A Measurement and Prediction Method for determining Helicopter Noise Contours

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Abstract

This paper describes the techniques that have been developed in DERA to measure the acoustic directivity characteristics of helicopters and to predict noise level contours on the ground, using the DERA HAMSTER technique and the DERA HELIACT contouring tool, respectively. These techniques have been specifically developed for those military training and civil operations when the helicopter may be flying close to the ground, or within valleys in hilly terrain. In these circumstances the important radiation directions are often within 30° of the horizontal plane rather than directly underneath the helicopter. However measurement of the acoustic radiation pattern close to the horizontal plane may be difficult to interpret because of the continually changing influence of atmospheric refraction. The paper addresses this specific problem and proposes the use of the HAMSTER technique to derive accurate characterisation of the free-space acoustic radiation pattern over a directivity hemisphere. This data is applied in HELIACT to establish the helicopter noise contours, for flight over varied terrain and under the influence of atmospheric refraction due to meteorological effects.

1. Introduction

The determination of helicopter noise contours is becoming an important requirement for assessing the environmental impact of civil and military operations, both to reduce the noise exposure to the general public and to protect endangered species, particularly birds. These issues are addressed in the reports ([1] and [2]) of the NATO Committee on the Current Challenges of Modern Society (NATO CCMS) which recommended improvements in the measurement of the noise source and of the modelling of the radiated noise.

The sound radiated from helicopters has very strong directional characteristics that depend on flight condition and frequency. The radiation is not symmetric and there are large differences in the sound level under the helicopter compared to that to the side. The differences in the source noise level from front to rear, and across the range of flight conditions, may amount to 20dB or more. In addition the sound propagation is strongly influenced by the meteorology and terrain. All these features make the characterisation of the source, through measurement or prediction, a complex task. But it is very important to accurately represent these characteristics, since a 20dB variation can make the difference between the helicopter noise being environmentally tolerable or intolerable, with the latter possibly leading to the threat of legal action.

The starting point in constructing a model to predict noise contours is the accurate description of the helicopter source characteristics. Many research organisations, in Europe and the rest of the world, are developing aeroacoustic prediction techniques that could be used to determine the sound radiation from the main and tail rotors throughout the flight regime. However these techniques may be heavily dependent on CFD methods and consequently are currently too computationally intensive to be used in real time for true flight profiles. Practical prediction speeds can be achieved by interpolation within a pre-calculated database, for a range of flight conditions, of the far field sound level directivity around the helicopter. Usually only the sound level detail over a hemisphere covering the underside of the helicopter is needed since only in very rare circumstances is the sound radiated above the helicopter required. However, although the aeroacoustic techniques are very useful design tools, the accuracy has not been fully validated, particularly for the tail rotor, over the full range of flight conditions and in all relevant directions. An alternative interim approach, which is the subject of this paper, is to use measurements to establish the true free field helicopter directivity for use in predicting noise contours under a variety of conditions. A second objective of the measurements is to produce accurate data against which aeroacoustic techniques can be validated.

In 1998 the NATO CCMS arranged a trial in Moose Jaw, Canada, involving 11 organisations from the US, Canada and Europe to test several measurement techniques, for characterising the helicopter source directivity, using a Bell 412SP helicopter as the test vehicle. Most of the microphones, which were deployed in the trial by NASA, USAF and the RAF, were either mounted flush with the ground or were elevated but close to the ground. The USAF also used 4 individual microphones highly elevated to various heights. DERA adopted a vertical beamform array of 14 microphones, as shown in figure 1, to measure the directivity in the horizontal plane to overcome the problems associated with interpretation of measurements at grazing incidence, when the received sound could be influenced by the continually changing effects of atmospheric refraction. The results and theory behind the application of this technique are provided in reference [3].

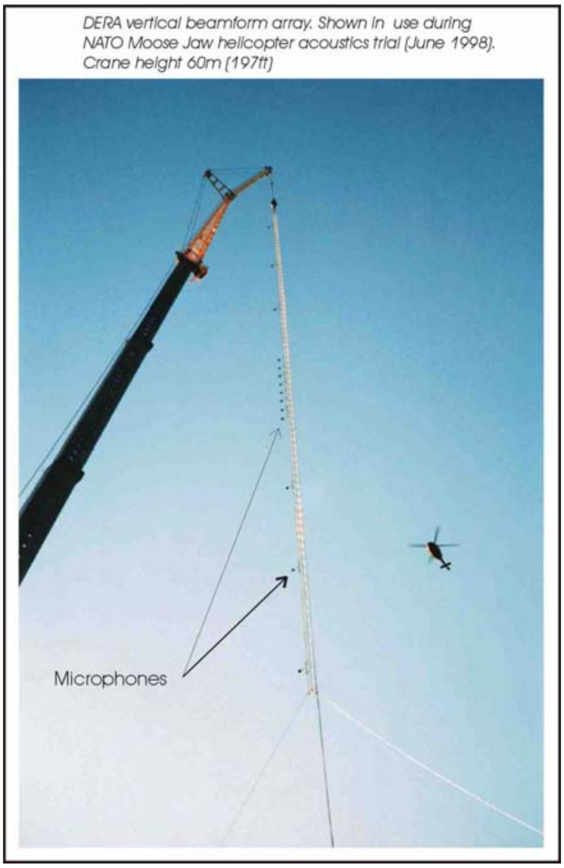

Figure 1. DERA beamform array

Section 2 of this paper discusses the potential problems of accurately measuring the sound level and the techniques adopted by DERA to overcome these problems to produce accurate sound directivity hemispheres. The helicopter acoustic contouring tool, HELIACT, being developed in DERA, is described in section 3 and illustrated in figure 2. Refraction of the radiated sound by temperature and wind gradients can have a very strong influence on both the measurement and contour prediction. It is these meteorological effects

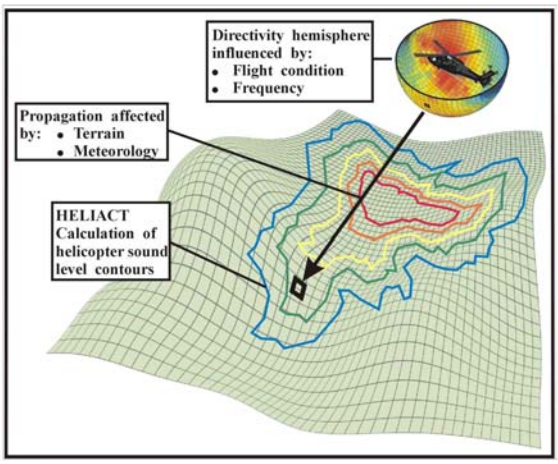

Figure 2. HELIACT - Helicopter Acoustic Contouring Tool

that form the main part of the discussion in this paper.

