New insights into perception of aircraft and community noise events

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ABSTRACT

The current practice of basing all noise monitoring on A-weighted day/night levels has often been criticised. Questions as to what is really happening in the "noisescape" have been raised, with consequences for managing complaints and future planning. At the same time, some permanent noise monitoring terminals are now available to record simultaneously A-weighted, C-weighted, Z-weighted, stationary loudness, non-stationary loudness, and effective perceived noise levels of noise events. These data, together with other available functions in permanent monitors such as dominant pitch, frequency percentile measures and neural network source characterisation, provide useful resolutions of the more complex events that are not purely due to aircraft. The collection of two years of continuous records of all of these parameters with audio, from a modified permanent airport noise monitor, that is exposed to a variety of community, traffic and aircraft sounds, provides a valuable data set for further study. In particular, event-threshold parameters, maximum levels and exposure levels based on the perception metrics, in comparison with the common A-weighted metrics, have been obtained. Together with recordings from some other sites, new insights into what is really happening in noise events are presented.

Keywords: Noise, Aircraft, Perception

1. INTRODUCTION

Complaints about aircraft noise from the general population have forced authorities in an increasing number of countries to prescribe the installation of noise monitoring systems in the neighbourhood of airports. Such systems are required to record appropriate measures of the noise that arises from aircraft movements. The collection of data and their subsequent processing from such systems greatly assists the airport operator in managing incoming complaints and in planning modifications of operations to reduce noise levels and complaints. At the same time, the airport operator has to satisfy the requirements of air travel and to maintain a viable business. People complain about noise because the noise is too loud or is annoying in some other sense. However, neither loudness nor annoyance is measured by the systems commonly installed. Instead, the international standards prescribe that A-weighted sound pressure level be measured and that the sound level be correlated in some fashion with actual aircraft movements, so that the noise can be ascribed in some sense to individually specified aircraft. In fact this is an extremely difficult matter to do with much accuracy, as there are many factors that raise uncertainties about what is realistically meaningful or even possible (21). More success has been achieved by appropriate averaging over day, week or monthly periods.

In this paper we limit the discussion to just one aspect: which acoustic parameters are actually measured and how are such measurements related to the perception of noise at the sites of the measurements.

2. A-WEIGHTING, AIRCRAFT NOISE AND LIMITATIONS

The A-weighting curve, expressing weighted sound pressure level as a function of frequency, is an approximation to the difference between 40 dB and the frequency-dependent level of a single tone that is perceived to be equally loud as a 1 kHz tone at a level of 40 dB. As has been known since the

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nineteen-twenties, it does not provide a good approximation to either loudness, or noisiness of single tones, let alone of more complex sounds, that are equally loud as a 1 kHz tone at 60 dB or higher levels, (1, 2). Nevertheless, in response to an urgent need to achieve an international standard that could conform to the instrumentation commonly available in the late nineteen-fifties, A-weighting became the basic parameter on which to base aircraft noise monitoring. Somehow in the rush to reach a standard, the intention to use B-weighting, which provides a better approximation to tones equally loud as a 1 kHz tone at 60 dB, was lost and A-weighting ended up as the default (4). In any case it was only intended as a temporary measure (3), to give time to develop a more rational but readily implementable standard. Its main usefulness has been in providing equivalent and maximum sound pressure levels over daily or monthly periods, as well as a comparison between noise events from different aircraft flying close to a monitoring microphone, when the spectral content at the time of closest approach does not exhibit wide variation from one aircraft to another. A consequence is that simple comparisons between jet, turbo-prop and helicopter aircraft are in general not valid, without the application of various adjustments to the recorded A-weighted levels. The limitations in working with A-weighted parameters have been raised many times during the past sixty years, e.g. (1-8). In view of the enormous advances that have been made in electronic technology and software in the last decade, there is no excuse for adhering to an old standard simply because the instrumentation to achieve something much better has not been made available by some of the suppliers.

