Field Assessment of
Air Source Heat Pump Noise

Future Homes Project Acoustics Team

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EXECUTIVE SUMMARY

Net Zero targets in the UK require a shift to low or zero carbon emission technology, which is supported by the UK government funding to support the installation of Air Source Heat Pumps (ASHPs) for domestic heating provision. ASHPs offer better thermal efficiency than traditional boiler systems and have no direct carbon emissions. Research is needed to understand the interaction and impact of multiple ASHPs operating in close proximity or in cases in which ASHPs are numerous within a small residential area. This study focuses on the noise from ASHPs rather than ground source heat pumps because the latter are not subject to the same noise testing as ASHPs due to their configuration. This report presents the key findings of two field studies: i) a measurement for the acoustic characterisation of a pair of ASHPs in close proximity; and ii) a further measurement of a single ASHP at noise sensitive locations at neighbouring properties. The ASHPs measured were located in the back gardens of dwellings at a new-build housing estate in Nottinghamshire. A subsequent study is planned and will focus on the case of multiple ASHP units operating in a small residential area.

The analysis of the data gathered in these two studies suggests that:

1. Simple power summing (i.e., logarithmic dB addition) of noise from two ASHPs, as is standard in environmental noise assessments, was seen to be adequate for the case studied. There were some microphone positions where the calculation underpredicted the SPL measured when both ASHPs were operating. These underpredictions could be explained through adverse conditions that affected the final measurement, however; they will be further investigated in future studies. For unaffected microphones the agreement between power summing calculations and measurements was very close.

2. Low-frequency tones are more prominent and audible in the neighbouring property, with a wooden fence (with boards approximately 15mm thick) providing minimal sound attenuation for this frequency range. This emphasises the importance of selecting the appropriate placement and orientation of the ASHP, and potentially a need for fences with better acoustic performance at low frequencies.

3. There is no confirmation of significant low frequency interaction between the closely spaced ASHPs measured under the specific operation conditions tested.

However, further investigation is recommended to investigate human (psychoacoustic) perception of such low frequency tones.

4. There is no change in compliance status between MCS 020 (2019) and MCS 020 a) (2025) calculation protocols for the specific case evaluated in this study. In addition, MCS calculations for ASHP noise limits were in good agreement with measured sound levels.

CONTENTS

ACRONYMS

ASHP	Air Source Heat Pump
BPF	Blade Passing Frequency
FS	Fluctuation Strength
HPA	Heat Pump Association
JNM2	Joint Nordic Method 2 (ISO 1996-2)
MCS	Microgeneration Certification Scheme
OASPL	OverAll Sound Pressure Level
PSD	Power Spectral Density
RMS	Root-Mean-Square
RPM	Revolutions Per Minute
SLM	Sound Level Meter
SPL	Sound Pressure Level (as measured at a microphone)
SWL	Sound Power Level (as output by a sound source)
TOB	Third-Octave Band

1 INTRODUCTION

The aim of this study was to make quantitative measurements of Air Source Heat Pumps (ASHPs) in-situ, determining ASHP noise at the homes where they are installed and at the neighbouring properties.

The main topics of interest and research questions for this study are:

- Cumulative effects of multiple ASHPs in close proximity:
    - Can the combined level of multiple ASHPs operating in close proximity be estimated by simply summing the power?
    - Are there low frequency sound interaction effects?
- Application of the Microgeneration Certification Scheme (MCS) standards, comparing the MCS 020 (2019) and MCS 020 a) (2025) calculation protocols:
    - Does the compliance status of the ASHP measured in this case study change between the two versions of the standard?

The site that the HPA negotiated for Future Homes researchers to access had four unoccupied properties with adjoining gardens, suitable for needs of the study. This is depicted in Figure 1.

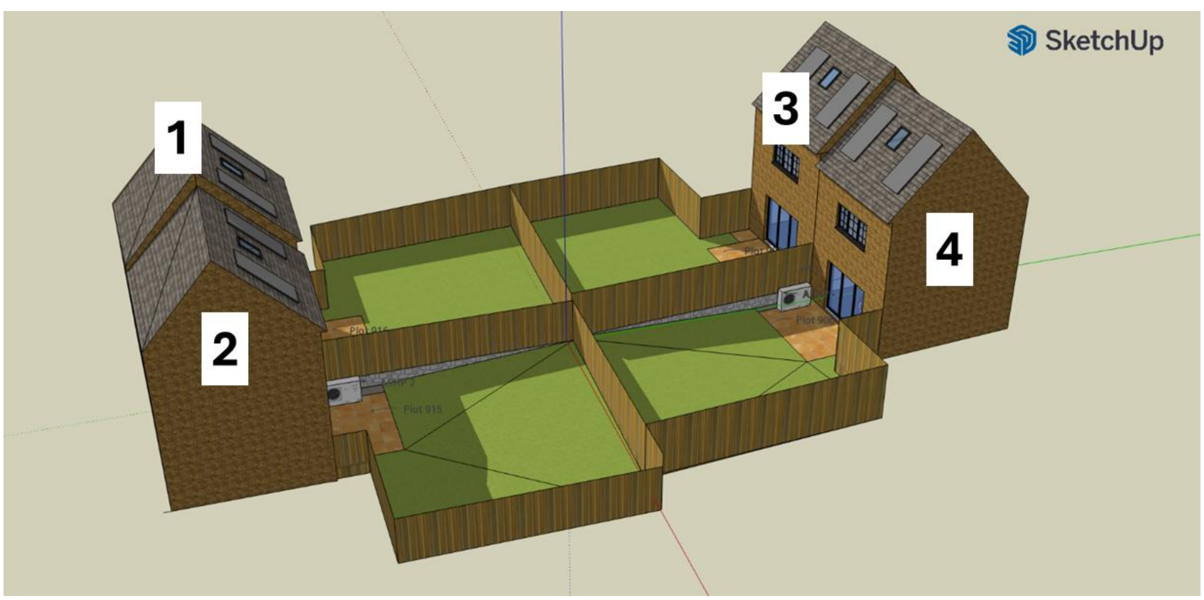

Figure 1: SketchUp 3D drawing of the site layout with properties 1, 2, 3, and 4 labelled.

Properties 1 and 2 were used for the first study, which took place in December 2024. This examined ASHPs 1 & 2 only, but with a detailed nearfield survey looking for evidence of cumulative noise effects and with the option to control their operating state. This was possible as these homes were still owned by the housebuilder and researchers were allowed to enter. The measurements used a 2.5m semi-circular arc of microphones positioned over the pair of ASHPs to capture their acoustic radiation characteristics plus the effect of the fence.

The second phase of the experiment, which used all four properties and took place in January 2025, was undertaken after properties 1 and 2 had transferred to other ownership – as had already happened for properties 3 and 4 – meaning that the properties could no longer be entered and the state of their ASHP controlled. Only exterior access to the garden was permitted. Nonetheless, it was expected that all ASHPs would operate at some point since it was a cold evening in the middle of winter, and the test campaign was designed based on this premise. Microphones were located at the 4 ASHPs, the patio doors, and upstairs rear bedroom windows of the four houses, simultaneously capturing the acoustic pressure at all sources and all critical reception points. A further six microphones were located at positions along the boundary fences to monitor propagation paths. Unfortunately, as events transpired, only the heat pump at property 2 operated, but the data gathered remained useful; notably it was used for a comparison between the MCS 020 (2019) and MCS 020 a) (2025) calculation protocols for ASHP noise.

Figure 2: Photograph of properties 1 and 2 taken during experimental set up

1.1 Specifics of the ASHP and Positioning

The rear facades of the four properties were all identical except for reflective symmetry. The layout is shown in Figure 3. The sizes and shapes of the gardens differed, with gradient in places, but all contained a flat 2.5m deep patio spanning the rear of the property on which the ASHP was installed. At the rear of the patio were bifold doors leading to a combined kitchen / living room space.

Each pair of houses had a 40cm height difference between them, which was reflected in the relative patio elevation. The fence height was 1.8m but buttresses between the differing height gardens varied this in effect in places; notably near HP2 and HP4 the fence behind the unit was buttressed by 40cm so was 2.2m in height. The fence was ‘closeboard’, comprising overlapping planks approximately 15mm thick nailed onto a substantial wooden frame.

The ASHPs were all identical, being Panasonic WH-MDC05J3E5. This is a 5kW unit, 865mm high by 1283mm long and 320mm deep. According to the manufacturer, it has a sound power (part-load, heat) of 59 dBA (ErP label and manufacturer specification document). Here the ‘A’ in ‘dBA’ indicates that the sound power has been ‘A-weighted’ in frequency according to BS EN 61672-1:2013. The A-weighting curve aims to mimic the sensitivity of the human ear at a loudness similar to that at which ASHPs are likely to be experienced, so is an appropriate choice for displaying data herein.

The heat pumps were installed back-to-back on opposite sides of the fence that protruded perpendicular to the properties, at an equal spacing of 32cm from it and the property. The outlet fan is located asymmetrically on the unit, so was closer to the property for Properties 2 and 3 than it was for Properties 1 and 4.

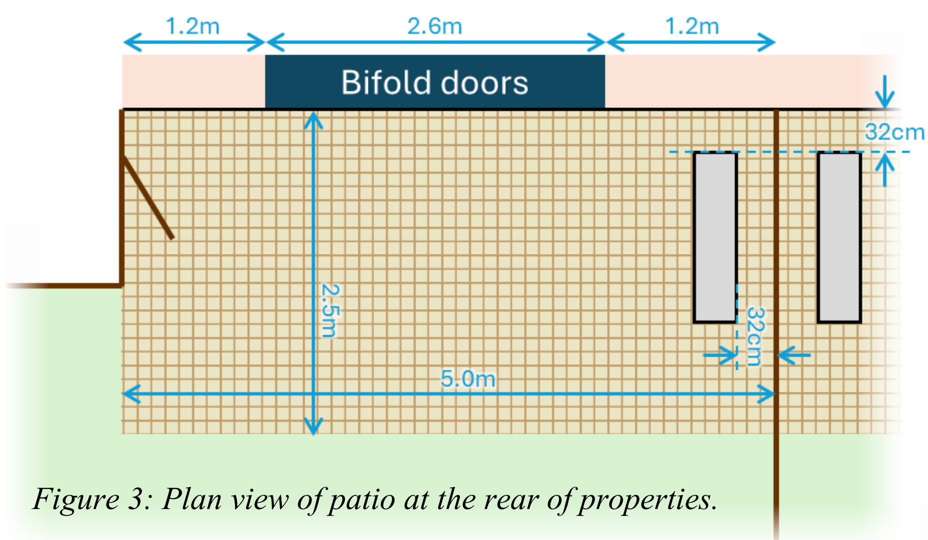

Figure 3: Plan view of patio at the rear of properties.

1.2 Scope of the Study

This report provides a comprehensive overview of the measured data, performing analysis pertinent to the research questions posed at the outset of the study. The results presented here includes analysis and observations that offer insights into the acoustic characteristics and human response to ASHP noise.

However, when drawing conclusions from this field study and subsequent data analysis, it is important to consider that the noise measurements were taken on a single site. It cannot be assumed, therefore, that the findings presented herein match the average findings that would arise were it possible to perform a large campaign of studies covering a broader range of layouts of properties, barriers and ASHPs. Notably the site, while ideal in many ways, did have some undesirable features:

1) The differing heights of the gardens. While not shown to be significant, it will be seen later that a systematic asymmetry occurs in the phase 1 results, and it has not been possible to eliminate this as a possible cause.
2) The site was close to a noisy road. While great care was taken to screen measurements for significant car pass-by noise, it cannot be guaranteed that background noise did not fluctuate slightly between measurements and – due to the ASHP noise being only marginally louder than the background noise level – this may also have led to biases that it is not possible to eliminate.

Nonetheless, this remains a representative site for semi-detached dwellings in close proximity, which was instrumented in a far more sophisticated manner than conventional noise surveys demand. It is, therefore, a valuable, high-quality dataset and – while it cannot be assumed that the conclusions will necessarily generalise to a wider range of property configurations – they are the best available for this specific site configuration.

1.3 Structure of this Report

Section 2 will define the methodologies used for the phase 1 and phase 2 components of the field study. Section 3 will present the results obtained through analysis of the measurements obtained. Section 4 will draw conclusions, surmise implications for policy, and identify areas requiring further research.

2 METHODOLOGY

2.1 PHASE ONE: TWO ASHPS IN CLOSE PROXIMITY

The aim in this fieldwork was to examine the behaviour of two ASHPs in close proximity in a residential setting. In particular, it aimed to examine the cumulative effects of those two units and how this might vary with angle over the boundary.

2.1.1 Microphone Arc

A bespoke microphone array consisting of a 2.5m diameter scaffold arc was used, with 9 microphones mounted at –80°, –60°, –40°, –20°, 0°, +20°, +40°, +60°, and +80°, with respect to the vertical fence line, with the ASHP for property 1 (hereafter HP1) and negative angles located in property 1 (right) and the ASHP2 for property 2 (hereafter HP2) and positive angles located in property 2 (left). Due to the difference in floor/ground height of 40cm between the two gardens, the microphones are not aligned the same way vertically at each ASHP: -80° is exactly opposite the fan of HP1, whereas +80° is 40cm higher than the fan at HP2. This means that the –80° mic is less susceptible to flow noise than the one at +80°.

Meteorological conditions were stable, and all microphones had windshields, but due to the low acoustic levels being measured, some measurements still had to be repeated due to air flow noise caused by the occasional light gust of wind.

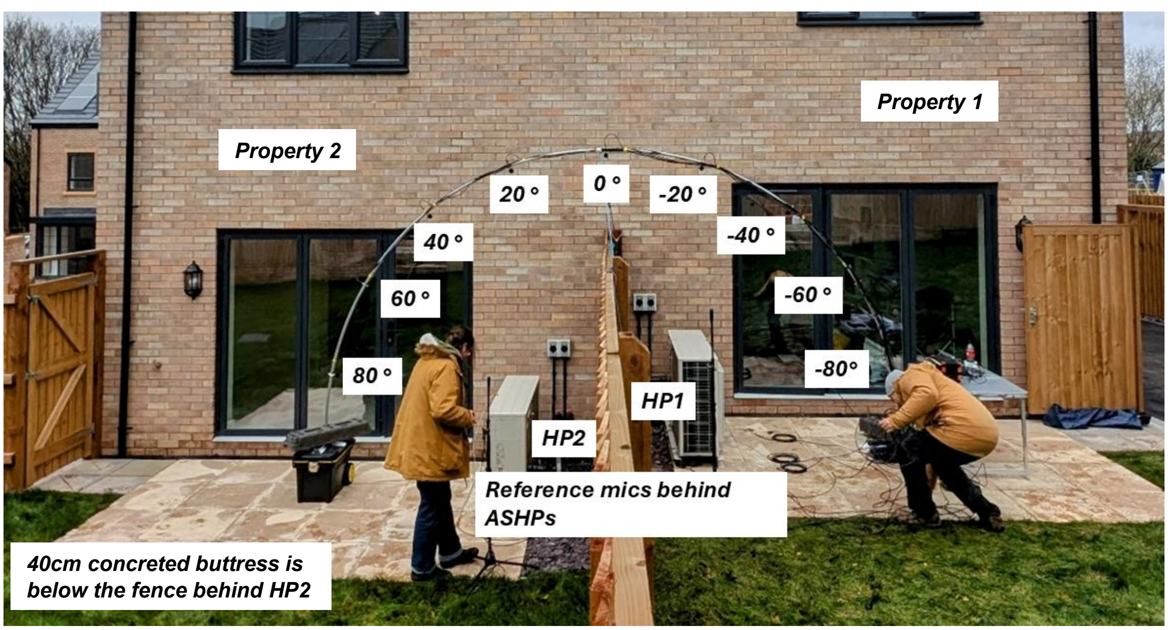

Figure 4: Microphone arc in-situ, encompassing both ASHPs outside the dwellings.

