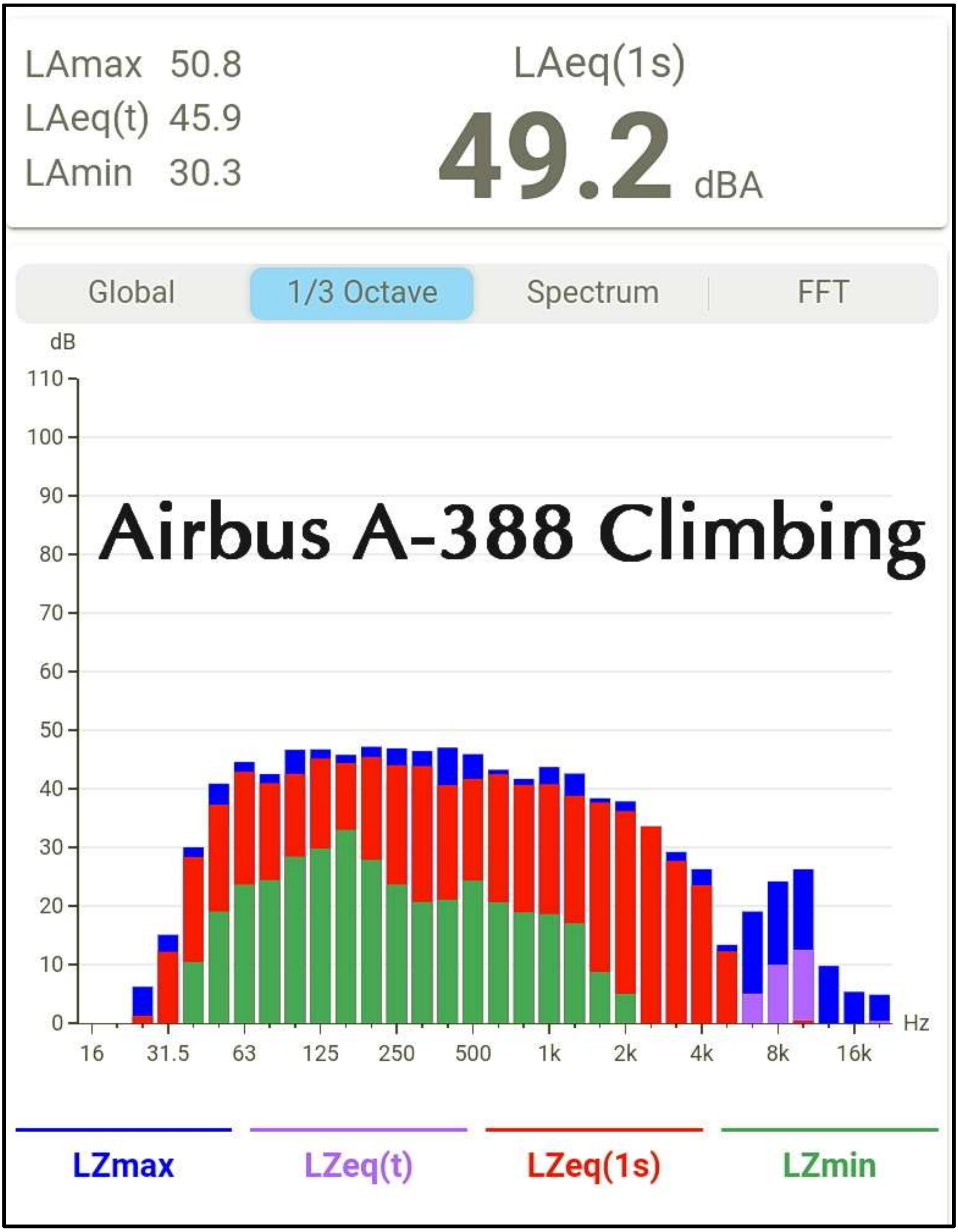
Australia - Aircraft Noise Metrics



OpeNoise screen capture showing noise spectrum of an Airbus A380 climbing after take-off from Brisbane airport

Australia - Aircraft Noise Metrics

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The audible aircraft noise annoying you is *not* the low frequency noise harming you.

Background

The recent Senate Inquiry's task, in brief, was to identify means for reducing the harmful effects of aircraft noise on Australian society.[1] It assumed, correctly, that aircraft noise harms people, communities and businesses. This submission relates most directly to points (a) and (c) in the Inquiry's terms of reference. By implication including identifying metrics and means for measuring, monitoring and regulating aircraft noise pollution.

Currently there are no adequate legislative means to limit or control aircraft noise. Since the 1970s legislative initiatives have been enacted as necessary to reduce pollution, including noise, in all other sectors of the Australian economy. Without a legal framework for monitoring and enforcement it is difficult to imagine how aircraft noise can be controlled and harms reduced. Arguably, legislation is the first essential step, followed by regulations defining technical standards and education and enforcement.

We contend there are two intertwined issues for the Inquiry to consider. First, is it necessary for Australia to enact its own aviation noise pollution standards as means of reducing harms? Second, if the answer is Yes, what might the Inquiry recommend be the basis for these standards, with respect to aircraft noise. The first issue is for the Inquiry alone to decide, the choices for second, basis for standards, is discussed here.

Lack of Australian Standards – Impacts

Australia has no modern technical standards or mandated regulations controlling aircraft noise pollution. Airservices confirms on their website:

> *"There is **no regulated maximum noise level for aircraft flying over residential areas**. Without any maximum level set out in legislation or regulation, there is no objective measure to determine whether any aircraft flying in Australia is 'too noisy,' or whether the combined load of aircraft experienced by a community is 'too much' noise."*[2] [emphasis added]

The *Air Navigation (Aircraft Noise) Regulations* 2018, stipulate import certifications but do not regulate noise emissions or exposure as per Airservices explanation:

> *"In Australia, aircraft noise standards apply **before** an aircraft is allowed to operate here, rather than in the course of its day-to-day flying activities. Before an aircraft begins operating in Australia it is required to meet international noise standards that specify the amount of noise that may be emitted by that type or model of aircraft. … once an aircraft passes this certification process, **there is no legislation or regulation that enables any agency, including Airservices, to police its noise levels.**"* (*ibid.*) [emphases added]

In this regard we are a global laggard among advanced economies. The reasons for this lack are complex and not explored here. We are taking this opportunity to submit to the Senate Inquiry, some 'in principle' standards necessary to keep Australians not just safe in the air but on the ground **safe** and to protect them from harm. These take account of

[1] The impact and mitigation of aircraft noise on residents and business in capital cities and regional towns, with particular reference to: (a) the effect of aircraft noise on amenity, physical and mental wellbeing and everyday life of residents; (b) the effect of aircraft noise on small business; (c) any proposals for the mitigation and limitation of aircraft noise, including flight curfews, changes to flight paths and alternatives to air travel; (d) any barriers to the mitigation and limitation of aircraft noise.