2. Measurement of Source Directivity

It is normal practice to measure the noise from helicopters using microphones that are either mounted flush with the ground or are elevated but close to the ground. A typical fly-by situation for level flight along a straight-line path is illustrated in figure 3 for a microphone placed flush with the ground. Here the co-ordinate system (r, θ, ϕ), adopted in this paper, is centred on the helicopter

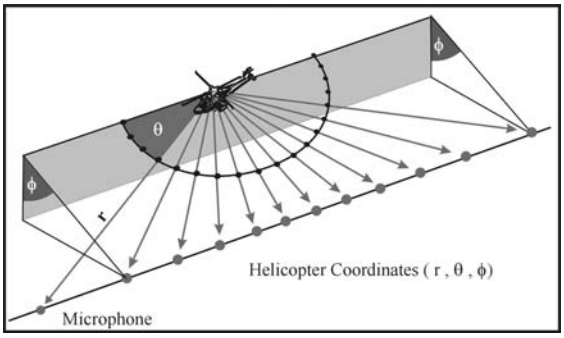

Figure 3. Co-ordinate system (r, θ, ϕ).

hub where r is the radiation distance to the microphone, θ is the angle to the flight line and ϕ represents the angle to the vertical though the rotor hub. During a perfect fly-by the microphone will appear to pass the helicopter in the plane of constant ϕ, whilst the angle θ to the flight path increases from 0^o on approach to 180^o on departure. Knowledge of the position of the helicopter at all times, using a suitable tracking system, allows the microphone recordings to be related to emission time. Then in principle, with the detail of the propagation characteristics, each component of the analysed spectrum, as 1/3rd Octave levels and tonal levels, can be collapsed to represent the level on an arc of constant radius, illustrated in figure 3. By placing the microphones at different sideline positions, measurements at different values of ϕ can be recorded and hence, by collapsing to the same radius, the noise levels on slices through a hemisphere can be created. Thus a directivity hemisphere can be built up for each frequency component for the specific flight condition. Because of the highly lobed character of the sound radiation it is recommended that the data is sampled to achieve a 5° resolution in both θ and ϕ.

There are two important considerations in deciding where to place the microphones. The first is the placement to minimise the influence of refraction due to atmospheric wind and temperature gradients. This leads to requiring short distances. The other is the requirement for a narrow band frequency resolution, to capture the tonal components of the spectrum, at an angular resolution in θ of 5°. A narrow band analysis assists in discriminating between the deterministic frequency components of helicopter noise and the unwanted background random noise. At the higher helicopter speed this requires the helicopter to be at large distance. Thus the microphone placement is a compromise between the requirements for short distance, to avoid refraction effects, and long distance to obtain good narrow band and angular resolution. It is important that these detailed considerations are addressed in order that the measurements have adequate sensitivity and accuracy.

2.1 Frequency and Angular Resolution

An angular resolution in θ of 5° is used in the DERA procedure to capture the lobed characteristics of the sound and also to prevent smearing of the frequency content of the sound. The angle swept out, *Δ*θ, in any increment in time, *T,* is dependent on the distance, *r,* of the helicopter

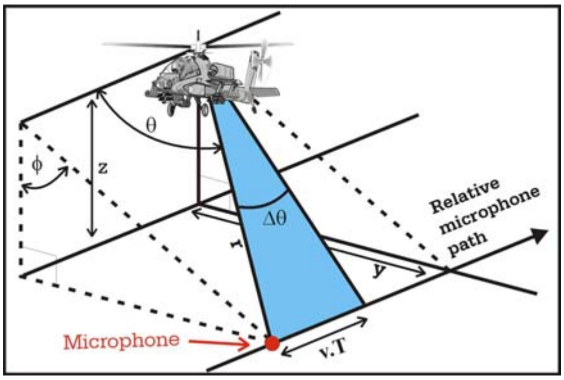

Figure 4. Change in θ over sample time T.

from the microphone, the angle θ and the helicopter speed *v*, as illustrated in figure 4. As the frequency resolution *Δf* is also related to the time *T,* in which a sample is taken to obtain a frequency spectrum (i.e. *Δf* = 1/T), *Δf* can be related to the required angular resolution *Δ*θ , viz.:

$$\Delta f = \frac{v}{r}\left\{\cos(\theta) + \sin(\theta)\cot(\Delta\theta)\right\} \qquad (1)$$

This relationship shows that if the distance r to the microphone is increased the resolution *Δf* in frequency can be improved, so r is the minimum acceptable range to achieve the required resolution at the given value of θ. In level flight at constant flight speed the angle, *Δ*θ , swept out in time *T* is small when θ is close to 0° and 180° and largest when θ is 90°. Thus the largest value of *Δ*θ is given at the closest distance, r = r_n , in the fly-by; at which point θ is 90° and then

$$r_n = \frac{v}{\Delta f}\cot(\Delta\theta). \qquad (2)$$

For a flight speed of 120 kts and for an angular resolution *Δ*θ = 5° it is noted that a frequency resolution of *Δf* = 1Hz would require a minimum radiation distance of 686m. However at this minimum distance, r_n, the microphone measurements are likely to be significantly influenced by the meteorological refraction effects. By relaxing the frequency resolution to *Δf* = 3.5Hz then the measurement distance is reduced to the more reasonable value of r_n =196m. Although the aim is to obtain a low value of *Δf* in order to discriminate between the deterministic helicopter acoustic frequency components and the undesirable random background noise, the compromise of *Δf* = 3.5Hz is acceptable under most circumstances. It should be noted that r_n is the distance to the closest point, when θ is 90°, during a fly-by, so better resolution is obtainable (cf. equation 1) at other values of θ*,* where $r > r_n$. Also at slower helicopter speeds a better frequency resolution is obtainable if r_n remains fixed at the value for the highest speed.

2.2 Effects of atmospheric refraction

The peculiarities of propagation, particularly the effect of atmospheric refraction, complicate any measurement exercise to characterise the sound radiated from a helicopter. For this reason the civil certification procedure requires specific meteorological conditions to be adhered to, and in particular the wind speed must not exceed 5m/s at 10m above ground along the line of flight. The positioning of the microphones for civil certification and the flight height are such that the maximum noise levels at the microphones, at ϕ = 45°, 0°, -45°, will occur at large angles of declination, over short distances and, where the refraction effects are small. However to generate footprints in all flight situations requires detail of the sound in the full range of ϕ and the influence of refraction for ϕ in the range 60° to 90°could be significant. To examine this issue the parabolic equation (PE) approach of West et al [4] has been used to calculate the effects of real wind and temperature gradients on the propagation from a uniform source at helicopter height, within the meteorological limits acceptable for civil certification.

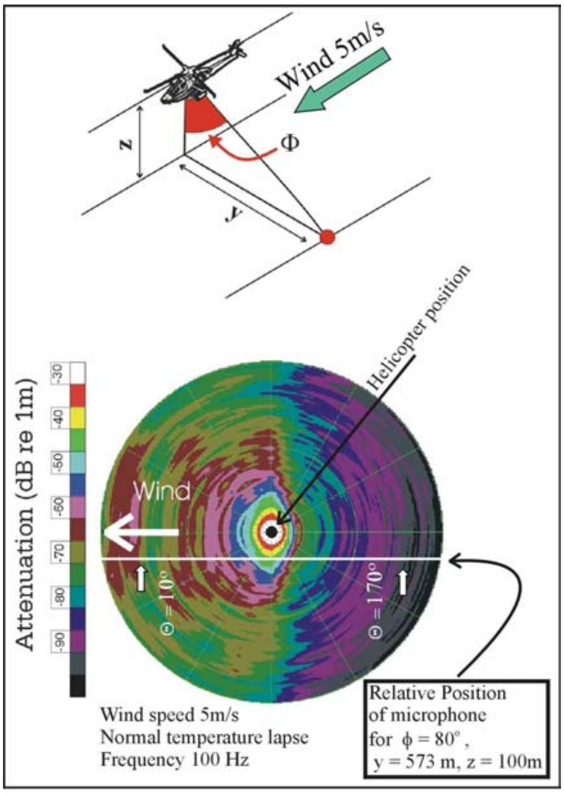

Figure 5. Effects of atmospheric refraction, calculated using MAPE [4].