3. PERCEPTION METRICS

Attempts to introduce more rational metrics, based on what people actually perceive, and to persuade the industry and clients to accept them were thwarted by the limited technological development of readily available instrumentation at the critical time when it was most needed, namely, when good algorithmic procedures based on observations with real people, were first proposed. Loudness, noisiness, perceived noise level and effective perceived noise level were introduced and incorporated in pre-eminent standards (9-12). In the case of aircraft noise, the application of effective perceived noise level was prescribed for land-use planning. However, to carry this out according to the standard, consultants were forced to perform their own measurements under demanding conditions at specified sites, followed by laborious hand calculations, graphical and other procedures to obtain useful data. As a result, the procedure was often regarded as too difficult or too messy and either computer modelling under dubious assumptions was adopted, or 13 dB was added to the measured A-weighted exposure level (13), to provide plausible results for planning. But procedures for the automatic calculation of perceived noise, tone-corrected perceived noise, effective perceived noise and stationary loudness levels from continuously measured sound pressure had been implemented in permanent noise monitoring terminals by 1994, if not earlier. Such capability was largely ignored, or regarded as a curiosity.

4. IMPLEMENTATION OF PERCEPTION BASED METRICS

In order to show the capabilities of the perception metrics in real-life monitoring situations, particularly in comparison with the A and C-weighted based metrics, it was decided to trial the addition of the dynamic loudness capability in an existing permanent noise monitoring terminal that had been operating in the field for several years. Besides additional software, this required an increase in the clock frequency of the DSP, thereby leading to more heat dissipation with initially unknown consequences. However, some two years after the modification was effected there has been no loss of reliability or accuracy in collecting both the conventional data being supplied to the client and the dynamic loudness data. Furthermore, the data are sufficiently complete to enable productive off-line experimentation and comparisons with different thresholds, defining metrics and event durations.

4.1 Loudness and loudness level parameters

The measure of loudness, denoted by N, is determined by how people perceive that the loudness of a test sound is equal to that of a reference single 1 kHz tone at known sound pressure level. When the level of the reference 1 kHz tone increases by 10 dB, the corresponding test sound, which is judged to be equally loud, is perceived to have doubled in loudness. This applies if the level of the reference tone >= 40 dB. At lower levels a more complex relationship applies. In our implementation, there are four loudness parameters to be distinguished. The first is “stationary” loudness, N_stat, produced at every 0.5s interval. It is derived from the Leq,0.5s values of 28 third octave filters (in actual fact one-tenth decade filters in our implementation). It is "stationary" in the sense that there is no variation within each 0.5s interval because it is derived from average values of the third-octave filter outputs over that interval. The other three parameters are all non-stationary or dynamic (12), as opposed to derivable from averaged values. They are derived from third octave filters in which the output of each filter is modified by a prescribed time constant (12).

