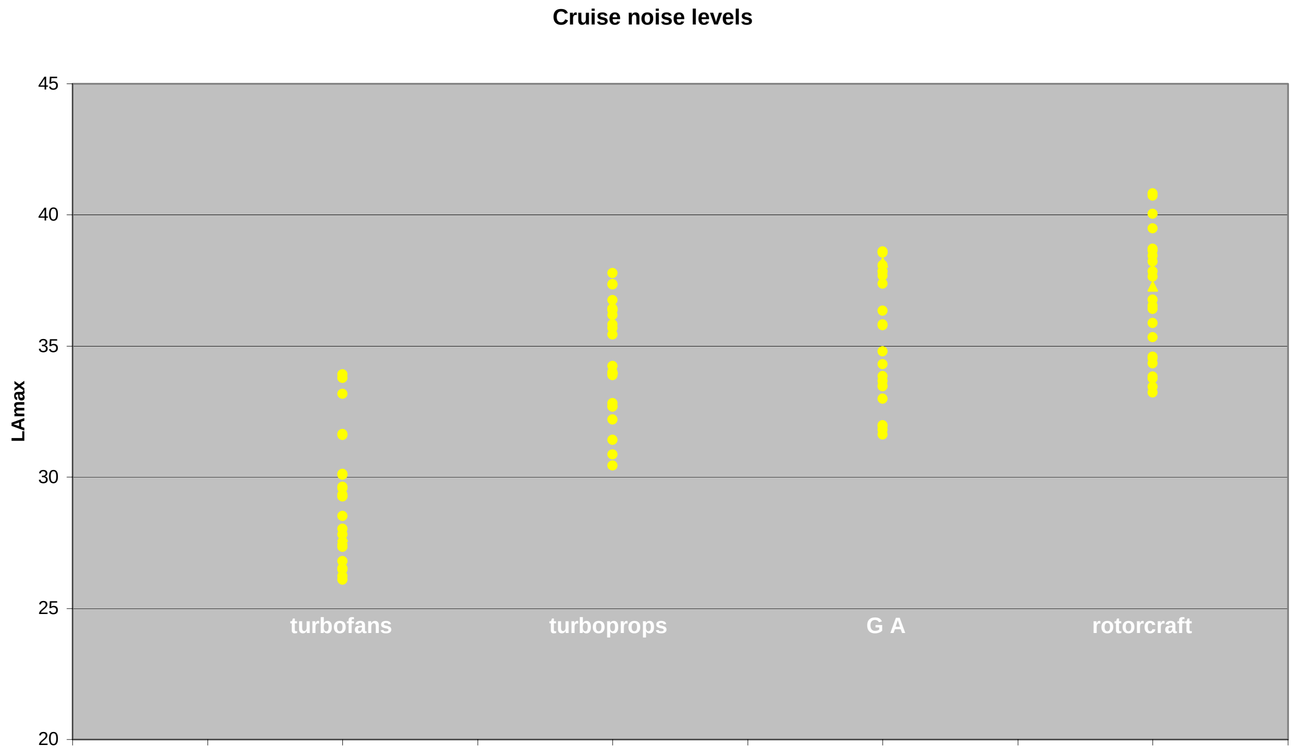
Variation of noise over the sound spectrum

For the large distance between aircraft and observer, typical for cruise, high frequencies will most probably have been attenuated below detectable levels before reaching the ground. A shift to lower frequencies will occur. At these lower frequencies the reduction due to the A-weighting will be significant. This behaviour may be used to give an indication of the low frequency contents of a spectrum. To this end the LAmax can be compared with the linear level (Lmax). The following graph presents the difference Lmax-LAmax for the various aircraft types. The higher this difference, the more low frequency contents can be expected in the spectrum.