In figure 5 is illustrated the attenuation contour plot at a frequency of 100hz, as predicted by the MAPE software [4], for a 5m/s wind blowing from behind a uniform source at a height of 100m with a microphone receiver at ground level on grass. The calculation includes the average influence of atmospheric turbulence, obtained from repeated calculations with random turbulence levels. Very different attenuation characteristics upwind and downwind of the source can be observed in this figure. Superimposed on the contour plot is the path, relative to the source, which a microphone would appear to follow if placed on the ground to capture the θ variation of the noise level in the plane of ϕ=80°. For this value of ϕ and a 100m source height, the lateral position, y, of the microphone is 573m, which is already large. The points at which θ = 10° and 170° would be represented during a fly-by are indicated on the relative path of the microphone. It will be observed that there is a difference of at least 15dB in the attenuation characteristics at these two θ values. Unfortunately, although the MAPE calculations are believed to be accurate, it is not easy to remove the influence of refraction from the measurements. This is because the results are dependent on an accurate representation of the meteorology, which may be varying rapidly over a short time and there may also be large random excursions due to turbulence. Thus it is important to establish the limits on the range and angles (θ,ϕ) over which the assumption of a uniform atmosphere is acceptable.

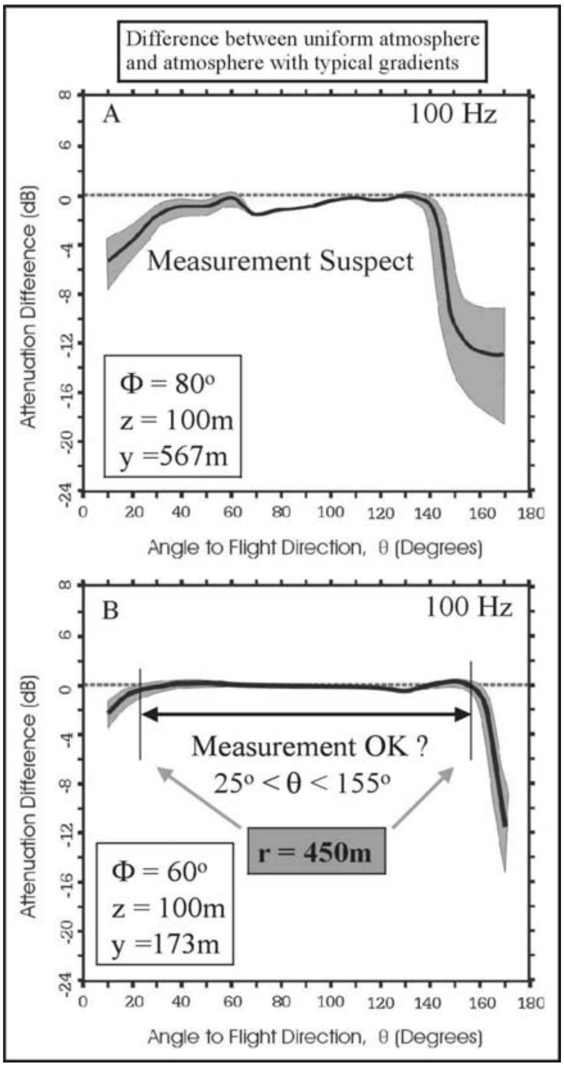

Figure 6. Influence of refraction, as a function of θ, on measurements for ϕ = 60°, 80° for a fly-by at 100m above ground level.

Figure 6A shows the difference between assuming a uniform atmosphere, through the use of standard propagation techniques [5, 6] based on Chessell's theory [7], and the MAPE calculation [4] of the effects of refraction for the case illustrated in figure

5 for ϕ=80°. The influence of turbulence, which is represented by the shaded area in this figure, can be observed to increase, as expected, at the ends of the θ range, where the distances are large. The figure reveals that errors of the order of 2dB can be anticipated in the range 40° < θ < 140° and very large randomly varying errors can be expected outside this range. Similar results for ϕ = 80° are obtained for other frequencies and with other source heights.

The influence of the refraction effects reduces with reducing ϕ. This is illustrated in figure 6B for ϕ=60° where it is shown that the assumption of a uniform atmosphere can be applied over the range 25° < θ < 155°. Thus even for ϕ=60° it is not possible to obtain accurate data at the extremes of the θ range using microphones close to the ground. An important observation is that the propagation distance r, covering the acceptable θ range, is less than 450m. This limit of r= 450m appears to apply in general over a range of heights and (θ,ϕ) angles, for measurements at the limit of certification meteorology.

The conclusion from this study of the influence of meteorology is that:

- the propagation distance should be limited to r<450m,
- the use of ground plane microphones should be limited to -60°≤ϕ≤ 60°.

2.3 Elevated microphones

It would appear that by elevating the microphone, as illustrated in figure 7, many of the problems associated with measurement for 60° <|ϕ| ≤ 90° can be eliminated. A reduction in the radiation distance is then achieved and also an elevated microphone is further away from the strong sheer layer close to ground, where the refraction effects may be significant. However there are a number of additional problems. For an elevated microphone the interference between the direct and reflected waves can lead to difficulties of interpretation when they add out of phase. If the microphone is high off the ground there is the added complication that the direct and reflected waves are emitted at different times and at different angles, as illustrated in figure 8. There are then essentially two unknown source levels, each with different (θ,ϕ), and only one measurement; i.e. the problem is undetermined. So some assumptions need to be made about the 3D directivity, which is the characteristic we are trying to measure.

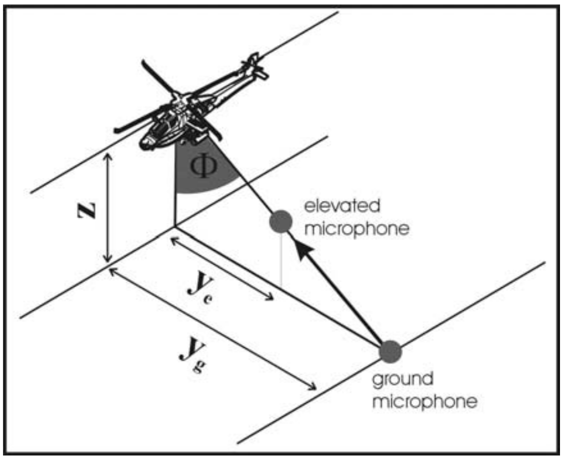

Figure 7. Elevation of microphone to reduce radiation distance.ground,

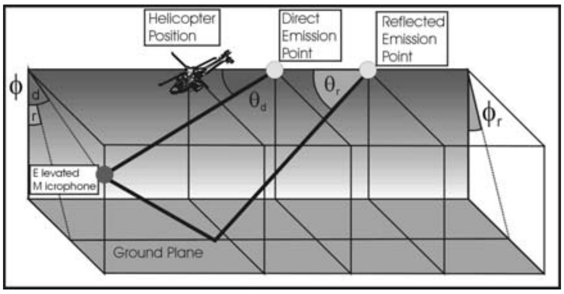

Figure 8. Incident and reflected rays for a highly elevated microphone.

