Noise measurements from eVTOL aircraft: A review of available data

CAP 2506

Published by the Civil Aviation Authority, 2025

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The work reported herein was carried out under a Letter of Agreement placed by the Department for Transport. Any views expressed are not necessarily those of the Secretary of State for Transport.

First published 2023

Although the term eVTOL is now in common use to describe passenger-carrying Advanced Air Mobility (AAM) aircraft, it was used as an umbrella term in this report to describe any type of electric propulsion aircraft capable of vertical take-off and landing, including Unmanned Aviation Systems (UAS) which are often referred to as drones.

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The latest version of this document is available in electronic format at: www.caa.co.uk/CAP2506

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Chapter 1
Introduction

1.1 When proposing an airspace change, government guidance[1] requires airspace change sponsors to explain to the CAA how the sponsor has considered and assessed the likely noise impact of its proposal. Currently, however, detailed noise data is not readily available or documented for airspace change proposals involving Unmanned Aircraft Systems (UAS) or Advanced Air Mobility (AAM).

1.2 Electric vertical take-off and landing (eVTOL) aircraft in the UK, for example, are not subject to noise certification requirements and as a result limited data exists on their noise characteristics.

1.3 Although voluntary guidance on the measurement of noise from UAS vehicles is currently being developed separately by EASA[2] and ISO[3], there remains a lack of publicly available noise measurement data. In addition, there are currently no formal calculation methods to model noise specifically from eVTOL ('drone' or 'air taxi') operations.

1.4 To bridge the current knowledge gap, an initial review has been undertaken on conference papers, reports and other available research papers on noise emissions of lightweight UAS (less than 25 kg in mass) as part of a wider review of noise considerations for emerging technologies on behalf of the Department for Transport (DfT). A review of the proposed new guidance from EASA and ISO is not, however, covered in this report.

1.5 There is also emerging evidence that noise from eVTOL aircraft can be perceived as more annoying compared to conventional aeroplanes and helicopters. The CAA has undertaken a separate review to provide a summary of the state of knowledge on the human impacts of noise from UAS operations, based on relevant published research on the topic, including literature presented at the Quiet Drones Symposium[4] and Inter-Noise[5] (published as CAP 2505).

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[1] *Air Navigation Guidance 2017: Guidance to the CAA on its environmental objectives when carrying out its air navigation functions, and to the CAA and wider industry on airspace and noise management.* Department for Transport, October 2017.

[2] *Guidelines on Noise Measurement of Unmanned Aircraft Systems Lighter than 600 kg*. European Union Aviation Safety Agency, October 2022.

[3] ISO/DIS 5305, *Noise measurements for UAS*. International Organization for Standardization.

[4] https://www.quietdrones.org/

[5] https://internoise2022.org/

1.6 The outcome of this review is intended to provide data to support initial development of a CAA noise modelling capability for UAS operations. Information obtained from the review will also inform CAA guidance to assist airspace change sponsors with noise assessments for their UAS activities. The focus on UAS is due to this category of eVTOL aircraft being closer to significant commercial deployment than AAM; the latter will be considered for a future study.

1.7 Given the intended outcome, this review has largely focussed on field study reports of measurement practices and noise emission characteristics, particularly in relation to overflight (flyover) data, rather than laboratory-based measurements or investigations. This is because laboratory measurements are typically performed in an anechoic chamber to obtain *sound power levels*[6] for the hover condition only. The applicability of such data after conversion to *sound pressure levels*[7] to the noise emitted outdoors by the same aircraft under actual flight conditions currently remains unproven.

1.8 The review was structured around two key themes associated with the measurement and quantification of environmental noise from UAS operations:

i. Noise measurement and flight procedures (Chapter 2)

ii. Noise metrics and reported results (Chapter 3)

1.9 During the initial screening stage, studies that were considered to be of poor methodological quality were excluded from further consideration. Reasons for exclusion included the use of low-quality noise instrumentation, non-standard measurement procedures and/or ambiguous data reporting.

1.10 A list of terms and abbreviations used in this report is provided in Appendix A[8]. References are provided in Appendix B.

1.11 Appendix C provides details of studies conducted by the CAA in 2021 to measure the noise from several different eVTOL aircraft.

1.12 Appendix D provides a summary of available overflight data covered in this review, with a focus on overall L_{ASmax} sound pressure levels for vehicles at a reference height of 400 ft (120 m).

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[6] Sound power level information allows a comparison to be made of the noise produced by different machines. With additional information on the directional properties of the noise source, the sound pressure level at any position relative to the source may be calculated.

[7] Sound pressure level is the physical quantity normally used for the assessment of environmental noise, which depends on the distance between the source and the receiver, the position of the source and also the local environment.

[8] The terms ‘UAS’ and ‘drone’ are used interchangeably throughout this document. However, the correct regulatory term is UAS.

Chapter 2

Noise measurement and flight procedures

UK CAA (2021)

2.1 In 2021 the UK CAA conducted two separate studies to measure the noise from several different eVTOL aircraft (Appendix C). The first series of tests were conducted at a test site situated on open farmland in Newbury to measure take-off, landing and overflight noise from a hybrid fixed-wing eVTOL aircraft (16.9 kg) and a DJI M300 quadcopter (6.4 kg).

2.2 The second series of tests were undertaken at Cranfield Airport and involved the measurement of overflight levels for seven different models of quadcopter (ranging from 0.3 kg to 6.3 kg in mass) from a number of different drone operators. Overflight measurements were made using an inverted ground plane (IGP) microphone and a microphone mounted at the standard height of 1.2 m above the ground.

2.3 The inverted ground plane microphone setup was in accordance with recommended guidance described in SAE (2007). The same microphone setup is specified in ICAO Annex 16 and FAA Part 36 for the noise certification of light (small) propeller-driven aeroplanes, since it minimises ground reflection effects that can occur in the same frequency range as the fundamental and harmonics of the propeller blade-passing frequency when compared to using a microphone mounted at the standard height of 1.2 m above ground level[9].

2.4 There are however a number of practical issues associated with the use of an inverted ground plane microphone which can make them less straightforward to deploy compared to a standard 1.2 m microphone arrangement, including:

- the requirement to use a ½ inch pressure-field microphone rather than the more conventional free-field design typically supplied with most sound level meters;
- the necessity to use custom-built parts including a ground plate and inverted microphone support;
- ensuring the correct installation of the ground plate into the local ground surface on-site; and

[9] Measured sound pressure levels obtained using a 1.2 m high microphone can be up to 3 dB higher than equivalent free-field noise levels due to ground reflection interference effects.

- ensuring the correct positioning, vertical spacing and horizontal alignment of the microphone diaphragm above the ground plate.

2.5 It should also be noted that while the SAE guidance states that 6 dB should be subtracted from measured sound pressure levels obtained from an inverted ground plane microphone to obtain equivalent free-field levels, the ICAO and FAA noise certification requirements for light propeller-driven aeroplanes require that the measured noise levels are reported directly.

2.6 For the quadcopters in both studies, the tests involved a series of alternate overflights, passing backwards and forwards along the same ground track at heights of 100 ft and 200 ft (and also 400 ft for the largest/noisiest drones), with the noise monitoring equipment located at the midpoint. For the Newbury tests, take-off and landing noise (to/from a height of 400 ft) was also measured at a lateral distance of 15 m for the quadcopter and 50 m for the hybrid fixed-wing aircraft. Information on the rates of ascent and descent was not reported.

2.7 The overflight procedure for the hybrid fixed-wing aircraft involved flying a series of clockwise circuits, passing over the noise monitoring equipment at a height of 200 ft above ground level. Background noise levels on the day at the Newbury site were too high to accurately measure noise levels at any higher altitude and, due to safety limitations, it was not possible to operate the hybrid fixed-wing below 200 ft. Flight speeds for all the tests were left to the individual drone operators who were advised that the aircraft should be flown at the maximum normal operating speed for the relevant phase of flight.

2.8 The noise certification requirements for light propeller-driven aeroplanes and helicopters limit average wind speed to a maximum of 5.1 m/s (10 knots). Average wind speeds were monitored during both studies using an on-site meteorological station and were considered favourable for noise monitoring, generally remaining below 5 m/s at Newbury and below 2 m/s at Cranfield.

2.9 In most cases at least six valid overflight measurements were recorded for each series of tests, although this was not always possible due to contamination from other noise sources or because of flight/technical issues. GPS flight data were made available by the drone operators in the Newbury tests to confirm the actual heights that were flown but similar data were not made available for the Cranfield tests. This meant it was not possible for the CAA to verify the extent of any differences between the target heights and the actual reported heights flown by each drone at the Cranfield event.

Cabell, R et al (2016)

2.10 Cabell, R et al (2016) describes a study conducted by NASA to measure the noise from four small commercially available UAS aircraft, including one piston engine-powered fixed-wing model aeroplane and three eVTOL multicopters: a tricopter (2.5 kg), quadcopter (1.6 kg) and hexcopter (7.3 kg).

2.11 Noise measurements were conducted at two different airfields in 2014 and 2015. In both studies the measurement system consisted of ½ inch random-incidence microphones, each covered with a hemispherical foam windscreen and placed on an acrylic ground board (41 cm in diameter with a thickness of 1.9 cm)[10]. All measured noise data were adjusted to equivalent free-field conditions to account for assumed pressure-doubling by the microphone ground boards[11].