[2] https://aircraftnoise.airservicesaustralia.com/2020/04/30/how-much-noise-are-aircraft-allowed-to-make/

current knowledge of the relevant parts of the acoustic spectrum of aircraft noise, to reduce health, social and economic impacts on people, communities and businesses.[3]

Low flying jet aircraft (<4,000ft) typically subject people at ground level to noise at or above 70 dBA, disrupting communications and concentration, annoying and angering people. Chronic aircraft noise at these levels also damages people's health. Arriving aircraft in Brisbane and other cites, for example, commonly fly at low altitude for some 10-25 km approaching an airport for landing, travelling across densely populated urban residential, educational, commercial areas. As a result hundreds of thousands of people have their lives, work and study disrupted by aircraft noise up to 100 times a day. Night flights over urban areas disrupt the sleep of tens of thousands of people. In Brisbane our conservative estimates suggests nearly one million people live and work in suburbs afflicted by severe or moderate aircraft noise day and night.[4] The actual figures may be much higher.

Currently the means used to define 'allowable' intensity and extent of aircraft noise are derived from land use zoning standards, originally intended for urban planning. The definition (ANEF[5]) is based on responses to an out-dated sociological survey from about 1982 (ibid). Current ANEF modelling is geographically limited to the area adjacent to airports – out to about 10 km. In Brisbane the inadequacy of ANEF is starkly apparent, with continuing complaints about severe aircraft noise coming from some 30 km west and northwest of the airport. Nor is ANEF suitable for use in already densely populated urban areas, e.g. where new runways, increased air traffic and ever denser urban populations multiply the number of residents and communities affected by aircraft noise.

The flawed and outdated ANEF approach to model noise contours – required under the *Airports Act* 1996 – is not sufficient to inform communities of what experiences to expect, this has been known since 2003:

> *"… these [ANEF] contours do not normally show a picture of current or near-term noise exposure patterns around an airport. Experience has shown these contours, which are based on logarithmically averaged 'annual average day' aircraft noise energy, do not portray noise in a way that the non-expert can readily relate to. Given the above, land use planning contours such as* ***ANEFs are not considered suitable for use as an aircraft noise information tool."***[6]

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[3] To avoid repetition, 'aircraft noise' includes other forms of aviation pollution: jet exhaust combustion products - gases, particulates and fluids; turboprop exhaust products, especially lead and heavy metals. Likewise'low frequency' noise/sound includes both low frequency noise and infrasound.

[4] Foley, S (2023) "Brisbane - Aviation Noise Pollution and Community Health" see BFPCA website.

[5] Australian Noise Exposure Forecast, has been used [for three decades] to delineate where and what type of development can take place around airports; to determine which buildings have been eligible for insulation around Sydney and Adelaide airports; for technical assessments of airport operating options in Environmental Impact Statement (EIS) processes; and as a tool for providing information to the public on noise exposure patterns around airports.

[6] *Guidance Material for Selecting and Providing Aircraft Noise Information*, July 2003, p. 7, ironically this government report is still available at the Australian Government's Department of Infrastructure, Transport, Regional Development, Communications and the Arts: https://www.infrastructure.gov.au/media-centre/publications/guidance-material-selecting-and-providing-aircraft-noise-information.

Residential development is only deemed "acceptable" outside the ANEF 20 contour, which represents an average noise exposure level of 20 aircraft noise events per day. Residential developments located within or near the ANEF 20 contour are typically subject to additional planning assessments and mitigation measures to manage the potential noise impacts on future residents. For example, near the proposed Western Sydney Airport new residential developments will not be permitted where the ANEF exceeds 20. However, the term "acceptable" itself is questionable as this quote explains:

> *"In the first instance it is considered important that the wording 'acceptable' and 'unacceptable' in the [ANEF] Standard be replaced by more objective terms such as 'no building restrictions' or 'building not permitted/recommended.' As discussed at a number of points in this paper, what is considered to be 'acceptable' by the Standard is not necessarily 'acceptable' to the individual."*[7]

The Australia Government in its 2016 National Airports Safeguarding Framework suggested again that the ANEF approach is flawed:

> *"Experience has shown a **range of problems** with relying solely on the ANEF as a noise information tool as there are limitations in using the ANEF to describe aircraft noise exposure to laypeople.*
>
> *While the populations with the highest aircraft noise exposure often live within the 20 ANEF contour, experience shows the **majority of noise complaints that are received come from residents living outside the 20 ANEF contour**. Traditionally the residents of these areas have been given **little information** on aircraft noise through the ANEF system other than that the area is considered 'acceptable' for housing. Some people living outside the 20 ANEF contour have been given an expectation of receiving little or indeed no aircraft noise and as a consequence find the levels of noise actually experienced to be **unacceptable**.*
>
> *[…] land use planning could be improved through recognition that **aircraft noise does not suddenly stop at the 20 ANEF contour.**"*[8]

Land use planning policies in states and territories, as well as the current "manner of endorsement"[9], of ANEFs approved by the Minister of Infrastructure and Transport in April 2017 do not take the government's **own** advice into account.

The experience with Brisbane Airport's flawed noise modelling in the 2007 MDP/EIS and since then has shown that:

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[7] *Expanding Ways to Describe and Assess Aircraft Noise*, March 2000, p. 55, ironically this government report is also still available at the Australian Government' s Department of Infrastructure, Transport, Regional Development, Communications and the Arts: https://www.infrastructure.gov.au/media-centre/publications/expanding-ways-describe-and-assess-aircraft-noise-discussion-paper

[8] *National Airports Safeguarding Framework, Guideline A: Measures for Managing Impacts of Aircraft Noise, Attachment 1 – Supplementary Aircraft Noise Metrics*, 2016, p. 1, ironically this government report is still available at the Australian Government's Department of Infrastructure, Transport, Regional Development, Communications and the Arts: https://www.infrastructure.gov.au/infrastructure-transport-vehicles/aviation/aviation-safety/aviation-environmental-issues/national-airports-safeguarding-framework/national-airports-safeguarding-framework-principles-and-guidelines

[9] https://www.infrastructure.gov.au/sites/default/files/migrated/aviation/environmental/airport_safeguarding/files/2017_ANEFs.pdf

- Communities are not easily able to translate decibel noise levels provided in an ANEF contour into a lived experience, and the comparisons are often flawed, e.g. "70 db = Passenger car at 60 km/h and 7m distance."
- The level of noise nuisance is also impacted by the frequency of overhead flights, the topography, the difference between experienced ambient noise levels in residential areas and flight events, and whether any respite – if at all – is being afforded to residents. Brisbane Airport and Airservices have created an aviation super highway above Brisbane that provides no respite whatsoever.
- The logarithmic units of the decibel metric are difficult to understand.