2.4 Beamforming vertical array

A better solution is to use an elevated vertical array of microphones with the centre of the array in the direction of interest. Beamforming techniques [8] can then be used to reduce the interference resulting from the reflected wave. A beamformed array has several advantages over using a single elevated microphone. Interference from the reflected wave is greatly reduced due to the directional nature of the array. Signal to noise ratio is increased due to the inherent processing gain and the uncorrelated nature of the random background noise on each microphone. The propagation distances can be minimised, thereby reducing the effects of absorption and refraction. Measurements of the reflected wave can also be made by steering the beam towards the reflection point rather than towards the helicopter. If the helicopter were flown higher than the centre point of the array then the beam can be steered to obtain the directivity in the region 60° < |ϕ| < 90°, which is the problematic region for ground plane microphones. Also if it is possible to raise the array above the helicopter then the directivity in the 90° < |ϕ| region could also be obtained. The basic theory for the DERA beamform approach is given by Browne & Munt [3] but has been extended to cover the incidence of spherical wavefronts.

The array that is currently being used by DERA is shown in the photograph of figure 1. It consists of 14 microphones fixed to a 30m frame. The array is designed so that two sub arrays are formed, each of 8 microphones. Array 'A' is formed from microphones 1-4 & 11-14 and array 'B' is formed from microphones 4-11. The positions of these microphones are given in table 1. The two arrays cover different frequency ranges. The widely spaced array, 'A', is used in the frequency range 20-160 Hz, covering the lower harmonic frequencies of the main and tail rotor for typical helicopters. The finely spaced array, 'B', covers the 160-1600 Hz frequency range.

The mid point of the whole array was set to 35m above ground level, which fixed the height for the helicopter to fly at to capture data for $\phi = 90^o$. A crane with a 50m reach was therefore required to hoist the array. A 3.5Hz resolution narrow band frequency analysis is determined to be sufficient to measure the sound pressure level (SPL) of each of the main and tail rotor harmonics. As the radiation distance then needs to exceed 196m (cf. section 2.1) the array is erected 200m away from the flight track. However the full range of θ cannot be achieved from this position, because both the direct and reflected waves may be simultaneously within the beam for θ approaching 0° or 180° and also the radiation distances may then exceed the upper bound of 450m for the acceptable range. So a second array at 75m from the flight track is also used. The ranges of θ covered by these two vertical arrays are illustrated in figure 9.

Table 1: Vertical array microphone positions

Microphone number	Height (m)
1	50.0
2	45.7
3	41.4
4	37.1
5	36.5
6	35.9
7	35.3
8	34.7
9	34.1
10	33.5
11	32.9
12	28.6
13	24.3
14	20.0

The beamform directivity pattern of the low frequency array 'A' is shown in figure 10. Using this array in the range 20 Hz to 160 Hz, the pattern enhances the direct sound compared with sound in the reflection direction, and allows measurements to be taken with an error of better than ±2dB.

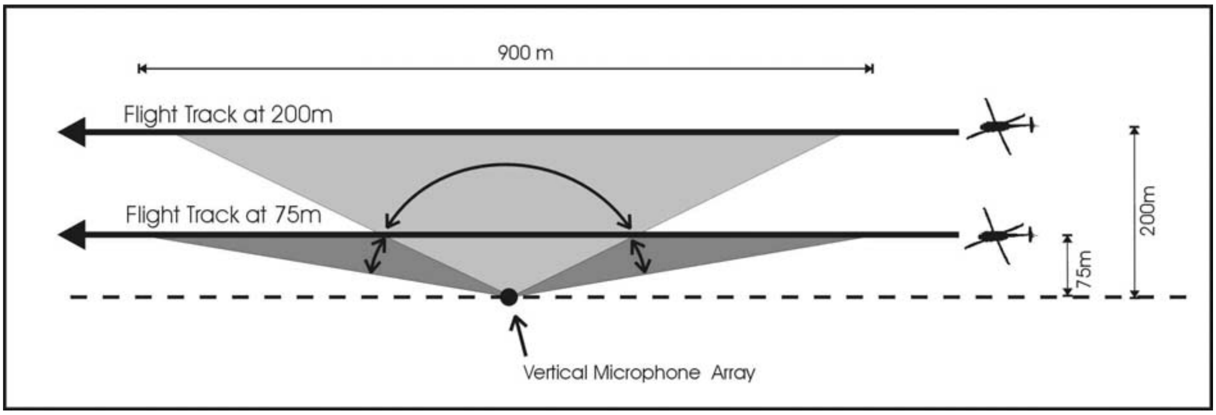

Figure 9. Ranges of θ covered by vertical arrays at 75m and 200m.

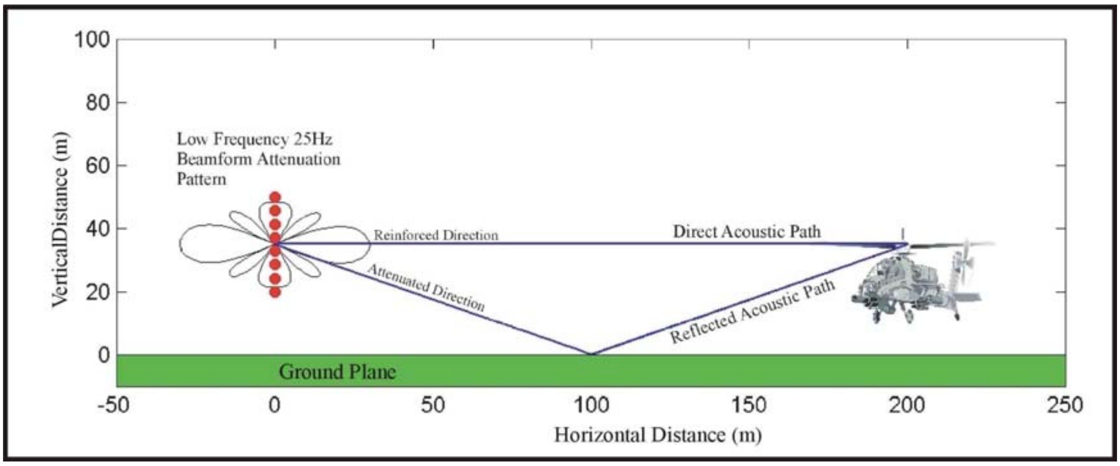

Figure 10. Beamform attenuation pattern for array A at 25 Hz

2.5 Beamform performance

The performance of the beamform solution, in measuring the directivity at an elevated position, was tested analytically using simulated data for the hover condition. For the purposes of testing the beamforming technique only the thickness noise component [9] of rotor noise was used to simulate the directivity pattern of the radiated sound, as this was a simple calculation which never-the-less gave a realistic directional sound source. Only the main rotor tones were simulated for this purpose.