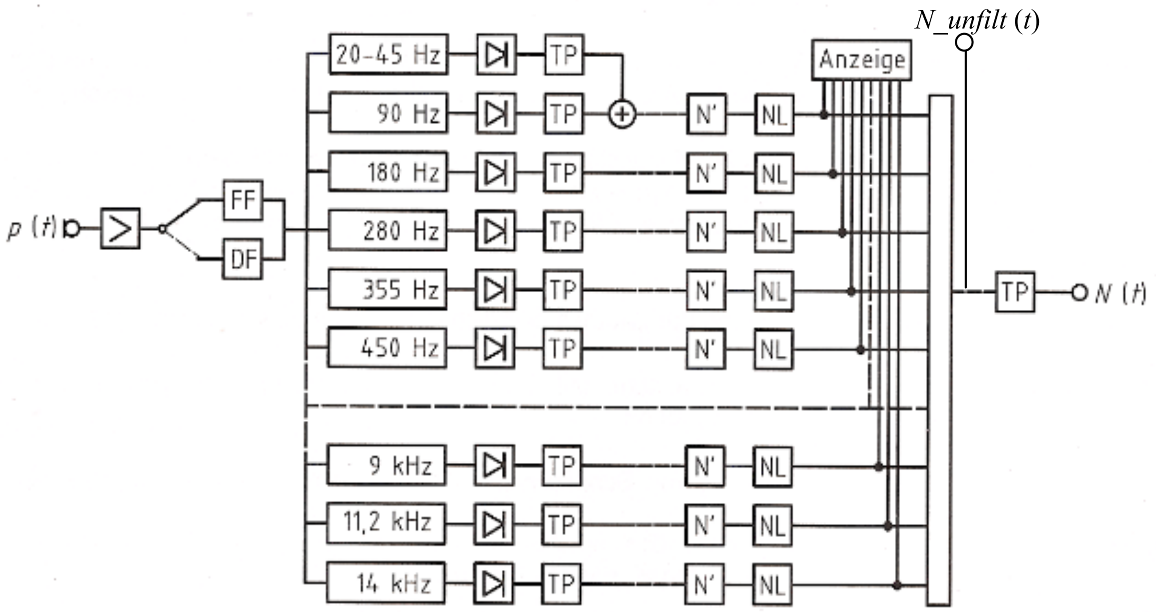

Figure 1 –Block diagram of the dynamic loudness algorithm (12); FF = free field; DF = diffuse field; TP=low-pass filter; N' = critical-band loudness process; NL = nonlinear masking process; Anzeige = display;

The second parameter is the maximum value of the non-stationary loudness in each 0.5s interval, N_max,0.5s. The third parameter is the fifth percentile of the loudness in each 0.5s interval, N5,0.5s. The standard (12) prescribes that the specific and total loudness shall be determined in each 2 ms interval. However, in our implementation, because of the particular architecture, it was much more convenient to determine the specific and total loudness at each 0.5 ms interval. This means that N5,0.5s is the loudness that is exceeded by 50 samples in the 0.5 s interval. The fourth parameter, a maximum loudness, is what we have called N_unfilt_max,0.5s. It is obtained by tapping off a signal just before the final low-pass filter in the algorithm (Fig.1). Originally introduced as a diagnostic procedure to check the correctness of the implementation, it turns out to be very useful in characterizing some features of noise events (14, 15). In all that follows, we work with loudness level, rather than loudness, to facilitate easy comparison with A-weighted levels. The loudness level, LN, is defined as

$$LN = 10 * \lg(N)/\lg(2) + 40, \quad (N >= 1); \qquad LN = 40 * (N + .0005)^{0.35} \quad (N < 1, \quad LN >= 3); \qquad (1)$$

We also work with a fifth percentile loudness exposure level, which, in the absence of a better definition, we define similarly to other exposure levels:

$$LN5E = 10 * \lg(0.5 * \sum_{i=1}^{m} 10^{(0.1*LN5,0.5s,i)}) \qquad (2)$$

5. SOME NOISE EVENTS

Noise events that have been recorded close to airport runways are almost always loud and with very clear, easily recognisable characteristics. There is then little doubt that they are due to aircraft. The more difficult, and thus more interesting, cases are when the noise-monitoring terminal is further away and other non-aircraft sources are responsible for some of the noise. The noise-monitor chosen for collecting the data for this study is situated at 3.8 km from a local (light-aircraft) airport and 3.6 km from the end of, and in line with, a runway of an international airport. Furthermore, the immediate surroundings include primary schools with noisy children at certain times of the day, a railway, a busy road, as well as occasionally quite loud sources of community noise.

One of the useful and readily applicable tools for recognising some types of non-aircraft noise (14, 15) is the parameter LNdiff,0.5s = LN_unfilt_max,0.5s – LN5,0.5s. This parameter is particularly sensitive to impulsive noise because of its good time resolution (based on 0.5 ms sampling). We have found that if LNdiff,0.5s >6.5 phon, then the predominant sound is unlikely to be due to fixed-wing aircraft. In the case of helicopters, however, LNdiff,0.5s can be up to 9 phon. In scanning through a list of noise events that have been correlated to aircraft movements, we find that there are several in which the maximum value of LNdiff during an event exceeds 10 phon. These events then need further scrutiny.