The aviation industry's predictions of growth in air traffic appear overly optimistic (5-6% pa) in the near-term and wholly unrealistic in the medium- to long-term. While there is little doubt there will be modest increases for some years into the future, the need for aviation to meet increasingly stringent GHG emissions reduction targets will likely impose external limits on allowable emissions and, consequently, air traffic. These are likely to make air travel more expensive, curtailing non-essential travel, e.g. tourism.

There is ample, long-term scientific evidence from overseas – UK, EU, US – of the harmful effects of chronic exposure to severe aircraft noise pollution on health, and learning. Significant economic losses include reduced productivity, disrupted education and higher health costs, all increasing as air traffic increases. There are a wealth of overseas peer-reviewed results to draw upon, despite no substantive research being conducted in Australia. This does not diminish the need for initiating well planned, executed and funded short- and long-term research in Australia.

The almost universal metric used for measuring aviation noise is narrow and outdated. Called the A-filter decibel scale – abbreviated 'dBA' – it does quite a good job of measuring noise (sounds) in the frequency range (1,000 Hz-6,000 Hz) humans normally hear.[10] Noise above about 60 dBA is historically classified as 'annoying'. There is no well-founded linkage of aircraft noise in this frequency range to clinical harms to humans health, but these harms are well documented.

The A-filter scale was selected, in part, due to technical limitations on capability of instrumentation available prior to integrated circuits becoming more common in the 1960s. Today, fairly accurate sound/noise monitors are available for download and use in smart phones. These can be used to quickly monitor and display noise using the A-, C- and Zero-filters, the *OpeNoise* app is one example; more accurate professional equipment is also available.

Aircraft noise spans a wide frequency range from infrasound (0-20 Hz) to low frequency sound (20-200 Hz), a significant amount is typically between 200 Hz and 500 Hz, and up to well above 6,000 Hz. The lower frequencies travel for great distances (>10-20 km) and transmit most of the sound energy, higher frequency energy is quickly attenuated in the atmosphere. The A-filtered decibel scale is insensitive to the almost inaudible low frequencies, especially those below about 500 Hz.

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[10] The specifications of what is now know as the A-filter (not A-weighting) was proposed in 1933 by Fletcher & Munson, other filters (B-, C-, D- and G-filters followed), each filtering out a different portion of the acoustic spectrum, which is most completely and accurately represented by the Z- or Zero filter.

As discussed later, it has been known for a long time that human tissue and organs resonate to a range of low and very low frequencies, typically 1-200 Hz. More recently it has been shown noise energy from aircraft flying up to ~4,000' has sufficient energy to cause resonance and damaging changes in human tissue. This is the altitude of most aircraft arriving in Brisbane. Extensive research, mainly in Europe, has shown chronic aircraft noise is definitively linked to increasing risks for cardiovascular disease (CVD) and other ailments. This is a major concern, as these low frequencies are not captured by the A-filter scale and, consequently, ignored when establishing 'safe' levels of exposure to chronic, severe aircraft noise.

It is regarded as essential any proposed Australian standard take into account the full spectrum of aircraft noise, especially frequencies below 500 Hz. This is most simply done by making the Zero-filter – i.e. no preferential filter – the standard for measurements. This will ensure aircraft noise considered 'annoying', i.e. that measured by dBA, and that known to damage human health, i.e. below 500 Hz, are all measured and monitored.

Scientific Context

There is a substantial and growing body of research clearly identifying aircraft noise as responsible for increasing the risk of a wide range of human ailments (see Annex). Until less than a decade ago these linkages, while definitive, were based on epidemiological findings, causal linkages for the clinical effects in the human body remained unidentified. Much exploratory work has since been done in Europe and the US.

In the last decade the clinical causes of these ailments have been identified and the types of damage caused painstakingly uncovered. There are now several lines of evidence indicating the proximate cause is vibrational resonances in the human body, and its vital organs and systems initiated by infrasound and low frequency aircraft noise (1-200 Hz).

Scale of the Challenge

Transport noise is a sufficiently significant health problem in Europe that managing and reducing it has led to a range of scientific reports, standards definitions, and enactment of the European Noise Directive (END) in 2020. The END includes the major classes of transport: road, rail and aircraft, plus industry. It has also led to annual estimates of the geographical extent of problems, including health and socioeconomic effects. The latter are called DALYs/year (Disability Adjusted Life Years). The DALYs for aviation can be considered as a 'time slice' of accumulating socioeconomic damage, caused by aircraft noise.

In 2017 over four million people in Europe were exposed to 'harmful' levels of aircraft noise. Of these, over one million people were suffering 'high annoyance' and a further quarter of a million from 'high sleep disturbance' from aircraft noise (EEA 2020). These people are a relatively small portion of the over 100 million people exposed to harmful levels of noise in Europe.

It is regarded as likely many of these people are being affected by infrasound (<20 Hz) and/or low frequency (20-200 Hz) noise. These frequencies are not captured by the monitoring standards commonly used – dBA – which selectively monitors noise to which the human ear is sensitive in the range 1,000-6,000 Hz.

As discussed below, in 2017 DALYs/year for 'Ischaemic heart disease' can reasonably be considered to be mainly caused by infrasound and low frequency sound from aircraft; infrasound and low frequency noise from road, rail and industry is also important. It is almost certain the number of people affected by aircraft noise has increased since, due to population growth and increased air traffic.

Noise Metrics

Two noise measurement standards in common use: the 'A-filter' (dBA) which probably accounts for almost all professional and other measurements, and the C-filter (dBC) which accounts for only a small proportion of measurements. For example, the UK Civil Aviation Authority (CAA) only uses and reports measurements using the A-filter.