2.1.2 Summation of SPL from two ASHPs

2.1.2.1 Summation of SPL for sounds that are incoherent / decorrelated

A common assumption in Environmental Acoustics is that sound from different sources are ‘incoherent’, meaning there is no fixed temporal correlation between the sounds that the two sources are making. This is usually a justifiable assumption (see e.g. Bies, Hansen & Howard 2017, section 1.10.1) since the sources creating the sound are usually independent. Propagation over long distances typically also leads to this property holding true outdoors since time-variance in propagation time – due to wind primarily – leads to decorrelation and incoherence.

Computing the time-averaged total SPL when incoherent sounds sum is straightforward. Interference effects can be ignored, since the incoherence means these vary with time and hence average out, so the total SPL can be found simply by adding the power present in each signal. Acoustic power is proportional to pressure squared, hence (Bies, Hansen & Howard 2017, eq. 1.95):

$$\langle p_{\mathrm{tot}}^2 \rangle = \langle p_{\mathrm{A}}^2 \rangle + \langle p_{\mathrm{B}}^2 \rangle \qquad \text{Eq. 1}$$

Here p_{A} and p_{B} are the pressure measured at a microphone from two sources separately, and p_{tot} is the pressure resulting from the summation of both of them. The angular brackets $\langle \dots \rangle$ indicate averaging over time, as is done in all acoustics SPL measurements.

SPL L_p is stated in dB (decibels) referenced to 20µPa RMS pressure:

$$L_p = 10 \times \log_{10}(\langle p^2 \rangle / (20\mu\mathrm{Pa})^2) \qquad \text{Eq. 2}$$

After some manipulation it can be shown from eq. 1 and 2 that:

$$L_{p,\mathrm{tot}} = 10 \times \log_{10}\left(10^{L_{p,1}/10} + 10^{L_{p,2}/10}\right) \qquad \text{Eq. 3}$$

Here $L_{p,1}$ and $L_{p,2}$ are respectively the SPLs of the two constituent sounds, and $L_{p,\mathrm{total}}$ is the SPL that occurs when both sounds are present. Famously, if the two constituent sounds are the same SPL, so $L_{p,2} = L_{p,1}$, then $L_{p,\mathrm{tot}} = L_{p,1} + 3\mathrm{dB}$.

Eq. 3 is the “dB addition” formula widely used in environmental noise, present in many textbooks (e.g. Bies, Hansen & Howard 2017, eq. 1.96) and standards (e.g. in step 7 of MCS 020a and rearranged to subtract SPLs in BS4142:2014+A1:2019 eq. 2). These standards are also the basis of computer-aided environmental noise software such as CadnaA, thus this noise summation principle is used therein too.

2.1.2.2 Summation of SPL for sounds that are coherent / correlated

Adding sounds that are correlated / coherent with one another is more complicated, since interference now becomes important and their relative properties will affect whether this occurs constructively or destructively. At one extreme – 'in-phase' constructive interference – the pressure of the two waves will add, leading to an equation similar to eq. 1 but without the time-averaging or squaring. In this case if the two constituent sounds are the same SPL, so $L_{p,2} = L_{p,1}$, then $L_{p,\text{tot}} = L_{p,1} +$ 6dB, a 3dB increase compared to the incoherent case. At the other extreme – 'anti-phase' destructive interference – the pressure of the two waves will subtract. If they are the same SPL, then this could in theory lead to zero pressure ($-\infty$ in dB).

For environmental noise planning for ASHPs, we are concerned over whether any conditions could lead to coherent constructive interference, since this will lead to levels exceeding what environmental noise modelling techniques predict by up to 3dB (the destructive case is of less concern since it leads to lower SPLs).

The possibility that ASHPs installed in close proximity might produce sound that interferes constructively has been postulated mainly due to the low frequency tones they produce (the audibility of which is considered in the next section). Although multiple units operate independently, if the RPM of the fan and/or compressor are very similar then it is possible for them to produce tones that remain correlated for a length of time that is long with respect to the averaging time present in both Sound Level Meters (SLMs) and the human auditory system, leading to a perception that these tones are louder than simple sound power addition according to eq. 3 would suggest.

Moreover, depending on the RPM difference between adjacent units, sounds may alternate between constructive and destructive interference, leading to modulation of loudness over time and/or 'beating' effects, both of which can increase the auditory awareness of the sound and/or increase annoyance (Moore, 2012). The methodology for assessing effects is described in section 2.1.4, which follows.

We also note that the power addition question is only expected to apply to heat pumps in close proximity because the time-varying outdoor propagation paths for units located some distance apart would themselves lead to decorrelation.

It is unlikely that broadband airflow noise from the fans would ever be correlated since it is generated by small-scale chaotic turbulence. The full audible bandwidth

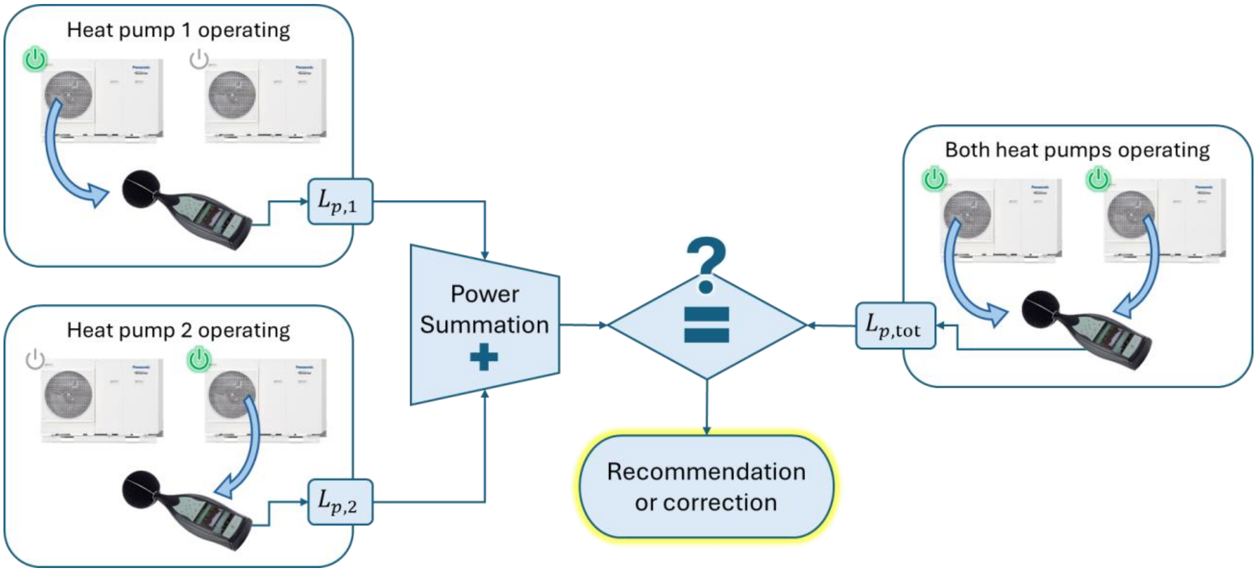

Figure 5: Flow chart illustration the methodology for establishing whether two ASHP in close proximity obey standard sound power addition rules or not.

is nonetheless included in the analysis as some of the tones observed were at quite high frequencies.

2.1.2.3 Methodology used in this study

This study will test the hypothesis that noise from two closely located ASHPs can be added using the standard power-summation approach of eq. 3. It will do this by measuring all three combinations as illustrated in Figure 5:

i) Heat pump 1 running and heat pump 2 off (top left),
ii) Heat pump 1 off and heat pump 2 running (bottom left),
iii) Both heat pumps running (right).

The SPL measured in cases (i) and (ii) is subsequently summed according to eq. 3 and then compared to case (iii), hence testing the hypothesis. Agreement or otherwise here will lead to recommendations or possibly a proposed correction, depending on the result. Additionally, the above process is repeated with HP1 on boost mode to see if the same trends occur when the units are in different modes.

Figure 5 illustrates the sound being measured by SLMs but a multichannel acquisition was used for this analysis, comprising three Dewesoft SIRIUSi frontends with GRAS 46AO ½" microphones and Bruel and Kjær accelerometers. This was done because it allows synchronous, time-locked signal acquisition with all microphones, allowing quantities such as coherence between sensors to be analysed.

Limitations of the methodology are that, for it to be exact, the heat pumps must run in precisely the same way during each measurement and the background SPL must be the same in all cases. However, neither of these requirements is guaranteed to be met.

Firstly, heat pumps change their behaviour based on the outdoor environmental conditions (temperature and humidity) and the thermal conditions / demand from the property they are attached to. The system was configured to minimise these effects: the heating was set to a flat compensation curve (to achieve a fixed flow temperature regardless of outdoor temperature) and windows at the higher floors of the property were opened to allow heat to escape. Domestic hot water was set for peak demand (though taps were not run). Nonetheless, both operations can have variations in fan and compressor speed and/or load, so these cannot be ruled out. These are most likely to show up in the 'narrowband' results, where tones shifting slightly in frequency due to changes in fan or compressor RPM will cause positive and negative changes at the frequencies they move to and from, respectively.

Secondly, background noise will sum with the noise from the units under test in each case. If these levels are high enough compared to the 'specific' SPL coming from each unit then this will bias the measured SPL. Notably the 'power summed' SPL (eq. 3 and left-hand side of fig. 5) will include this bias twice. Moreover, if those background levels – which cannot be independently measured due to the noise from the heat pumps – change between any of the three cases in Figure 5, then this will bias the comparison process. Thus, a key requirement for this methodology to be valid is a consistently low background noise level.

The extent to which these requirements were met during this field study will be commented on in the results chapter.

2.1.3 Tonality Assessment

A tonality assessment was conducted for the ASHP units operating at Properties 1 and 2 during Phase 1. This assessment followed the methodology outlined in Annex D of BS 4142:2014+A1:2019, aiming to evaluate and verify the presence of audible tones. This approach, also referred to as the "Joint Nordic Method 2" (JNM2), is defined in ISO 1996-2 and is based on the psychoacoustic concept of critical bands. According to this concept, sound outside a given critical band does not significantly contribute to the audibility of tones within that band, while sounds within a band will interact in terms of auditory masking (the phenomenon where one sound is not perceived because of the presence of another sound). The Joint

Nordic Method also includes a tonal correction value ranging from 0 dB to +6 dB depending on the audibility of tones. Values are assigned on a scale from not tonal to highly tonal.

2.1.4 Fluctuation Strength

Fluctuation Strength (FS) is a metric designed to quantify slow amplitude modulation or ‘beating effects’, such as can be perceived when sound from two machines operating at close – but not identical – RPMs is combined. It has been postulated (Hill & Harvie-Clark, 2024) that such effects could manifest from closely located ASHPs. Thus, an FS analysis was conducted for the two ASHP units considered in phase one. The analysis was performed using the open-source Sound Quality Analysis Toolbox (SQAT) for MATLAB (Felix Greco, Merino-Martínez, Osses, 2023). The FS metric, measured in a unit called ‘vacils’, was calculated using the model developed by Osses, Garcia, and Kohlrausch (2016).

2.2 Phase Two: Four Properties

A further experiment was conducted in January 2025 at the same site, consisting of a long-term measurement from late evening into night, and at dawn. The campaign was designed with the expectation that all four units would operate, but ultimately only a single ASHP was active during this period due to a change in property ownership.

Figure 6 shows the layout of microphone positions with respect to the four adjacent properties. On the left is the plan view and, on the right, a simplified depiction of

Figure 6: Layout of microphone positions with respect to the 4 properties. Fence microphones in yellow, ASHP microphones in red, patio door microphones in blue, and bedroom window microphones in green. Left: Plan view. Right: Elevation

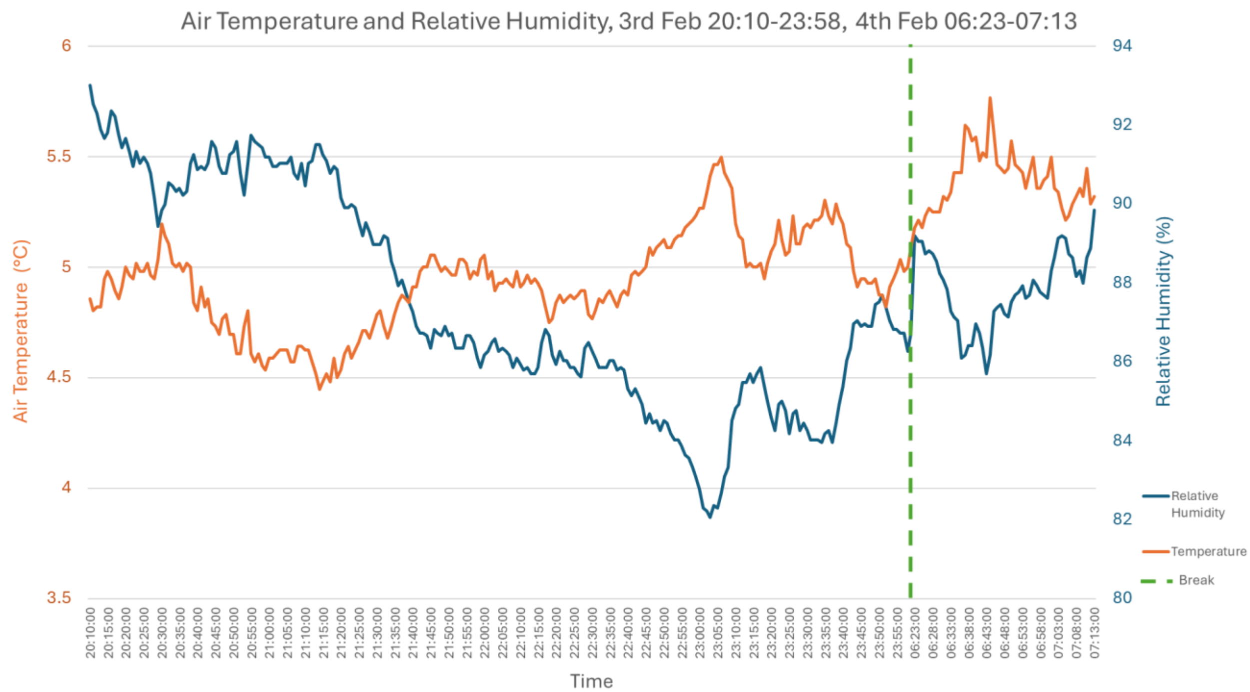

Figure 7: Temperature (orange) and humidity (blue) data for the phase 2 tests. Dashed green line indicates the break between evening and early morning capture.

the elevation. On each pump there was installed an accelerometer and a microphone at a 20cm distance directly above the centre of the unit (shown in the figure as red filled circles) to detect which units were operational in what states at what time. Microphones were also placed at noise sensitive positions on all four properties, being the centre of the kitchen / living room glass bifold doors (blue) and the bedroom window (green). Six additional microphones in total were located along the fences between the properties to monitor transmission paths (yellow).

