Aircraft noise modelling validation through the use of full 4-D flight trajectories including thrust calculation

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Abstract

The European Harmonised Aircraft Noise-Contour Modelling Environment (ENHANCE) is a EUROCONTROL Experimental Centre (EEC) project sponsored by the EUROCONTROL Directorate for Safety, Airspace, Airports and Information Services (DSA). It aims to improve the quality of noise contours produced by the United States Federal Aviation Administration's (FAA) Integrated Noise Model (INM) or other noise models. The task mainly consists in improving the quality of the input data used by these models and validating the calculated noise levels against measured data recorded by ground monitoring systems. In order to accomplish this objective, an interface/pre-processor combination is used to enable full 4-D trajectories taken from smoothed radar data (or from an ATC simulator) to be used for noise calculations. Additionally, thrust is calculated from these trajectories, rather than from standard default procedures.

Several campaigns of data collection have been initiated in Manchester (UK), Madrid (Spain) and Schiphol (Netherlands) airports. These data collections have provided preliminary sets of Radar, Flight Data Recorder (FDR) and Noise Monitor (NM) data for flights under operational conditions. The radar data were smoothed into 4-D trajectories using the Multi-Radar Trajectory Reconstitution facility – MURATREC. These smoothed trajectories were used to produce noise values that were compared with the NM values. The effect of taking local weather information into account was also evaluated. The FDR data were used to evaluate the ENHANCE thrust model.

In parallel to this work, effort has been provided through a contract with AM Airbus to provide noise and performance data for several Airbus aircraft, thus enabling accurate values for these aircraft to be taken into account rather than having to use aircraft "substitutions". The FAA and Boeing are providing similar effort to update noise and performance data for Boeing aircraft.

It is a programme of collaborative work in Europe, sponsored by EUROCONTROL, as a complement to the work being conducted in voluntary CAEP (ICAO Committee on Aviation Environmental Protection) and ANCAT (ECAC Abatement of Nuisance Caused by Air Transport) working groups, which will ultimately propose revisions to the noise modelling methodologies published by these bodies.

1 Introduction

The increasing use by airports of modern aircraft noise and flight path monitoring systems has led to closer scrutiny of noise contour methodologies and, in turn, to concerns that, in general, existing models are insufficiently accurate for many applications.

In September 98, the EUROCONTROL Experimental Centre (EEC) conducted a survey of its stakeholders to determine their views on what activities the EEC should be working on in the domain of Environment and Air Traffic Management (ATM). One of the principle activities proposed was "Methods and models for calculation of noise; validation of the Integrated Noise Model (INM) against real measured data". The response (from the 51 stakeholders who replied) was a very significant approval (94%) for this activity, together with some explicit suggestions to co-ordinate work on this subject.

The European Harmonised Noise-Contour Modelling Environment (ENHANCE) project has been undertaken by the EEC, with sponsorship from the EUROCONTROL Agency's Directorate for Safety, Airspace, Airports and Information Services (DSA), in order to help alleviate the concerns expressed above by providing a harmonised, user-friendly interface for noise contour modelling, independent of the actual model used and enabling these models to take simulated data, radar data and European aircraft characteristics into account.

The overall objectives of the ENHANCE project are:

1. a robust, industry-built, validated, noise-modelling environment catering for the different noise models in use in Europe thus enabling increased European commonality;
2. improved quality of noise-model input data (use of full 4-D trajectories instead of standard "nominal" trajectrories) thus enabling improved noise contours to be computed by these models;
3. an evaluation of the reliability of enhanced noise contour models for use in airport noise mitigation studies by comparing calculated and measured noise levels;
4. a database relating to European fleet mixes and operating conditions allowing more accurate modelling of noise around European airports;
5. input for updated International Civil Aviation Organisation – Committee on Aviation Environmental Protection (ICAO-CAEP) and European Civil Aviation Conference (ECAC) guidance material;
6. the incorporation of accurate noise impact assessments into air traffic simulation.

This paper is primarily concerned with the following aspects of the project:

- input data improvement, through the use of full 4-D trajectories;
- comparison of calculated and measured noise levels;
- aircraft database improvement (Airbus aircraft).