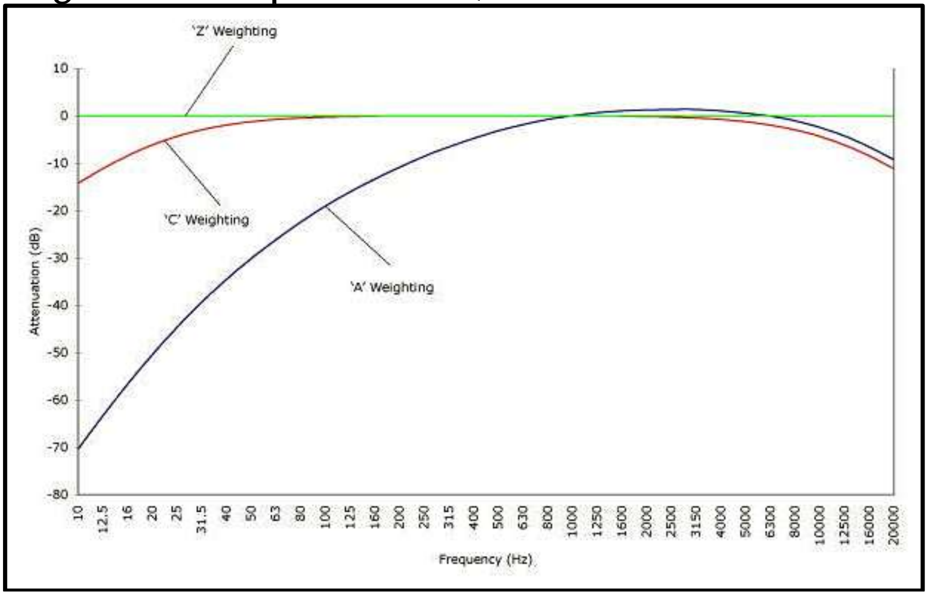
Measurements using A-filter approximate the frequency sensitivity of human hearing (range 20Hz-20kHz, most sensitive ~500 Hz-6 kHz), while the C-filter also includes frequencies below 500 Hz. The figure below illustrates the characteristics of both A- and C-filter. An alternative to both is the Zero-filter (dBZ) where there is zero filter to any part of the spectrum. Zero-filter may be particularly appropriate when measuring or discussing infrasound (1-20 Hz) or low frequency (20-200 Hz) sound. A flat line at '0' dB in the figure below illustrates the dBZ 'filter'. If this is not available for low frequency noise then a C-filter is to be preferred.

It made sense to develop and use the A-filter early in development of modern aviation, as it captured, and still does, the range of frequencies best heard by the human ear and consequently, most closely associated with what is called aircraft noise 'annoyance'. However, we now know that the focus on aircraft noise *annoyance* has unwittingly masked attention to lower frequency aircraft noise closely associated with a range of life threatening ailments – it is a long list, see Table 4. In brief, noise monitoring using the A-filter needs to be complemented, ideally, with the Zero-filter, less ideally with C-filter measurements.

To improve monitoring and policy surrounding management of aircraft noise it is essential standards systematically taking account of the full sound spectrum be employed. This particularly important when it is realised frequencies now known to be most harmful are those below 500 Hz, frequencies systematically diminished using the A-filter.

Figure 1 and Table 1 below provide a graphical and quantitative perspective of differences between A- and C-filter; the Zero-filter makes no changes to the relative importance of different frequency bands. The diminution below 500 Hz caused by the A-filter inevitably results in the known effects on humans of low frequency aircraft noise being 'masked' and ignored.

Figure 1 – Comparison of A-, C- and Z- Acoustic Filters



Source: Cirrus Research: https://www.cirrusresearch.co.uk/blog/ Note: The term 'filter' is used instead of 'weighting'.

Using a C- or Zero-filter directs greater attention to the magnitude of aircraft noise at low frequencies. However, further work is required to define the range of frequencies that should be included in monitoring data, not just singular decibel readings. Assuming further research is able to identify which frequency bands appear to be associated with specific or a cluster of ailments would, potentially, allow mitigation measures to be directed to reducing noise in these frequency bands. A corollary of this would be the possibility of defining and/or refining dose-response curves for aircraft noise.

Frequencies and Wave Lengths

A simple three variable formula links wave length, velocity of sound and frequency. In brief, the lower the frequency the longer the wave length. The second column in Table 1 illustrates this relationship: Wave length = Velocity of Sound/Frequency ($\lambda=V/f$).[11]

As is clear, frequencies captured using the A-filter metric (highlighted) only include a small portion of the whole noise spectrum and wave lengths shorter than a metre. Higher frequencies with shorter wave lengths are rapidly attenuated in the atmosphere, while the lower frequencies and longer wave lengths travel further, making it possible for them to reach ground level even from an altitude of at least 4,000ft, where than can affect humans (tissue and organ resonance) even if they cannot be heard.

[11] The approximate velocity of sound at sea level is 340m/sec, declining at higher altitudes.

Table 1 – One-Third Octave Band Frequency Ranges, A- and C-filter

Centre Frequency (Hz)	Wave Length (m)	Effective Band (Hz)	A Filter (dBA)	C Filter (dBC)
31.5	11	22.1 - 44.2	-39.4	-3
63	5.4	44.2 - 88.4	-26.2	-0.8
125	2.7	88.4 - 177	-16.1	-0.2
250	1.4	177 - 354	-8.6	0
500	0.69	354 - 707	-3.2	0
1000	0.34	707 - 1,414	0	0
2000	0.17	1,414 - 2,828	1.2	-0.2
4000	0.09	2,828 - 5,657	1	-0.8
8000	0.04	5,657 - 11,314	-1.1	-3

Note: Frequencies captured and *not* significantly modified using A-filter metric shaded in orange. Source: https://www.vernier.com/til/3500; IEC 61672:2013

For comparison, frequencies from 1,000 Hz to 10,000 Hz are attenuated at the rate of between 1.0 and 10 dB per 100m, while frequencies from 1 Hz to 1,000 Hz are attenuated by progressively less than 1.0 db per 100m. For noise at 200 Hz, for example, the strength of the sound is attenuated at about 0.05 db per 100m. (Ancich, E, pers. comm.) In practical terms and approximately, low frequency noise at 200 Hz (or lower) from an aircraft at, say, 4,000ft will only be attenuated by about 2 db at ground level, while noise at 2,000 Hz from the same altitude will be attenuated by about 45 dB and be inaudible to a human at ground level.[12]

This largely explains why aircraft noise heard at ground level is dominated by lower frequencies, which travels further with little attenuation. It may also go some way to explaining why lower frequency (e.g. 300-600 Hz) aircraft noise from higher altitudes remains stronger and more noticeable, and why it causes reverberations and resonances in hilly terrain, between large buildings and even within interior spaces.