A hygrometer was also utilised for this measurement, collecting temperature and relative humidity readings for the outdoor area. This was located in garden 3. Data captured by it is presented in Figure 7, showing that temperature was on average around 5°C and 88% humidity, the latter dipping in the late evening. Early morning measurements were taken until 7:15am but had to be aborted at that point due to wind gusts affecting the tall microphone stands (for the bedroom windows) and rapidly increasing road noise. Data from the morning measurements is not included in this report, but recordings are included in the dataset for comparison.

2.2.1 Application of MCS Assessment Procedure

The data collected during phase 2 of the case study was compared against the calculation guidelines outlined in the MCS 020 standards. Given that these guidelines were recently updated, both the MCS 020 (2019) and MCS 020 a) (2025) calculation methods were applied and their predictions compared.

The MCS 020 (2019) standard comprised a ten-step procedure to assess whether the combined background noise level and the ASHP sound pressure level remained at or below the noise limit. This method required using the highest A-weighted sound power level provided by the manufacturer, along with considerations for distance, noise barrier correction, and a fixed background noise level of 40 dBA. This version required the ASHP unit's sound pressure level to remain at or below 42 dBA. However, due to the addition of the fixed background noise level, the effective noise limit for the ASHP itself was 37.8 dBA (Torjussen *et al.*, 2023).

On 21 March 2025, MCS 020 as it pertains to heat pumps was updated to MCS 020 (a) Issue 1.0, introducing changes to the calculation process. While retaining key elements of the original approach, the revised version replaced the stepwise method with a formula for determining attenuation of sound, a significant improvement since this prevents the 'thresholding' effect that occurred due to the 'steps' in the original calculation process. This revision also eliminated several correction steps, including distance reduction (now integrated into the formula), the fixed 40 dBA background noise level adjustments, and other corrections. The SPL limit for the ASHP is lowered to 37.0 dBA, a reduction of 0.8 dB once the removal of background noise from the calculation is taken into account. The guidance on barrier type and line of sight is now more clearly expressed.

Additionally, clarity was added on which ASHP sound power level (SWL) should be used. While the previous version issued required "the highest specified SWL", it didn't specify the load conditions under which the highest SWL value should be determined, only stating that the SWL for "low noise mode" should not be used. This was problematic as the loudest operating mode tested varied between manufacturers and is not what was stated on the product's Energy-related Products (ErP) label. The revised version of the MCS standard requires use of the SWL obtained from the product fiche, energy label or MCS product database. The energy label SWL should be compatible across products since this specifies the operating point clearly (under standard rating conditions specified in BS 14511, 12102 and 14825), although it should be noted that installers may choose to refer to the product fiche, which may not state the test or operating point. At the time of publication, the MCS Product Directory had not yet been updated to include the SWL data. However, MCS has confirmed that the directory will be capable of holding the data from September 2025 onwards. When this information is added, it should include clear information on the operating point. MCS020 a) states that '[t]he conditions in which the sound power level is determined can be found in the Sound Power Testing for Heat Pumps document found on the MCS website.' However, it is not clear what document is referred to.

The ASHP unit used for the MCS assessment was installed in the back garden of Property 2 (Figure 2). Assessments positions were 1 metre external to the centre point of any door or window leading to a habitable room, following MCS 020a. Two assessment positions were selected per property: one outside the combined kitchen-living room window (KW) and the other outside the bedroom window (BW) on the upper floor (Figure 5). In addition to the neighbouring properties, an assessment is also conducted for Property 2 (which contains the active ASHP), and Properties 3 and 4.

It should be noted, however, that the equivalent microphone positions used in the field measurements were as close to the windows as feasible, instead of 1m distant assessment position specified by MCS. This was done to minimise wind noise and because it is the pressure acting directly on a window that dictates the sound transmission through it. This may lead to slight SPL differences, as discussed later.

3 RESULTS

Results from the two phases of testing are presented in this chapter: results from phase 1 in section 3.1 and those from phase 2 in section 3.2.

3.1 PHASE ONE: TWO ASHPS IN CLOSE PROXIMITY

This section presents the results for phase one, as undertaken in December 2024. Herein: section 3.1.1 reports the background noise levels, section 3.1.2 presents data for each ASHP running separately, section 3.1.3 tests the power-summation hypothesis (following the methodology in section 2.1.2), section 3.1.4 presents the tonality assessment, and section 3.1.5 shows results for fluctuation strength. The keys trends and implications of these findings are summarised in section 3.1.6.

3.1.1 Background Noise Level

Figure 8 shows four plots characterising the background noise measured at the start and end of testing, being recorded at 20:40 and 21:49 respectively.

The top and middle plots, a & b, show Third-Octave Band (TOB) SPL versus frequency (Hz, horizontal axis) and microphone position (vertical position) for the start and end of the test, respectively. The colour scale indicates A-weighted SPL, where the range extends from dark blue at 15 dBA to bright yellow at 45 dBA. In both cases a brighter band can be seen across the middle of the figure between approximately 0.8 and 2 kHz. This is largely due to the A-weighting curve, which mimics the maximal sensitivity of the human ear in this frequency range.

Traffic is the dominant source of noise in both these measurements, leading to maximum TOB SPL of up to 35 dBA in the ‘before’ case (a) and 32 dBA in the ‘after’ case (b), the latter being due to the gradual reduction in traffic over the period that measurements were taken. For case a, SPL is highest in mics at the top of the arc (-20° to +20°) due likely to those being less shielded from the traffic noise by the surrounding fences, an effect less prominent in case b. Also visible in case a is increased level around the 63Hz TOB. Listening to the raw audio, this again appears to be due to traffic noise but is absent from the later recording.

The bar plots c and d show overall SPL (OASPL) for the start and the end of the testing period, respectively, with mic position now as the horizontal axis and SPL now as the vertical one. SPL values seen in these plots are always higher than those in the TOB SPL plots, since these show the cumulative SPL across all TOBs; each bar is essentially summing (in power) a horizontal strip across the TOB plot.

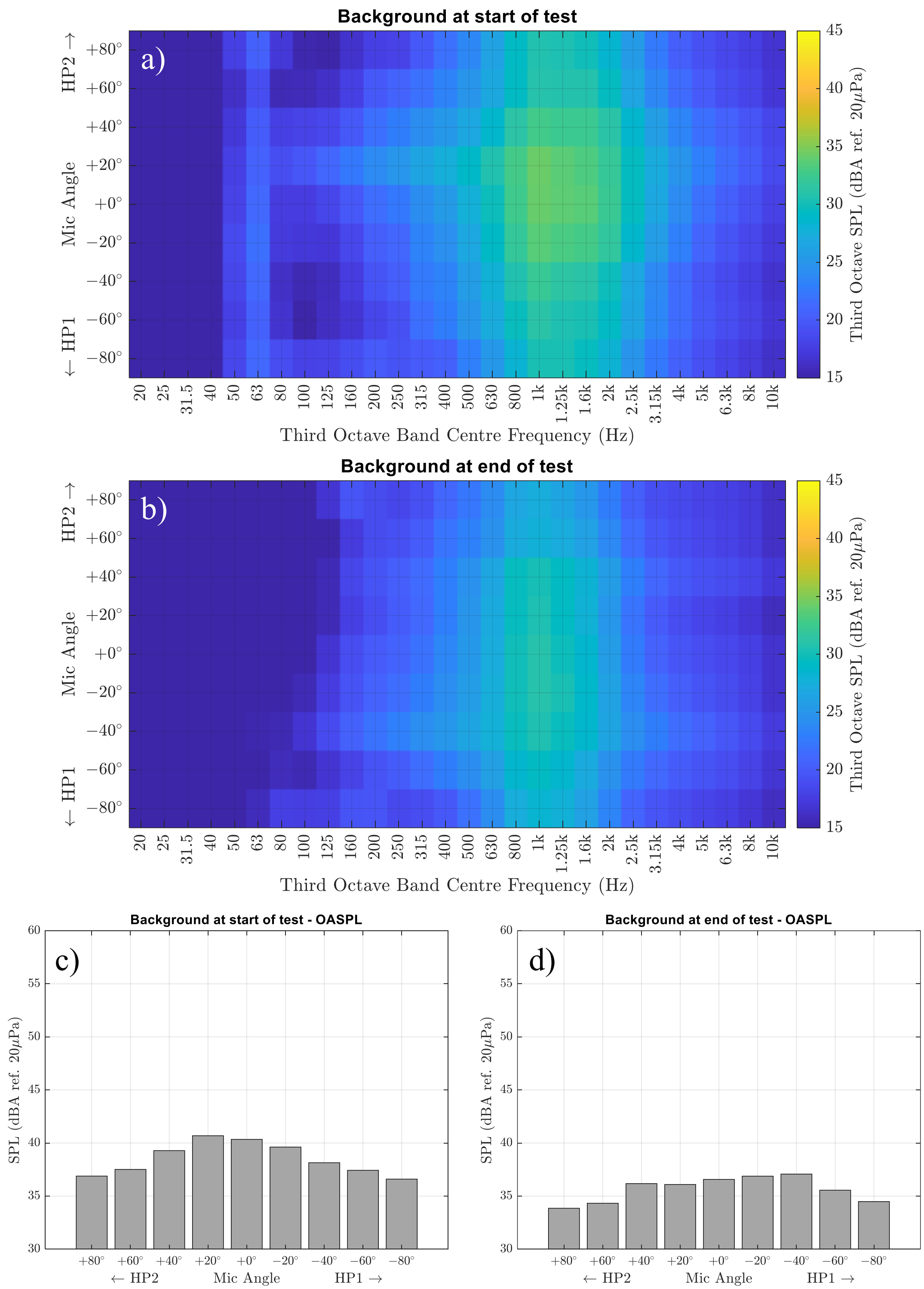

Figure 8: Background SPL versus mic angle: a) at start of testing in TOBs; b) at end of testing in TOBs; c) at start of testing overall; d) at end of testing overall.

These confirm the broadband trends above, notably that the highest SPLs were measured at higher degrees of elevation at the start of testing (c) but there was less variance across the microphones by the end of testing (d). SPLs vary from 36.6 to 40.7 dBA in the 'before' case (a), with a mean of 36.6 dBA, and from 33.8 dBA to 37.1 dBA in the 'after' case (b), with a mean of 35.7 dBA. With the exception of the 'before' SPL at 0° and +20°, these are all below the 40 dBA background SPL assumed in MCS 2020 (2019), so represent acceptable background noise levels with which to conduct this study. This will be discussed further in the sections that follow.

3.1.2 ASHPs running separately

3.1.2.1 Overall SPL

Figure 9 shows the OASPL as before for the three cases:

a) HP1 running in normal mode and HP2 off,
b) HP2 running in normal mode and HP1 off,
c) HP1 running in boost mode and HP2 off.

The figures show the expected increase in SPL measured at the microphones close to the operating ASHP, with less energy measured close to the ASHP that is not operating. This gives some insight into the effectiveness of the fence as a barrier, though it should be borne in mind that the acoustic directivity of the ASHP – meaning how its acoustic radiation varies with angle, and which is unknown – could also contribute to this effect. Case c also shows that higher SPL occurs when an ASHP is in boost mode compared to normal mode, again as expected.

The background levels (on the side of the fence where the ASHP is not operating) for cases a and c are close to the background levels from Figure 8. Notably, case c suggests that the broadband attenuation by the fence may be 14 dB, or possibly even higher (since the SPL here has reached the background threshold).

The reverse is not quite true, however, with case b showing an SPL near HP1 that is 4-5 dB above the expected background level. Listening to that audio, it appears that increased traffic noise is the dominant factor causing this increase in SPL, which might also explain why the most elevated mics see less drop in SPL compared to the mics closest to the active ASHP than in cases a and c. This increase in traffic noise is surprising, since this was one of the last cases to be measured (21:39) and it has been screened for discernible pass-bys. But nonetheless, it seems the background noise from traffic was temporarily louder.

3.1.2.2 Third-Octave Band

Figure 10 shows the same data as Figure 9 but plotted in TOB with the same ranges and formatting as Figure 8 a&b. These again show the expected trend that higher SPL (yellow) is always seen on the side of the arc where the active ASHP is facing. The increase in SPL above background levels is also clear.

The ability to discern how SPL varies with frequency makes these plots more informative, however. Notably, it can be seen how the fence is an effective barrier at frequencies above 500Hz but that it provides relatively little attenuation at lower frequencies, with elevated SPLs evident around 100 Hz that are very similar on both sides.

For case c, where HP1 is operating on boost, it can be seen that the increased OASPL arises both from a slightly increase in SPL in the frequency range where the normal mode radiated most (500 Hz to 1.6 kHz) as well as a broadening of that range, with more substantial increases as low as 80 Hz and as high as 6.3 kHz. Listening to the audio, this appears to be due to an added mechanical sound that is likely either flow noise, or a panel or internal component vibrating.

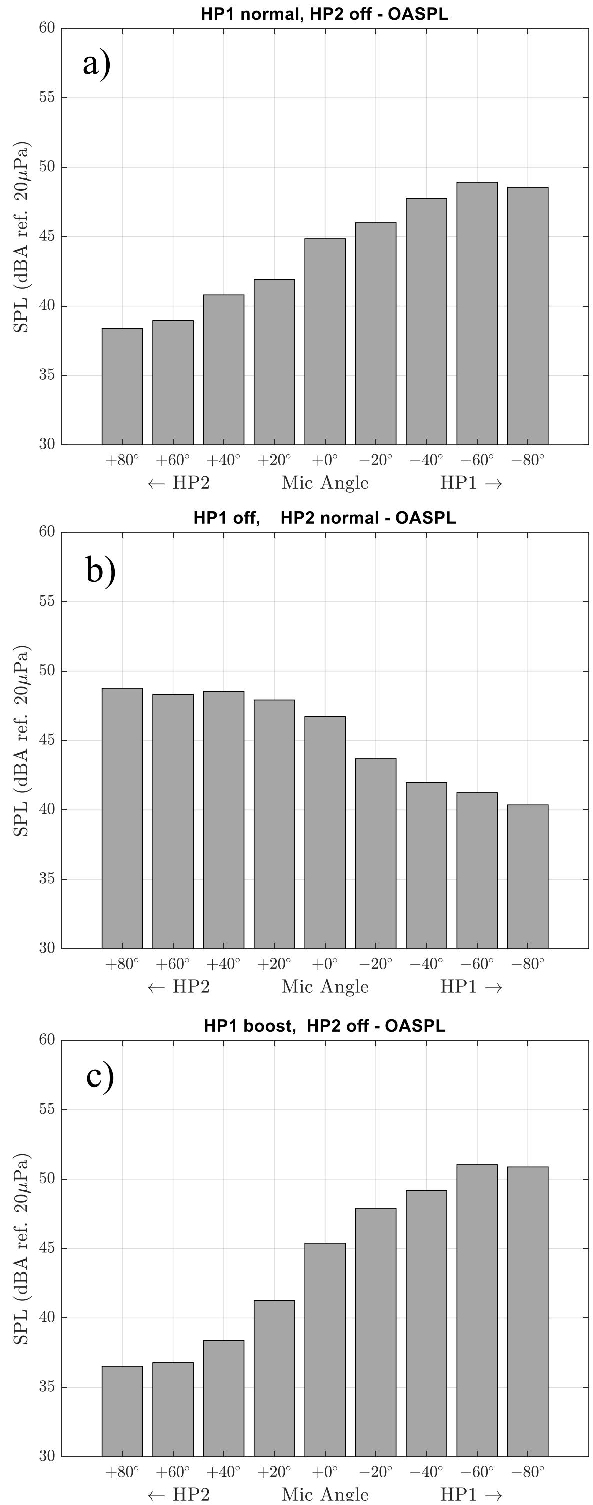

Figure 9: OASPL versus mic angle:
a) HP1 running on normal & HP2 off;
b) HP2 running on normal & HP1 off;
c) HP1 on boost & HP2 off