2 Aircraft Noise Contour Modelling: the state of the art

Different models are currently employed throughout the world for modelling the noise produced around airports by aircraft's taking off and landing. The main reason of the existing disparity is probably the complexity of the problem, leading to the development and the use of more or less sophisticated solving methodologies.

These models can be actually classified according to two main categories/approaches:

- The simulation approach
- The integrated approach

2.1 The simulation approach

This approach consists in simulating the sound propagation from the moving noise source (i.e. the aircraft) to the receiver on the ground (ray tracing method, for instance). That kind of sophisticated methodology has the advantage to be able to account for physical parameters affecting noise during its propagation (meteorological effects, terrain and barrier effects). Another advantage of the simulation approach is its ability to calculate the time history of sound pressure level as the single event noise descriptor. From this, it is indeed easy to calculate in a post processing way noise levels and contours according to any type of noise metrics (based on energy, maximum sound pressure levels, etc…), with no need to re-run the simulation. Nevertheless, this approach needs a very high computing power, often inconvenient to calculate noise impact resulting from a whole traffic around airports.

2.2 The integrated approach

This approach is based on work performed by the American Society of Automotive Engineers' (SAE) A21 aerospace committee. This committee's work on aircraft noise calculation was published in a document entitled "Procedure for the calculation of airplane noise in the vicinity of airports", generally known by its reference number "AIR-1845". This model has been adopted by ICAO in its publication "Recommended Method for Computing Noise Contours around Airports", known as "Circular 205", and subsequently by ECAC in "Report on Standard Method of Computing Noise Contours around Civil Airports", referred to as "Doc. 29". Though these last two contain some modifications to the original work, the underlying models they describe are basically the same. A good example of tools applying this type of methodology is probably the FAA's INM (Integrated Noise Model).

The integrated approach is based on the use of integrated noise data (aircraft noise database), derived either from aircraft noise certification data or from measurements at local airports (therefore under operational conditions). These aircraft noise data, usually called NPD's (for Noise Power Distance), are a set of noise curves specifying for different aircraft types the perceived noise level as a function of the shortest distance between the aircraft trajectory and the ground receiver, for different aircraft thrust power settings. These curves are "integrated" in the sense they directly provide noise values according to the different usual single event noise indicators (SEL, Lamax, etc…), instead of delivering the instantaneous sound pressure level. Moreover, these NPD's are normalized: they represent the noise produced by infinite path flybys (with constant height and speed), under standard meteorological conditions. To calculate the noise produced by a "real" flight, at a particular airport, the methodology globally consists in applying corrections to the baseline of noise levels obtained from the NPD curves, to account for differences between the actual operating conditions, and the normalized ones. For exposure-based noise metrics (ex: SEL), some models divide the real trajectory into small straight sub-segments (segmentation) on which aircraft parameters are near constant. The noise contribution of each finite sub-segment is calculated by applying a noise fraction adjustment to the noise level obtained from the NPD's for an infinite segment. Another major aspect of the methodology is the application of a lateral attenuation correction, to account for differences between noise perceived under the trajectory and noise at lateral positions. The most commonly used lateral attenuation correction model is provided by the SAE "AIR1751" document, but some countries use their own model, derived from measurements at local airports.

Its main advantage, compared to the simulation approach, is to be computationally faster to calculate noise contours resulting from a whole traffic. Moreover, the aircraft database (noise data but also aircraft performance data) of models using this approach are often more advanced (exhaustive) than those of simulation models.

Whilst some countries use specific noise models based on the simulation approach and developed in response to particular requirements at specific airports, most of the countries use the integrated approach, and the Integrated Noise Model (INM) in particular. This model has two main attractions – it is relatively inexpensive and it is supported by the FAA who incorporate many of the suggestions and requests emanating from its international body of users.

2.3 Limitations in current noise modelling practice

The simulation approach requires a highly detailed characterisation of aircraft noise source (spectrum and directivity) which is particularly complex to reach. Practically, the existing noise models applying this approach focus on limited aircraft "families", operating at specific airports, under specific conditions.