2.12 An array of ground plane (GP) microphones (three microphones in the first tests and four in the second tests) was placed in a line perpendicular to the runway centreline and the drone pilot was instructed to fly over one of the microphones. Information on the exact microphone spacing was not reported.

2.13 Time-stamped position data for each flight was obtained using a detachable Flight Data Acquisition System (FDAS) which added 590 g to the mass of each vehicle. The FDAS system featured real-time kinematics (RTK) functionality for improved positional accuracy over standard GPS. Flight procedures for the eVTOL aircraft included level flyovers at various altitudes and speeds, and also hovers at various altitudes.

2.14 Specific numbers of flights and altitudes flown per vehicle were not discussed, although the authors did state that flyover altitudes for the quadcopter and hexcopter varied between 5 m and 22 m above ground level. The relatively low flyover heights in the NASA study illustrate the importance of accurately determining a vehicle's position under such conditions. For example, a GPS height error of ±1 m at 5 m (20%) will have a much greater influence on any measured result than the same error at 120 m (<1%).

2.15 All vehicles were flown manually during the tests. The report authors noted that the pilot may have caused additional unsteadiness in the vehicle flight path relative to an auto-piloted vehicle, indicating that an autopilot may have avoided this issue. It was also noted that not all of the flights yielded high quality acoustic data due to noise from other noise sources unrelated to the flight tests.

US FAA (2021)

2.16 In 2021 the US Federal Aviation Administration (FAA) issued a Notice of Proposed Rulemaking that would apply only to the noise certification of the 13 kg Matternet[12] model M2 quadcopter (FAA 2021a). The Notice states that without

[10] It is assumed the microphones were placed horizontally on the ground boards although information on their exact orientation and placement is not specified.

[11] It is assumed by subtraction of 6 dB from the measured levels, although this is not made explicit in the report.

[12] https://mttr.net/

this proposed rule, Matternet would be unable to certificate its aircraft until such time as the FAA was able to establish a rule of general applicability for Unmanned Aircraft (UA) noise certification.

2.17 The proposed rule is based around existing FAA requirements (FAA 2021b) for the noise certification of small helicopters defined in Part 36, Appendix J, but with technical differences tailored to the size and features of the Matternet quadcopter. Most notably, the reference height for the flyover test is 250 ft, rather than 492 ft in Appendix J.

2.18 The lower reference height is to help ensure that measurement noise levels exceed the background noise at a typical test site by an acceptable amount (at least 15 dBA is required for certification testing). The Notice also states that as tests are conducted, the applicant may be directed by the FAA to fly the aircraft at an altitude lower than the 250 ft reference height in order to achieve a signal-to-noise ratio that meets the certification test requirements. Microphone requirements in the proposed rule specify a pressure-response microphone mounted at 1.2 m above ground and oriented for grazing incidence, which is consistent with Appendix J (and with the equivalent requirements of ICAO Annex 16).

Read, D R et al (2020)

2.19 In 2019 the U.S. Department of Transportation Volpe Center conducted a study on behalf of the FAA to measure the noise from three eVTOL multicopters and one fixed-wing drone (Read, D R et al. 2020). Measurements took place at a test site in Oklahoma that was noted by the authors as being conducive to noise testing due to its low ambient noise. The tests were conducted in a manner similar to existing FAA Part 36 noise certification requirements for small propeller-driven aircraft and light helicopters (Appendix G and Appendix J, respectively).

2.20 Three microphones were used in the study, each connected to a class 1 sound level meter[13]. An inverted ground plane microphone installed in compliance with Appendix G and a 1.2 m pole-mounted microphone installed in compliance with Appendix J were placed on the test flight centreline, approximately 10 ft apart. A second inverted ground plane microphone was placed at a lateral location offset 20 ft from the centreline ground microphone to provide supplemental data. The report authors note that the offset position of the second ground microphone was not in compliance with Appendix G requirements but was included for research

[13] IEC 61672-1:2013 gives electroacoustical performance specifications for two categories of sound level meters, class 1 and class 2. The tolerance limits for class 1 instruments are tighter than those for class 2.

purposes. The hover/landing point for the multicopters was also located on the main centreline at a distance of 20 ft from the primary ground microphone.

2.21 Overflight measurements were conducted at a height of 150 ft above the microphones (in alternating north-to-south and south-to-north passes) at two different flight speeds ('slow' and 'fast') designed to represent minimum and maximum power operations over the microphones. In addition, the multicopter tests included a series of simulated take-offs and landings to/from a height of 150 ft[14], as well as a hover manoeuvre at 4 ft that included each of the four cardinal compass directions (held for 30 seconds each during measurement). The authors also provide a "rough comparison" of the multicopter noise measurements collected in the Oklahoma study with other known UAS noise tests conducted to date (including the NASA study of overflight noise levels reported by Cabell, R et al).

2.22 Local meteorological data were captured during the entire measurement study in a manner compliant with the Part 36 requirements. It was noted that wind-generated noise was the dominant ambient sound.

2.23 Time-stamped position data for each flight was obtained from a GPS-based vehicle tracking system developed by Volpe. The START (Survey and Tracking Apparatus for Research in Transportation) system relies on a Rover installed on the vehicle of interest and a Base Station located on the ground to produce position information to a greater level of accuracy than a typical GPS. The authors note that because most drones are quieter than conventional aircraft, they must fly closer to the microphones than specified in the noise certification requirements to achieve an adequate signal-to-noise ratio. However, the closer the drones fly to the microphones the more any uncertainty in their position can influence the quality of the measured noise data.

Schäffer, B et al (2021)

2.24 Schäffer, B et al (2021) describes the results of a literature review that was undertaken on drone noise emissions. The objective of the review was to give an overview on (i) measurement practices and noise emission characteristics such as sound power levels and directivity, and (ii) noise effects on humans.

2.25 A total of 24 studies were included in the review on noise measurement practices and emissions (the subject of this review), with primary focus on studies that discussed measurement methodologies for drones or provided indications for the formulation of empirical emission models or emission data.

2.26 Of those 24 studies, 14 describe laboratory investigations and the remaining 10 describe field study measurements. Included in the review were papers from

[14] Information on the rates of ascent and descent was not reported.

Cabell, R. et al (2016), Read, D R et al (2020), and Senzig, D A et al (2018), which are covered separately in this review.

2.27 Key data from the studies were reviewed and extracted into a summary table with information on drone models, flight manoeuvres, study type (laboratory or field), microphone setup and the type of emission data recorded. Noise emission values from 10 of the 24 studies[15] that were deemed by the report authors to be the most comprehensive and well documented were subsequently converted into comparable acoustical quantities for multicopters in hover and forward flight. A review of the conversion methodology is provided in Chapter 3 of this report.

Senzig, D A et al (2017)

2.28 Senzig, D A et al (2017) describes work undertaken by the U.S. Volpe Center to support the FAA’s development of UAS noise certification and noise measurement criteria. The report provides an overview of Volpe's START portable tracking system which can be installed on a UAS aircraft. The authors explain that accurate positioning information is increasingly important due to the typically shorter distances that are required between microphones and (relatively quiet) UAS vehicles, resulting in two competing constraints that had not generally been a concern in conventional aircraft tests:

- fly close to the microphone to maximise the signal-to-noise ratio, or
- fly farther from the microphone to minimise the relative error in the positioning to improve range accuracy.

2.29 Using an example of the position information provided in Appendix G of Part 36 as the standard required accuracy, the authors determine that an accuracy of 1.5% of the distance between the vehicle and the microphone would be necessary. The authors note that in practice GPS has the poorest positioning accuracy in the vertical dimension compared with the lateral dimension.

2.30 Among the technical challenges associated with the development of the START system, the authors state that the system relies on cumbersome Original Equipment Manufacturer (OEM) software and as such is not well suited for field use in terms of quick and efficient setup and safeguards against human error. The report recommends that custom software be developed to better suit the Volpe end-use.

2.31 The Volpe report also provides an update on a 2016 noise certification test that was conducted on a Navmar TigerShark UAS according to CFR Title 14 Part 36 Appendix G regulations, although it was noted the TigerShark failed to meet the noise standard due to its excessive noise levels. Whilst detailed results of the

[15] Covering four laboratory studies and six field studies.

TigerShark noise tests are presented in the report, they are not discussed in this review because the TigerShark is a fixed-wing, piston-engine UAS.

2.32 Finally, the report also provides a summary of UAS measurement programs that Volpe staff had participated in, both as observers and as test leads. On two occasions Volpe staff observed NASA UAS noise measurement studies that are covered separately in Cabell, R et al (2016). For practical reasons the Volpe team have also carried out various flight and noise tests on the Volpe campus in Cambridge, Massachusetts. Whilst the authors acknowledge that ambient noise levels on the campus can be too high to conduct uncontaminated noise tests (owing to its metropolitan location), the site is considered acceptable when only scoping-level results are needed.

Senzig, D A et al (2018)

2.33 Senzig, D A et al (2018) describes a flight test conducted by the U.S. Volpe Center on a small commercially available quadcopter (1.3 kg) to determine the applicability of the duration correction for altitude that is applied to measurements of Sound Exposure Level (SEL), as specified in the Part 36, Appendix J noise certification standard for helicopters. The authors explain that the Appendix J procedure is the primary focus of the report due to the majority of UAS vehicles currently operating in the United States using rotary-wing propulsion and lift.