In this simulation, the time histories for the direct and reflected sound fields, assuming a perfectly reflecting ground, were calculated. From this the total field (direct + reflected) at each of the microphone positions was derived for a helicopter hovering at 35m above ground level and 220m away from the array. The beamform algorithm is then applied to calculate the spectrum for the horizontal directivity. The harmonic levels, calculated using the beamform technique, can then be compared to the direct field levels to calculate the error, which is introduced by employing this technique.

Also standard reflection correction theory [5,6,7] is applied to the total field for an isolated elevated microphone and again compared with the analytic solution.

The error introduced using these two techniques is compared in Figure 11. This shows the theoretically calculated main rotor tones (circles), the beam-formed calculation of the direct field (stars) and the direct field calculated from standard reflection theory (crosses). The solid line in figure 11 shows the errors, which might be expected when using a beamform array compared with the known direct field. The error between the beamform measured direct field and the known direct field is better than ±1 dB.

When applying standard correction theory to the total field at a single elevated microphone the error introduced to estimate direct field, can be nearly 10dB as shown by the broken line in figure11.

3. Measurement and Analysis Procedure

DERA currently use two vertical beamform arrays, positioned at 75m and 200m from, and to one side of, the flight track. The 200m distance is selected because it represents the minimum acceptable range to allow narrow band, 3.5Hz, analysis whilst retaining a 5^o resolution in θ; as described earlier in section 2.1. At the extremes of the θ range the radiation distance may exceed the 450m limit, deduced in section 2.2, and in the beamform process the undesirable condition of having the reflected wave within the beam may also be reached. The 75m array is therefore introduced to capture data at the extremes of the θ range. The data from the 28 microphones, associated with these arrays, is analysed using the DERA HAMSTER (Helicopter Acoustic Measurement System for Trials and Experimental Reduction) procedure to cover the region $60^o \leq |\phi| \leq 90^o$ in 5^o

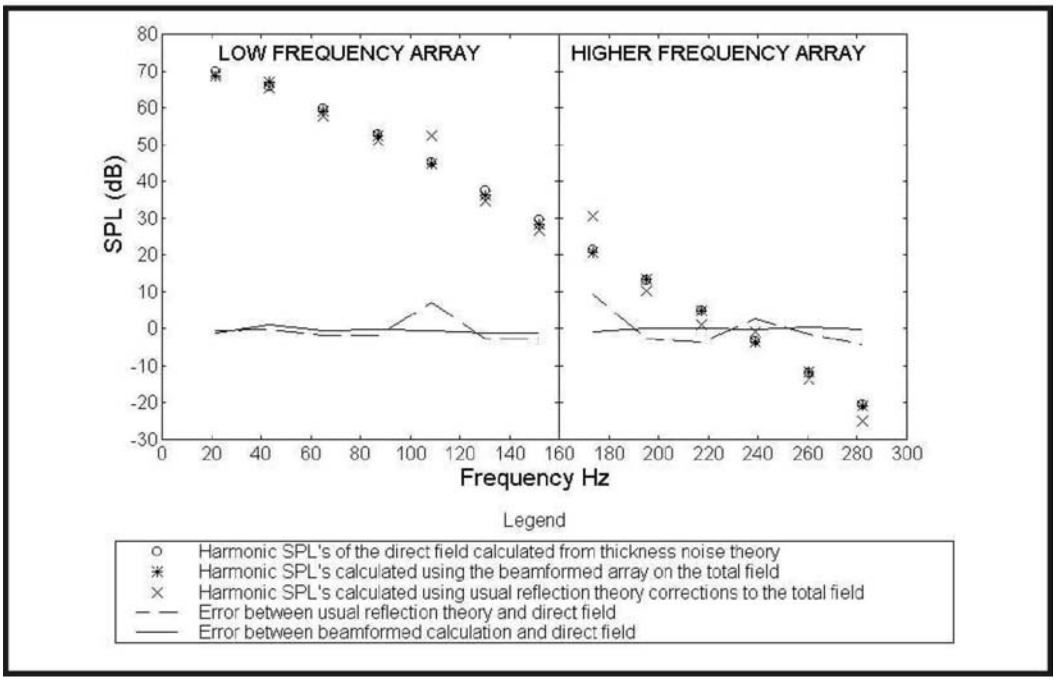

Figure 11. Beamform performance compared with standard reflection corrections using theoretical data.

increments in ϕ using beamsteering. To cover the range $-60^o \leq\phi \leq 60^o$ an array of 15 ground plane microphones is used, whose positions are listed in table 2. These microphones are mounted inverted with the diaphragms at 7mm above an extensive flat hard surface. In most circumstances the ground plane microphones have been located along the centre of a tarmac runway. The arrangement of the total of 43 microphones in the ground array and 2 two vertical arrays is illustrated in figure 12. All the microphones are located on one side of the flight track as illustrated, primarily because of the lack of microphone resources to simultaneously cover both sides, so that to obtain the complete directivity pattern the helicopter needs to fly in alternate directions.

Table 2: Positions of ground array microphones

Microphone number	Lateral distance y (m)
1	0.00
2	6.17
3	12.54
4	20.24
5	25.48
6	29.37
7	35.26
8	41.06
9	59.68
10	72.79
11	83.42
12	115.47
13	123.55
14	178.76
15	190.53

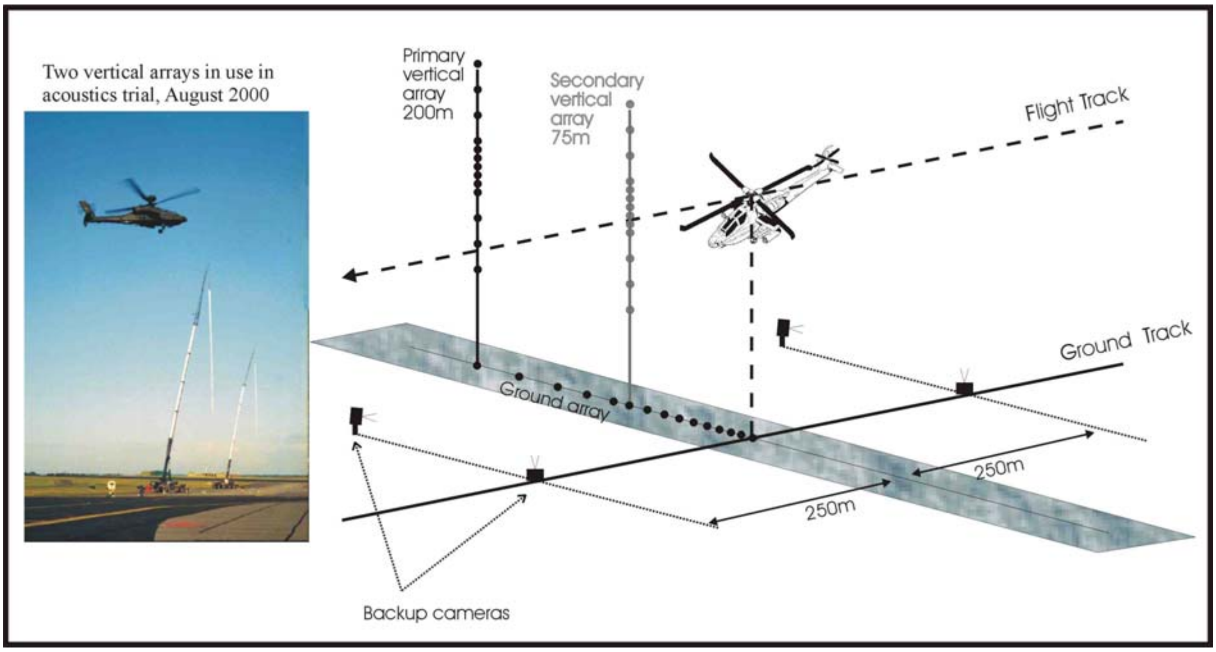

Figure 12. Arrangement of microphones used in HAMSTER for helicopter acoustic characterisation