The integrated approach can not properly take into account acoustical effects occurring during sound propagation (refraction for instance). More precisely, the propagation effects (except terrain effects) are implicitly taken into account in the NPD's and the lateral attenuation model, but only for standard atmospheric conditions. For local conditions differing from the standard ones, this approach can not completely account for the resulting changes in sound propagation.

In addition to the limitations described above and resulting from the solving methodologies (i.e. simulation or integrated approach), the way to define the input data has a strong effect on the calculated noise contours. Indeed, there is often a lack of adequate information about the way in which aircraft are actually operating (trajectories, flight profiles, etc…).

International working groups, such as ICAO-CAEP Model 1, or ECAC-ANCAT, aim at proposing revisions of official guidance (ICAO C205 and ECAC Doc29 documents) in terms of best practice in aircraft noise modelling.

In particular, the Model 1 working group has reviewed different existing aircraft noise models, to assess their performance and to determine where improvements might be achieved. Currently, results from different models show considerable variance. Such a variance comes not only from the solving methodology but also from the way to specify the input data (i.e. the aircraft types and their flight trajectories).

An important improvement would be particularly the development of an international and reliable aircraft database (including noise data but also operational data) which all model users could refer to.

2.4 INM specific limitations

INM, though an excellent tool, has several drawbacks from a European perspective:

- it is based on the notion of a ground track and a standardised height/thrust/speed profile read from a database of aircraft performance characteristics and aircraft flight profiles;
- use is generally made of nominal tracks based in Standard Instrument Departures and Standard Arrivals (SIDs and STARs) with Gaussian dispersion around these tracks to represent the differing tracks of several aircraft; no vertical dispersion is applied;

- the Noise-Power-Distance (NPD) curves and performance data in the INM database are, in the great majority, those of aircraft most often found in US fleet mixes: substitutions have, therefore, to be made for Airbus aircraft;
- aircraft standard profile data are those generally in use at a typical US airport and are not necessarily applicable to European airports.

These inaccuracies in input data lead to inaccuracies in the noise contours produced and to an inability to validate the model for European use.

3 ENHANCE approach

The ENHANCE project aims at improving modelling practice by:

- Allowing a tool like INM to easily use (through a friendly user interface and a pre-processor) full 4-D trajectories taken from radar or simulator data - each flight being modelled individually;
- calculating thrust from these 4-D trajectories;
- passing a contract with AM Airbus for the provision of NPD curves and performance data for Airbus aircraft.

ENHANCE provides a means of comparing the noise values modelled using true aircraft trajectories with measured values

3.1 Use of full 4-D aircraft trajectories

In order to calculate noise contours, a model like INM needs successive values of five basic parameters: x and y ground position, height, speed and thrust (to access the NPD curves). INM usually takes the x and y values from nominal ground tracks. All the aircraft of a given studied fleet mix are assumed to follow these nominal tracks, with possibly a ground Gaussian (symmetric) dispersion around the backbone tracks to integrate more realism.

Values for height, speed and thrust corresponding to the successive values of x and y are obtained by INM in one of two different ways, depending on data available for a given aircraft type in the INM databases.

1. Profile points: values for height, speed and thrust are given in a fixed points profile database as a function of the travelled ground distance for a given aircraft.
2. Procedure: values for height, speed and thrust are calculated from take-off or arrival procedures pre-defined for each aircraft type.

In any case, no vertical dispersion is applied.

The approach of ENHANCE consists in replacing nominal ground tracks and standard pre-defined height and speed profiles with full 4-D trajectories taken from radar or simulator data - each flight being modelled individually. In such a way, real dispersion, not only on the ground but also vertically can be taken into account in the noise modelling process.