We consider first an apparently straightforward event to illustrate the different parameters (Fig.2). However, this event has an LNdiff_max = 8.57 phon, which indicates something unusual at this site. The first thing to notice is that, while the perception metrics (excluding LN_unfilt) are close together, the A-weighting metric is some 15 dB lower than the LN5 metric. The A-weighting is not a good indication of loudness or perceived noisiness in any sense, and it is not a good metric to be used in assessing the noise impact of such an event. The next obvious feature is that the curves are not smooth, but with an almost-periodic-like structure. Together with LNdiff_max = 8.57 phon, a helicopter event is indicated. Further evidence is that the dominant frequency for much of the event is 25 Hz. Also, the neural network logged the event as 15.5 s jet, 6.5 s propeller-aircraft, 2 s background and 0.5 s unknown. Finally, listening to the audio recording (albeit down-sampled to 8 kHz because of limited storage in the monitor) confirms the typical helicopter sound with a strong jet-engine component. The profile of the sound recording (Fig. 3) is not that of a typical fixed-wing aircraft flying close to the microphone. The event was correlated to an aircraft at a distance of 458m and elevation of 71^{o}.

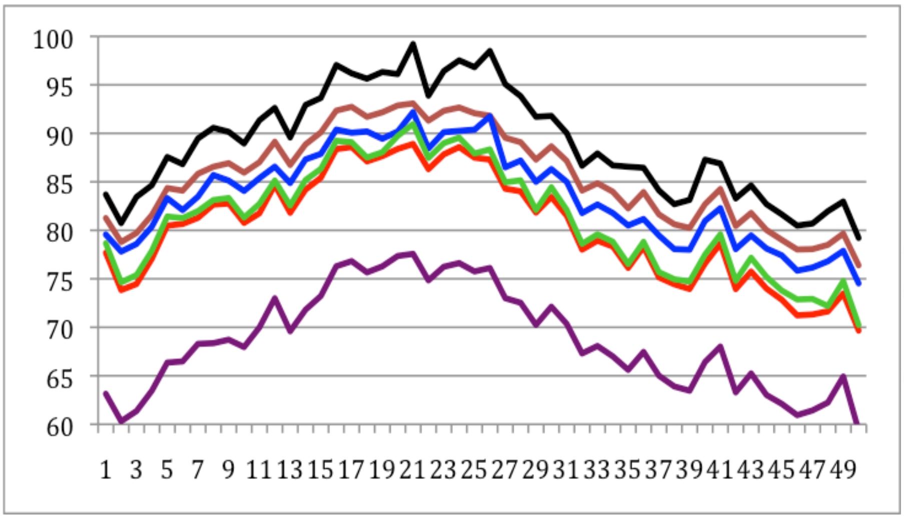

Figure 2 – Metrics of the first interesting event at the experimental site. Scale: dB (phon) vs. half-secs

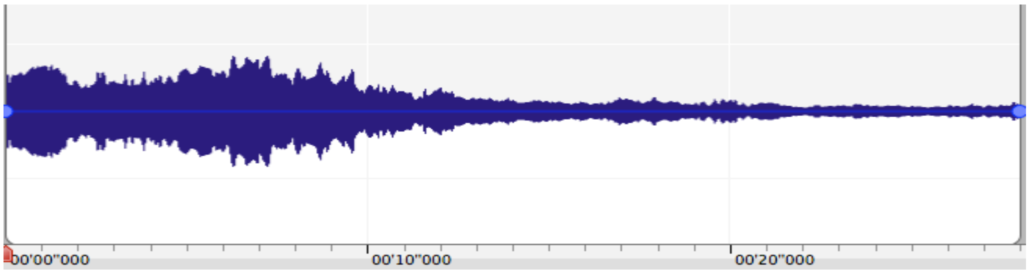

Figure 3 – Audio recording of the first event – helicopter

The second interesting event, with an LNdiff_max = 11.98 phon, shows the following data:

Table 1 – Characteristics of the second event

LAS_max (dB)	LAE (dB)	LN5_max (phon)	LN5E (phon)	Duration s
71.18	83.66	86.25	97.16	63

correlated with an aircraft at a distance of 608 m and elevation of 84^{o}.