The position versus time log of the helicopter needs to be recorded and synchronised with the recordings in order to establish emission times and co-ordinates to enable the reduction of the data to a directivity hemisphere. Whenever possible a differential global positioning system has been used to log position to an accuracy of better than 1m every 0.2 seconds. However dropouts can occur when appropriate satellites are temporarily obscured from the antenna, which intermittently occurred in the NATO CCMS trial in Moose Jaw. As a back-up DERA use fixed video cameras to determine the time and accuracy of the flight track for the helicopter passing specific points along the nominal flight track within the measurement range.

To maintain all measurements within the radiation range 200m< r <450m, as required (cf. section 2.1 and 2.2), and to cover the full range of ϕ under the helicopter with a 5^o resolution it is found that 5 flight heights, of 35m, 50m, 70m, 110m and 200m, are necessary. However the horizontal directivity and most of the data immediately under the helicopter, within $-45^o \leq\phi \leq 45^o$, can be acquired with just the two flight heights of 35m and 200m. The area of the (θ,ϕ) matrix covered by these two heights and the five heights is illustrated in figures 13a and 13b, respectively. The ordinate range in this illustration is 0^o to 180^o for θ and 0^o to 90^o for ϕ; i.e. one side of the hemisphere. Although there are small gaps in the area covered for the comprehensive set of heights, in practice these gaps usually disappear because of small deviations in the flights from the nominal track.

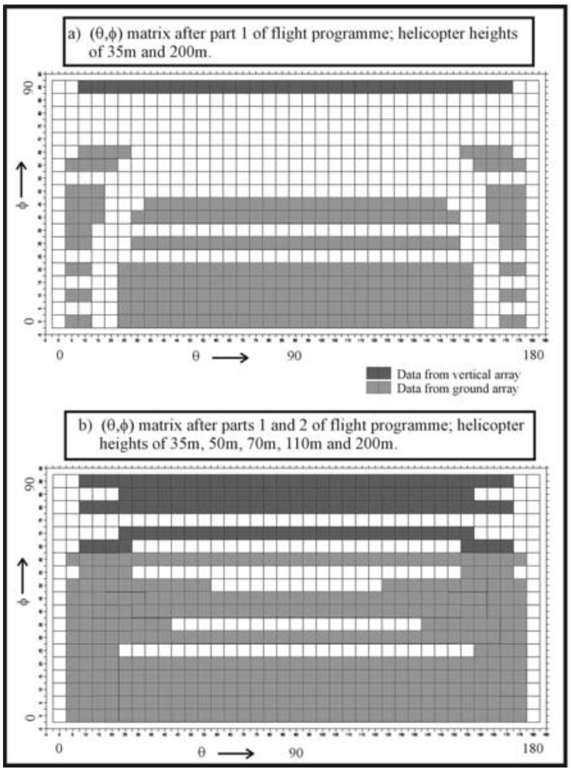

Figure 13. Matrix of angles (θ, ϕ) covered, in bins of 5°, by a range of flight heights.

If the flight programme is restricted to just the 2 flight heights, of 35m and 200m, then there are significant regions where measurement is absent that are of relevance to the prediction of the environmental impact, as illustrated in figure 14. By using interpolation between the data it is possible to make estimates of the sound where no data is recorded. However with only two flight heights the region over which the interpolation is required is large, and this could lead to significant errors in the estimation of the noise. The interpolation procedure utilises the geometry to weight the data according to the proximity of points on the hemisphere surface. Indeed it is important to note, in figure 13, that the vertical line where θ = 0° represents just one point at the front of the hemisphere. Likewise the line where θ = 180° also represent a single point at the rear of the hemisphere. At the present time bi-linear interpolation is adopted to fill in the gaps.

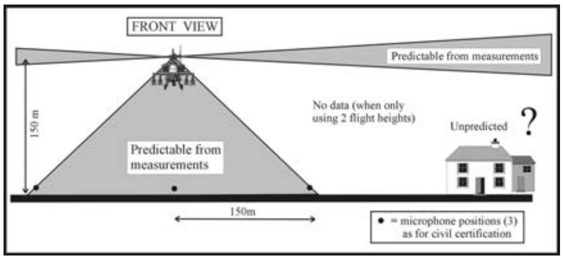

Figure14. Restrictions imposed with measurements from only 2 flight heights.

In figure 15 a directivity hemisphere of A-weighted over-all sound pressure level, OASPL (A), has been constructed from the 1/3rd Octave levels purely for the purpose of illustration. In practice only the spectral components are held as directivity hemispheres and the OASPL(A) is only generated after constructing the spectrum at the reception point on the ground.

For approach (landing) and take-off angles, HAMSTER generates a hemisphere that is tilted to the angle of ascent or descent.