Figures 1 and 2 illustrate these two different approaches:

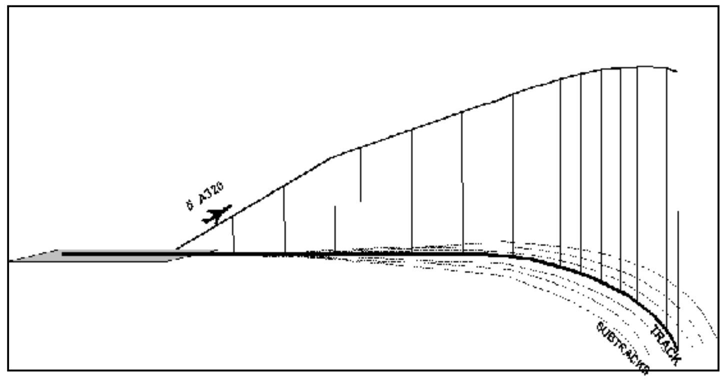

Figure 1: INM input data formalism

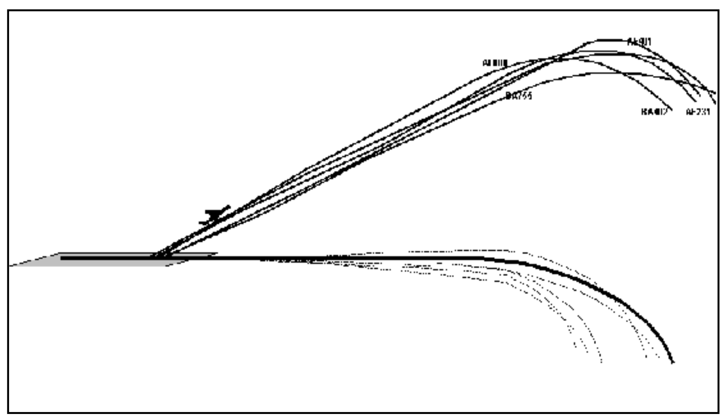

Figure 2: ENHANCE full 4-D trajectories approach

Real dispersion resulting from aircraft performance, operational weights, local meteorological conditions and any ATC effect (in particular for arrivals) has a significant effect on the resulting noise contours.

Figure 3 illustrates this effect, for a specific departure procedure at Toulouse Blagnac airport, by comparing noise contours produced by INM “stand alone”, using the theoretical track combined with standard INM flight profiles, and ENHANCE associated with INM to fully account for real trajectories (radar):

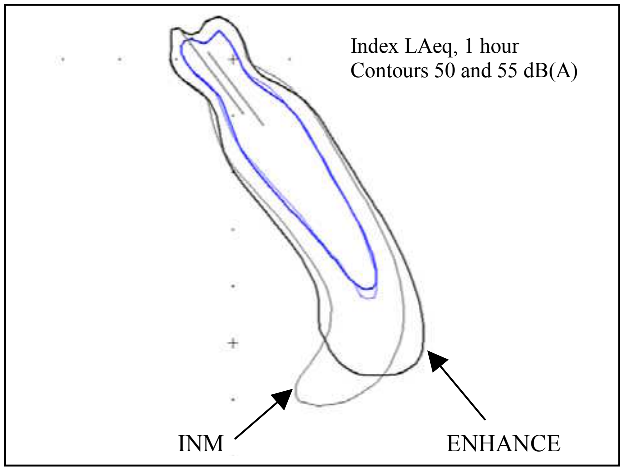

Figure 3: Effect of using real trajectories on noise contours

3.2 Calculation of Thrust Profiles from 4-D Aircraft Trajectories

When using radar data (or even simulated data), the missing parameter to calculate noise contours is engine thrust. ENHANCE automatically calculates thrust profiles, in a reverse-engineering way, by using the thrust equations of the INM aircraft performance model.

For departures, the following equation is used to calculate the Corrected Net Thrust per engine:

$$F_n/\delta = E + F\,v + G_A\,h + G_B\,h^2 + H\,T_C$$

where
F_n/δ corrected net thrust per engine (lbs),
δ pressure ratio at aircraft altitude
v equivalent/calibrated airspeed (knots),
h pressure altitude (feet) MSL,
T_C temperature (°C) at the aircraft,
E, F, G_A, G_B, H: Jet coefficients that depend on power state (max-takeoff or max-climb power).