2.34 The SEL duration correction in Appendix J potentially allows the operator to fly the aircraft at an altitude other than the prescribed reference level flyover altitude of 492 ft (150 m). And since UAS vehicles may not generate an acceptable signal-to-noise ratio at the prescribed altitude, flying at a lower altitude during the certification test may improve the signal-to-noise ratio. The authors state however that applying a duration correction that was developed for helicopters (based on experimental results) to UAS certification flight tests may not be appropriate due to the significantly different heights that may be required during testing.

2.35 The Appendix J duration adjustment for an off-reference altitude is specified as follows:

> *<delta>J1 = 12.5 log10(HT/492) dB;*
>
> *where <delta>J1 is the quantity in decibels that must be algebraically added to the measured SEL noise level to correct for an off-reference flight path, HT is the height, in feet, of the test helicopter when directly over the noise measurement point, and the constant (12.5) accounts for the effects on spherical spreading and duration from the off-reference altitude.*

2.36 The 12.5 log10 relationship corresponds to a SEL decay rate of 3.8 decibels per doubling of distance (dB/dd). The authors comment that in a past helicopter noise measurement report from Rickley E J et al (1993), a 10 log10 relationship between the reference height and closest points of approach is specified, which would correspond to a SEL decay rate of 3 dB/dd, although no discussion of the derivation of the relationship is given.

2.37 Two microphone setups were used for the Volpe flight tests (each connected to a class 1 sound level meter) – an Appendix J setup with a 4 ft (1.2 m) pole mounted microphone and an Appendix G setup with an inverted ground plane microphone. The Appendix G setup was added to the test to provide a comparison between the two different certification microphone methods. Local meteorological data were collected during the study which included wind speed, wind direction, temperature, and relative humidity.

2.38 The flight tests included a series of level flights at 25 ft, 50 ft, 100 ft and 200 ft by a DJI Phantom 3 drone over a set of microphones, which were conducted at the same ground speed so that only the altitude varied between each series of flights. Each series of level flights was flown in alternate opposite directions to minimise any effects due to wind.

2.39 The report authors also ran a limited number of 400 ft flight tests but measured noise levels did not rise to 10 dB above the ambient level for the measurement by the Appendix J pole-mounted microphone. The same events measured by the Appendix G ground-plate microphone did however rise above the ambient by 10 dB (by virtue of the 6 dB ‘pressure-doubling’ effect of the ground-plate setup[16]).

2.40 Although the DJI drone carried a Volpe-developed tracking system during the tests, several of the flights were not recorded by the system due to data dropouts. Internal positional and altitude data recorded by the DJI drone was therefore used to determine the drone’s position during post-processing.

2.41 The study found that the nominal 25 ft SEL measurement, after applying the Appendix J correction, adequately captured the SEL measured at the 50 ft flyover height. However, the Appendix J correction was found to under-predict the noise at the 100 ft and 200 ft flyover heights. Likewise, the 50 ft flyover measurement under-predicted both the 100 ft and the 200 ft flyover heights, and the 100 ft measurement under-predicted the 200 ft measurement. The authors conclude that the Appendix J duration correction should not be used for large adjustments of flyover altitudes.

[16] The pressure-doubling assumption is generally considered valid for sound incidence angles within 30 degrees of overhead (SAE 2007).

Chapter 3

Noise metrics and reported results

UK CAA (2021)

3.1 In the studies conducted by the UK CAA at Newbury and Cranfield (Appendix C), Sound Exposure Levels (SEL) and maximum sound pressure levels (L_{ASmax}) were obtained for a number of different eVTOL aircraft at flyover heights of 100 ft and 200 ft (and also 400 ft for the largest drones). In most cases at least six valid overflight measurements were recorded for each series of tests to obtain an average measured noise level.

3.2 The average wind speed during the Newbury tests was approximately 3-4 m/s. During the flight tests it was observed that the measured noise levels for the DJI M300 were consistently higher, by approximately 4-5 dB, when the aircraft was being flown directly into a headwind compared to a tailwind. This was caused by higher power levels being required by the drone to maintain the same ground speed (15 m/s) when flying into the headwind. Given the relatively large noise level differences observed between headwind and tailwind conditions, results for the DJI M300 at Newbury were analysed separately based on the compass direction that was flown (north-easterly or south-westerly).

3.3 At Cranfield on the other hand, where the wind speed was 2 m/s or less, measurements for two other DJI M300 drones were found to be less variable under headwind and tailwind conditions, exhibiting differences of only 1-2 dB depending on direction of travel. For this reason the Cranfield data were not separated according to headwind component.

3.4 As noted in Chapter 2, GPS flight data for the drones flown in the Cranfield tests were not made available by the drone operators. This meant it was not possible to verify the extent of any differences between the target heights and the actual reported heights flown by each vehicle. Details of the ground speeds that were flown by the vehicles at Cranfield are also not known.

3.5 Inspection of the measured noise profiles for four of the Cranfield drones (two DJI M300s, a DJI Inspire 1 V2 and a DJI Mavic Air) provided reasonable confidence that they were flown close to their target altitudes (exhibiting, for example, relatively consistent noise levels between each series of overflights). The data for these flights are therefore considered suitable for the purposes of this review. Results for the remaining four Cranfield drones (Parrot ANAFI, DJI Mavic 2 Pro, DJI FPV and DJI Matrice 210) on the otherhand are considered unreliable and have not been evaluated.

3.6 A summary of the eVTOL aircraft measured in the CAA studies that are considered to have acceptable overflight results is shown in Table 1. Based on measurements obtained for each drone at the highest test height available[17], corresponding estimates of the average equivalent free-field overflight L_{ASmax} noise levels at 400 ft (120 m) are also reported[18].

Table 1 CAA (2021) overflight noise measurement summary

Study	Vehicle	Mass, kg	Ref. free-field L_{ASmax} at 400 ft, dB
CAA, Newbury	DJI M300	6.4	51.9 (IGP mic, headwind conditions) 53.0 (1.2 m mic, headwind conditions) 47.2 (IGP mic, tailwind conditions) 48.5 (1.2 m mic, tailwind conditions)
	Hybrid fixed-wing	16.9	42.7 (IGP mic) 42.8 (1.2 m mic)
CAA, Cranfield	DJI M300 (1)	6.3*	48.6 (IGP mic)
	DJI M300 (2)	6.3*	49.2 (IGP mic)
	DJI Inspire 1 V2	3.1*	39.1 (IGP mic)
	DJI Mavic Air	0.4*	36.1 (IGP mic)

*Nominal mass stated by the manufacturer. Actual flight mass unknown.

3.7 Comparison of average take-off and landing measurements (L_{ASmax}) obtained in the Newbury study indicates that take-off noise levels for the DJI M300 and the Hybrid fixed-wing were approximately 3-4 dB quieter than on landing, see Table 2.

Table 2 CAA (2021) take-off and landing noise measurement summary

Study	Vehicle	Mass, kg	Free-field L_{ASmax}, dB
CAA, Newbury	DJI M300	6.4	58.2 (take-off, 1.2 m mic at 15 m lateral) 62.5 (landing, 1.2 m mic at 15 m lateral)
	Hybrid fixed-wing	16.9	66.4 (take-off, IGP mic at 50 m lateral) 70.0 (landing, IGP mic at 50 m lateral) 68.9 (take-off, 1.2 m mic at 50 m lateral) 71.7 (landing, 1.2 m mic at 50 m lateral)

[17] To minimise possible distance adjustment errors.

[18] Results from the 1.2 m Cranfield microphone are not summarised in Table 1 but are reported in Appendix C.

Cabell, R et al (2016)

3.8 In the NASA report published by Cabell, R. et al (2016), the upper range of the measured maximum A-weighted sound pressure levels, adjusted to a 15 m flyover altitude, are reported as 63 dBA for the DJI Phantom 2 quadcopter and 68 dB for the Prioria Hex hexcopter. The report also provides the corresponding range of flyover noise levels in EPNdB, although these are not adjusted to a common flyover height.

3.9 The authors do not state the time-weighting that was applied by their noise instrumentation but it is assumed the Slow setting was used. The report also does not provide average L_{ASmax} values and individual results are only shown graphically. However, Read, D R et al (2020) provides a summary of the NASA test results for a reference height of 400 ft (120 m). The reference L_{ASmax} values cited in the Volpe report for the NASA study (which are assumed to represent mean free-field values) are 44.9 dBA for the DJI Phantom 2 and 45.9 dBA for the Prioria Hex, see Table 3.

Table 3 Cabell (2016) overflight noise measurement summary

Study	Vehicle	Mass, kg	Ref. free-field L_{ASmax} at 400 ft, dB
Cabell, R et al (2016)	DJI Phantom 2	1.6	44.9 (GP mic)*
	Prioria Hex	7.3	45.9 (GP mic)*

*As reported in Read, D R et al. 2020

Read, D R et al (2020)

3.10 Read, D R et al (2020) provides a summary of average overflight measurements for three different multicopters at a height of 150 ft above the microphones for 'slow' and 'fast' flight speeds, which are intended to represent minimum and maximum power operations. Based on spherical spreading, the corresponding 400 ft reference L_{ASmax} levels were also calculated, as summarised in Table 4[19].