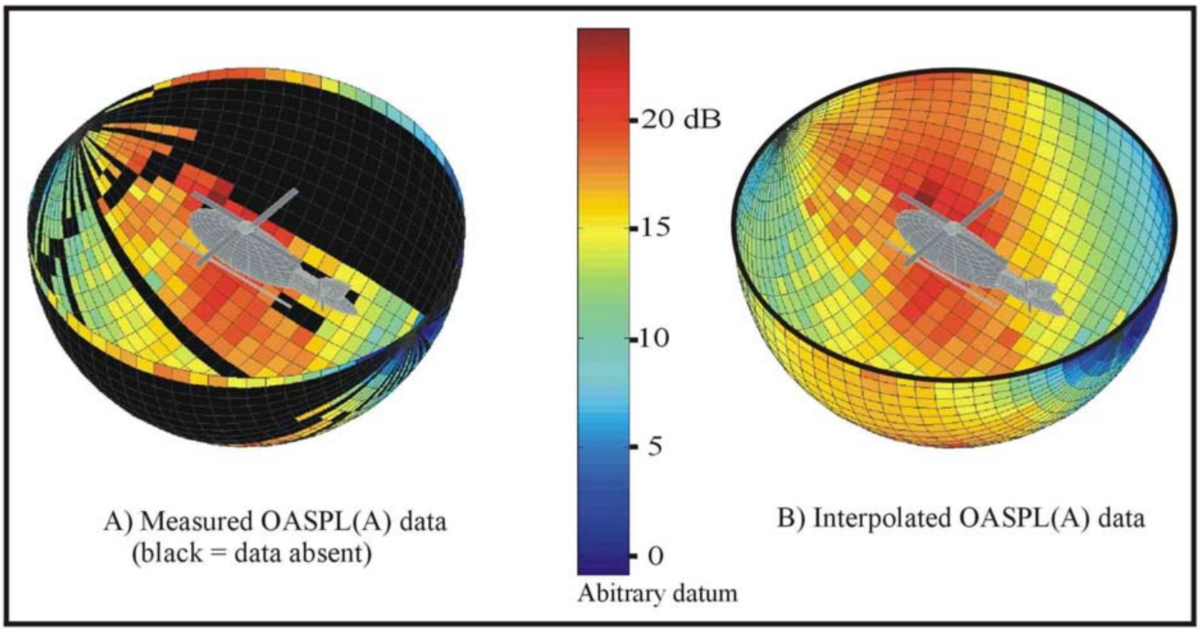

Figure 15. Directivity hemisphere for OASPL (A), from data measured from flight at 35m and 200m, and interpolation to fill in the gaps. Constructed from 1/3rd Octave directivity. Flight speed is 90 kts.

The HAMSTER procedure generates a directivity hemisphere for each of the 1/3[rd] Octave components up to 8 kHz and for each of the low frequency tonal levels corresponding to the harmonics of the main and tail rotor blade passing frequencies. A reference radius of 1m is chosen for these hemispheres for convenience to simplify the application of the propagation algorithms to the source data. Only measurements for which the radiation distance is within 200m<r<450m are analysed for generating the directivity hemispheres. The effects of reflection [5] and atmospheric absorption [10] are removed in the data reduction process. The stored database of these hemispheres consists of the mean sound level, the standard deviation and the number of samples contributing to this statistic, at each 5^o x 5^o (θ, ϕ) element of the hemisphere. Where no data exists, the number of samples is set to zero. The statistics are generated from at least 6 over-flights per condition, which is the number of repeats adopted in all DERA flight trials. The retention of these statistics permit the addition of further data at the same frequency and flight condition from subsequent trials, thus providing the ability to improve the database and its statistical confidence. A companion database is also generated using interpolation to populate the whole of the hemisphere, as a pre-processor to the HELIACT acoustic contouring calculation.

4. Acoustic Contouring Tool

The HELIACT, helicopter acoustic contouring tool, is constructed in modular form, consisting of the following basic elements:

- acquire source characteristics for a specific flight condition for each element of the flight profile (held at waypoints).
- establish local terrain for specific flight position.
- calculate propagation characteristics from source to receiver for each frequency component.
- determine the receiver level for the required acoustic metric.
- plot contours of the acoustic metric.

The procedure is illustrated in figure 2. The source 'hemisphere' characteristics are obtained for a specific flight condition by interpolation in the database across closest conditions.

The most complicated element is that dealing with propagation. This component must account for:

- spherical spreading
- atmospheric absorption [10]
- variable surface impedance conditions [5]
- detail of meteorology
- refraction and turbulence effects [4, 11,12]
- diffraction over hills/obstacles [13,14, 15]

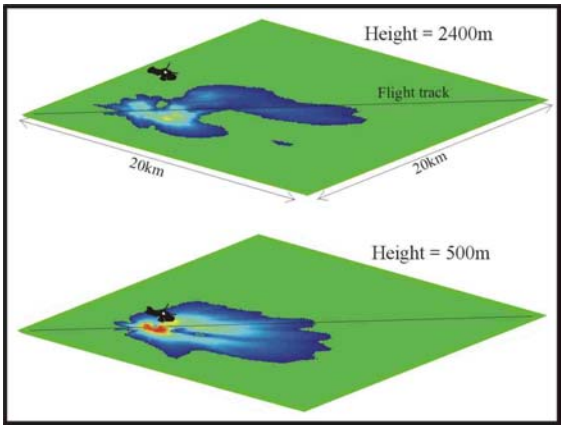

Figure16. Effect of different flight heights on OASPL(A) noise contours for level flight at 90 kts.

If the refraction effects are excluded then the calculation is fast and almost in real time. The influence on the noise contours of varying the helicopter height for propagation over flat terrain is shown in figure 16 for a helicopter in level flight at a speed of 90 kts. It will be observed that different features in the highly directional noise source are experienced on the ground at the two heights.

Diffraction effects [14] are also relatively easy to account for if the refraction effects are excluded. An example of a typical HELIACT noise contour calculation for flight in mountainous terrain, but excluding refraction, is given in figure 17.

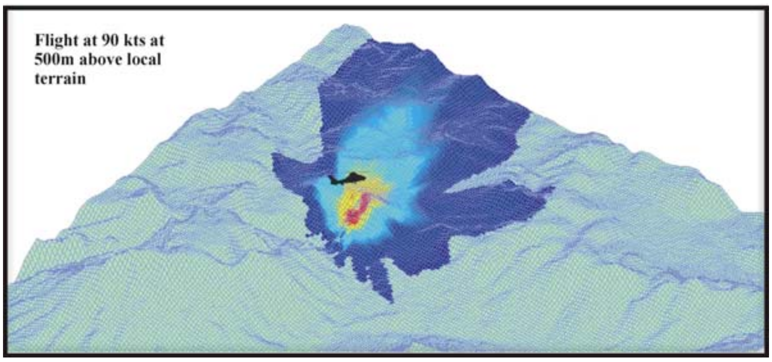

Figure17. OASPL(A) noise contours for flight at 500m over hilly terrain

Ray tracing [11] can produce fast predictions of the effects of refraction. It is being included as an option within HELIACT, however problems can be encountered with caustics and multiple reflection paths that can introduce errors into the calculations. Currently the parabolic equation (PE) method [4] is preferred because it is more reliable and accurate [12].

Inclusion of the effects of refraction by wind and temperature gradients using the PE approach can be a very protracted calculation, especially to cover all frequencies of relevance (up to 8 kHz) and to account for differences in meteorology experienced at different locations over the terrain.

Propagation over large distances in hilly or mountainous terrain is a complex problem of both diffraction and refraction, primarily because of the strong influence of the terrain on meteorology. Indeed compression of the vertical variation of the meteorology over a hill can produce very strong gradients such that refraction, rather than diffraction, is the important propagation mechanism. However advances have been made [15] to account for both diffraction and refraction in hilly terrain using the PE method and propagation predictions have been generated for some special cases.