Aircraft noise is a complex mixture of sounds spanning several thousand Hertz, at the low end sounds down to 0.1-2 Hz, at the upper end to over 15 kHz, it includes many harmonics. The human body and its internal organs and system are known to resonate at a wide range of frequencies, almost all well below about 200 Hz. Fairly recent work suggest the whole human body resonates at approximately 12 Hz with a range of 9 to 16 Hz.[13] However, parts of the human body have differing resonant frequencies, and the resonant frequency varies with body mass and magnitude/amplitude of the sound.

For almost a century it has been known that human cells vibrate and external sounds can cause resonances. Since then considerable work has been done to quantify the

[12] The acoustic 'footprint' of low frequency aircraft noise is paricularly relevant for low altitude (<4,000ft) flights across densely populated urban areas, of which Brisbane is just one example. Regulatory agencies often choose to depict a 'noise swath' as quite narrow (~2km) – even this is quite wide in an urban context – rather than approximately 11 km for low frequency noise, as calculated using applied physics methods.

[13] Brownjohn, J. & Zheng, . "Discussion of human resonant frequency." Proceedings of SPIE, 02 February 2016. https://doi.org/10.1117/12.429621

frequencies and magnitudes of these vibrations and determine resonance frequencies of various parts of the body.

Bryan Johnson (2018) proposed ‘health based criteria’ as the basis for managing aircraft noise.[14] This makes intuitive and practical sense. It is widely recognised that chronic and severe aircraft noise is a public health issue affecting millions of people in Europe, as recognised, for example, in the WHO (Europe) guidelines.

Johnson demonstrated that even noise from high flying aircraft had sufficient strength at ground level to cause vibrations in human tissue. Using an innovative experimental set up he identified low frequency sounds (<200 Hz) as the probable source of harm, monitoring these vibrations in a container of ‘ballistic gel’ (to simulate human tissue) to observe and measure resonances caused by low frequency aircraft noise.

For our purposes the most relevant of his specific objectives was:

- To determine the significance of the contribution of infrasound and the vibrations they produce towards degraded cardiovascular health consequences and if these effects apply to aircraft noise. (p.5)

Human Body and Resonances

The human body, internal tissues and organs responds to a wide range of frequencies, including infrasound and low frequency sound. They have natural resonant frequencies, and whole body exposure to external low frequency sound, i.e. aircraft noise, can cause internal resonance which amplify the strength of vibrations, in some cases leading to subtle internal damage.

Table 2 – Human Resonant Frequencies

Organ/ Body Part	Resonant Frequency
Inner ear	0.5 to 10 Hz
Eye	20 to 90 Hz
Head	20 to 30 Hz
Chest wall	50 to 100 Hz
Abdomen	4 to 8 Hz
Lungs	4 to 8 Hz
Spinal column	10 to 12 Hz
Shoulders	4 to 8 Hz
Hands and arms	20 to 70 Hz
Maxilla	100 to 200 Hz
Skin – Merkel Cell	5-15 Hz
Skin – Meisser’s corpuscles	20-50 Hz
Skin – Pacinian corpuscles	60-400 Hz

Source: Havas & Colling, Leventhall, Duarte and Pereira [15]

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[14] Bryan Johnson (2018) “Health Based Criteria for use in Managing Airport and Aircraft Noise.” Masters thesis, Harvard University. https://dash.harvard.edu/handle/1/37945140

[15] Havas, M., & Colling, D. (2011). Wind turbines make waves: Why some residents near wind turbines become ill. Bulletin of Science, Technology & Society, 31(5), 414-426. oi:10.1177/0270467611417852. Leventhall, G Pelmear, P & Benton, S (2003) A Review of Published Research on Low Frequency Noise and its Effects, Defra Publications, UK.
M.L.M. Duarte and M. de Brito Pereira (2006) “Vision influence on whole-body human vibration comfort levels.” Shock and Vibration 13 (2006) 367–377, IOS Press.

The list in Table 2 is a limited sample of the range of organs affected by resonance to low frequency sound, currently it is not known precisely which and at what intensity external sounds leads to specific, clinical conditions. It appears the cardiovascular and lymphatic systems – specifically the endothelium - are particularly sensitive to sounds below about 200 Hz. It is noted that chronic exposure to aircraft noise also results in psychosomatic conditions, e.g. depression, anger, migraine, dizziness or vertigo.

Health Impacts

Table 3 lists the responses of human organs and systems that have resonant frequencies affected by low frequency aircraft noise. These have been identified over the last two decades in a range of epidemiological (medical and psychological) studies. Not all of the responses have negative consequences or increase risks. On the other hand, there are well established cause-effect linkages between aircraft noise and, for example, increases in blood pressure and heart rate.

Table 3 – Health Impacts from Infra and Low Frequency Sound

Organ, Process	Effect	Frequency Range
Thyroid function*	Increased activity	14 Hz
Brain function *	Response rate	12 & 36 Hz
Cognitive learning *	Reduced	6-25 Hz, peak 13 Hz
Balance	Interference	40 Hz
Blood pressure #	Significant increase	Systolic 6 & 16 Hz
Blood pressure #	Significant increase	Diastolic 12 & 16 Hz
Heart rate @	Increase	2-14 Hz
EEG rhythms **	Variations in morphology	13 Hz

Source: * Persinger, 2014, # Danielsson & Landström, 1985, @ Qibai & Shi, ** Kasprzak, 2013.[16]

Comparing human body organs and processes affected by low frequency above with the ailments listed below (Table 4) indicates the strong likelihood that it is indeed whole body exposure to chronic low frequency aircraft noise as the probable cause. Table 4 lists well documented clinical and biomedical, mental and social effects of aircraft whole body noise exposure. The caveat being that chronic noise exposure increases the risks of these ailments occurring, even if it is not the direct cause.

[16] Persinger, M (2014) "Infrasound, human health, and adaptation - An integrative overview of recondite hazards in a complex environment.", Nat Hazards (2014) 70:501–525, DOI 10.1007/s11069-013-0827-3; Qibain, CHY & Shi, H, "An Investigation on the Physiological and Psychological Effects of Infrasound on Persons." J. Low Frequence Noise, Vibration and Active Control, p. 71-6; Kasprzak, C (2013) "The influence of infrasound on humans ." 20th International Congress on Sound and Vibration, Bangkok. Branco, N.A.A.C et al (2007) op cit.