[19] Results for the IGP microphone are based on the average of both ground microphones in the Volpe study. Noise levels for the IGP microphone in Table 4 have also been adjusted to free-field conditions by subtracting 6 dB from the measurements reported by Volpe.

Table 4 Read (2020) overflight noise measurement summary

Study	Vehicle	Mass, kg	Ref. free-field L_{ASmax} at 400 ft, dB
Read, D R et al (2020)	Yuneec Typhoon	2.4	44.1 (IGP mic, fast flyover) 46.4 (1.2m mic, fast flyover) 43.9 (IGP mic, slow flyover) 46.2 (1.2m mic, slow flyover)
	DJI M200	6.1	46.2 (IGP mic, fast flyover) 48.2 (1.2m mic, fast flyover) 45.9 (IGP mic, slow flyover) 47.5 (1.2m mic, slow flyover)
	Gryphon Dynamics GD28X	20.0	58.1 (IGP mic, fast flyover) 59.9 (1.2m mic, fast flyover) 56.2 (IGP mic, slow flyover) 57.9 (1.2m mic, slow flyover)

3.11 From the same study, Table 5 provides a summary of the average take-off and landing measurements (L_{ASmax}), adjusted by the authors to a reference lateral distance of 100 ft. Whilst average measured noise levels for the Gryphon Dynamics GD28X on take-off are slightly higher than on landing, the reverse is true for the Yuneec Typhoon and DJI M200, where landing noise for both drones was measured higher than on take-off (a finding consistent with CAA 2021).

Table 5 Read (2020) take-off and landing noise measurement summary

Study	Vehicle	Mass, kg	Ref. free-field L_{ASmax} at 100 ft, dB
Read, D R et al (2020)	Yuneec Typhoon	2.4	48.1 (take-off, IGP mic) 55.7 (landing, IGP mic) 49.9 (take-off, 1.2m mic) 57.3 (landing, 1.2m mic)
	DJI M200	6.1	51.4 (take-off, IGP mic) 58.6 (landing, IGP mic) 51.9 (take-off, 1.2m mic) 59.3 (landing, 1.2m mic)
	Gryphon Dynamics GD28X	20.0	64.8 (take-off, IGP mic) 62.7 (landing, IGP mic) 67.5 (take-off, 1.2m mic) 66.0 (landing, 1.2m mic)

Schäffer, B et al (2021)

3.12 As mentioned in the previous chapter, key data from 10 of the 24 studies reviewed by Schäffer, B et al (2021) were extracted by the report authors and converted into comparable acoustical quantities for multicopters in hover and forward flight. The reference acoustic quantity was A-weighted sound pressure level at a distance of 1 m under free-field conditions and at a radiation angle of -30º relative to the rotor plane. Results were plotted as a function of mass.

3.13 No explanation is given by the report authors for the choice of -30º but the same reference angle was used (also without explanation) in one of the 10 studies selected by the authors for further review (Heutschi, K et al 2020). Schäffer et al also noted that drones exhibit a pronounced vertical emission directivity but radiate rather uniformly in the horizontal plane.

3.14 Conversions to the reference acoustic quantity were made by the report authors on the following basis:

> (i) *Translation dB(Z) into dB(A): For a typical drone emission spectrum, the two sum levels differ only slightly, so where necessary they were set equal.*
> (ii) *Geometrical spreading: Point source far-field behaviour in the form -20log(d).*
> (iii) *For a pressure zone microphone mounting on a ground plate, a sound pressure doubling or level increase by 6 dB is assumed with respect to free field.*
> (iv) *The drone is assumed to emit 3 dB more in the A-weighted level vertically downwards than at -30º.*
> (v) *The emission level is estimated from the sound power level by:*
> $L_{p,A,1m,-30^{\circ}} = L_{W,A} - 11$ *dB.*
> (vi) *The amplification effect of the ground for a microphone at a height of 1.0 to 1.2 m is assumed to be 1 dB(A) above grassland and 3 dB(A) above hard ground.*

3.15 While the technical bases for the conversions described in points (ii), (iii) and (vi) are generally recognised, the rationale for the conversions described in points (i), (iv) and (v) are less well understood. In addition, no information is provided regarding the conversion of Sound Exposure Levels into maximum sound pressure levels (L_{ASmax}).

3.16 On point (i), analysis of the summary data compiled by the report authors indicates that the translation from dB(Z) into dB(A) was applied specifically to Z-weighted Sound Exposure Levels (SEL) reported in a study by Alexander, W N and Whelchel, J (2019). However, a preliminary analysis of the eVTOL data collected by the UK CAA indicates the difference between Z-weighted and A-weighted SELs for the same event can differ by several decibels, with Z-weighted SEL being consistently higher than A-weighted SEL, rather than being equal in level as assumed by Schäffer et al.

3.17 On point (iv) the assumption that multicopter drones emit 3 dB more in the A-weighted level vertically downwards than at -30º appears to be based on a generic vertical radiation directivity model developed by Heutschi, K et al (2020) using drone noise recordings taken in a semi-anechoic room. However, a detailed description of the noise instrumentation and measurement procedures used by Heutschi to capture the recordings is not provided.

3.18 On point (v), whilst the general basis for the conversion of a sound power level to a sound pressure level is recognised, the conversion as described does not appear to include a Directivity Factor term, which would seem contrary to the statement made by the authors under point (iv) regarding directivity.

Senzig, D A et al (2018)

3.19 In the Volpe report by Senzig, D A et al (2018), overflight noise measurements for a DJI Phantom 3 Advanced multicopter were reported for heights of 25 ft, 50 ft, 100 ft and 200 ft over two microphone configurations – an Appendix G setup with an inverted ground plane microphone and an Appendix J setup with a 4 ft (1.2 m) pole mounted microphone.

3.20 While the focus of the Volpe report was on measured Sound Exposure Levels (SEL) and the Appendix J duration correction, maximum A-weighted noise levels (L_{ASmax}) were also reported for each series of overflights. Based on the L_{ASmax} measurements obtained for the 200 ft series of tests, corresponding estimates of average free-field overflight noise levels at 400 ft have been calculated, see Table 6[20].

Table 6 Senzig (2018) overflight noise measurement summary

Study	Vehicle	Mass, kg	Ref. free-field L_{ASmax} at 400 ft, dB
Senzig, D A et al (2018)	DJI Phantom 3 Adv.	1.3	42.7 (IGP mic) 45.4 (1.2 m mic)

3.21 Due to spherical spreading, and ignoring the influence of atmospheric absorption, the sound pressure level from a noise source will typically reduce by 6 dB for each doubling of distance. It is worth noting however that the average decay rates[21] measured by Volpe for the DJI Phantom 3 drone do not appear to follow the expected -6 dB spherical spreading relationship, see Table 7. A similar phenomenon can also be observed in the CAA's eVTOL test data (Appendix C). The reason(s) for these differences are not yet understood.

[20] Noise levels for the IGP microphone in Table 6 have been adjusted to free-field conditions by subtracting 6 dB from measurements as reported by Volpe.

[21] Calcuted using data reported in Tables 10 and 11 of Senzig, D A et al (2018).

Table 7 Mean measured L_{ASmax} decay rates for the Volpe DJI Phantom 3

Change in aircraft height, ft	Noise decay, dB (1.2 m mic)	Noise decay, dB (IGP mic)
25 to 50	-5.7	-5.3
50 to 100	-4.5	-4.6
100 to 200	-4.7	-4.8

Chapter 4

Summary and recommendations

4.1 A review of available literature on noise emissions from eVTOL aircraft has been undertaken. The outcome of the review is the provision of suitable data to support the development of a CAA noise modelling capability for UAS operations. Information obtained from the review will also inform CAA guidance to assist airspace change sponsors with noise assessments for their UAS activities.

4.2 The review has largely focussed on outdoor field study reports of measurement practices and noise emission characteristics in relation to overflight data, based on maximum A-weighted sound pressure level. A summary of available L_{ASmax} overflight data for a range of eVTOL aircraft at a reference height of 400 ft (120 m) is provided in Appendix D. Average measured take-off and landing noise levels have also been reported where available.

4.3 These initial findings could be used as the basis for modelling A-weighted noise levels from eVTOL aircraft assuming a point-source behaviour, with sound radiating uniformly in all directions. Based on this review however, there is some evidence that suggests eVTOL multicopters exhibit a pronounced vertical emission directivity.

4.4 Depending on the drone noise modelling approach taken forward by the CAA, it may be necessary to obtain additional information on noise directivity (possibly including spectral information) for a range of different vehicles. Further work may also be required to better understand noise decay rates for eVTOLs and to determine an appropriate duration correction adjustment for SEL.

4.5 In addition to adopting general good practice in the measurement and reporting of environmental noise, it is recommended that any future CAA guidance to airspace change sponsors on drone noise measurement methodology takes into consideration the following technical issues which have been highlighted in this review:

Wind conditions

i. In windy conditions the noise generated by trees and long grass, as well as wind-induced noise at the microphone, can become significant, making it difficult to obtain a satisfactory signal-to-noise ratio when undertaking noise measurements (see also the paragraph on signal-to-noise ratio below). In addition, high wind speeds can not only make the control of a drone more difficult but will also require more power when flying into a headwind, causing an increase in noise level. The noise certification requirements for light propeller-driven aeroplanes and helicopters limit average wind speed to a maximum of 5.1 m/s (10 knots). In the absence of data to the contrary, it is recommended that similar test requirements are included in any future CAA guidance on drone noise measurement.