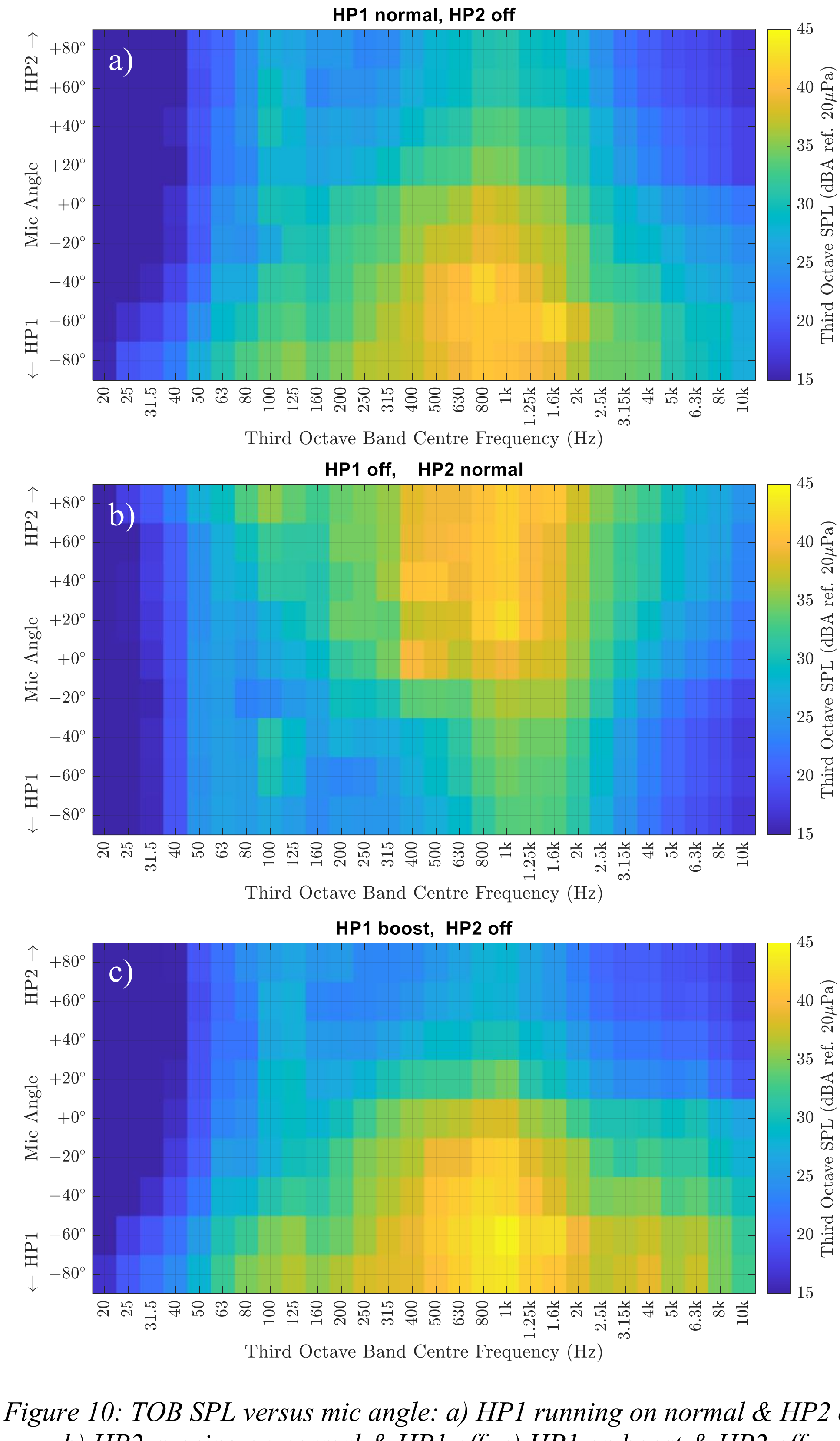

Figure 10: TOB SPL versus mic angle: a) HP1 running on normal & HP2 off; b) HP2 running on normal & HP1 off; c) HP1 on boost & HP2 off .

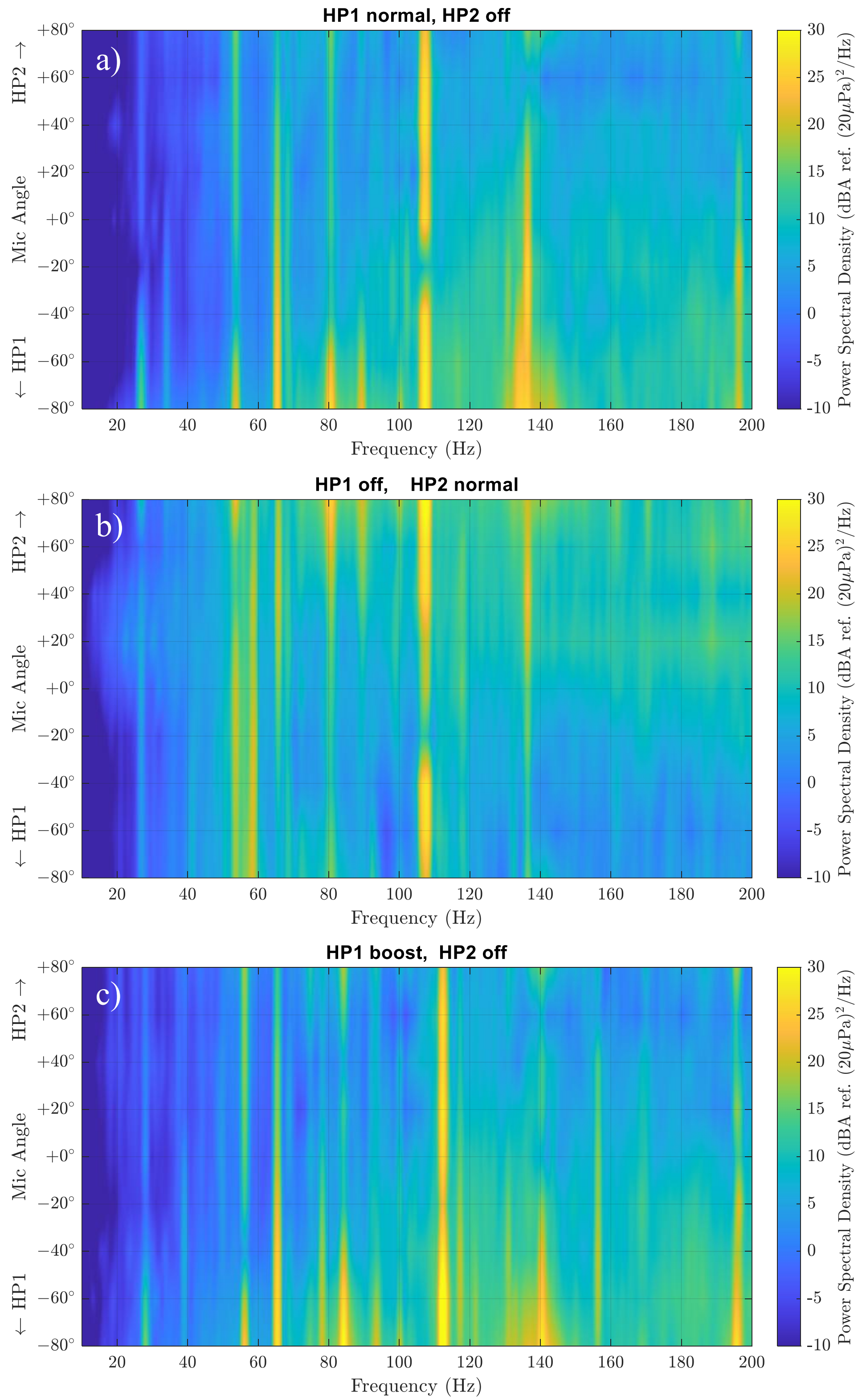

Figure 11: Narrowband PSD versus mic angle: a) HP1 running on normal & HP2 off; c) HP2 running on normal & HP1 off; c) HP1 on boost & HP2 off.

3.1.2.3 Low-Frequency Narrowband

Figure 11 shows the same data as the previous two figures but analysed in narrowband. Since the focus here is low frequency tones, data is shown only up to 200Hz. The analysis is performed at ½ Hz resolution – sufficiently narrow to show tonal content effectively. Unlike the TOB results, which are based on filtering signals in accordance with BS EN 61260-1:2014, narrowband analysis uses a Fast Fourier Transform (FFT) and Welch's method (see, e.g., chapter 12 of Bies, Hansen, & Howard 2017). The signals were still A-weighted before analysis. The resulting data is termed power spectral density – a quantity not widely used in environmental acoustics – which means the dB reference and range are different, but this is unimportant for comparative purposes; the dB SPL presented here can still be compared in the usual way. The narrowband plots do, however, use a slightly widened colour scale range (40 dB) compared to the TOB plots (30 dB).

For each ASHP operating in 'normal' mode a close correlation of dominant frequencies – seen as yellow vertical lines – can be observed. HP2 (b) appears to show some additional energy at 59Hz and HP1 (a) does similar at 196.5 Hz, but otherwise the sequence of tones matches, being: 53.5 Hz, 65.5 Hz, 80.5 Hz, 89.5 Hz, 107.5 Hz, and 136.5Hz. When HP1 is switched into 'boost' mode in case c, these become: 56 Hz, 65.5 Hz, 78.5 Hz, 84.5 Hz, 112.5 Hz, 140.5 Hz. 156.5 Hz, and 195.5 Hz. Here, 65.5 Hz and 195.5 Hz are notable because they do not move, indicating they are associated with a component of the ASHP that is invariant between these modes of operation. This is likely to be the fan, since data from the controller within the property indicated that the change of mode caused the compressor RPM to change but no change in fan RPM was obvious. It is also notable that 195.5 Hz is – subject to measurement resolution – the third harmonic of 65.5 Hz. Unfortunately, however, no RPM data for the fan was available.

The controller stated that the compressor frequency was 33 Hz in normal mode and 39-40 Hz while on boost, but neither of these appear to be related to the emission frequencies measured acoustically. Scrutinising the accelerometer narrowband data (not shown in this report), it seems more likely that the compressor frequency was 27 Hz on normal and 28.5 Hz on boost, since both the fundamental and several harmonics of this can be seen in the spectra.

In summary, various tonal activity is observed, some of which varies with operational states and some of which is invariant. The audibility of tonal components will be considered further in section 3.1.4.

3.1.3 Summation of SPL from two ASHPs

This section contains the results that test the 'power summation' hypothesis described in section 2.1.2, following the methodology depicted in Figure 5. Section 3.1.3.1 presented this for overall SPL, 3.1.3.2 for third-octave band SPL, and 3.1.3.3 for low frequency tones. Two cases are considered: one where both ASHP are operating in normal mode, and another where HP1 is operating in boost mode.

3.1.3.1 Overall SPL Comparisons

Figure 12 shows the overall SPL comparison. In the top and middle plot:

- Case x (HP1 normal, HP2 off, blue in a) is the same data shown in Figure 9a.
- Case y (HP1 off, HP2 normal, red in both) is the same data shown in Figure 9b.
- Case z (HP1 boost, HP2 off, blue in b) is the same data shown in Figure 9c.
- The purple bars are the power summation (by eq. 3) of the red and blue bars, being the separate measurements on the left-hand side of Figure 5.
- The yellow bars are the same scenario measured directly, being the case on the right-hand side of Figure 5 for comparison.

The key question is whether the yellow and purple bars agree. To emphasise this, the difference between these in dB, being the height of the yellow bars minus the height of the purple bars, is shown for a in c and for b in d. Here a difference value below zero is interpreted as being good, since the true measured level is lower than power summing would predict, offering a margin of safety to modelling based on this premise, whereas a difference value greater than zero is interpreted as bad, since the modelling has underpredicted the SPL that occurred in reality.

It can be seen most clearly from Figure 12 c & d that the measured SPL agrees closely with the power summation on the property 2 side of the fence, whereas on the property 1 side there is a discrepancy with the power summation underpredicting the SPL by as much as 1.72 dB in the 'normal-normal' case (a & c) and 2.23 dB in the 'boost-normal' case (b & d). Comparing the constituent raw audio recordings, it seems that in the 'normal-normal' case this is due to HP1 having moved into a different, louder operational state at the time when HP2 was operational too. In the 'boost-normal' case, the noise from HP1 is not significantly changed compared to when it operated alone, but increased traffic noise can be heard, which may explain the discrepancy.

Thus, it appears that modelling based on power-summation is sufficient for overall SPL, since discrepancies can be traced to issues with the measurements.

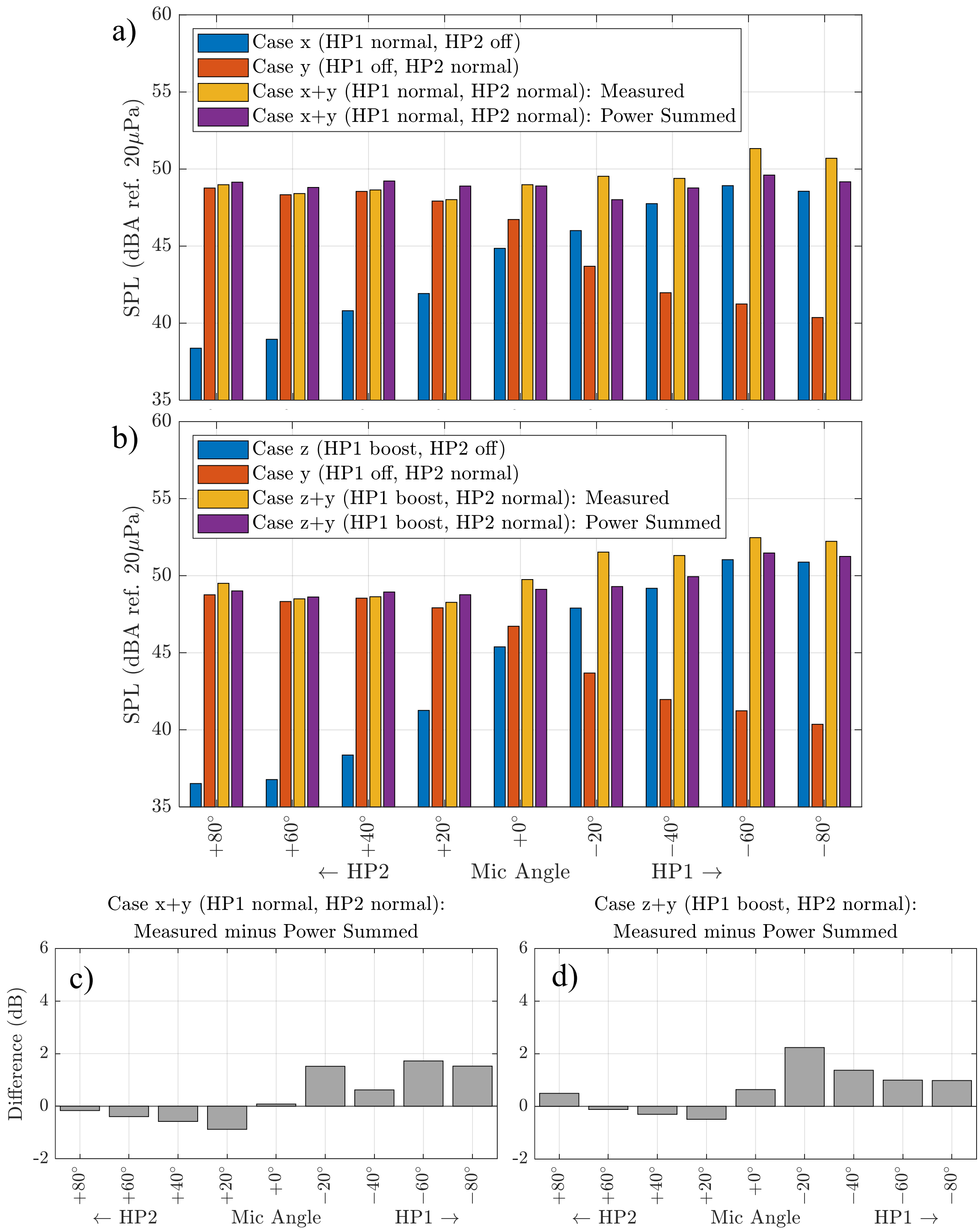

Figure 12: SPL summation comparison for pairs of ASHPs versus Mic angle, with each unit on individually plus measurements and predictions of both running together:
a) comparisons with both ASHP on normal;
b) comparisons with HP1 on boost and HP2 on normal;
c & d) difference between yellow (measured) and purple (prediction) for a & b