At first sight, this seems quite reasonable and consistent with general experience. But if we now exclude from the calculation of LAE_A/C the half-second samples, with LNdiff > 6.5 phon, we find the following values to be attributed to aircraft:

Table 2 – Aircraft characteristics of the second event

LAS_max (dB)	LAE (dB)	LN5_max (phon)	LN5E (phon)	Duration s
71.18	81.95	86.25	95.81	47

The inbuilt neural network gives the following values for aircraft and non-aircraft noise levels:

Table 3 – Neural network verdict of the second event

LAE_A/C	LAE_non_A/C	LN5E_A/C	LN5E_non_A/C	Dur_A/C	Dur_non_A/C
81.94	78.81	95.57	91.52	32.5	30.5

Although the differences between Table 1 and Table 2 are not large, they are still significant and indicative of something else of interest that is happening. It is significant how closely the neural network verdict agrees with the analysis based on LNdiff. However, in view of the general uncertainty about all noise monitoring, such a very close agreement, although encouraging, should be seen as fortuitous. There is further information available from the results of the simple inbuilt procedures in the noise-monitor. An examination of the dominant third-octave response as a function of time shows that there are sudden large jumps in frequency indicating further impulsive behaviour. A visual and aural examination of the sound recording reveals that a dog is responsible for much of the event. And even when the aircraft is at the point of closest approach, the dog sounds louder than the aircraft, at least to this author.

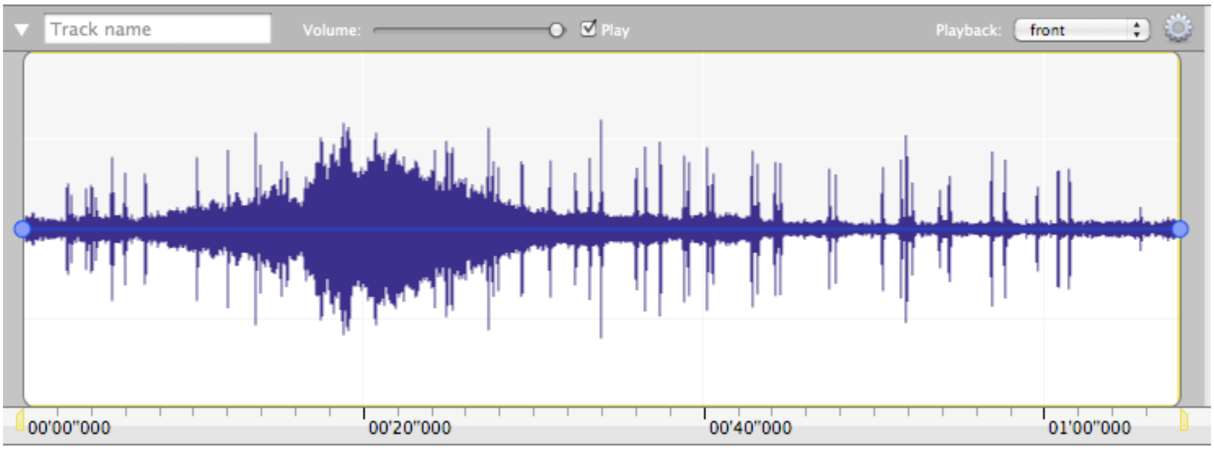

Figure 4 – Audio recording of the second event – a dog and turbo-prop aircraft

The third interesting event has an LNdiff = 15.39 phon. It appears to be similar to the second event, except that the neural network indicates something rather different:

Table 4 – Neural network verdict of the third event

LAE A/C	LAE background	LAE Unknown	LN5E A/C	LN5E background	LN5E unknown	Dur. A/C	Dur non_A/C
49.69	71.94	66.06	67.57	91.05	77.79	1	41.5

The dominant third octave response reveals many sudden jumps in frequency as a function of time. If the same technique as in the second event is applied, viz. removal of the contribution to LAE_AC and LN5_A/C of all samples with a LNdiff > 6.5, we find

Table 5 – Aircraft characteristics of the third event

LAE_non_A/C)	LAE_A/C	LN5E_non_A/C	LN5E_A/C	Dur_A/C	Dur_non_A/C
77.03	75.52	88.48	88.01	29.5	13

The event was correlated with an aircraft at a distance of 2321 m and elevation of 11°.

However, examination of the audio recording shows that the entire noisescape was a solo performance by a dog (probably the same one as in the second event) with a brief pianissimo bird accompaniment. From the audio recording we estimate that the dog's performance occupied 12.5% of the total event time. The sound from the aircraft could not be heard in the recording, so that in this case the neural network came very close to correctly characterising the event as non-aircraft. The significance of the LNdiff_max parameter was in alerting that this was not simply an event with predominantly diffuse background noise, but contained a coherent message, namely, the dog was expressing his displeasure.

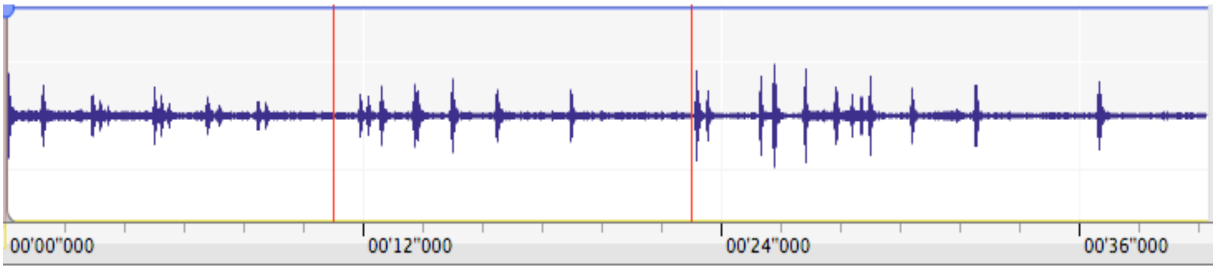

Figure 5 – Audio recording of the third interesting event – a solo dog performance with brief bird accompaniment

The data at this site show that there are many dog events and several helicopter events. All of these were detected by the value of LNdiff_max > 8, and supported by the verdict of the neural network, viz., by the proportions of the time classified as background, jet, propeller or unknown. Helicopters, with or without dogs, were then confirmed by the methods described in the first and second interesting events. One rather difficult event was first suspected to be due to a helicopter by LNdiff_max = 8.19. The neural network verdict was 2 s background, 20 s jet. Listening to the audio recording did not reveal the typical helicopter sound pattern; it could have been fixed-wing aircraft at some distance. In addition a bird could be briefly heard at 20-21 secs, which agreed with the verdict of the neural network for those samples. However, the appearance of the sound recording did suggest a helicopter and the time variation of LN5 throughout the event revealed the telltale almost-periodic-like pattern of Fig. 2, establishing the event as almost certainly being due to a helicopter. Nevertheless, the event was correlated to a fixed-wing aircraft at a distance of 570 m and elevation 81°. Correlation depends on the aircraft having an active transponder, which helicopters normally do not have.