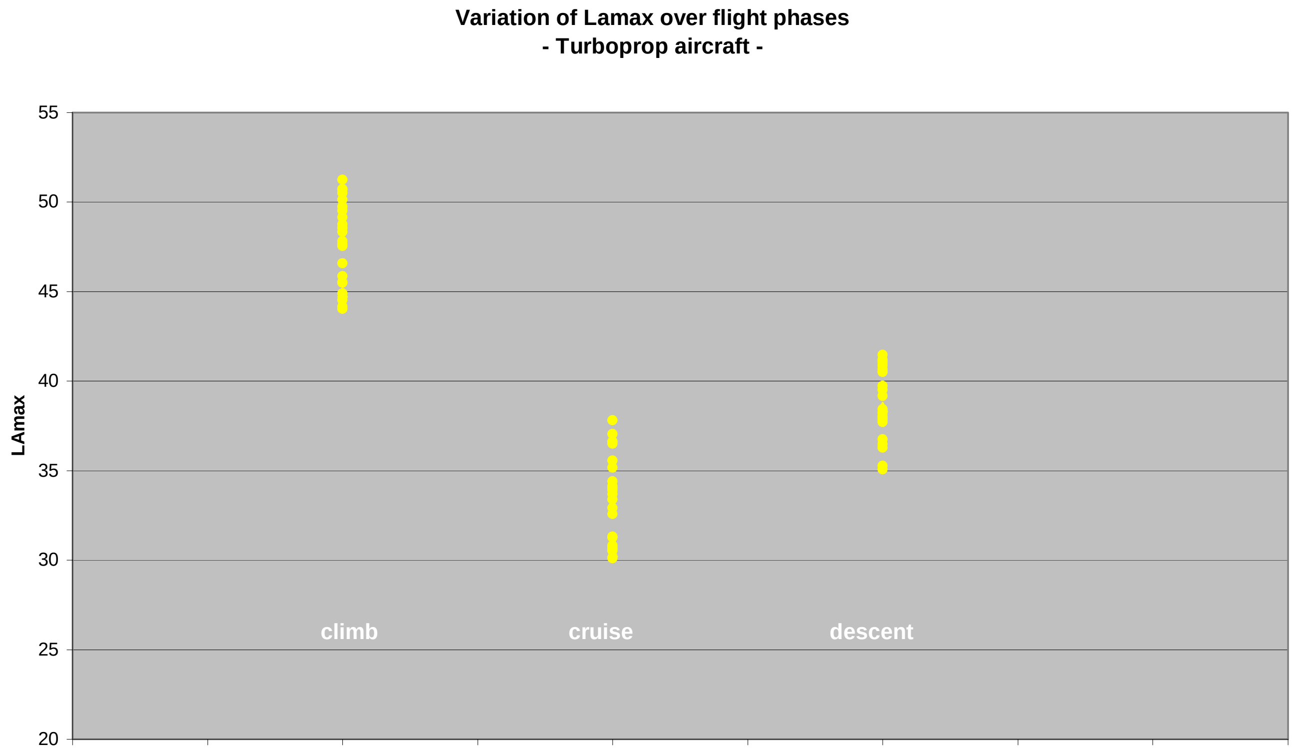
<u>Variation of noise over aircraft types</u>

As was seen in section 2.3 the different aircraft types (turbofans, turboprops, general aviation and rotorcraft) generate different en route noise levels, due to different noise sources involved and the difference in cruise altitude. The following graph is proposed to demonstrate this variation.



Variation of noise over flight phases

For the various flight phases of interest the noise received will be different, due to different operating conditions and distances. The following graph is proposed to demonstrate this variation.



# 5 Options for further Research

From the present study it became clear that no database exists with en route noise levels representative for the current aircraft fleet. In order to support development of future legislation for new aircraft or powerplant concepts, for which en route noise might be an issue, such a database would be highly desirable. Further research efforts should thus be directed towards obtaining that database, which then should serve as a reference.

Basically 2 approaches exist to obtain such a database: Modelling or Measuring.

## 5.1 Option 1: Modelling

From the present study it became clear that one should be very cautious when extrapolating data acquired at low altitudes and low speeds to cruise conditions. Integrated models like INM are not well suited for this purpose, mainly due to limitations in the applicability of the NPD database. This problem could (at least partly) be overcome when the NPD data would account for the effects mentioned in section 2.3.2. This would require re-analysis of the original data, applying the pertinent corrections to make them representative for en route conditions. If at all possible, this would require a new correction procedure, which should be developed and validated. Apart from this technical challenge, a probably more problematic issue would result to be the answer to the question “Who would do this job?”. The original data is usually manufacturers proprietary and it is very unlikely that they would want to share these data with a third party to perform the re-analysis, nor can one expect them to do it themselves.