Microphone setup and noise measurement

ii. The use of an inverted ground plane (IGP) microphone in place of a standard 1.2 m high microphone can eliminate unwanted ground reflection effects and improve the reliability of the measured noise source, particularly if an analysis of spectral information is required. There are however practical issues associated with the use of an IGP microphone in terms of the required hardware and the precise method of on-site installation.

iii. On the basis that any new CAA drone noise modelling capability is likely to be based on the calculation and propagation of overall A-weighted noise levels, the influence of ground reflection effects on measurements obtained using a 1.2 m high microphone is likely to be less significant.

iv. A standard 1.2 m high microphone mounted over soft ground (typically grass) may therefore be considered a practical compromise, allowing a more straightforward and cost-effective collection of UAS noise measurements by airspace change sponsors. Irrespective of the microphone setup that is adopted, any future CAA guidance should clearly set out requirements for the documentation of test results, including any adjustments or corrections that should be applied to measured levels.

Signal-to-noise ratio

v. The noise certification requirements for light propeller-driven aeroplanes specify that the measured L_{ASmax} level of each test flight should exceed the background noise by at least 10 dB. For the certification of light helicopters (which requires the determination of SEL, calculated over the highest 10 dB of the time-history), measured L_{ASmax} levels should exceed the background by at least 15 dB.

vi. On the basis that airspace change sponsors would be required to measure and report both L_{ASmax} and SEL noise metrics, any CAA guidance should also require that measured L_{ASmax} levels exceed the background by at least 15 dB. Where this requirement cannot be met it would be necessary to repeat the tests on another day or fly the vehicle closer to the noise instrumentation (see below).

Flight procedures and vehicle tracking

vii. The review has highlighted technical challenges associated with accurately determining a vehicle's position. While flying closer to the microphone helps ensure that measured noise levels exceed the background noise by an acceptable amount, the closer a drone flies to the microphone the more any uncertainty in its position can influence the quality of the measured noise data.

viii. Overflight procedures should therefore be conducted at the highest practical altitude possible. While additional overflights conducted at progressively lower altitudes may provide useful information on drone noise propagation characteristics, any increased uncertainty in the drone's position at those lower altitudes should be recognised when attempting to adjust measured levels to different propagation distances.

ix. Vehicles that are flown manually are more likely to exhibit non-steady flight paths relative to auto-piloted vehicles. Airspace change sponsors should therefore be advised to fly their vehicles autonomously wherever possible during noise tests, using pre-programmed waypoints and at a fixed and level height relative to the noise monitoring equipment.

x. To minimise any effects due to wind, overflight tests should be conducted in opposite directions along the intended flight path in order to obtain an average noise level that includes both headwind and tailwind conditions. For multicopter vehicles this can be achieved in practice by flying backwards and forwards along the same ground track. For hybrid fixed-wing aircraft, it would be necessary to fly two different circuits over the noise instrumentation (for example, clockwise and anti-clockwise).

xi. As a minimum, internal GPS-based positional and altitude data recorded by the drone should be used to determine its position relative to the measurement microphone(s). Positional data should be logged at sufficiently precise intervals (for example, at least once per second) over the duration of the flight test to allow an accurate depiction of the flight path at all times. Whilst separate on-board positional tracking systems capable of providing improved positional accuracy over standard internal GPS may be preferrable, their use may introduce additional costs and technical challenges to the airspace change sponsor for little additional gain.

APPENDIX A

Glossary of Terms and Abbreviations

Abbreviations	
AAM	Advanced Air Mobility. Air transportation services for people and/or cargo using revolutionary new aircraft.
A-weighted	A frequency weighting that is applied to the electrical signal within a noise measuring instrument as a way of simulating the way the human ear responds to a range of acoustic frequencies. If no frequency weighting is applied within the noise instrument, the signal is said to be Z-weighted.
dB (or dBA)	Decibel units describing sound level or changes of sound level. It is used in this report to define levels measured on the A-weighted scale, which incorporates a frequency weighting approximating the characteristics of human hearing.
DfT	Department for Transport (UK)
EASA	European Union Aviation Safety Agency
EPNdB	Effective Perceived Noise decibels. The measurement unit for Effective Perceived Noise Level (EPNL).
eVTOL	electric Vertical Take-off and Landing. An electric propulsion aircraft capable of vertical take-off and landing.
FAA	Federal Aviation Administration (US)
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IGP	Inverted Ground Plane
L_{ASmax}	The maximum sound level measured during an aircraft event (using frequency weighting A and time weighting S).
SEL	The Sound Exposure Level generated by a single aircraft at the measurement point. This accounts for the duration of the sound as well as its intensity.
Time-weighting	A parameter that defines the response speed of the detector in a sound level meter, typically either S (‘Slow’) or F (‘Fast’). Standard practice is to measure aircraft noise using the S time-weighting.
UAS	Unmanned Aircraft System. A powered aircraft without a human pilot on board, which may be remotely piloted.

APPENDIX B

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APPENDIX C

CAA eVTOL noise measurements 2021

Introduction

C1 In 2021 the CAA participated in two studies to measure noise from several different eVTOL aircraft to support a better understanding of the noise characteristics and potential noise impacts from commercial UAS operations.

C2 The first series of tests were organised in conjunction with Envirosuite[22], Skyports[23] and Trax International[24] and took place on 16 April 2021 at a test site situated on open farmland in Newbury. Measurements of take-off, landing and overflight noise were undertaken for a hybrid fixed-wing eVTOL aircraft and a commercially available quadcopter.

C3 The second series of tests were undertaken at Cranfield Airport on 19 July 2021 and involved the measurement of overflight levels for a number of commercially available quadcopters. The study was organised by Cranfield University in partnership with Envirosuite and drone industry group ARPAS-UK[25], and observed by the CAA.

C4 Noise measurements for both studies were made using an inverted ground plane (IGP) microphone supplied by the CAA and a 1.2 m microphone supplied by Envirosuite.

C5 The inverted ground plane microphone was set up in accordance with recommended guidance described in SAE (2007). The same microphone configuration is specified in ICAO Annex 16 and FAA Part 36 for the noise certification of light (small) propeller-driven aeroplanes, since it minimises ground reflection effects that can occur in the same frequency range as the fundamental and harmonics of the propeller blade-passing frequency when compared to using a microphone mounted at the standard height of 1.2 m above ground level[26].

[22] https://envirosuite.com/

[23] https://skyports.net/

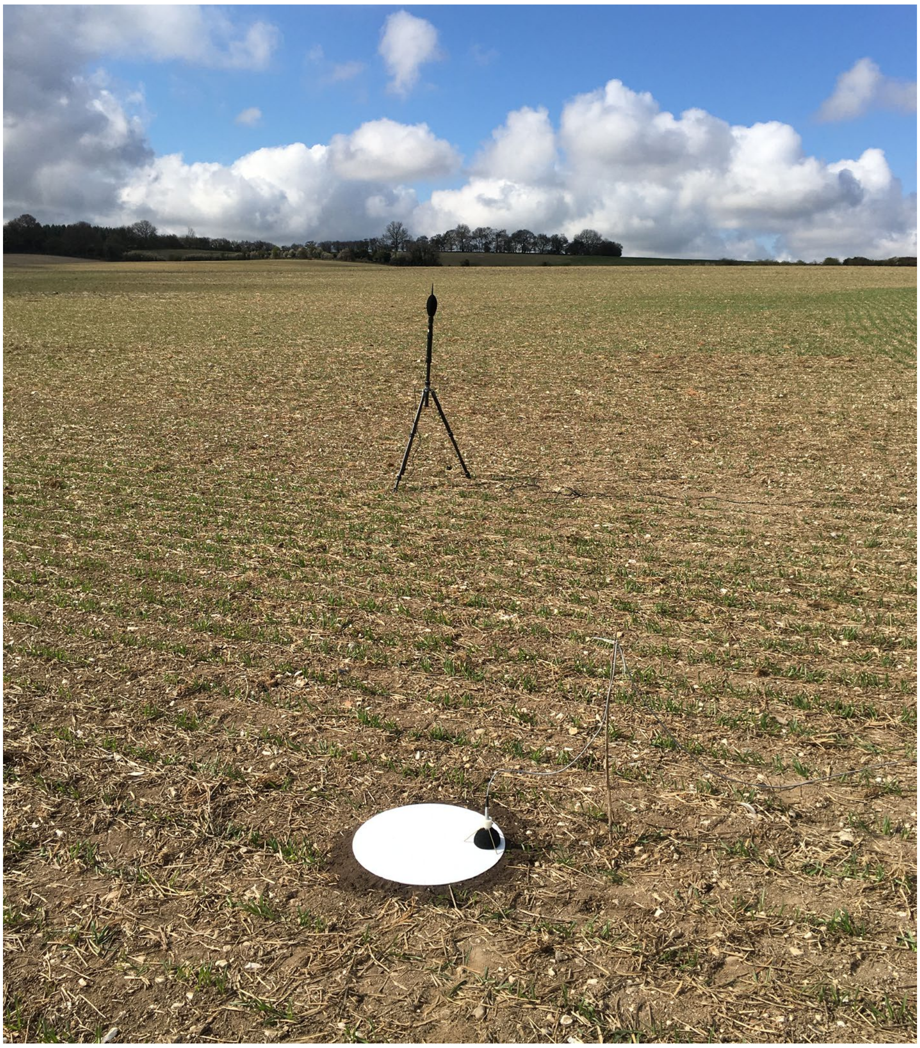
[24] https://traxinternational.co.uk/

[25] https://www.arpas.uk/

[26] Measured sound pressure levels obtained using a 1.2 m high microphone can be up to 3 dB higher than equivalent free-field noise levels due to ground reflection interference effects. 6 dB may be subtracted from measured sound pressure levels obtained using an Inverted Ground Plane microphone to provide an approximation of free-field noise levels.