6. PERCEPTION-BASED THRESHOLDS AND EVENTS

In the previous sections we have focussed on events defined in the conventional way. An event commences when a prescribed A-weighted threshold level is exceeded. With perception-based metrics, the threshold should also be a perception-metric level. Then the question arises how should one choose the threshold to provide results that, in some sense, could be seen as comparable to historical A-weighted data. There is no simple or obvious answer to this question. From Fig. 2, we can see that the difference between LN5 and LAeq does vary throughout the event, ranging from 12.84 to 17.50 with an average of 14.84 dB (phon). For this type of event it would be reasonable to set the LN5 threshold at 15 phon above the LAeq threshold (dB). But if the event had a large part of its energy concentrated around the 1 kHz band, the difference would need to be set much smaller. Setting the threshold has to be based on the local situation of the most common types of event, having regard to the nature of complaints from residents in the noise-affected area. In fact this is what happens with A-weighted thresholds; they are determined by experience in the local area. Adjustment to basing the whole of the event process on a different metric is unavoidably going to lead to new data that do not match some of the historical data. That is as it should be. Some of the recorded A-weighted data are clearly wrong. Naturally, it would be nicer if we could abolish the whole concept of threshold and noise event and simply by appropriate classification decide for each half-second which sound source should be assigned the noise load for that half second. So far, we are not aware of any method to achieve such a result with an acceptable degree of accuracy, in spite of the best efforts of neural networks and other methods. Hence we are still obliged to stay with the current structure of noise events.

In previous work (15, 16) we have adopted the approach of choosing a threshold that would produce the same number of events in one day, as does the A-weighted threshold applied at the site. This approach led to useful comparisons of the effects of different metrics and especially between event maxima and total exposures. But a consequence is that a different threshold may need to be chosen for each day or other period adopted for comparison purposes. It is simpler to work with a fixed threshold for all days at a particular site, except that in some cases, lower thresholds are adopted during the night hours. A consequence of adopting a perception-based metric is that many individual events will appear to be quite different from the corresponding A-weighting dependent events. The durations can be quite different, the maxima of LAeq,0.5s and LN5,0.5s of each event occur at different times, but in many cases the magnitudes do not change. As a result, when correlating with aircraft movements, the distance and timing of the point of closest approach at the time of Lmax can change significantly, and conform better to the perception of the sound in relation to the observed aircraft position. Using this approach on 10 days of noise events (in total about 1000 events), we find the following picture:

Table 6– Daily exposure levels of all events

Day	LAE (dB) LAeq thresh	LN5E (phon) LAeq thresh.	LAE (dB) LN5 thresh	LN5E (phon) LN5 thresh	No. events LAeq thresh	No. events LN5 thresh
0228	95.53	109.60	95.19	109.52	43	36
0301	101.04	109.04	95.25	108.31	55	30
0302	102.14	115.50	101.42	115.27	127	101
0303	107.73	117.64	103.11	117.32	148	140
0304	105.38	119.76	105.39	119.80	191	192
0305	102.76	116.22	102.68	116.18	102	96
0306	100.56	113.60	99.58	113.44	91	74
0307	95.09	108.54	94.08	108.13	55	37
0308	100.12	114.13	100.06	114.10	71	65
0309	104.14	117.84	104.07	117.85	167	171

Some points to note from this table:

The LN5E exposure levels scarcely change when an LN5 threshold replaces an LAeq threshold.

The LAE exposure levels show changes that are generally small, but can be up to 5 dB in some cases.

In all except one case, the number of events is less in the case of an LN5 threshold. Lowering the difference in threshold levels from 15 dB (phon) to 14.5 or 14.8 might have reduced the difference in the number of events.

The differences between the N5 and A-weighted exposure levels with a LAeq threshold, and the corresponding levels with an LN5 threshold, range from 8.00 to 14.41, with an average value of 13.32. The range of values is simply a reflection of the different spectral contents of events that include aircraft and community noise sources. It would seem that at this site a change to an LN5 threshold is not likely to lead to a major upheaval in managing the noise load.