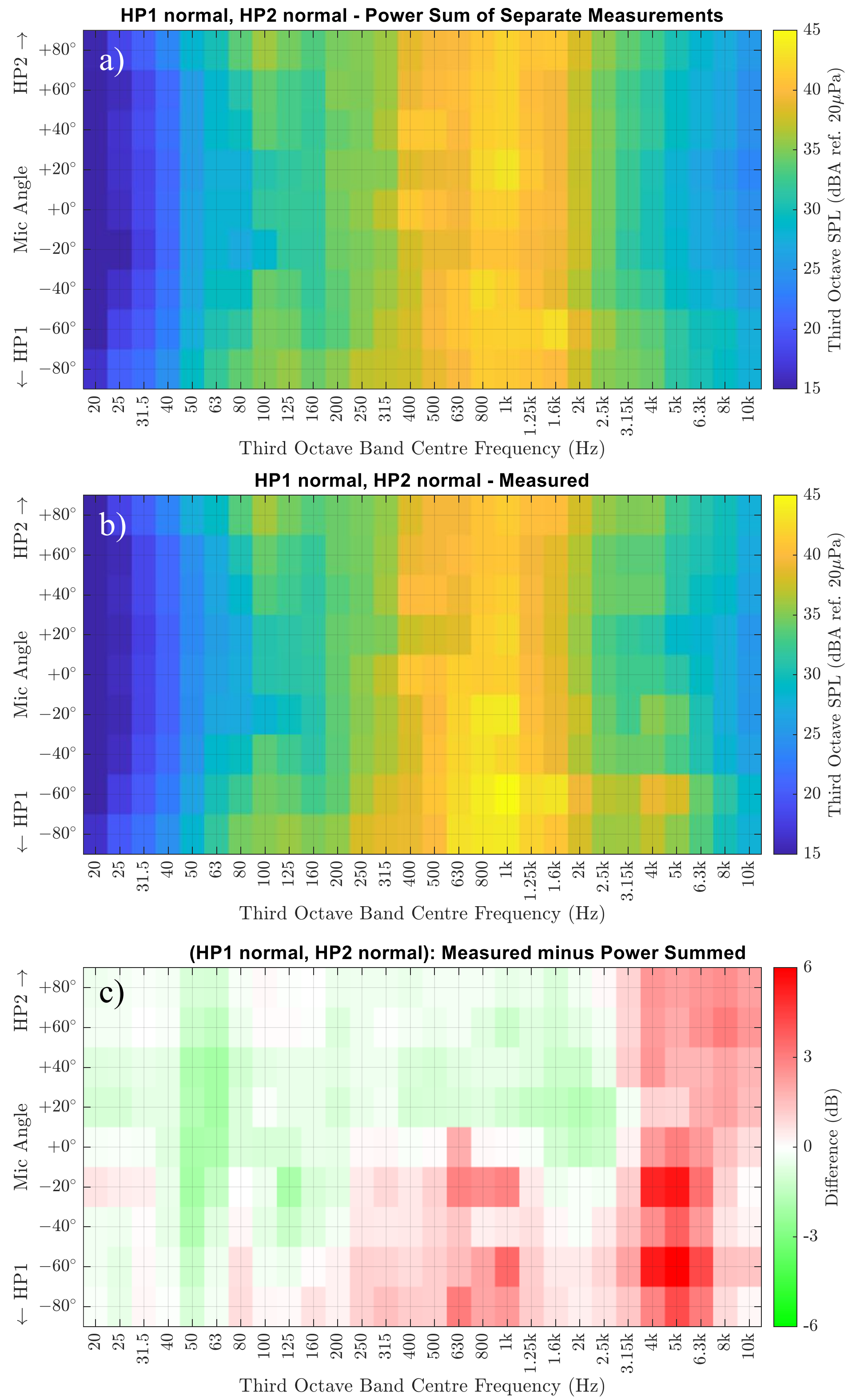

Figure 13: TOB comparison versus mic angle with both HP running on normal: a) Simulated (by power summing Figure 10 a & b); b) Measured; c) Difference

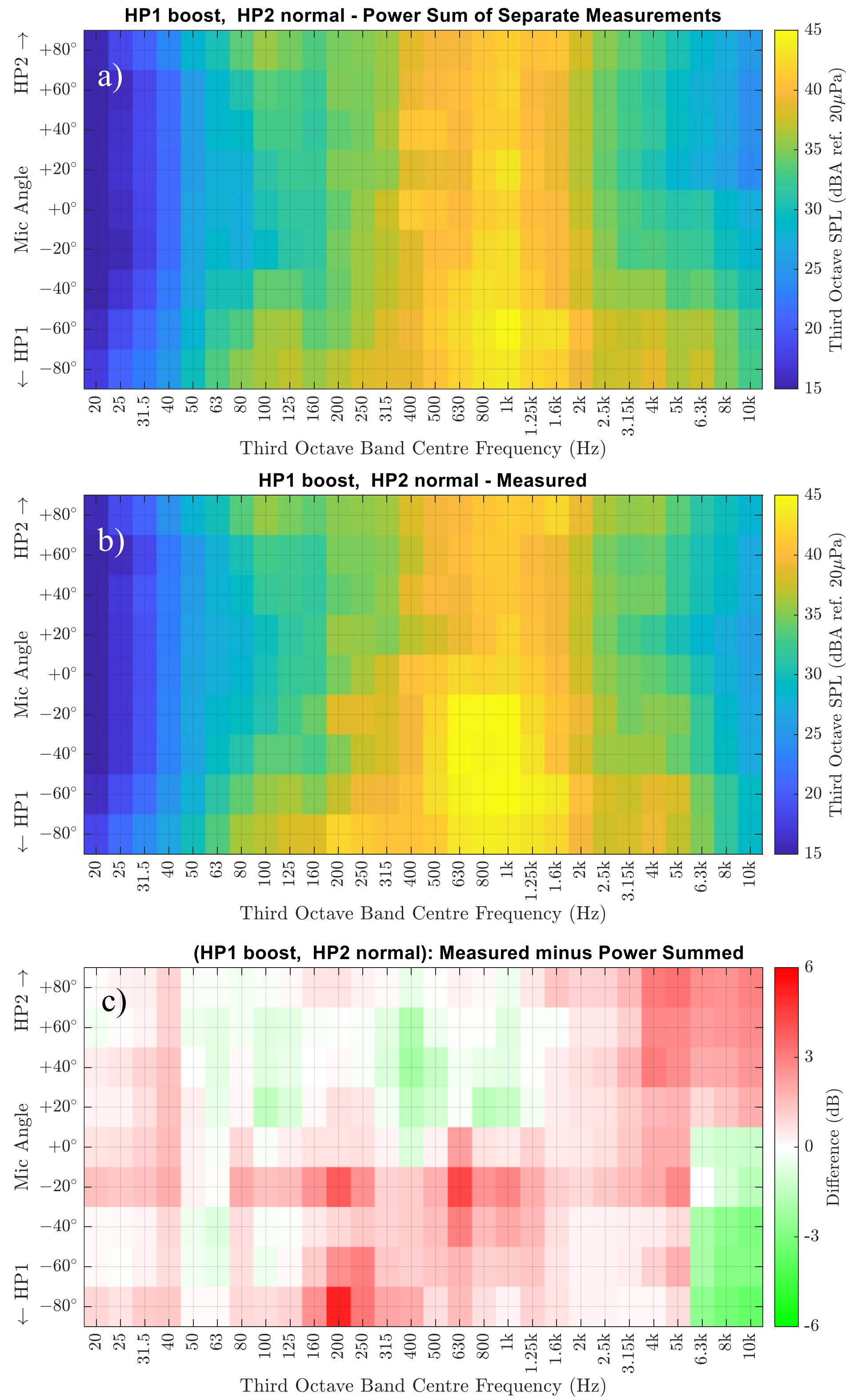

Figure 14: TOB comparison versus Mic angle with HP1 on normal & HP2 on boost: a) Simulated (by power summing Figure 10 b & c); b) Measured; c) Difference

3.1.3.2 Third Octave Band Comparisons

Figure 13 and Figure 14 show the same comparisons as Figure 12 but in Third-Octave Bands (TOB). Figure 13 is the ‘normal-normal’ comparison; here a is equivalent to the purple bars in Figure 12a, and is the power-summation (according to eq. 3) of Figure 10 a&b. Figure 14 is the ‘boost-normal’ comparison; here a is equivalent to the purple bars in Figure 12b, and is the power-summation of Figure 10 b&c.

In both cases the middle plot is a separate measurement of the case where both units are operational, equivalent to the yellow bars of Figure 12 a&b and the right-hand-side of Figure 5, and the bottom plot is of dB difference between the two above, being equivalent the grey bar charts in Figure 12 c&d. Here, however, a colour scale is used to emphasise the interpretation of these values: green for a negative difference where power-summation modelling overpredicts offering a margin of safety, and red for a positive difference where the real, measured SPL exceeded what the power-summation modelling predicted.

In Figure 13c the difference values are mostly quite close to zero except at high frequencies mainly, where some major discrepancy occurs. These are greater than +3dB at some frequencies and angles, which is not theoretically possible (see explanation in section 2.1.2.2) so must be due to a substantial change in background noise or ASHP operating state (see methodology limitations in section 2.1.2.3). This is consistent with what was observed from the raw audio for this case (see page 26), from which it appears that the latter issue occurred with HP1.

In Figure 14c the difference values show a positive bias, consistent with the measured case (b) having been affected by increased traffic noise (as discussed on page 26). Several TOB/angle combinations are outliers with much higher difference – it’s unclear the cause of these but they aren’t associated with audible artefacts or visible in a or b, so are most likely due to experimental uncertainty.

3.1.3.3 Low-Frequency Narrowband Comparisons

Figure 15 and Figure 16 show the same comparisons as Figure 13 and Figure 14 – with the subplots playing the same roles – but with low frequency narrowband analysis as described in section 3.1.2.3. Here the range of difference shown is much greater, which is possible as tones shifting in frequency will cause large differences. Green indicates a tone present in power-summed individual measurements that was not present in the combined measurement, and red effectively indicates the opposite.

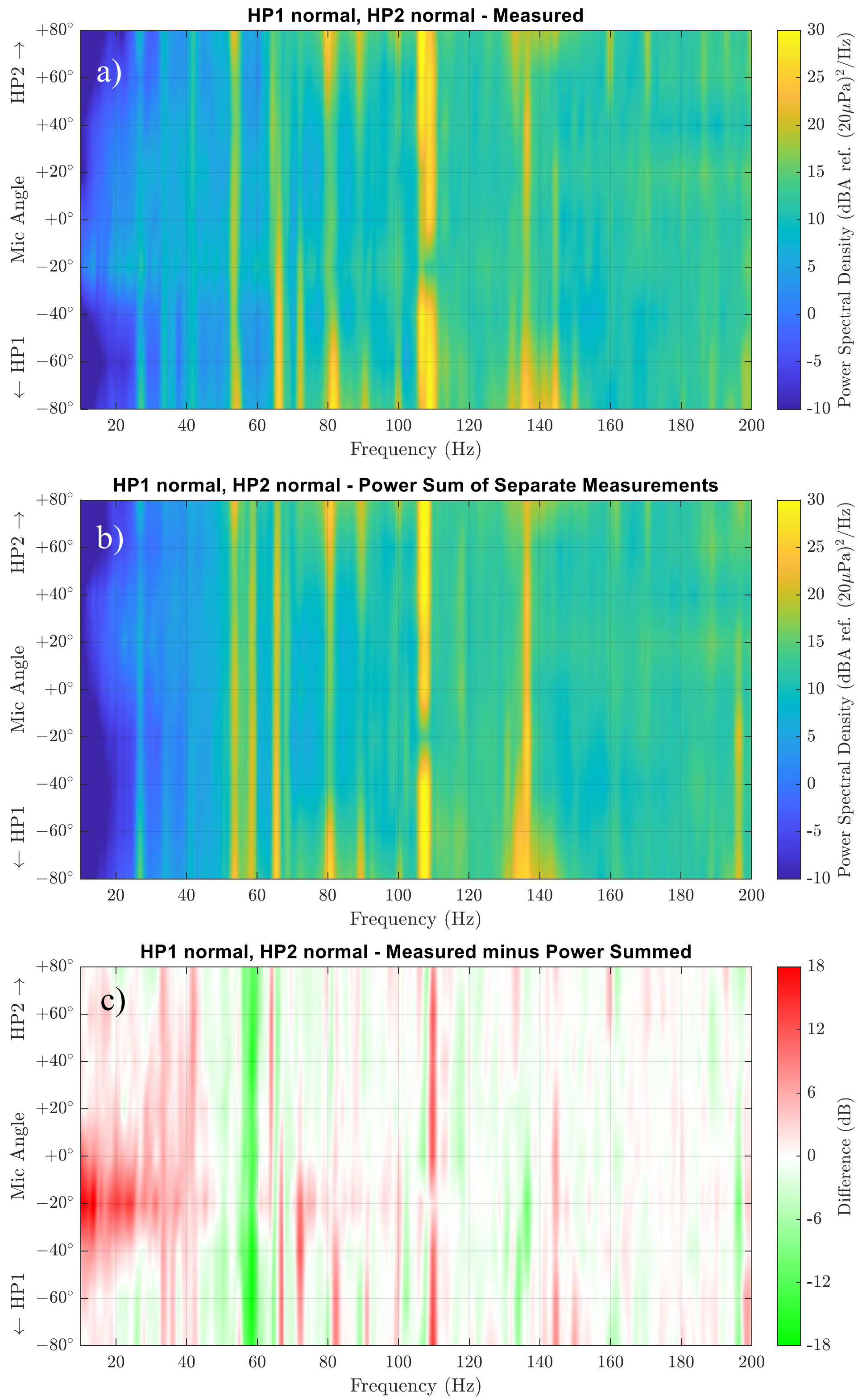

Figure 15: Narrowband PSD comparison versus mic angle with both HP running on normal: a) Simulated (by power summing Figure 11 a & b); b) Measured; c) Difference