Table 4 – Clinical & Biomedical, Mental & Social Effects

Clinical/Biomedical	Mental & Social
Cardiovascular diseases	Delays student learning
Endothelial dysfunction	Delayed cognitive development
Blood pressure elevated	Psychological/social stress
Respiratory Pathology	Depression, anxiety, suicide
Increased stress hormone	Migraines, headaches
Ischemic heart disease	Sleep disturbance
Myocardial infarction	Cognitive impairment
Heart failure	Annoyance
Haemorrhagic stroke	Reduced deep sleep
Ischemic stroke	Disrupts communications
Dysregulates genes	Disrupts social activities
Diabetes mellitus	

Sources: As for Tables 2 and 3. Notes: Clinical/biomedical ailments resonances caused by aircraft noise increase risks of their occurrence or exacerbate existing conditions. Aircraft noise appears to be the direct cause of many mental and social ailments and exacerbate underlying conditions.

Illustrating Aircraft Noise

To clearly illustrate the prevalence and importance of low frequency aircraft noise a free Android app called 'OpeNoise' was used to capture noise spectra from jet aircraft departing from Brisbane airport, Australia. Generally speaking, there are no publicly available detailed sound spectra for aircraft noise, an exhaustive internet search provided few results. Possibly the most important is for departures when the climbing aircraft noise is very loud, deep, booming 'climb power'; however, as in Brisbane, low altitude (<4,000ft) aircraft on arrival may disrupt the lives of even more people.

These aircraft directly (exactly) overfly the author's home at about 2,500-3,000ft on departure from Brisbane airport, which is located about 7 km northeast [17] The readings were taken outside from a point where there is an unobstructed view of the sky and the aircraft. When the wind changes to a more northerly direction aircraft arriving from the southwest also pass directly over our home, usually at an altitude of about 1,500ft and these are almost equally noisy.

The OpeNoise app makes provision for observing (and recording) sound in 1/3 octave bands (a standard metric) using a Zero-filter. The amplitude of each band is displayed as a stacked, coloured columns from 16 Hz up to16 kHz: LZ_{max} (blue), $LZ_{eq(t)}$ (purple), $LZ_{eq(1s)}$ (red), LZ_{min} (green). For each flight aircraft noise was monitored for approximately 15-20 seconds as an aircraft approached and passed overhead, then recording stopped. Another Android app called 'Screen Shot' captured an image of the screen, illustrating the amplitude of each 1/3 octave band (see Figure 4 below).

[17] Very heavy aircraft – B777, B787 and A380 – departing the airport usually have only climbed to about 2,500ft by the time they pass over our house.

This approach has the significant advantage of monitoring the complete aircraft noise spectrum in detail, rather than depending on a single, limited measurement of loudness, i.e. decibels, to measure aircraft (or other) noise.

It is highly likely by focusing on a single metric that for decades we have been missing critical information about the source of the known harms caused by chronic exposure to aircraft noise. The common metric, dBA, provides useful insights into the severity of aircraft noise that is 'annoying', but no information on if or why it might be harmful. None of the unitary metrics, e.g. 65 dBA or even 65 dBZ, provides information on this aspect of aircraft noise. It is only by examining the frequency spectrum we can gain insights into how the composition of this noise affects human wellbeing and/or causes illnesses.

Effects of Low Frequency Noise

It has been known for about 100 years the human body and its internal organs react to low frequency sound (20-200 Hz) and infrasound (0-20 Hz) sounds. In 2018 Bryan Johnson, an engineer in the US, as part of his thesis research at Harvard University, showed low frequency and infrasound noise from aircraft at up to an altitude of at least ~4,000ft still had sufficient energy at ground level to cause resonance in human organs. Johnson's 2018 work provided crucial evidence of direct physical linkage between low frequency aircraft noise and its effects on the human body.

We are aware (chronic) aircraft noise is damaging to humans and other living beings. In brief, there are social and psychological effects of many kinds: annoyance, anger, conversations lost, migraines, additional stress, interrupted concentration, communications and learning, etc. In addition, there are (subtle) clinical effects, e.g. increased risks of cardiovascular disease, hypertension, diabetes, etc. that have been definitively identified through extensive epidemiological research, mainly in Europe and the US; no studies have been done in Australia (to the best of my knowledge). Until fairly recently the mechanisms linking these to clinical effects in the body had not been definitively identified.

Branco and Alves-Pereira's first studies were published in 1999, five years later they published a comprehensive analysis based on more extensive data collection, confirming the existence of "Vibroacoustic Disease" (VAD. By 2006 they had determined that chronic exposure to low frequency vibration (noise) led to changes in cellular structures. They had named VAD a whole-body pathology:

> VAD is associated with the abnormal growth of extra-cellular matrices (collagen and elastin), in the absence of an inflammatory process. In VAD, the end-product of collagen and elastin growth is reinforcement of structural integrity. This is seen in blood vessels, cardiac structures, trachea, lung, and kidney of both VAD patients and ILFN-exposed animals.[18]

Their analysis and insights were based on detailed examination of hundreds of Portuguese aircraft technical ground staff, in whom, when "… echocardiography, brain MRI or histological studies are performed, where structural changes can be identified,

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[18] Alves-Pereira, M. &, Branco, N.A.A.C. (2006) "Vibroacoustic disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signalling" Progress in Biophysics and Molecular Biology 93 (2007) 256–279. doi:10.1016/j.pbiomolbio.2006.07.011.

all consistently show significant changes in VAD patients." (ibid) They continued this work and published a number of other studies deepening and confirming their initial findings. Despite this, and as far as is known, VAD is still not recognised as an occupational disease.

In 2007 they published a review paper covering 25 years of research into respiratory effects of VAD. They determined symptoms appear after about four years of exposure. Long-term exposure leads to "atypical pleural effusion, respiratory insufficiency, fibrosis and tumours." Concluding that "LFN [Low Frequency Noise] is an agent of disease and the respiratory tract is one of its preferential targets."[19]

More recently, Drs Thomas Munzel and Omar Hahad in Mainz, Germany identified disruption of the endothelium - the fine, single-cell lining of all blood vessels, the heart and lymphatic system - as the source of these clinical effects.[20] Despite being thin – a single layer of squamous cells - the endothelium is responsible for a range of critical control functions affecting blood flow and pressure in the body.

Several lines of evidence now suggest disruption of the endothelium is caused by resonances generated by low frequency and infrasound from aircraft noise. These frequencies are 'excluded', de-emphasised, by the A-filter, better captured by the C-filter and more accurately still by the Zero-filter. Also note, low frequency sound carries for great distances, >10's of km, while higher frequencies are quickly attenuated in the atmosphere.

Samples of aircraft noise spectra from eight types of medium and heavy jet aircraft climbing steeply on departure – all at about the same altitude, clearly illustrates the similarity of their noise spectra. The bulk of the acoustic noise, vibration and energy is below 500 Hz (Figure 4). The B737 is probably the most common type of use in use in Australia, the B777, B787 and A380 types are heavy long-haul exceptionally noisy aircraft, which all too often depart Brisbane in the middle of the night, as there is no curfew. Readings above about 1,000 Hz – in the orange rectangles, are essentially the noise we hear – the rest, the majority, lower and higher frequencies, having been removed by the A-filter.