A work-around might be the development of a semi-empirical correction procedure to be applied directly to the NPD data. However, it seems quite unlikely that such a correction method would give sufficiently accurate data.

Another option would be to rely on a full prediction scheme like ANOPP or SOPRANO. Although it seems feasible to include the mentioned effects in these models (albeit with a significant development effort), a similar issue will arise as with INM. This kind of models requires very detailed input data on both engine hardware and operating conditions, usually only available from the engine manufacturers. It can not be expected that they would want to share this information, nor that they would be willing to perform the work in-house.

Obviously both options for modelling would require a significant effort in development of new prediction methodology. In addition the validation of such new models would require comparison with measured data, which does not yet exist and should thus be generated. Access to the data required to perform the calculations with these models will most likely pose serious challenges.

At this stage it is not possible to estimate the cost involved, but it obviously will be far beyond the proposed budget range of 10 to 90 k€. Therefore it is not recommended to pursue modelling as a way to generate the required database of aircraft en route noise levels.

## 5.2 Option 2: Measuring

Measuring noise received from aircraft en route is a fairly straight forward way to obtain a representative database of sufficient quality. In order to extract as much information as possible from the data to be recorded the aspects mentioned hereafter should be addressed.

**Careful selection of the test site(s)**

The test site(s) should be selected such that a high traffic volume may be expected. This implies that the measurements should be carried out underneath main airways. Apart from the number of movements it is also important that the aircraft types expected to pass are representative for the current airline fleet. If at a certain test site only a segment of the fleet can be covered (e.g. only intercontinental traffic), more sites should be visited in order to extend the database to the whole range of current types.

In order to limit the scatter in the data care should be taken that the flight conditions of the passing aircraft are as constant as possible and representative for the flight phase covered. This means that the test site(s) should not be chosen close to points where transitions from one flight phase to another may be expected.

Obviously the noise levels to be measured are relatively low. Therefore care should be taken that the background noise level at the test site is as low as possible during the whole test period. Special attention should be addressed to sources of low frequencies and infrasounds like windmills which, even if they are located far from the test site, might contaminate the measurements significantly.

**Atmospheric conditions**

It is known that atmospheric conditions may alter significantly the noise received on the ground. It is therefore required that the measurements are carried out under several representative conditions. The timing of the measurement campaign(s) shall be such that main parameters like wind direction and gradients and temperature gradients are expected to be stable and representative for e.g. favourable and unfavourable propagation.

Information should be gathered on the atmospheric conditions during the test period. This information should be representative for the conditions at the test site and should at least contain wind speed and -direction, temperature, humidity and pressure for a range of heights as big as possible.

**Data related to the aircraft**

It is recognised that detailed information on e.g. the operating conditions of the aircraft measured will not be available, since this would mean having access to FDR data. However, in order to obtain a useful dataset at least a good estimate of the flight level above the test site will be required, in addition to an identification of the aircraft type and the flight phase (climb, cruise, descent). It is noted that for descent the noise levels are expected to be very low, if not undetectable. Some test time should be dedicated to this phase in order to confirm this assumption. The major part of the test time however should be dedicated to cruise and climb in an approximately 3:1 ratio. The record of the aircraft data shall be synchronised with the acoustic data in order to correlate both.