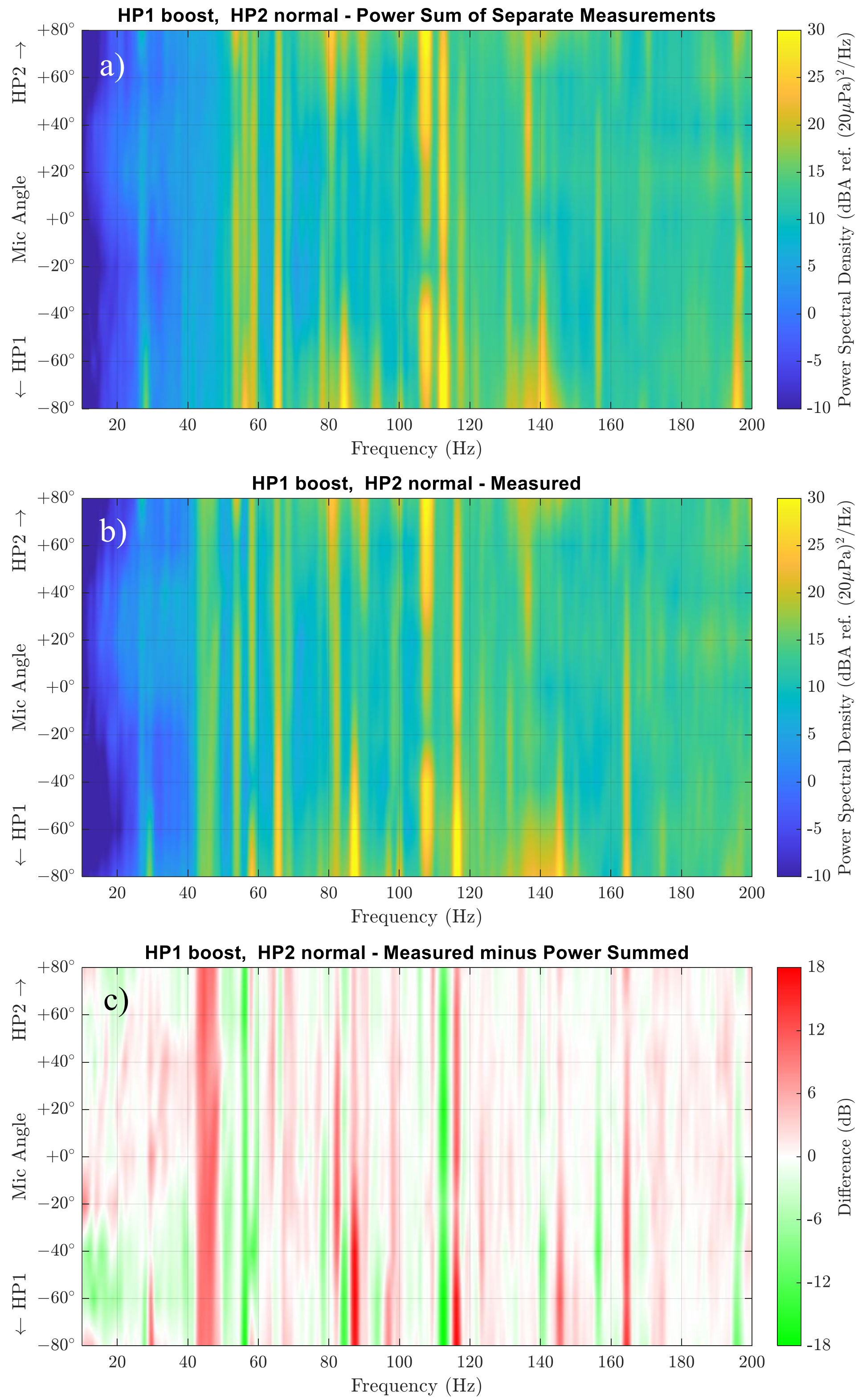

Figure 16: Narrowband PSD comparison versus mic angle HP1 on normal & HP2 on boost: a) Simulated (by power summing Figure 11 b & c); b) Measured; c) Difference

In both figures, the average difference appears close to zero, so the plots are primarily showing tones shifting to different frequencies rather than the addition of new tones, or changes in the level of certain tones. In Figure 15, the largest positive difference (ignoring the background noise below 30 Hz) is due to a change in the tone close to 110 Hz. In the combined measurement (a), additional energy at a slightly higher frequency seems to appear, causing a red vertical line in the difference plot (c). In contrast, a tone at 59.5 Hz is present in the separate measurements but not the combined measurement, leading to a green vertical line. These are consistent with the previous suggestion that HP1 has slightly changed its operating point, despite the controller still being set to 'normal'.

In Figure 16, trends are similar, though here red and green vertical lines appear together mainly in pairs, due to tones shifting away from one frequency to another close by. There is also a general bias towards positive difference (red), and a significant added band of energy between 40 and 50 Hz, which is mostly likely due to the increased road noise that can be heard on the combined measurement.

In summary, these results appear to tell a similar story to those in the preceding two subsections, the most significant change being that much greater changes in narrowband SPL are possible when tones are involved.

3.1.4 Tonality Assessment

Tonal assessments for HP1 and HP2 were conducted using the JNM2 as outlined in section 2.1.3. Two different operational scenarios were evaluated to assess the influence of interactions between the two units on tonality: (1) HP1 in normal mode while HP2 is off, and (2) HP1 off while HP2 operates in normal mode.

Table 1 shows tones detected by the method versus arc angle for the two ASHPs. The ΔL_{ta} value indicates the audibility of tonal components in the ASHP noise emissions (tonal audibility above the masking threshold), while the adjustment factor K_T – the value to be added to the L_{Aeq} for a time interval to give the tone-corrected rating level for that interval – is determined based on the prominence of these tones. The adjustment factor is linked to the audibility of tonal components. As the ΔL_{ta} increases, the K_T value also increases, up to a maximum of 6 dB. The frequency of the prominent tone and its sound pressure level (L_{pt}) are also determined using this method.

These results indicate consistent patterns. When only one ASHP is operational and running in normal mode, no audible tones are detected at the microphone positioned closest to ground level (either at −80° or 80°) and oriented toward the inactive ASHP. When HP1 was off and HP2 was operating in normal mode, no audible tones were detected at Mic 1 (-80°). However, audible tones at 110 Hz were detected at Mic 2 (-60°) and Mic 3 (-40°), with corresponding sound levels of 31.2 dBA and 31.9 dBA, respectively. For the microphones located at Property 2 (Mic 6-9, at 20°, 40°, 60°, and 80°), prominent tones were measured at 14038 Hz. Additionally, a prominent tone at 16895 Hz was observed at Mic 5 (0°), which is situated above the property boundary, just above the fence.

The same pattern is observed in the reverse scenario, where HP1 operates in normal mode while HP2 is off. A similar trend is also evident in the reference microphones: those positioned behind the inactive ASHP units exhibit prominent tones at 110 Hz, whereas those behind the operational ASHP units show prominent tones around 900 Hz. This suggests low-frequency tones are more prominent and audible in the neighbouring property, while high-frequency tones are more noticeable on the property with the operating ASHP. The low-frequency tones are likely to be the Blade Passing Frequency (BPF) of the fan, and this is influenced by the orientation of the unit. Further analysis is required to identify the exact source of the high frequency tones.

Table 1: Calculations for tonal audibility based on BS 4142:2014+A1:2029 Annex D. Mic 1 is located at Property 1, facing the fan grill of HP1, while Mic 9 is situated at Property 2, facing the fan grill of HP2. (K_T: Tonal Correction, ΔL_{ta}: Tonal Audibility, L_{pt}: Sound pressure level of tones in dB)

	HP1 off, HP2 normal				HP1 Normal, HP2 off			
	K_T (dB)	ΔL_{ta} (dB)	**Tone Freq.** (Hz)	L_{pt} (dB)	K_T (dB)	ΔL_{ta} (dB)	**Tone Freq.** (Hz)	L_{pt} (dB)
Mic 1 (-80°)	0.00	0.00	0	0.0	4.69	8.69	14160	22.2
Mic 2 (-60°)	2.40	6.40	110	31.2	1.44	5.44	1575	39.2
Mic 3 (-40°)	3.80	7.80	110	31.9	0.20	4.20	10608	18.0
Mic 4 (-20°)	0.00	0.00	0	0.0	2.39	6.39	9033	21.2
Mic 5 (0°)	0.93	4.93	16895	8.8	0.00	1.29	818	33.8
Mic 6 (20°)	0.50	4.50	14038	13.7	0.00	0.00	0	0.0
Mic 7 (40°)	4.64	8.64	14038	18.2	0.00	0.00	0	0.0
Mic 8 (60°)	3.95	7.95	14038	17.9	3.89	7.89	110	30.2
Mic 9 (80°)	6.00	10.06	14038	21.6	0.00	0.00	0	0.0
Ref. ASHP 1	6.00	10.37	110	40.2	2.60	6.60	818	46.1
Ref. ASHP 2	0.00	3.34	952	45.1	6.00	11.11	110	37.5

Furthermore, in terms of the tonal correction (K_t), the highest corrections are consistently required for the levels recorded at microphones directly facing the operating ASHP. When HP1 is off and HP2 operates in normal mode, the three highest K_t values are recorded at microphones oriented toward HP2 (Microphones 6–9 at 20°, 40°, 60°, and 80°) within Property 2. Notably, Microphone 9 (80°), which directly faces the fan outlet of HP2, has a K_t value of 6 – the maximum possible correction. Similarly, in the reverse scenario, when HP1 is operating and HP2 is inactive, the highest K_t value (4.69) is observed at Microphone 1 (−80°), oriented toward HP1. It should also be noted that the highest ΔL_{ta} and K_t values generally correspond to prominent tones at higher frequencies. An exception to this pattern is observed at Microphone 8 (60°) when HP 1 operates in Normal mode and HP2 is off; in this case, the prominent tone occurs at low frequency (110 Hz), with a ΔL_{ta} of 7.89 dB and a K_t of 3.89 dB.

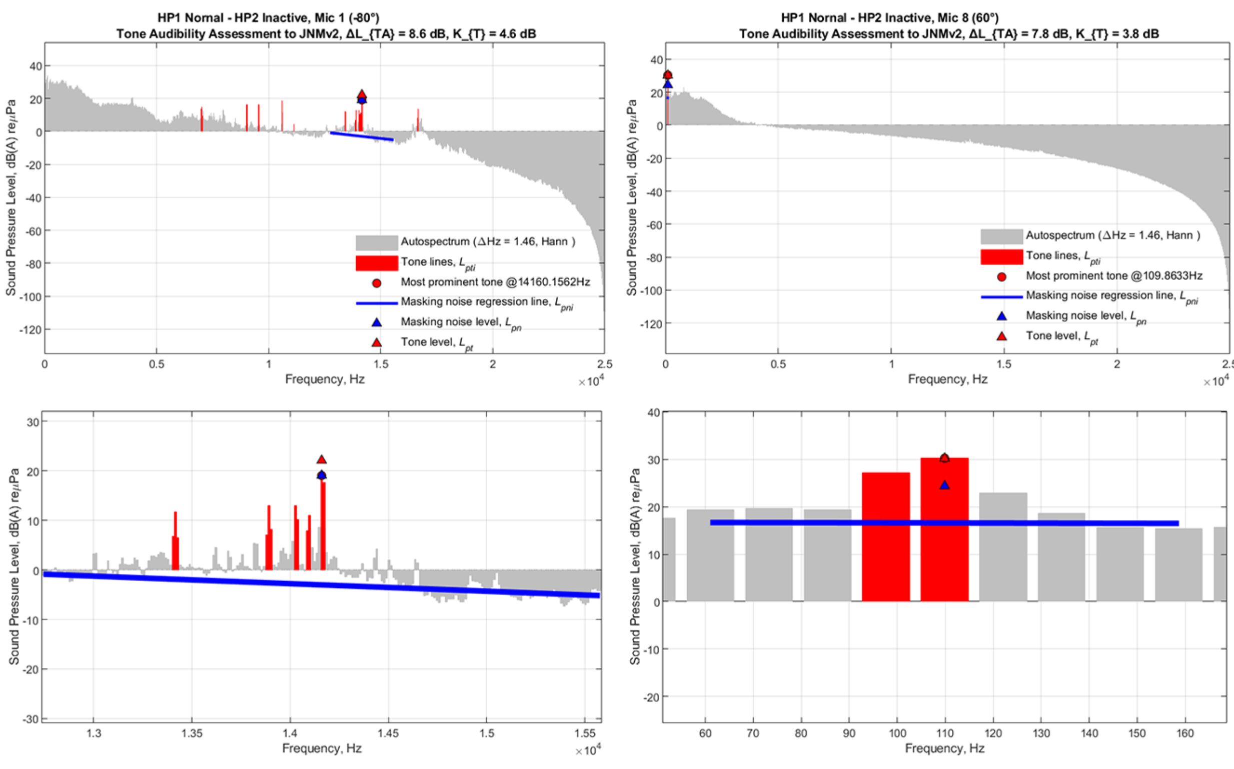

Figure 17: Tonal audibility assessment conducted in accordance with BS 4142:2014+A1:2019 Annex D at two positions on the arc, with HP1 operating in normal mode and HP2 inactive. Left: Mic 1 (−80°), oriented toward HP1; Right: Mic. 8 (+60°), oriented toward HP2. Top panels display autospectrum data (grey), extracted tonal components (red), and the most prominent tones (red circles) at 14.16 kHz (left) and 109.9 Hz (right). Masking noise regression curves are shown in blue, with blue triangles indicating masking noise levels and red triangles representing tone levels. Bottom panels present zoomed views of the critical frequency bands.

Figure 17 presents a tonality assessment example for two microphone positions, for the scenario where HP1 operates in normal mode and HP2 is inactive. The two selected microphones are: Microphone 1 (-80°), which is directly facing the operating HP1, and Microphone 8 (60°), which is oriented towards inactive HP2. Microphone 9 (80°), the direct opposite of Microphone 1 (-80°), is not considered for this scenario as it did not produce any audible tones, as noted earlier. The left panels show measurements from Microphone 1 (-80°), capturing a prominent tone from HP1 at 14.16 kHz, with a ΔL_{ta} of 8.6 dBA and a K_t of 4.6 dBA. The right panels show measurements from Microphone 8 (60°), oriented toward the inactive HP2, detecting a low-frequency tone at 109.9 Hz with ΔL_{ta} of 7.8 dBA and K_t of 3.8 dBA. In both cases, K_t exceeds the 3 dBA threshold, indicating subjectively prominent tones that warrant penalty adjustments (corrections) in environmental noise assessments. The contrast between high and low-frequency tonal components highlights differing impacts on the respective properties and suggests varying sound transmission behaviour through barriers such as fences.