One of the parameters used in the above equation is the Calibrated Air Speed (CAS), which cannot be obtained from 4-D trajectories, unless wind speed, temperature and air pressure are known. If these parameters are known, they enable calculation of CAS from ground speed under the following formula:

$$v = v_T\,\sigma^{1/2}$$

where
v calibrated airspeed (knots),
v_T true airspeed (= 3-D ground speed corrected for wind vector component)
σ air density ratio at aircraft altitude

For arrivals, the following equation, based on the zero-total-force principle, is used to calculate the Corrected Net Thrust per engine:

$$F_n/\delta = (W/\delta)\,[R_f - \sin(\gamma) / 1.03] / N$$

where
(F_n/δ) corrected net thrust per engine (lbs)
W approach or touch-and-go profile weight (lb),
δ pressure ratio at aircraft altitude,
R_f drag-over-lift coefficient that depends on flaps and gear setting,
γ average descent angle,
N number of engines.

ENHANCE takes 4-D trajectories from radar data or from simulator data and calculates the thrust values at each point of the trajectories, using the above formula and the associated INM thrust and drag-over-lift coefficients databases.

Moreover, some procedure assumptions have to be made. For departures, a thrust cutback altitude parameter is used. For arrivals, it is required to specify where (or when) changes in flap settings occur. In the current ENHANCE version, changes in flap settings are supposed to occur at specific altitudes (which can be easily modified by the user).

3.3 Smoothed 4-D radar trajectories

Radar data are, by nature, inaccurate. For any work involving the need for a high level of precision, such as calculating thrust profiles, these must be smoothed.

At present, work on radar data for use with ENHANCE makes use of the Multi-Radar Trajectory Reconstruction facility (MURATREC) included in the Surveillance Analysis Support System for Control Centres (SASS-C). This is a fairly large, albeit efficient, hammer with which to crack this nut! It is intended to include a smaller smoothing algorithm in ENHANCE at a later date.

Although MURATREC was primarily designed to smooth multi-radar data, by producing a series of cubic splines through the radar plots, it also works with the mono-radar plots normally available to cover the vicinity of an airport.

3.4 Aircraft Database Improvement

INM makes use of several databases in order to calculate noise contours:

- A noise database specifying noise characteristics of different aircraft types (NPD curves);
- An aircraft flight profile database specifying how aircraft fly under operational conditions (as a function of takeoff weight for instance):
  - For procedure-based profile calculation, thrust and drag-over-lift values are taken from INM coefficient databases;
  - For predefined fixed-points profiles, values are taken from a fixed-points profile database.

These databases are also used by most of the other noise modelling systems in use and, as is explained above, present certain inadequacies when used for modelling noise in Europe.

In 2000, the EEC let a contract with AM Airbus to supply aircraft noise and performance data for three Airbus aircraft - A320, A330 and A340. These data have ever been integrated into the INM 6.0 version. This work is going on for other aircraft types (A300, A310 and A321 in particular). As part of joint work carried out under EUROCONTROL/FAA R&D Action Plan 13 these new data will be supplied to the FAA who will integrate them into future versions of INM.

Additionally, as part of the "Study of Optimisation Procedures for Decreasing the Impact of Noise around Airports" (Sourdine II) project - performed under the auspices of the European Commission's Fifth Framework Programme - for which ENHANCE is the common tool for noise modelling, the FAA has agreed to fund similar work with Boeing for updating information on their aircraft in these databases.

4 Noise Modelling Validation

4.1 Data collection

For the purpose of comparing calculated with measured noise levels, several contracts have been initiated in 2000 and 2001 with airlines, airports and Air Traffic Service Providers:

- Schiphol - a major international airport - via the Dutch National Aerospace Laboratory (NLR)
- Madrid Barajas - a medium-sized international airport
- Manchester - a large regional airport

The following airlines have supplied FDR data

- British Airways
- Iberia
- Cathay Pacific Airlines
- KLM

In total, combined radar, FDR and noise monitoring data for a first set of flights have been collected.

Some meteorological information (wind vector, temperature and air pressure values) have been also gathered at the airports on the day of the recordings.

4.2 Thrust model validation

Whilst allowing validation of the underlying noise model, ENHANCE adds its own uncertainty in reverse-engineering thrust values from the 4-D trajectory supplied to it. One part of any ENHANCE validation exercise must, therefore, be to validate this thrust model.

The first step consists in checking that ENHANCE produces the same thrust profiles than the INM standard ones, when using INM standard height and speed profiles as input of ENHANCE.