The lowest frequencies (vibrations), i.e. below 200 Hz, carry the majority of the sound energy causing resonances in the human body and internal organs. It is probable, although more work is needed, these frequencies disrupt the normal functioning of the endothelium and other internal organs. Additionally, based on work by Alves-Pereira and Branco (op cit) they also result in unusual cellular growths and respiratory problems.

For even the most modern of these aircraft, e.g. Airbus A350 and A32N, low frequency noise appears to be even more prominent, even though noise measured using the A-filter may have decreased. Over twenty years ago the WHO Guidelines on Community Noise offered this advice:

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[19] Branco, N.A.A.C et al (2007) "Respiratory pathology in vibroacoustic disease - 25 years of research." Revista Portugesa Depneumonolgia, Vol XIII N.º 1 Janeiro/Fevereiro.

[20] Münzel et al (2023) "Too Loud to Handle? Transportation Noise and Cardiovascular Disease" Canadian Journal of Cardiology - (2023) 1-15, https://doi.org/10.1016/j.cjca.2023.02.018

> When prominent low-frequency components are present, noise measures based on A-weighting are inappropriate ... It should be noted that a large proportion of low-frequency components in noise may increase considerably the adverse effects on health. (WHO 1999)

If our findings are independently validated they imply the need for significant revisions of the metrics used to monitor aircraft noise, so as to measure frequencies known to damage human health and increase risks of disease.

Modern Aircraft – Less Noisy?

The exploration of noise spectra for a range of aircraft revealed something unexpected. We have been repeatedly told technological advances over the last decades have made aircraft less noisy, the measure being used is the familiar A-filtered decibel metric (dBA). For audible noise this is generally probably true, although rarely checked in the field, as opposed to just accepting manufacturer's and government data. Comparing the spectra of the B737 and the newer B737 MAX (Figure 4) suggests there is a small decrease in maximum noise level, despite the overall shape of the spectra being similar.

The measured spectra of a sample of modern heavy aircraft (e.g. A350, A380, B787), using the same methodology previously described, confirms audible noise levels measured using the A-filtered measurement is somewhat lower as compared to older aircraft.

When the noise spectra of these newer aircraft is examined more closely, however, it appears there is little change in the amplitude of the frequencies below 500 Hz. These are very similar overall to those of older aircraft. These may be less noisy in the audible part of the spectrum above about 1,000 Hz, but below this frequency there is little difference. (See Figure 4)

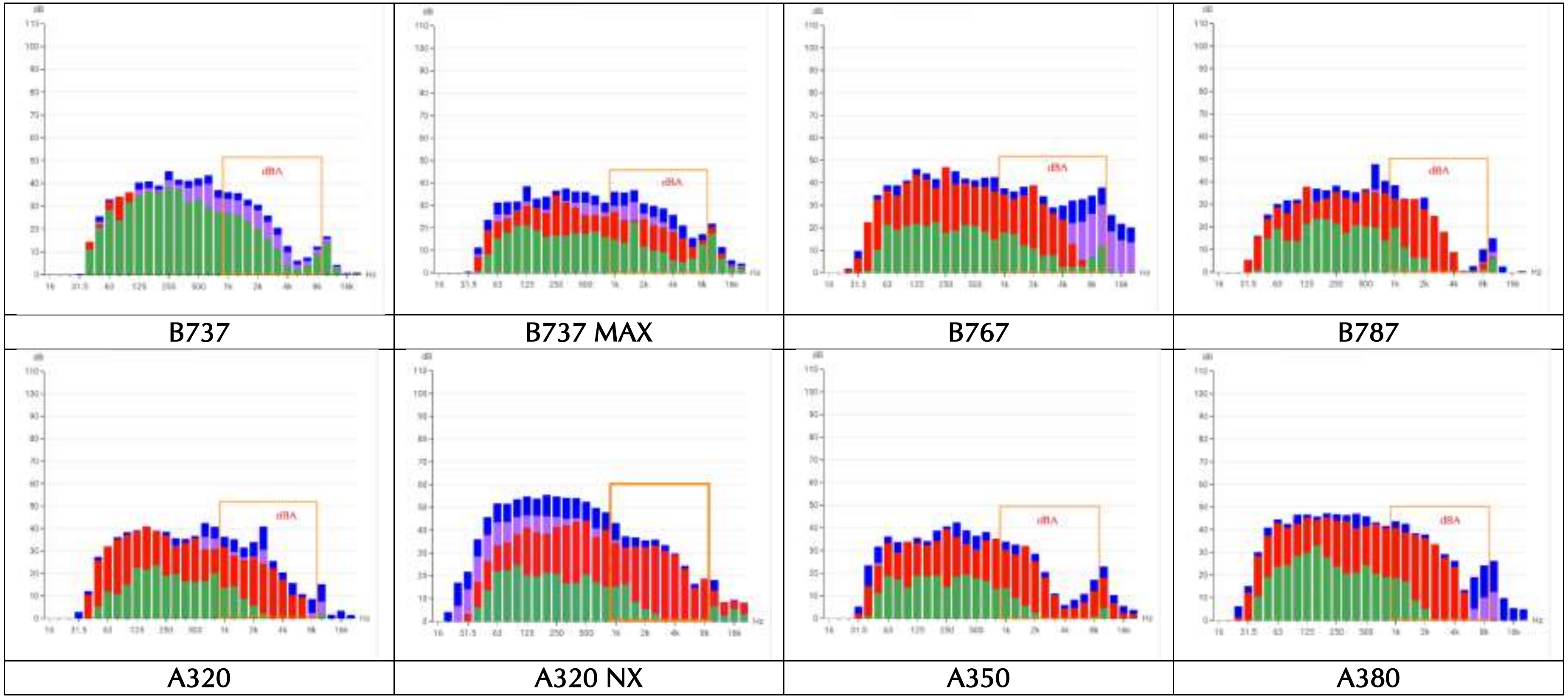
This lack of a significant reduction in low frequencies and infrasound is of serious concern, because these are the frequencies known to be harmful to humans.

The similarity in the shapes of noise spectra between older and newer aircraft, i.e. the preponderance of low frequencies – illustrates the inadequacy of relying on a single metric (dBA), especially when the metric is known to be insensitive to low frequencies. That is, while noise annoyance due to higher frequencies may be lower, the likely health effects of low frequency and infrasound remain largely unchanged.