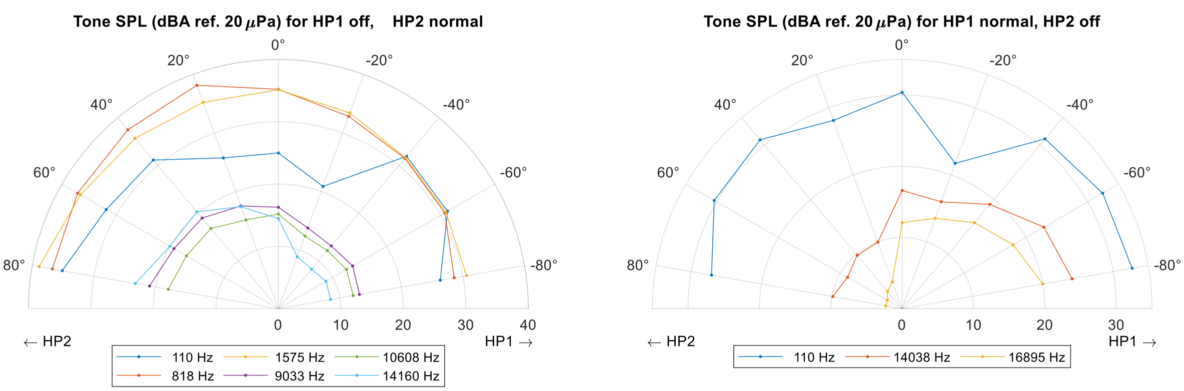

Figure 18: Directivity plots showing the A-weighted SPL of tonal components at the frequencies of prominent tones across the microphone arc, with only one heat pump operating.

Figure 18 presents the A-weighted SPL directivity patterns obtained using a narrow 1/24th-octave bandpass filter centred on the prominent tonal frequencies identified in Table 3. The results further support the observation that the neighbouring property is more affected by low-frequency tonal components, whereas the installation property experiences greater impact from high-frequency components. It is postulated that the shape of the 110Hz directivity curves, notably both with a notch at -20°, may result from the asymmetry of the terrain (the garden of property 1 raised 40 cm relative to property 2) combined with the effects of the fence, which cannot be assumed rigid or impenetrable at such a low frequency.

3.1.5 Fluctuation Strength

Four operational scenarios were compared to examine the impact of potential interactions between the units on FS: i) HP1 operating in normal mode with HP2 inactive; ii) HP1 inactive with HP2 in normal mode; iii) HP1 in normal mode with HP2 in boost mode; and iv) both HPs in boost mode. Although a beating effect was perceptible by ear – most notably behind the units – at certain times during the field measurements, the FS analysis yielded inconclusive results across scenarios. The observed FS values were low (predominantly < 0.1), and values remained below the Just Noticeable Difference (JND) threshold of 10% of 1 vacil (Figure 19). While 0.1 vacil does not definitively represent the absolute threshold of FS perception, values below this level suggest minimal or absent fluctuations. Consequently, further analysis is needed to draw conclusive findings regarding the presence and significance of FS in these operational conditions.

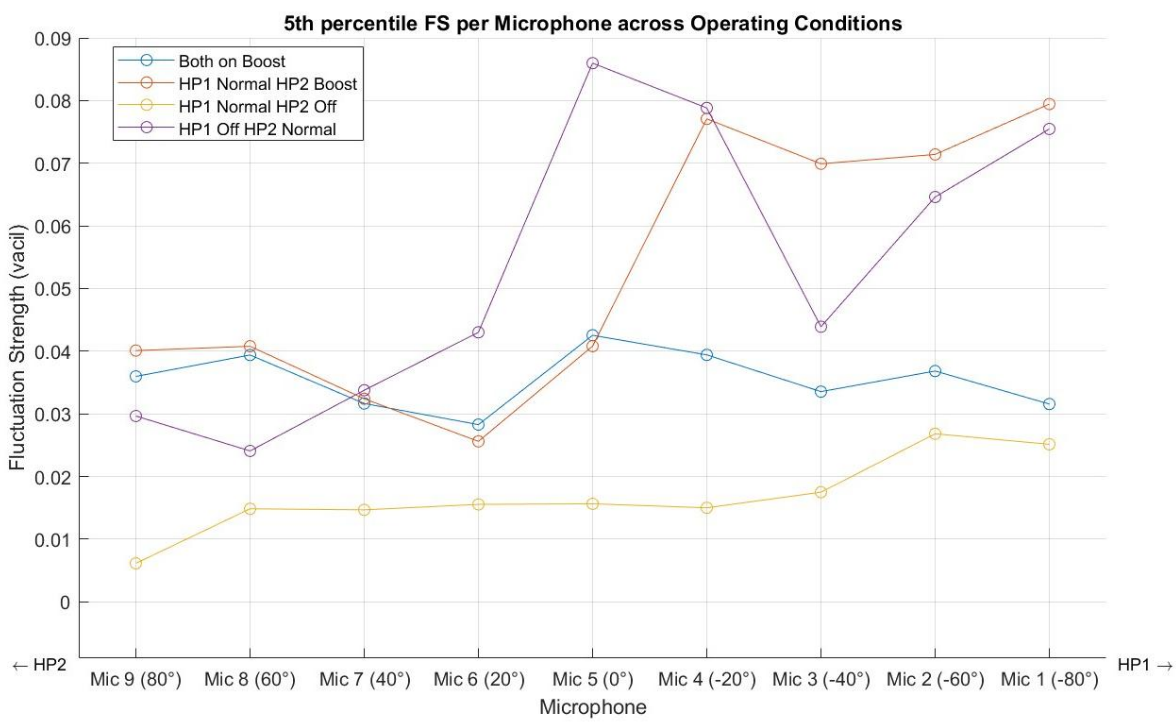

Figure 19: 5th percentile Fluctuation Strength (FS) values for the four operational scenarios.

3.1.6 Conclusions and implications from phase one findings

The phase one fieldwork, and the analysis that followed, set out to investigate whether close proximity of a pair of ASHPs led to any cumulative acoustic effects or interactions beyond what would be expected based on the units operating separately. An arc of microphones was used, allowing SPL to be visualised versus emission angle to assist this analysis.

Results for the ASHPs operating separately allow the effect of the fence to be clearly seen. For overall A-weighted SPL, as reported in section 3.1.2.1, the SPL difference from one garden to the other was seen to be as high as 14 dB. This is higher than the MCS 020 (2019, 2025) barrier attenuation factor for total occlusion (10 dB), despite the fence only being of basic 'closeboard' construction. This shouldn't be assumed to be a generalisable result, however, as the height difference between the gardens and resulting different distance of the microphones from the ground may have enhanced this effect; it is not, on its own, sufficient evidence to suggest an update to the MCS 020 barrier attenuation factor. Further analysis in third-octave bands in section 3.1.2.2 evidenced how the attenuation of the fence is strongly frequency-dependent, providing significant attenuation above 500 Hz but almost none at 100 Hz and below. This was confirmed in section 3.1.4 in which the SPL of several prominent tones was plotted versus mic arc angle, with the 110Hz tone notably exhibiting near identical SPL on both sides of the fence.

These findings emphasise the need for further research into the effectiveness of fences as noise barriers for ASHPs. A key aspect here is that most literature and standards concerning attenuation by barriers are intended for dedicated noise barriers, which are designed to be impenetrable to sound. Here, it is clearly seen that low frequencies must be passing through the fence, hence the nature and frequency dependence of this mechanism, and the interference with sound from this propagation path with that coming over the top, requires further research. This could, for example, inform design of fence treatments optimised for ASHP tones.

Regarding the question of whether SPL from nearby ASHPs can be added using the standard power-summation approach ubiquitous in environmental acoustics, this was tested directly by benchmarking it applied to SPL of two ASHPs operating independently to the SPL measured when they operate simultaneously. Limitations of this validation methodology were that it requires low and constant background noise, and for the ASHP to operate in identical states for each test, and both these issues occurred to some degree in the two comparisons. This limitation seems to explain the underprediction of combined SPL of up to 2.23 dB that was seen at some microphones. However, this will be investigated in further studies being planned. The remainder saw good agreement between the power-summation result and direct measurement, thus it is concluded that this method is appropriate, even for a worst-case with two ASHP extremely close, as was measured here.

The comparison was repeated with TOB analysis and low frequency narrowband analysis (½ Hz resolution up to 200 Hz). These backed up what had already been seen with overall SPL and displayed no further anomalies, though the narrowband presentation emphasised just how greatly narrowband SPL can change if a ASHP slightly changes operating state, causing tones to shift in frequency. This could be perceptually significant if these tones drift toward (or away from) frequencies that are emphasised by the acoustic conditions, for example the resonant frequencies of a bedroom, meaning a small frequency shift could cause a big change in SPL. This emphasises that – while a calculation procedure for planning purposes has a requirement to be simple – the true acoustic exposure that drives annoyance will depend on the fine detail of noise generated, its propagation path, and reception conditions, especially when low frequency tones are involved.

The tonality assessment in section 3.1.4 found several prominent tones that are expected to be audible. Some were at low frequencies matching those seen in the low frequency narrowband analysis, but others were at high frequencies (14–17 kHz), demonstrating that issues with tonal noise from ASHP are not restricted to low frequencies. High frequency tones were restricted mainly to the property with the operating ASHP due to the fence being an effective barrier at these frequencies, whereas low frequency tones manifested with equal SPL on both sides as already mentioned. The exact sources of high-frequency tonal components remain to be identified; additional measurement and analysis is recommended to identify the source and inform targeted mitigation strategies.

Finally, Fluctuation Strength (FS) was analysed to assess whether tones from the two ASHP might combine in a way that led to a perceptible 'beating' effect. Values derived from signals recorded during testing were consistently below perceptibility thresholds (<0.1 vacil), suggesting the absence of any audible effect. Conversely, researchers anecdotally thought they heard a beating effect, but this was behind HP1 – an unrealistic listening location – and was heard during the day when a nearby building site was active, so may have resulted from plant noise.

In short, no significant, unexpected acoustic effects were seen due to the proximity of the ASHPs, but further research is required to better understand whether any psychoacoustic effects are present. Further research is also required to fully understand the effectiveness of fences as noise barriers – including possible treatments – and of tonal components within the ASHP sound, including their generation mechanisms, possible mitigation strategies and subjective perceptibility. Barrier attenuation different to the MCS 020 (2019, 2025) calculation factor was observed, but this is single case study so is not justification to propose a modification. More field tests are required.

3.2 PHASE TWO: FOUR PROPERTIES

This section presents the results for phase two of the field study, as undertaken in January 2025. Section 3.2.1 reports the application of both versions of the MCS 020 assessment procedures to the case study. Section 3.2.2 then compares the measured SPLs to the MCS predictions, and comments on their accuracy. The key trends and implications of these findings are summarised in section 3.2.3.

3.2.1 Application of MCS Assessment Procedure

The four plots studied in phase 2 were used as a case study to compare the new (MCS 020 a 2025) and previous (MCS 020 2019) calculation methods.

Table 2 shows the calculation for the former standard and Table 3 following the latter. The mic-naming convention used here is “KW” for Kitchen Window and “BW” for Bedroom Window, followed by the property number (see Figure 6 for layout).

It should be noted that MCS 020 is intended to be used to support the installation of ASHPs as retrofit in existing properties via Permitted Development Rights, whereas the properties here are new builds. This means a different noise calculation will have been used in their planning process. Nonetheless, it is a representative layout of nearby properties – not unlike that in Hill & Harvie-Clarke, 2024.

Despite changes in the calculation process, the two assessment methods yielded identical compliance status at all assessment positions. The sound pressure levels for assessment positions at Property 1 (BW1 and KW1), located adjacent to the ASHP installation at Property 2, failed to meet the 42 dBA limit required by the previous MCS 020 and the 37 dBA limit stipulated by the current version.

Table 2: Calculations according to the previous MCS 020 procedure. The SWL value used in this calculation is as required by this version of MCS 020 Issue 1.3 (2019), from manufacturer's data; use the highest A-weighted sound power level stated.

MCS Steps (2019 version)	Assessment Positions							
	KW1	**BW1**	**KW2**	**BW2**	**KW3**	**BW3**	**KW4**	**BW4**
ASHP SWL	64	64	64	64	64	64	64	64
Directivity	8	8	8	8	8	8	8	8
Distance (m)	3.58	5.58	2.1	4.2	17.2	17.8	17	17.7
Distance Reduction	-11	-16	-8	-14	-25	-25	-25	-25
Barriers	-10	-5	0	0	-10	-10	-10	-10
SPL calculation (dBA)	43	43	56	50	29	29	29	29
Background Noise	40	40	40	40	40	40	40	40
Difference between ASHP SPL & BN	-3	-3	-16	-10	11	11	11	11
Decibel Correction (dBA)	45	45	56	50	40	40	40	40
Compliance	No	No	No	No	Yes	Yes	Yes	Yes

Table 3: Calculations according to the new MCS 020 a) Issue 1.0 procedure. The SWL value used in this calculation is the A-weighted sound power level found on the manufacturer's product fiche, product energy label, or the MCS product database.

MCS Steps (ISSUE 1.0)	Assessment Positions							
	KW1	**BW1**	**KW2**	**BW2**	**KW3**	**BW3**	**KW4**	**BW4**
ASHP SWL	59	59	59	59	59	59	59	59
Directivity (Q)	8	8	8	8	8	8	8	8
Distance (m)	3.58	5.58	2.1	4.2	17.2	17.8	17	17.7
Barriers	-5	-2.5	0	0	-5	-5	-5	-5
SPL (dBA)	41.0	39.6	50.6	44.6	27.3	27.0	27.4	27.1
Compliance	No	No	No	No	Yes	Yes	Yes	Yes

Although not mandatory, MCS assessments were also conducted for two positions (BW2 and KW2) at Property 2, where the operating ASHP was sited. As expected, these positions exceeded the SPL limits set by both versions of MCS 020. The assessment positions at Properties 3 (BW3 and KW3) and 4 (BW4 and KW4) complied with the SPL limits required by both versions of MCS 020. If the calculation is done again using the SWL as per MCS 020 a), i.e., a value of SWL = 59 dB(A) from the manufacturer's product energy label is used in the MCS 020 (2019) calculation, compliance outcomes change for Kitchen Window 1 (KW1) and Bedroom Window 1 (BW1) from "No" to "Yes", which differs from the outcome for MCS 020 a) (2025).

3.2.2 Comparison of measured SPL to MCS thresholds

To more concretely connect the MCS calculation in the preceding section to the field study, Figure 20 compares measured SPLs to the thresholds used to judge MCS compliance. This provides a direct means of assessing that methodology, subject to the significant caveat that it cannot be known if the ASHP was operating so as to produce exactly the manufacturer's stated sound power (as is the starting point of the MCS calculation).

HP2 came into operation a few minutes past 10pm. Following some initial checks and ramp up it ran at a moderate level for just under 5 minutes. Subsequently, it ramped up to a higher level that it ran at for 50 seconds, then shut down. The subplots in Figure 20 are analysis of segments taken: a) before HP2 came into operation, thus capturing the background SPL, b) during the higher-level phase, and c&d) during the moderate level phase.

All three segments were 30 seconds long and selected to be free from car pass-by noise (which was still frequently occurring even this late in the evening). Only six of the eight measurement positions are presented; those on property 4 were excluded due to higher exposure to background noise – mostly traffic – which masked all ASHP noise. The fence mics were excluded from the analysis too because their intended role – to help identify relative contribution from different units – was not required since only one ASHP operated.

It isn't known exactly what operational state the ASHP's controller was holding it to for these two phases, or what output SWL that would correlate to, but it was observed that the SPL change at a nearby microphone between the two phases was 5dB, the same as this particular unit has between SWL for the differing operational states required as input by the 2019 and 2025 MCS assessment procedures. Thus, these are, by serendipity, the correct dB difference to interpret for these purposes.