Figure 4 shows the comparison for an A320 departure, under standard conditions of temperature and pressure:

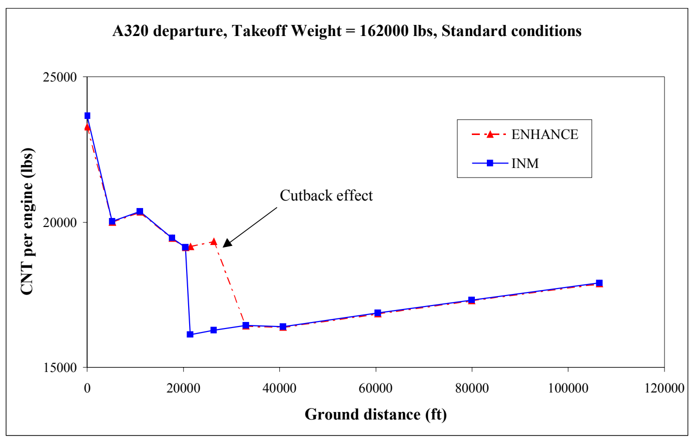

Figure 4: ENHANCE vs INM thrust profiles

The only observed difference comes from the thrust cutback criterion which, in the ENHANCE process for this example, was not the same as in the standard INM procedure (in ENHANCE, thrust reduction occured at a higher altitude). But the thrust cutback parameter can be easily modified from within the tool interface.

A similar evaluation is currently being conducted for thrust profiles calculated under non standard conditions of temperature and pressure, and for arrivals thrust profiles (the thrust calculation process for arrivals having been more recently integrated into ENHANCE).

To evaluate the ENHANCE thrust model (and implicitly the INM thrust model) against "real" thrust profiles, FDR data are used to provide Engine Pressure Ratio (EPR) or Fan Rotation Speed (N1). CAS, Temperature, Air pressure and Altitude parameters are also required to convert EPR or N1 into Corrected Net Thrust (CNT).

An evaluation has been started, based on the use of the available model within INM to derive Corrected Net Thrust from EPR or N1 (using regression coefficients depending on aircraft type). The CNT calculations thus obtained are compared with values calculated by ENHANCE, taking into account the weather information recorded at the same time as the flights.

Figure 5 makes the comparison for a B737-300 operating at Schiphol airport (departure):

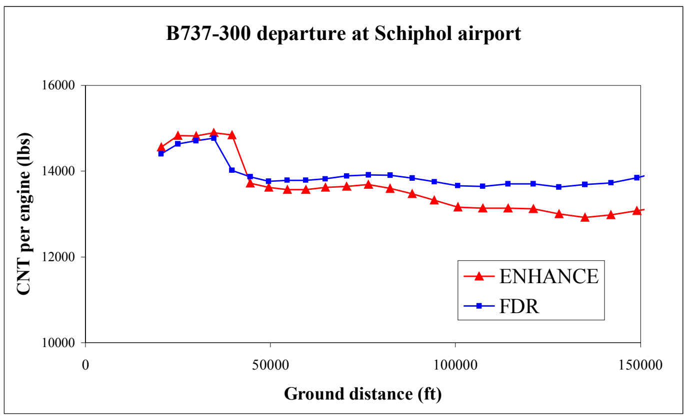

Figure 5: ENHANCE vs FDR thrust profiles

In this example, significant differences are observed, mainly after thrust reduction, from which ENHANCE under-estimates CNT. Similar results have been found for other aircraft types.

Nevertheless, this preliminary result should be taken very carefully since the reliability of the model which has been used to derive CNT from EPR/N1 has to be demonstrated. To go on with this thrust validation process, it is planned to use "real" manufacturer data instead to derive CNT from EPR/N1 (accounting for Mach number).

4.3 Calculated against measured noise levels comparison

Even if the thrust model still needs to be validated/improved, in order to provide accurate values for thrust, the noise values produced by ENHANCE have been compared with those measured on the ground for a selection of flights whose 4-D trajectories have been obtained from smoothed radar data.