C6 The microphone used in the CAA ground plane set-up at both test sites was a Brüel & Kjær 4192L pressure response microphone connected to a class 1 Brüel & Kjær 2250 sound level meter[27]. The 1.2 m high microphones used for both tests were class 1 Envirosuite 'Sentinel' units. Figures C1 and C2 show details of the different microphone installations[28]. Sound level calibration checks were conducted at the start and end of both measurement studies using a Brüel & Kjær 4231 sound calibrator.

Figure C1 IGP and 1.2 m microphone installation at Newbury



[27] IEC 61672-1:2013 gives electroacoustical performance specifications for two categories of sound level meters, class 1 and class 2. The tolerance limits for class 1 instruments are tighter than those for class 2.

[28] The ground plate at each site was bedded firmly into the surrounding ground surface using an additional layer of top soil to ensure there were no voids beneath the plate.

Figure C2 IGP and 1.2 m microphone installation at Cranfield Airport

C7 Maximum sound pressure levels (L_{ASmax}) were obtained for each noise event along with Sound Exposure Levels (SEL). The duration of each event was defined by the ‘10 dB-down’ points of the event L_{ASmax} time-history. In most cases at least six valid overflight measurements were recorded for each series of tests, although this was not always possible due to contamination from other noise sources or because of flight/technical issues.

C8 Flight speeds for all the tests were left to the individual drone operators who were advised that the aircraft should be flown at the maximum normal operating speed for the relevant phase of flight. GPS flight data were made available by the drone operators in the Newbury tests to confirm the actual heights and ground speeds that were flown but similar data could not be made available for the Cranfield tests.

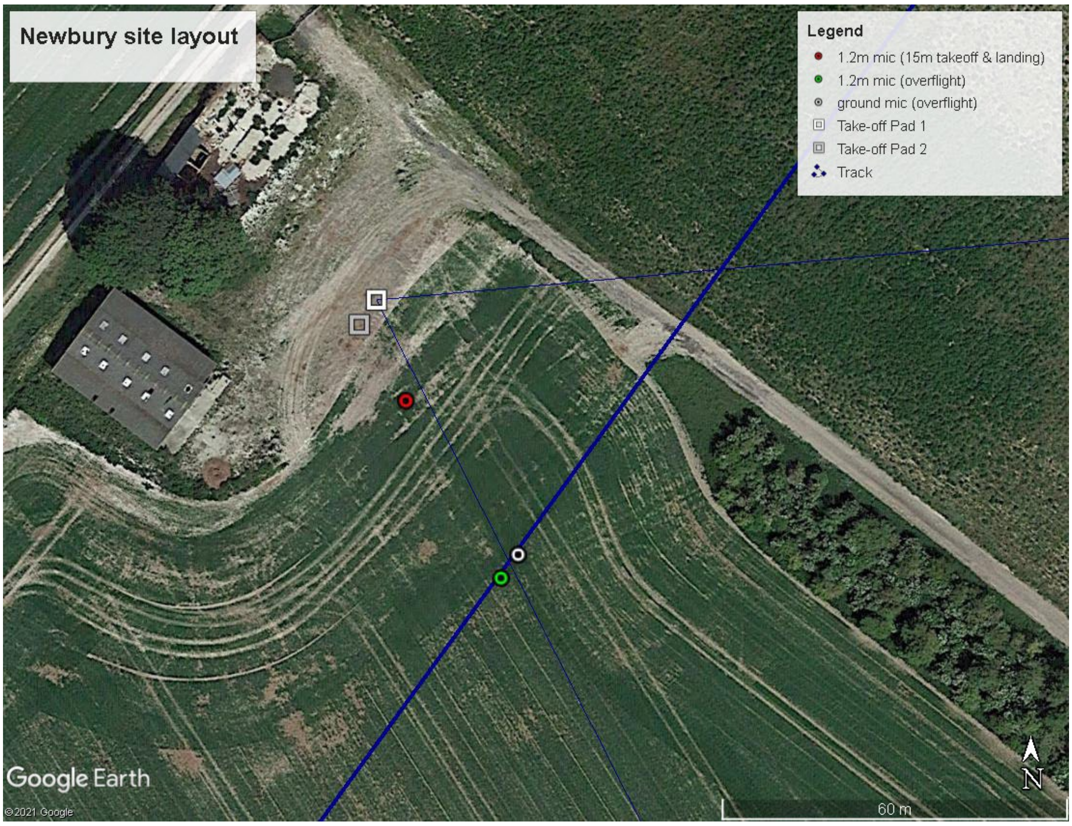
C9 Initial analysis has been limited to A-weighted noise measurements. However, digital audio recordings and one-third octave band spectra were also obtained for each measurement for possible future analysis.

Newbury study

C10 For the Newbury study, take-off, landing and overflight noise levels were measured for a hybrid fixed-wing eVTOL aircraft (16.9 kg) and a DJI M300 quadcopter (6.4 kg). Weather conditions on the day were dry and overcast with an average temperature of approximately 7°C. A north-easterly wind with an average speed of approximately 3-4 m/s was monitored at the site over the duration of the tests, which was considered favourable for noise monitoring.

C11 Figure C3 shows the layout of the Newbury test site in relation to the nominal flight path over the noise instrumentation, which was aligned in a north-east to south-west direction. The test flights for both aircraft were flown using pre-programmed GPS waypoints. The overflight tests for the DJI M300 involved a series of alternate overflights, passing backwards and forwards along the same ground track at heights of 100 ft and 200 ft, with the noise monitoring equipment located at the midpoint[29]. Background noise levels on the day were too high to accurately measure noise levels at higher altitudes. Take-off and landing noise (to/from a height of 400 ft) was also measured at a lateral distance of 15 m for the quadcopter and 50 m for the hybrid fixed-wing aircraft[30].

Figure C3 Newbury measurement site



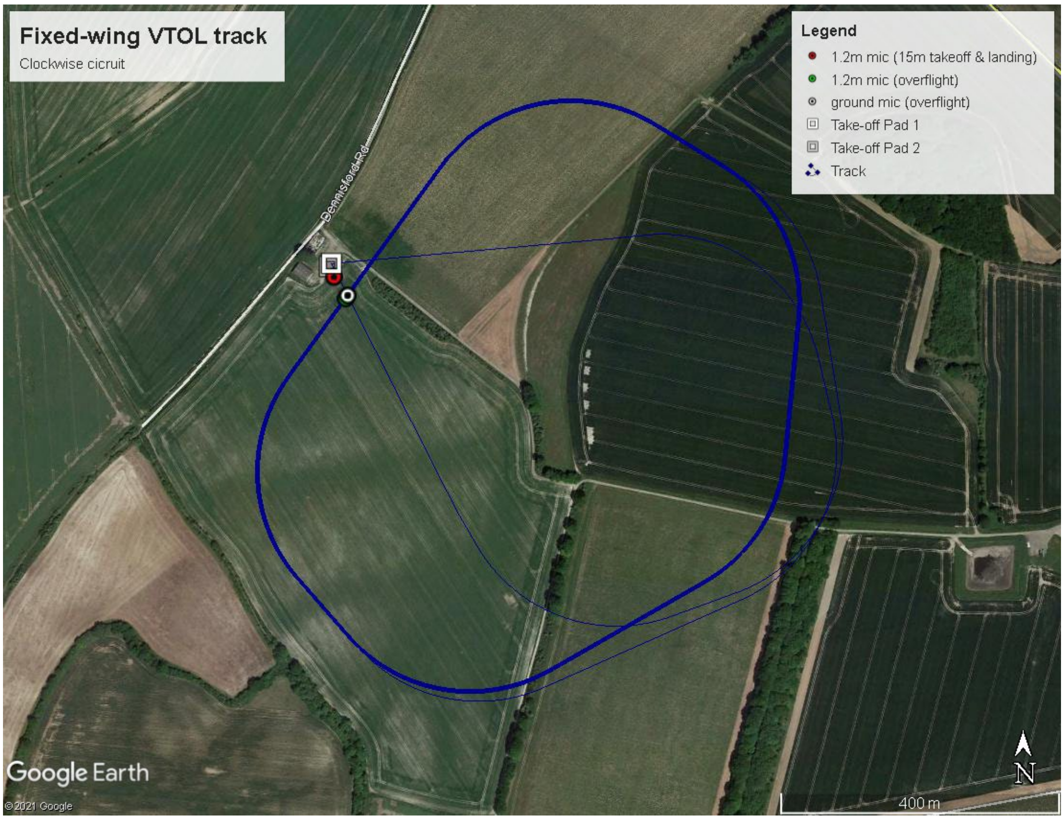
C12 The overflight procedure for the hybrid fixed-wing involved a series of clockwise circuits, passing over the noise monitoring equipment at a height of 200 ft above ground level, see Figure C4**.** Background levels were too high to accurately

[29] The total length of the ground track was approximately 500 metres.