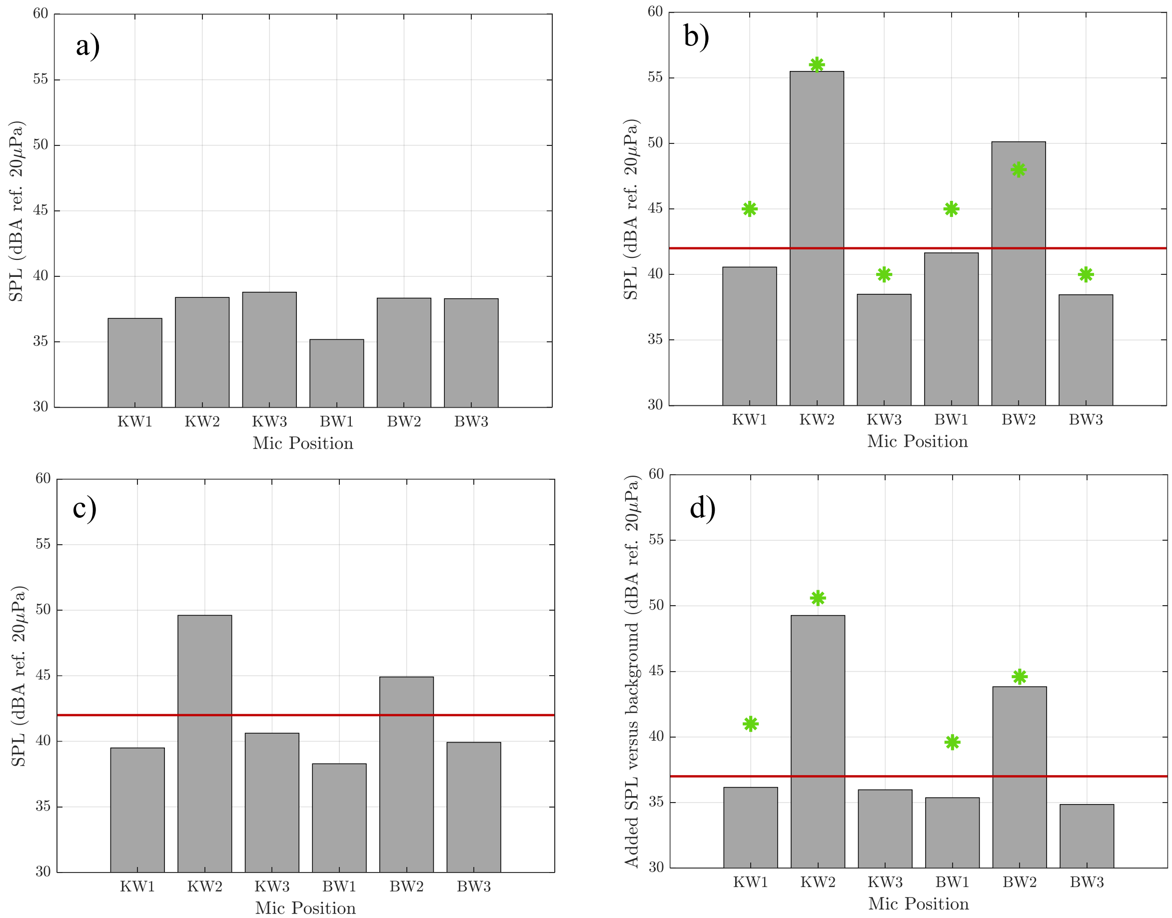

Figure 20: SPL measured in phase 2 test at bedroom and kitchen / diner windows of properties 1-3: a) Background; b) HP operating in higher-level state; c) HP operating with partial load; d) as c but with background (a) subtracted to give 'specific' SPL. Red line is the MCS 020 acceptance threshold (v1 42 dBA background in b&c and v2 37 dBA specific in d). Green stars are the MCS predictions from tables 1& 2.

Another difference between the measurement setup and the calculation procedure was that the pressure was measured as close to the windows as it was feasible to put a microphone instead of the 1m distant assessment position specified by MCS. This was done to minimise wind noise and because it is the pressure acting directly on a window that dictates the sound transmission through it. But nonetheless, this difference could lead to SPL differences of a few dB.

Figure 20b is a bar plot showing SPL for the higher-level state as is inferred equivalent to the 2019 MCS calculation method's requirements. This 2019 method adds an assumed 40 dBA background noise level, so the result predicted is the total SPL including both, termed 'ambient' SPL in BS4142 parlance. That is what the microphones measured so this is equivalent without further manipulation, subject to the assumption that the background noise level is roughly what the MCS calculation assumed.

Figure 20a shows the measured background noise levels before HP2 began operating, thereby examining that assumption. It is seen that the background SPL values are all lower than the 2019 MCS calculation method would assume, but only by a few dB. This is unlikely to affect the *ambient* SPL significantly due to the way dB SPL values sum (background SPL is the lower SPL so has weaker influence).

Returning to Figure 20b, the red line is the 42 dBA limit of 2019 MCS 020, which is meaningful here since this is *ambient* SPL. The green markers are the MCS-predicted SPL calculated according to the 2019 method, as per Table 2. The prediction agrees with the measurement almost perfectly for the Kitchen Window of Property 2 (KW2), right next to the ASHP, implying that the SWL of the ASHP is very close to what the 2019 MCS method had assumed (this is a short, direct transmission path with no obstruction, so should be more accurate due to fewer assumptions). SPL at the bedroom above (BW2) is predicted a few dB low, which might be due to its location in the slightly lower garden with the 40cm buttress wall diverting more energy back towards the same property instead of allowing it through to property 1. The measured SPL values for Property 1 (KW1 and BW1) are both lower than predicted, which would be consistent with such an effect, and/or that the MCS prediction does not fully capture the nature of the ASHP / fence interaction. SPLs at Property 3 (KW3, BW3) are again overpredicted but by a smaller amount. A key outcome is that the predictions see the ASHP (HP2) meet the 42 dBA SPL threshold only for microphones at Property 3, whereas the measurements see it meet them for all neighbouring properties, a significant difference for planning.

With a view to the 2025 update to MCS 020, Figure 20c, shows measured SPL for the earlier, moderate-power (partial load) state. All SPLs at properties 1 and 2 are lower due to this, but the SPL values at Property 3 (KW3 & BW3) have actually increased, which is almost certainly due to higher background noise levels at this time. However, the 2025 standard requires ASHP SPL without added background noise, what BS4142 terms '*specific*' SPL. To find this from measurement, the measured background noise must be subtracted. This is presented in Figure 20d, over which it is now appropriate to overlay the 37 dBA threshold from MCS 020 a (2025, red line) and the results of that prediction (green markers) from Table 3.

In terms of the ‘error’ between measurements and predictions, these remain very similar except that the prediction markers for Property 3 have dropped below the bottom of the plotted SPL range, while the bars for those cases remain high having been biased by increased background noise on the measurement. Nonetheless, both prediction and measurement put the ASHP SPL below the background SPL for this property, meaning it is probably inaudible. Changes in error seen for properties 1 and 2 are small, and likely just due to the unnecessary rounding steps in the 2019 method having been removed in the 2025 version, though the changed barrier penalty will have affected the prediction for Property 1. Finally, it is pointed out that the pass/fail status is the same as Figure 20b in all positions.

In summary, even though only one ASHP functioned during the test (HP2), its two operational levels and the 5dB step between them meant they could be serendipitously interpreted as equivalent to the differing states required by the 2019 and 2025 MCS calculation processes. Agreement between MCS prediction and measurement is rather good for all the cases observed; it follows the correct trends though overpredicted the critical near-neighbour case by at least 4 dB in all cases. To answer whether such findings are generalisable to other property layouts and garden topologies would require a much broader study of more sites.

3.2.3 Conclusions and implications from phase two findings

This phase of the field study did not deliver the intended suite of operating conditions involving multiple ASHPs but nonetheless provides a useful, if limited, dataset for comparing an MCS calculation to measurements.

Section 3.2.1 reported the MCS 020 calculation, comparing the original 2019 method to the updated 2025 version. The key finding here was that the compliance status was identical between the methods for all assessment positions. This might make it sound like the update was unnecessary, but this is not the case since it brings several significant improvements as noted in section 2.2.1, notably the elimination of ‘stepped’ distance attenuation tables and greater clarity over what operating point the ASHP sound power level should be for. In light of this, the absence of a change of outcome is positive, since it suggests that changes in planning outcomes due to the update are relatively unlikely.

Section 3.2.2 then compared these predictions to measurement, subject to the significant caveat that it was not known at exactly what point the ASHP was operating, and thus how its true sound power compared to that used in the MCS 020 calculations. Two operating states were studied, whose relative SPL conveniently matched the difference between the SWL used in the 2019 and 2025 MCS calculations.

A key outcome was that the MCS 020 predictions see the ASHP at Property 2 meet compliance thresholds only for microphones at Property 3 (at the far end of the gardens), whereas the measurements see it meet them for the (attached) Property 1 too, a significant difference for planning. Here, it is tempting to generalise and suggest that the MCS methods are overly cautious for near neighbour properties, but this should be resisted since this is only one case study and the height difference between the gardens is atypical and may have an effect. Moreover, this is the arrangement where getting the barrier attenuation due to the fence correct is most critical, and section 3.1.6 identifies this as an area where more research is required. Finally, noise from an immediate neighbour's ASHP is arguably the most sensitive scenario, so one could take the perspective that a slightly conservative noise level prediction is no bad thing, since it reduces the probability of disputes.

Nonetheless, some quite close agreement between MCS predictions and measurements are seen, which is encouraging, if not robustly so as this is only one ASHP in one test case. Further field work, sampling a greater variety of likely scenarios, is required in order to generalise and inform policy, as stated already.

Two further concerns that arose during this comparison centre on the 'Q' factor due to reflective barriers and the evaluation position. On 'Q' factor, MCS 020, like many standards in environmental acoustics, adds 3dB for every reflecting surface. This, however, fails to consider the transmissibility or absorption of said surface, and its extent. This is most apparent for the fence, where is it quite conceivable that one could add 3dB due its presence, yet it then be shown in practice that it allows sound to pass through (for low frequencies especially). This leads to a paradox where an acoustically weak barrier, which allows sound through or around, is treated in the calculation as if it is 100% reflective, meaning it could increase calculated noise levels at some angles. This is nonsensical, leading to the notion that barrier 'Q' factor adjustments should be made compatible with the attenuation factors ascribed to them. How this might best be done requires further research.

Furthermore, when dealing with low frequency tones, it should really be respected that both barrier attenuation and SPL increase due to reflective surfaces are frequency-dependent effects. Such detail would be unfeasible to include in a calculation tool for planning but might be useful to include in a more sophisticated diagnostic tool aimed at helping installers avoid or mitigate tonal noise problems.

Related to the frequency-dependent reflective surface effect noted above, we also moot that it is worth considering whether SPL measurement (and/or assessment) very close to a window / façade is more appropriate than measurement at 1m distant. The latter is widely assumed in environmental acoustics and is justified for noise egress, but the case for noise ingress is less clear. We aim to produce a short study evaluating this, with the aim of informing best practice.

Finally, it is worthy of mention that an extra, second phase two dataset was captured in the early morning. This was not analysed in this report because it was too compromised by background noise, being traffic noise and birdsong. Nonetheless, this may make a valuable dataset for Public Engagement purposes, since it demonstrates that the level of sound energy as perceived by a human ear of an operating ASHP may be lower than that of known – and in the birdsong case, usually desirable – sources of residential noise.

4 CONCLUDING REMARKS

4.1 KEY FINDINGS

The key findings documented in this report are:

- Power summation (logarithmic dB addition) of noise from two ASHPs was seen to be adequate for the case studied in this report. On average, the measurement of the two ASHP operating together was between 0.38 dB and 0.64 dB (depending on the specific operating conditions) louder than was expected based on combining measurements of the two ASHP operating individually. For some microphones the agreement between power summing calculations and measurements was very close. However, there were some microphone positions where an underprediction of up to 2.23 dB was observed compared to measurements. These underpredictions could be explained through adverse conditions that affecting the final measurement, i.e., small differences in operating conditions and background noise when performing the measurements with single and combined ASHPs. These findings will be further investigated in future field studies.
- Low frequency tones are dominant at the neighbouring property from an ASHP, with a wooden fence providing minimal sound attenuation for this frequency range. Meanwhile, high frequency tones are dominant at the ASHP installation property. This finding underscores the importance of careful placement and orientation of the ASHP, as well as the potential need for acoustic fencing with improved low-frequency performance, to mitigate noise impact on neighbouring properties.
- Current analyses cannot confirm significant low-frequency interaction effects generated by two ASHPs in close proximity. However, this highlights an opportunity for further advanced analysis to ensure comprehensive and well-supported conclusions.
- When comparing compliance with the original MCS 020 assessment protocol and the 2025 MCS 020 a) Issue 1.0 assessment protocol, no change in outcome was seen for the active ASHP measured in the phase 2 test (HP2 at Property 2). Both MCS protocols have shown good agreement with measured sound levels.

4.2 IMPLICATIONS FOR POLICY

In terms of policy implications, several points can be drawn from the studies documented in this report.

- Appropriate placement and orientation of the ASHP is required to minimise impact on neighbouring properties due to low frequency tonal noise. Orienting the heat pump with its back towards the owner's dwelling might reduce the emission of low frequency tonal noise to the neighbouring property, but a dedicated study is required to confirm this.
- Further research is needed into the effectiveness of fences of different types, materials and thickness as noise barriers for ASHPs. This will allow a better understanding of the frequency dependent sound transmission characteristics in typical fences, and the interference with sound transmitted through the fence with that coming over the top. This could inform the design of fence and wall treatments optimised for ASHP tonal noise.
- Further research is needed into the best methodology for choosing optimal 'Q' directivity factors to correct for reflecting surfaces close to an ASHP. Cases where the reflecting surfaces are of limited extent and/or are acoustically penetrable require particular consideration, as the current, simplistic approach may not always be valid for these.
- The updated 2025 method, MCS 020 a), shows only minor changes in error for Properties 1 and 2, primarily due to the removal of unnecessary rounding steps present in the 2019 version. The revised barrier penalty has also contributed to a more refined prediction for Property 1. Furthermore, while MCS predictions show the ASHP meeting the 42 dBA SPL threshold (for MCS 020, 2019) only at Property 3, actual measurements demonstrate compliance at all neighbouring properties.

4.3 FURTHER WORK

There are multiple avenues for continuation of work on the data collected so far. The collected data will form the basis of a detailed simulation or modelling exercise aimed at understanding cumulative ASHP noise effects. This simulation will improve understanding of the potential impact of ASHP noise on the surrounding environment and will support the development of strategies to mitigate any adverse effects. Data measured using a scanning intensity system will also be incorporated into the further exercises (Barton *et al.,* 2024).

Additionally, the Ambisonic recordings made during phase 1 of the testing will be used as stimuli for subjective testing. This testing will measure human response to ASHP noise, providing valuable data on the perceived annoyance and acoustic comfort levels associated with different noise profiles. These analyses will be compared to any similar studies in the existing literature to ensure robustness and validity, and significant findings may be used in academic publications.

The further analysis and modelling/ simulation will be used to inform another experiment as part of the continuation of the partnership in the second phase of the Future Homes Project, during which a further field study measuring multiple ASHPs at noise sensitive locations in a small residential area is projected to take place in winter 2025. An additional accompanying study into the behaviour of fence panels in response to ASHP noise under laboratory conditions is also planned. This will provide insight into the validity and robustness of acoustic barrier calculations in MCS 020 a) and other standards.

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