7. ACCURACY AND PRECISION

All of the dB and phon values quoted here are to two decimal places. This doesn't mean that sound pressure levels in the field can be measured to this accuracy, or even correct to one decimal place. The raw measurements are taken as given, however inaccurate they may be. What is important in this context is that any numerical process on the raw data does not generate any further significant error. That means, that at all stages of processing, adequate precision of significant bits, in relation to the numerical operations at hand, must be maintained. In the final stages of our processing work, two decimal places are usually adequate, but for some functions, four decimal places are required. For many years, the calculation of background noise exposure, by subtracting aircraft noise exposure from total noise exposure, was commonly applied when only 3 significant figures were available. This process was actually incorporated in a standard for many years. The often-nonsensical results arising from this process were exposed at Zürich airport in the nineteen-nineties (17). In this case the only valid procedure for calculating background noise exposure is to separately calculate the total sound exposure from aircraft events and the sound exposure from non-aircraft events together with exposures from below threshold only by addition, *never* by subtraction, as was implemented at Zürich airport.

Apart from these issues of precision, the accuracy of field measurements of sound pressure is naturally very important. The most vulnerable part of the measurement process is in the microphone. The microphone of an unattended permanent noise monitoring station is subject to the exigencies of weather and air pollution. For this reason it is very important that its functionality can be regularly monitored remotely, since site visits can be very costly and subject to delay. For these reasons, the internal monitoring system of the DM3 (digital) microphone was developed (18). Besides the common "calibration check", consisting of the application of an electrostatic force to the diaphragm at 1 kHz, this process can be sequentially applied at all the third-octave frequencies from 10 Hz to 20 kHz. However, even more important than this check, is the monitoring of polarisation voltage, leakage current (a leakage current of 1 nA through a 10 GΩ resistor causes a 10 V drop in polarisation voltage), internal temperature and humidity, electrostatic actuator voltage and current. All of these data are readily added to the digital stream of the output microphone signal and stored in the database of the noise monitor (18).

The microphone, however, can only record the sound pressure incident at its diaphragm. Noise monitoring entails many other areas of uncertainty that go well beyond the scope of this paper (21).

8. CONCLUSON

The addition of extra software functionality to a standard outdoor noise monitor enables much improved diagnosis of the nature of noise events to be realised. The inbuilt neural networks, perceived noise and "stationary" loudness metrics have been available for more than a decade. The addition of non-stationary (dynamic) loudness provides a new tool that significantly enhances the easy detection of non-aircraft noise, such as due to birds or dogs and facilitates the discrimination of helicopters from fixed-wing aircraft. At the same time it provides a better approximation to the perception of loudness than the other perception metrics. An experimental noise monitoring station that, besides providing continuous standard monitoring data to a customer, also adds new interpretations of events by applying the full collaborative capability of the additional tools has proven a valuable resource for current and future research.

Apart from these advantages, the time is ripe to dispose of A-weighting metrics once and for all and focus on the various perception metrics, of which loudness, and especially non-stationary loudness, is the foremost. The future addition of at least some of the other psychoacoustic metrics (19) would strengthen the ability to monitor noise properly and especially in relation to its perceived annoyance.

The decision to employ the fifth percentile, rather than the mean or maximum value of loudness has very good psychoacoustic backing. However, there is the question over which period of time the fifth percentile should be calculated. Our decision to use a half-second interval is arbitrary and could be readily changed if there were good arguments to do so. But then a period longer than 0.5 sec would blunt the effectiveness of its use in event diagnosis. Most aircraft noise monitors record one-second data, but some record half-second data, even if the only interest is in A-weighting. The half-second data stream is required by the 1978 standard for perceived noise, and in our experience it has much to recommend it in general use. One-second data can easily be generated from half-second data, with the exception of percentile measures.

Finally, one should note one limitation of loudness and perceived noise. If the output of any of the third octave filters, on which both algorithms depend, exceeds 120 dB, then there is no valid output of loudness or noisiness. It would probably be unethical to try and extend the range of perception beyond 120 dB with human subjects. However, this is not merely an academic question. Noise levels of 170 dB (with unspecified weighting) have been recorded from modern military aircraft on the ground (20). The projected deployment of increasing numbers of such aircraft raises new challenges for the environmental management of noise.

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