Monitored flights have to be categorised into arrivals and departures, INM-known and INM-unknown aircraft types, flight paths to noise monitor location geometry (in particular, lateral distance and elevation angle), meteorological conditions at the time of the event, etc. to enable detailed analysis of the sources and sizes of errors.

Initially, this involves a pre-selection, and a careful examination of each flight. Many problems have been found in the collected mixed-origin datasets like these - incorrect (biased) timestamps, incomplete data for a flight from one of the sources, offsets in ground position, radar range and/or azimuth, etc. Some of these problems may be corrected, others necessitate that the flight be discarded. Additionally, NMs can not be taken into account for flights that are too far from them (measured noise levels being too low in that case).

The exploitable flights sample size has been therefore drastically reduced. A much larger amount of data will be required to determine statistical errors (i.e. observed differences between estimated and measured noise levels) as a function of the different parameters discussed above.

Figure 6 gives nevertheless a preview of the magnitude of the observed differences between estimated and measured LAmax levels (maximum noise levels) for several departures at Manchester airport (microphones located under flight paths):

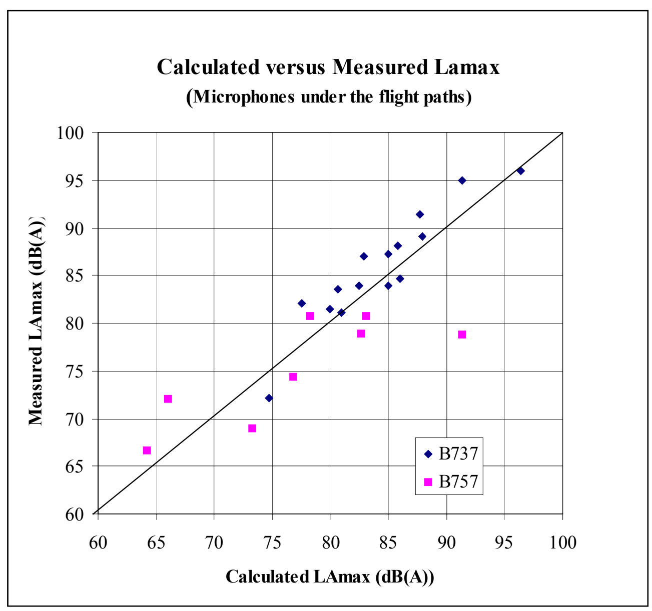

Figure 6: Calculated vs measured LAmax

This example shows in particular that despite the potentially large number of modelling errors, a good correlation between calculated and measured levels can be found for particular flight events. Such a good correlation has to be considered carefully: in some cases, it can result from a mutual cancellation of several modelling errors when combining together.

5 Further work

The thrust validation/improvement will be performed using manufacturer data to derive the required Corrected Net Thrust parameter from EPR/N1 information provided by FDR data. Moreover, other aircraft performance/thrust models like BADA (Base of Aircraft Data, a total energy based model) should be also investigated as a possible alternative or complement to the current ENHANCE thrust model.

The data collection process will be reinforced for the purpose of validating calculated noise levels against measured ones. In parallel, a theoretical sensitivity study has been started in order to determine which input parameters of the model are the most sensitive in the noise calculation process and which are least sensitive (study of the propagation of input errors through the model). It will also determine how several modelling errors combine together to produce the final output errors (i.e. noise errors).

Moreover, ENHANCE is the noise modelling environment used for the Sourdine II project, which is largely concerned with defining noise abatement procedures in approach. New NPD-type curves will be required that include aircraft configuration settings, thus enabling airframe noise to be better taken into account. Co-operation between EUROCONTROL, AM Airbus, the FAA and Boeing on Sourdine II will lead to the production of these more detailed databases.

6 Conclusion

This paper has presented preliminary results of work at the EEC into validating / improving INM, the major noise contour modelling system in use today, by using the European Harmonised Aircraft Noise Contour Modelling Environment - ENHANCE. It has shown how this validation is enabled through the use of 4-D aircraft trajectories, and carried out through a data collection exercise. It is hoped that future co-operation between EUROCONTROL and the FAA will lead, in time, to integration of ENHANCE techniques and INM to produce input for updated international guidance material.

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Authors biography

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