[30] Take-off Pad 1 was used by the hybrid fixed-wing aircraft. Take-off Pad 2 was used by the quadcopter.

measure noise levels for the hybrid fixed-wing aircraft at any higher altitude and, due to safety limitations, it was not possible to operate the aircraft below 200 ft.

Figure C4 Circuit layout for the hybrid fixed-wing aircraft



C13 Results for the DJI M300 take-offs and landings are presented in Tables C1 and C2 respectively. Tables C3 and C4 present the M300 results for the 200 ft overflights using the IGP microphone and 1.2 m microphone respectively. Tables C5 and C6 present the M300 results for 100 ft overflights using the IGP microphone and 1.2 m microphone. The overflight L_{ASmax} measurements in each table have also been normalised to a reference distance of 400 ft using the relationship 20*log10(d/400), where d is the closest point of approach (CPA).

C14 Measured overflight noise levels for the DJI M300 were consistently higher, by approximately 4-5 dB on average, when the aircraft was being flown directly into a headwind compared to a tailwind. This was caused by higher power levels being required by the drone to maintain the same ground speed (15 m/s) when flying into the headwind.

C15 Given the relatively large noise level differences observed between headwind and tailwind conditions at Newbury, the mean noise levels reported for the DJI M300 in Tables C3 to C6 have been averaged separately based on the compass direction that was flown (north-easterly or south-westerly).

Table C1 DJI M300 take-offs to 400 ft, 1.2m microphone at 15 m

Run Number	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	13:11:29	13:11:51	57.9	67.3
2	13:13:05	13:13:31	58.0	67.7
3	13:14:42	13:15:20	Contaminated noise event	
4	13:16:16	13:16:37	58.4	67.6
5	13:17:47	13:18:09	57.8	67.5
6	13:19:09	13:19:29	58.7	68.1
Mean	-	-	58.2	67.6
Std. Dev	-	-	0.4	0.3
90% CI	-	-	0.4	0.3

Table C2 DJI M300 landings from 400 ft, 1.2m microphone at 15 m

Run Number	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	13:12:13	13:12:45	62.8	73.2
2	13:13:48	13:14:13	62.6	72.5
3	13:15:41	13:16:11	61.6	71.9
4	13:16:53	13:17:21	62.3	72.7
5	13:18:21	13:18:53	Contaminated noise event	
6	13:19:51	13:20:13	63.0	72.6
Mean	-	-	62.5	72.6
Std. Dev	-	-	0.5	0.5
90% CI	-	-	0.5	0.4

Table C3 DJI M300 200 ft overflights, Inverted Ground Plane microphone

Run Number	Direction	Ground Speed, KT	Event Start	Event End	L_{ASmax}, dB	SEL, dB	CPA, ft	Norm. L_{ASmax} (400ft), dB
1	SW	29	10:35:13	10:35:26	59.3	66.8	197.8	53.2
2	NE	28	10:35:59	10:36:16	64.0	72.0	197.9	57.9
3	SW	29	10:36:49	10:37:15	Contaminated noise event			
4	NE	27	10:37:48	10:38:03	63.9	72.2	198.1	57.8
5	SW	29	10:38:58	10:39:12	58.7	66.7	197.8	52.6
6	NE	29	10:39:45	10:40:00	63.6	72.2	197.8	57.5
7	SW	29	10:40:45	10:40:58	60.0	67.4	197.7	53.8
8	NE	27	10:41:32	10:41:46	64.3	72.0	197.9	58.1
9	SW	29	10:42:35	10:42:47	60.2	67.4	197.8	54.1
10	NE	27	10:43:22	10:43:36	63.9	71.9	197.7	57.8
11	SW	29	10:44:23	10:44:36	59.1	66.8	198.2	53.0
12	NE	27	10:45:11	10:45:26	63.9	72.1	198.2	57.8
13	SW	29	10:46:12	10:46:27	58.6	66.6	198.2	52.4
14	NE	27	10:47:00	10:47:14	64.3	72.2	197.8	58.2
15	SW	29	10:48:04	10:48:17	59.2	66.8	198.1	53.1
16	NE	27	10:48:52	10:49:06	64.1	72.0	197.9	58.0
Mean, SW direction			-	-	59.3	66.9	-	53.2
Std. Dev			-	-	0.6	0.3	-	0.6
90% CI			-	-	0.4	0.2	-	0.4
Mean, NE direction			-	-	64.0	72.1	-	57.9
Std. Dev			-	-	0.2	0.1	-	0.2
90% CI			-	-	0.2	0.1	-	0.2

Table C4 DJI M300 200 ft overflights, 1.2 m microphone

Run Number	Direction	Ground Speed, KT	Event Start	Event End	L_{ASmax}, dB	SEL, dB	CPA, ft	Norm. L_{ASmax} (400ft), dB
1	SW	29	10:35:12	10:35:28	54.6	62.9	193.5	48.3
2	NE	28	10:35:55	10:36:16	59.3	68.1	193.6	53.0
3	SW	29	10:36:49	10:37:15	Contaminated noise event			
4	NE	27	10:37:47	10:38:04	59.5	68.1	193.9	53.2
5	SW	29	10:38:58	10:39:12	54.2	62.4	193.5	47.9
6	NE	29	10:39:45	10:40:00	58.9	67.8	193.5	52.6
7	SW	29	10:40:45	10:41:02	55.0	63.0	193.6	48.7
8	NE	27	10:41:32	10:41:47	59.3	67.6	194.0	53.0
9	SW	29	10:42:35	10:42:48	54.8	62.7	193.5	48.5
10	NE	27	10:43:22	10:43:37	59.1	67.3	193.4	52.8
11	SW	29	10:44:23	10:44:36	55.2	63.0	193.9	48.9
12	NE	27	10:45:10	10:45:26	59.6	67.8	193.6	53.3
13	SW	29	10:46:12	10:46:27	54.1	62.2	193.8	47.8
14	NE	27	10:47:00	10:47:14	59.4	67.5	193.5	53.1
15	SW	29	10:48:04	10:48:17	55.4	62.8	193.8	49.1
16	NE	27	10:48:51	10:49:06	59.5	67.6	193.6	53.2
Mean, SW direction					54.8	62.7	-	48.5
Std. Dev					0.5	0.3	-	0.5
90% CI					0.4	0.2	-	0.4
Mean, NE direction					59.3	67.7	-	53.0
Std. Dev					0.2	0.3	-	0.2
90% CI					0.2	0.2	-	0.2

Table C5 DJI M300 100 ft overflights, Inverted Ground Plane microphone

Run Number	Direction	Ground Speed, KT	Event Start	Event End	L_{ASmax}, dB	SEL, dB	CPA, ft	Norm. L_{ASmax} (400ft), dB
1	SW	29	10:51:08	10:51:17	64.9	70.5	101.4	52.9
2	NE	28	10:51:57	10:52:05	69.0	74.7	101.5	57.1
3	SW	29	10:53:31	10:53:40	64.3	69.9	101.2	52.4
4	NE	29	10:54:20	10:54:29	68.9	74.5	101.6	57.0
5	SW	29	10:55:40	10:55:49	64.5	70.1	101.5	52.6
6	NE	27	10:56:28	10:56:38	69.3	75.0	101.6	57.4
7	SW	29	10:57:32	10:57:41	64.8	70.5	101.5	52.9
8	NE	26	10:58:22	10:58:31	69.5	75.4	101.6	57.6
9	SW	29	10:59:29	10:59:38	64.4	69.9	101.5	52.5
10	NE	27	11:00:20	11:00:40	Contaminated noise event			
11	SW	29	11:01:22	11:01:31	64.2	69.8	101.4	52.2
12	NE	27	11:02:12	11:02:22	68.8	74.9	101.3	56.9
13	SW	29	11:03:16	11:03:26	Contaminated noise event			
Mean, SW direction			-	-	64.5	70.1	-	52.6
Std. Dev			-	-	0.3	0.3	-	0.3
90% CI			-	-	0.2	0.2	-	0.2
Mean, NE direction			-	-	69.1	74.9	-	57.2
Std. Dev			-	-	0.3	0.3	-	0.3
90% CI			-	-	0.3	0.3	-	0.3

Table C6 DJI M300 100 ft overflights, 1.2 m microphone

Run Number	Direction	Ground Speed, KT	Event Start	Event End	L_{ASmax}, dB	SEL, dB	CPA, ft	Norm. L_{ASmax} (400ft), dB
1	SW	29	10:51:09	10:51:17	60.2	65.8	97.6	47.9
2	NE	28	10:51:56	10:52:05	64.0	69.8	97.8	51.8
3	SW	29	10:53:32	10:53:40	59.8	65.5	97.3	47.5
4	NE	29	10:54:19	10:54:29	63.8	69.8	97.8	51.6
5	SW	29	10:55:40	10:55:49	59.6	65.7	97.8	47.4
6	NE	27	10:56:29	10:56:37	64.1	70.1	97.4	51.8
7	SW	29	10:57:33	10:57:40	60.1	65.4	97.7	47.9
8	NE	26	10:58:22	10:58:32	64.4	70.7	97.8	52.2
9	SW	29	10:59:30	10:59:38	59.8	65.3	97.7	47.6
10	NE	27	11:00:20	11:00:42	Contaminated noise event			
11	SW	29	11:01:23	11:01:31	59.4	65.1	97.3	47.1
12	NE	27	11:02:12	11:02:21	64.0	70.1	97.5	51.7
13	SW	29	11:03:17	11:03:27	Contaminated noise event			
Mean, SW direction			-	-	59.8	65.5	-	47.6
Std. Dev			-	-	0.3	0.2	-	0.3
90% CI			-	-	0.2	0.2	-	0.3
Mean, NE direction			-	-	64.1	70.1	-	51.8
Std. Dev			-	-	0.2	0.4	-	0.2
90% CI			-	-	0.2	0.4	-	0.2

C16 Table C7 presents measurements for the hybrid-fixed wing aircraft on take-off up to 400 ft using the IGP microphone and 1.2 m microphone. Table C8 presents the hybrid-fixed wing landing measurements from 400 ft using both microphone types.