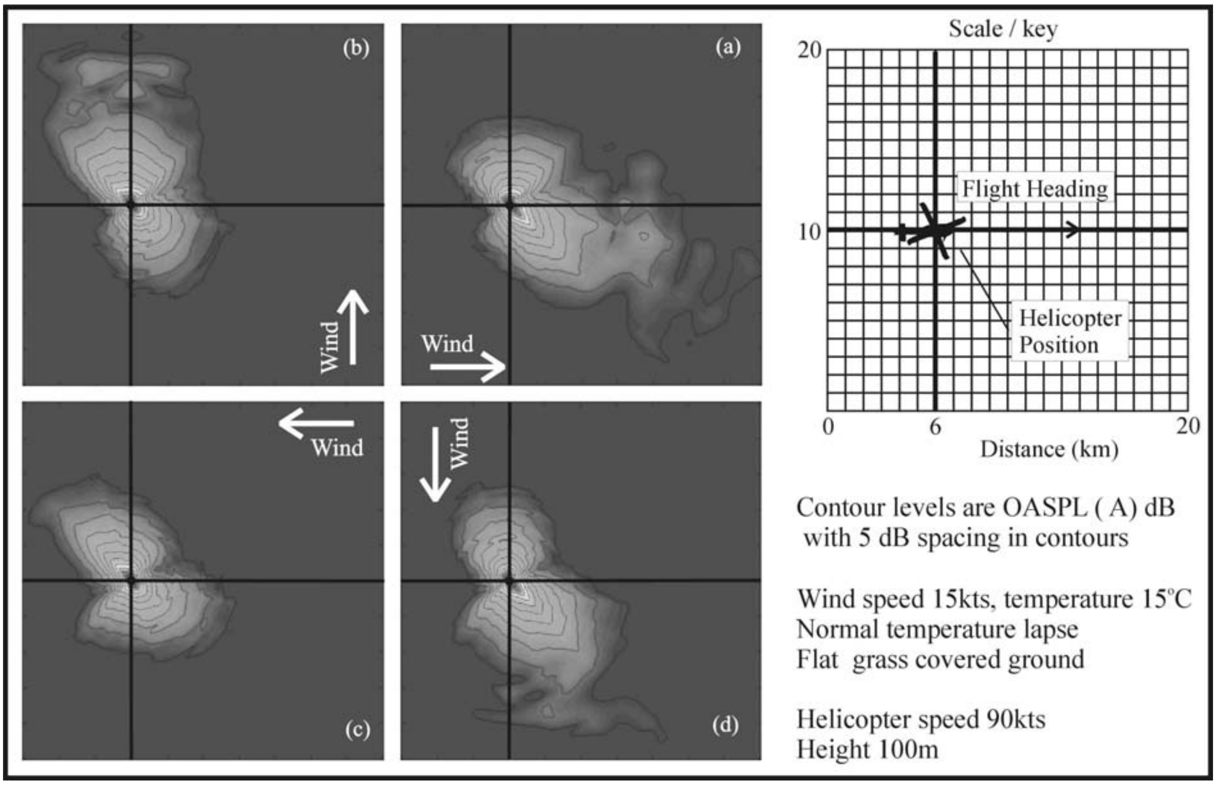

Figure 18. Influence of wind direction on noise contours

To achieve practical speeds in HELIACT the influence of refraction is currently pre-calculated for the specific meteorological condition and held in a database of attenuation characteristics. This attenuation database is generated under the assumption of a monopole source and, although in reality the source is highly directional, it is assumed the attenuation characteristics are broadly applicable in each direction of observation relative to the helicopter and wind direction. Predictions, based on the PE method, for the influence of different wind directions on the instantaneous noise contours about a helicopter in level flight at 90kts are shown in figure 18.

5. Conclusions

It has been demonstrated that the refraction effects of meteorology may significantly influence helicopter acoustic measurements, especially those close to the horizontal plane. It is recommended that:

- The use of ground plane microphones should be limited to measurement of the directivity below the helicopter within $-60^o \leq \phi \leq 60^o$, where ϕ is the angle to the vertical plane (see figure 3).
- Radiation distances r should also be kept within the range $200m < r < 450m$. The lower bound is needed to capture narrow band data whilst maintaining 5^o angular resolution. The upper distance bound is to minimise the influence of atmospheric refraction.

To tackle the measurement of the acoustic directivity in the remaining region close to the horizontal plane, where $60 \leq |\phi| \leq 90°$, the use of at least two vertical beamforming arrays is recommended. The DERA HAMSTER measurement and analysis method also includes a ground array to capture acoustic data in the range $-60^o \leq \phi \leq 60^o$. In total 43 microphones are utilised to obtain sufficient data to derive directivity hemispheres. The use of 5 flight heights over the array, combined with the microphone positions, enables directivity hemispheres of 1/3rd Octave levels and tonal levels of the frequency spectrum to be generated by HAMSTER for each flight condition of interest.

The directivity hemispheres generated by HAMSTER are utilised in HELIACT to generate noise contours for a flight profile described by waypoints, and flight conditions at these waypoints, over a terrain grid. Included in the HELIACT calculations are the effects of terrain and meteorological refraction. A prototype model for HELIACT has been used to generate the contours presented in this paper. Improvements in speed and further validation will be needed before it can be used routinely as a fast contour mapping tool.

References

1. NATO/CCMS "Final Report of the NATO/ CCMS Pilot Study on Aircraft Noise in a Modern Society". Report No. 185, November 1989.
2. NATO/CCMS "Helicopter Noise Prediction Modelling – A Report on the Working Group Study". Report 202, December 1994.
3. Browne, R W & Munt R M "A measurement technique for obtaining the acoustic directivity pattern of helicopters" American Helicopter Society 55th Annual Forum, Palais des congrés, Montréal, Quebec, Canada, May 25-27, 1999.
4. West, M, Gilbert, K & Sack R A "A tutorial on the parabolic equation (PE) model used for long range sound propagation in the atmosphere". Applied Acoustics **37**, pp 31-49 (1992). This is implemented in the multi-azimuth PE software, MAPE; West M, Salford University (January 2000).
5. ESDU "The correction of measured noise spectra for the effects of ground reflection" Engineering Sciences Data Unit. ESDU data item A94035, Dec 1995
6. Daigle, G.A., Embleton, T.F.W., & Piercy, J.E., "Some comments on the literature of propagation near boundaries of finite acoustical impedance." J. Acoust. Soc. Am., Vol **66**, No 3, pp. 918-919 (1979).
7. Chessell, C.I., "Noise propagation along an impedance boundary." J. Acoust. Soc. Am., Vol.**62**, No 4, pp. 825-834 (1977).
8. Coates, R.F.W., Underwater Acoustic Systems, MacMillan New Electronics Series, 1990, pp136-152.
9. Ffowcs-Williams, J E & Hawkings, D L "Sound generation by turbulence and surfaces in arbitrary motion" Phil. Trans. Roy Soc. (London) Ser. A, **264**, pp 321-342 (1969).
10. ESDU "Evaluation of the attenuation of sound by a uniform atmosphere" Engineering Sciences Data Unit. ESDU data item 78002, Dec 1977.
11. Turton J D, Bennetts D A and Nazer D J W "The Larkhill noise assessment model. Part I: Theory and formulation" Meteorological Magazine, **117**, (1988).
12. Attenborough K et.al. "Benchmark cases for outdoor sound propagation models" J Acoustic Soc Am 97(1) (1995).
13. ESDU "Estimation of noise shielding by barriers" Engineering Sciences Data Unit. ESDU data item 78002, Dec 1977.
14. Pierce A D "Acoustics – An introduction to its physical principles and applications" McGraw-Hill 1991
15. M. West and Y. W. Lam, "Prediction of sound fields in the presence of terrain features which produce a range dependent meteorology using the Generalised Terrain Parabolic Equation (GT-PE) model", Internoise 2000, Nice, France, 2000.

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