**Acoustic data**

During the measurement campaign(s) the acoustic signal received on the ground shall be recorded with a high quality system, capable of generating third octave spectra for each 0.5 s over a wide frequency range. For the long distances considered atmospheric absorption will reduce the high frequency contents of the spectrum to probably undetectable levels. An upper frequency limit of 10 kHz is therefore considered more than sufficient. However, the low frequencies will propagate more easily and envisaged future aircraft and powerplant concepts are expected to generate significant levels in this range. Although for covering the audible range a lower limit of 20Hz would be sufficient, low frequency sound incident on a building façade may excite structural parts (e.g. window panes) into vibrations. Although acoustically-induced structural vibrations may be imperceptible, they may cause rattle (intermittent loss of contact between two bodies due to vibration). Rattle causes secondary noise emissions in the audible range. Since phenomena like sonic boom generate noise in the range of frequencies well below 20 Hz, it is considered necessary to include infrasound in the analysis of the measurements. It is recognised that processing of transient signals may give rise to issues for the very low frequencies. Therefore, even though measurement hardware is capable of recording signals down to frequencies in the order of 5 Hz, it is considered more appropriate to set the lower frequency limit to around 10 Hz. In this frequency range special attention should be given to noise generated by atmospheric turbulence.

Due to the emphasis on the low frequency part of the spectrum it is considered essential to avoid ground reflection effects in this range, which thus implies measurements as close to the ground as possible. Therefore the microphone setup as prescribed in Chapter 10 of ICAO Annex 16 shall be used, where an inverted microphone is placed 7 mm above a ground plate of 40 cm diameter.

In order to study the appropriateness of different metrics, the measured data shall be presented with various weighting filters (i.e. at least Lin, A and C). These weightings shall be applied to both equivalent and maximum values. Whenever possible (i.e. if 10 dB down is reached) also the EPNL shall be calculated.

The recordings shall be made such that at a later stage the sound can be reproduced in the laboratory. It also should be possible to replay the recordings for re-analysis. The latter requires that calibration information is available so as to assign appropriate sensitivity to the recordings.

The time of day of each noise event shall be recorded.

The abovementioned characteristics can be found in both manned and unmanned systems. The main advantage of manned systems is that the correlation between acoustic and aircraft events will be (near to) 100%. Obviously this reliability comes with a cost, which will make it unviable to perform real long-term measurements. Unmanned systems can be placed at an appropriate site and measure for months without significant additional cost (although it should be noted that the requested (inverted) microphone setup does not seem appropriate for all weather measurements). However, the correlation between noise and aircraft events will most likely be lower than with manned systems. Even though current monitoring systems are capable of separating aircraft from non-aircraft events, their algorithms are usually based on higher noise levels than those expected here and in addition information from trajectory systems (e.g. radar) is usually required. The choice between the use of a manned or unmanned system will thus mainly be a choice between less measurements of high quality or many measurements of lower quality.

**Proposal for future work**

The following table gives a proposal for measurement campaigns for 3 different levels of available budget. The abovementioned aspects are common to all budgets. The work is based on the assumption that a manned system is used, operated in 2 shifts daily. The stated test time is presented to give an order of magnitude only, since it will obviously strongly depend on the hourly rate applied by the performer of the work.

| Budget [k€] | Description of work | Proposed deliverable(s) |
|---|---|---|
| 10 | Short test campaign (order of some days) at a single point.<br>*Note: Due to the very limited test time the resulting database will not be representative for a practical range of conditions. The added value of this option is therefore considered minimal.* | Test report |
| 40 | Medium test campaign (order of 3 weeks). This option would allow for 2 or 3 short test campaigns, distributed over quite separated sessions to cover more atmospheric conditions. A statistical analysis shall be performed on the test results.<br>*Note: This work fully addresses the gap indicated in 3.1 and partially that of 3.2.(scatter)* | Test report<br>Analysis report |
| 90 | Long test campaign (order of 8 weeks). This option would allow for several weeks long test campaigns, distributed over quite separated sessions to cover more atmospheric conditions. A statistical analysis shall be performed on the test results.<br>*Note: This work fully addresses the gap indicated in 3.1 and partially that of 3.2.(scatter)* | Test report<br>Analysis report |

Summarising, it can be concluded that a budget of 10k€ will not be adequate to address the knowledge gaps. With a budget of 40k€ a significant step forward can be made, although the statistical validity of the resulting dataset might not be sufficient. A budget in the order of 90k€ is considered sufficient to obtain a comprehensive database of en route noise levels of current aircraft and a good estimate of the scatter involved.

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