This lack of significant reduction in low frequency noise has potentially serious policy implications, taken in conjunction with the anticipated increase in air traffic in coming decades. Briefly, it suggests health impacts will continue to increase as frequency of overflights increases, despite there being some reduction in aircraft noise annoyance. Unless aviation industry regulators, i.e. governments, and the general public are aware of this divergence, i.e. health risk rising or unchanged while noise annoyance declines, the narrative from the aviation industry may lead to policy and regulatory complacency regarding the need to limit aircraft movements and markedly reduce low frequency noise.

Figure 4 illustrates the noise spectra of common Boeing and Airbus aircraft types operating from Brisbane airport. Qantas and Virgin Australia accounting for some 70% of domestic air travel, and a number of international airlines also fly into Brisbane.

Figure 4 – Aircraft Noise Spectra – Departures Brisbane Airport – Medium and Heavy Jet Aircraft



Source: Noise spectra collected and recorded by author using the Android apps ‘OpeNoise’ to record and ‘Screen Shot’ to capture the spectra. Observations taken from directly under a major flight path to and from Brisbane airport, outside the author’s house with an unobstructed view of the sky and aircraft. The cut-off below 20 Hz is due to the limitations of the Samsung Tab A smart phone used to capture sounds. Sound spectra for arriving aircraft are slightly lower but still dominate by low frequencies.

These noise spectra show the full spectrum for each aircraft type, recorded at about 7km from the airport with aircraft climbing to the south-west during departure. Each aircraft passes over our house at about 2,500ft - 3,000ft. The spectra cover the range of about 16 Hz to 20 kHz, while it is known aircraft noise extends to lower frequencies, the smart phone's microphone is not adequate to capture infrasound below about 30 Hz.

Each of the spectra has an orange rectangle outlining frequencies from about 1 kHz to 10 KHz, a slightly more generous range of frequencies than included in the A-filter, where there is near zero negative or positive differences from a Zero-filter, i.e. dBZ. From these graphs it is clear that all frequencies below about 1 kHz are not captured or measured. However, these are the range of frequencies, especially those below about 200 Hz, that are known to generate resonance in human tissue and organs, often leading to increased risk of a range of life-threatening ailments.

The emphasis here is not on precision graphs, i.e. the specific frequency ranges being captured, but on the overall pattern of frequencies, especially those below about 500 Hz.[21] It is clear that for all types of aircraft the great bulk of the noise generated is below 500 Hz, or even 200 Hz, for both older (e.g. B737) and the newest aircraft (e.g. A320 NX). This is a clear indication of the inability of the dBA metric to capture noise known to be harmful to humans (and other species). It reliably captures frequencies heard by most humans, which is generally classified as 'annoying'. It is widely recognised people's sensitivity to noise varies greatly, causing this measure to be disregarded as 'subjective' and being 'unscientific'.

Summary of Findings

There no longer remains any doubt chronic whole body exposure to aircraft noise damages human health, increasing the risks of various serious ailments. In the last few decades the biochemical and biophysical mechanisms underlying this damage have been identified, most recently those leading to increased risks of cardiovascular disease.

Nor can there be much doubt it is highly likely the main causes of human harms are low frequency and infrasound from aircraft noise. These frequencies have been ignored for too long in biomedical and related research, and now require thorough investigation to confirm and quantify their importance, so as to provide detailed evidence of does-response relationships.

Although not discussed in detail here, the social and mental health effects of aircraft noise have also been documented beyond reasonable doubt. These included delaying children's cognitive development and learning, sleep deprivation, disrupting of family communication and increased personal and social stress.

The range and depth of peer-reviewed scientific literature concerning the above issues is contained in hundreds of publicly available articles; additional confirmations being published almost monthly. This in itself indicates the seriousness of the public health issues posed by aircraft noise.

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[21] Because the focus is on low frequencey noise small variations in altitude (e.g. ~500ft) are not considered important given there is little attenuation of low frequency sounds in the atmosphere.

Almost total dependence by regulatory agencies and researchers on A-filtered decibel measurements has ‘hidden’ the critical role of low frequency and infrasound aircraft noise in harming humans and society. Once this oversight is corrected, and linked to how the human body responds to the resonances caused by low frequency sounds, it becomes apparent these frequencies are most likely the main source of clinical harm to humans. Noting, however, ‘annoyance’ by higher frequency aircraft noise remains important because of the social and psychological disruption it causes.

Recommendations

- We propose the name “Full Spectrum Metric” (**FSM**) for the revised policy, protocols and practice of using the complete sound spectrum from 0 Hz to 20,000 Hz for measuring and monitoring aircraft noise pollution.
- Governments and other organisation consider making it mandatory for the full spectrum of aircraft noise to be monitored and reported. Including testing, measuring and reporting on aircraft noise conducted for aircraft certification.
- Research protocols investigating the effects of aircraft noise be revised to ensure low frequency and infrasound frequencies are competently monitored, so that correlations and causation with clinical and socio-psychological effects can be explored and documented.
- Aircraft noise monitoring protocols of regulatory and commercial organisations be modified to ensure low frequency and infrasound aircraft noise is recorded for use in biomedical research, pollution control, enforcement and mitigation.
- Manufacturers be advised of these findings and requested to make the necessary modifications to their equipment, operation protocols and training to ensure low frequency and infrasound can be and is monitored and reported.

  Having adopted the Full Spectrum Metric as a national standard we urge government to propose and advocate its adoption in international fora, beginning with the UN ICAO.

About the Author

Dr Sean Foley BSc (Hons) PhD FRGS is an esteemed Australian environmental scientist. His academic journey commenced with a Bachelor of Science with Honours from Murdoch University in Western Australia, followed by the successful completion of a PhD in Human Ecology at the Australian National University (ANU). Recognised for his exceptional contributions to geography and environmental science, Dr Foley was elected as a Fellow of the Royal Geographical Society (FRGS). His work is widely acknowledged in the academic community, with more than 2,500 citations and an h-index of 17. His extensive research portfolio includes numerous peer-reviewed publications in renowned scientific journals, reflecting his commitment to scientific communication and public outreach. Dr Foley's interdisciplinary expertise spans natural resource and environmental management, environmental legislation, public health economics, international aid and development, policy analysis, and project design and management. He has also served as an Environmental Specialist with the World Bank, contributing his expertise to global environmental and developmental initiatives. Dr Foley's leadership extends beyond academia; he has been an Executive Board Member of the Australia and New Zealand Society for Ecological Economics, and since 2003 a Fellow and now immediate ex-Chair of The Samdhana Institute.

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