C17 Tables C9 and C10 present the hybrid fixed-wing 200 ft overflight data for the IGP microphone and 1.2 m microphone, respectively. The overflight L_{ASmax} measurements have also been normalised to a reference distance of 400 ft using the relationship 20*log10(d/400), where d is the aircraft height measured above the monitor.

Table C7 Hybrid fixed-wing eVTOL take-offs to 400 ft

	Inverted Ground Plane microphone					1.2m microphone				
Run Number	Event Start	Event End	L_{ASmax}, dB	SEL, dB	Nominal distance, m	Event Start	Event End	L_{ASmax}, dB	SEL, dB	Nominal distance, m
1	11:22:32	11:23:14	72.5	85.0	50	11:22:32	11:23:13	69.4	80.9	52
2	12:13:48	12:14:31	72.1	84.5	50	12:13:47	12:14:31	68.7	80.3	52
3	12:48:18	12:49:00	72.6	86.0	50	12:48:17	12:48:59	68.5	81.5	52
Mean	-	-	72.4	85.2	-	-	-	68.9	80.9	
Std. Dev	-	-	0.3	0.8	-	-	-	0.5	0.6	
90% CI	-	-	0.5	1.3	-	-	-	0.8	1.0	

Table C8 Hybrid fixed-wing eVTOL landings from 400 ft

	Inverted Ground Plane microphone					1.2m microphone				
Run Number	Event Start	Event End	L_{ASmax}, dB	SEL, dB	Nominal distance, m	Event Start	Event End	L_{ASmax}, dB	SEL, dB	Nominal distance, m
1	11:37:01	11:37:52	76.7	89.4	50	11:37:02	11:38:01	73.1	85.4	52
2	12:28:11	12:29:08	75.8	88.8	50	12:28:12	12:29:15	70.4	85.4	52
3	12:51:42	12:52:31	75.4	88.5	50	12:51:43	12:52:39	71.6	85.0	52
Mean	-	-	76.0	88.9	-	-	-	71.7	85.3	-
Std. Dev	-	-	0.7	0.5	-	-	-	1.4	0.3	-
90% CI	-	-	1.1	0.8	-	-	-	2.3	0.4	-

Table C9 Hybrid fixed-wing eVTOL 200 ft overflights, Inverted Ground Plane microphone

Run Number	Direction	Ground Speed, KT	Event Start	Event End	L_{ASmax}, dB	SEL, dB	Height, ft	Norm. L_{ASmax} (400ft), dB
1	NE	46	12:15:48	12:15:58	52.2	58.1	210.4	46.6
2	NE	47	12:17:19	12:17:30	52.3	58.3	207.4	46.6
3	NE	46	12:18:52	12:19:02	53.1	59.3	212.4	47.6
4	NE	48	12:20:14	12:20:35	Contaminated noise event			
5	NE	45	12:22:00	12:22:10	56.0	62.0	204.4	50.1
6	NE	48	12:23:35	12:23:44	54.7	60.6	212.4	49.2
7	NE	48	12:25:07	12:25:16	55.4	61.1	204.4	49.6
8	NE	45	12:26:40	12:26:49	57.2	63.1	203.4	51.3
Mean			-	-	54.4	60.4	-	48.7
Std. Dev			-	-	1.9	1.9	-	1.8
90% CI			-	-	1.4	1.4	-	1.3

Table C10 Hybrid fixed-wing eVTOL 200 ft overflights, 1.2 m microphone

Run Number	Direction	Ground Speed, KT	Event Start	Event End	L_{ASmax}, dB	SEL, dB	Height, ft	Norm. L_{ASmax} (400ft), dB
1	NE	46	12:15:46	12:16:00	47.0	54.1	206.0	41.2
2	NE	47	12:17:17	12:17:34	46.9	54.3	203.0	41.0
3	NE	46	12:18:50	12:19:03	47.5	54.6	208.0	41.8
4	NE	48	12:20:14	12:20:35	Contaminated noise event			
5	NE	45	12:21:58	12:22:12	50.0	57.2	200.0	44.0
6	NE	48	12:23:32	12:23:47	48.8	55.7	208.0	43.1
7	NE	48	12:25:06	12:25:16	49.4	55.5	200.0	43.4
8	NE	45	12:26:38	12:26:51	50.8	57.9	199.0	44.7
Mean			-	-	48.6	55.6	-	42.8
Std. Dev			-	-	1.5	1.4	-	1.4
90% CI			-	-	1.1	1.1	-	1.0

Cranfield study

C18 For the study at Cranfield Airport, overflight noise levels were measured for the following quadcopters[31]:

- Parrot ANAFI (0.3 kg)
- DJI Mavic 2 Pro (0.9 kg)
- DJI M300 [x2] (6.3 kg)[32]
- DJI Inspire 1 V2 (3.1 kg)
- DJI FPV (0.8 kg)
- DJI Mavic Air (0.4 kg)
- DJI Matrice 210 (4.8 kg)

C19 Weather conditions during the tests were dry with scattered clouds and an average temperature of approximately 28°C. A light north-easterly wind with an average speed of approximately 1-2 m/s was monitored at the site over the duration of the tests.

C20 Like the tests conducted at Newbury, the Cranfield study involved a series of alternate overflights, passing backwards and forwards along the same ground track at heights of 100 ft and 200 ft. An additional set of 400 ft overflights were also flown for the larger DJI M300 drones[33]. All operators were provided with GPS waypoints in advance of the tests for flight planning purposes. Figure C5 shows the layout of the Cranfield test site in relation to the nominal flight track[34].

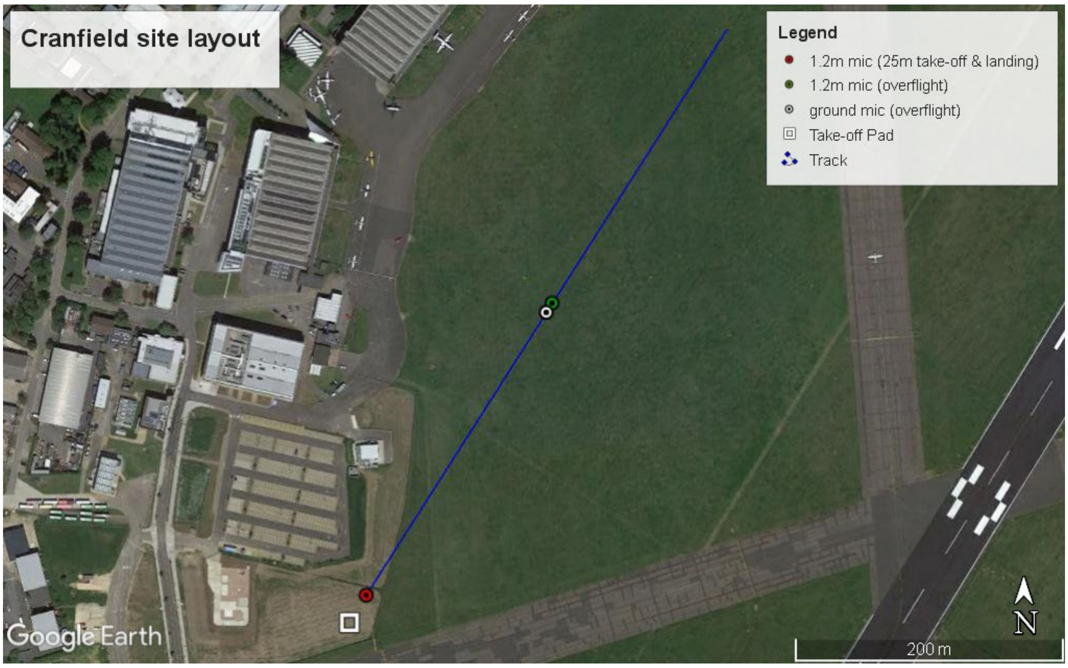
[31] The mass shown for each vehicle is the nominal mass stated by the manufacturer. The actual flight mass of each vehicle is unknown.

[32] Two DJI M300 drones were made available for the Cranfield tests, each flown by a different operator.

[33] Background noise levels on the day were too high to accurately measure noise levels at 400 ft for the other smaller/quieter drones.

[34] Figure C5 shows an additional 1.2 m microphone installed at a lateral distance of 25 m to measure take-off and landing noise. However, data from this microphone was not analysed for this study.

Figure C5 Cranfield measurement site

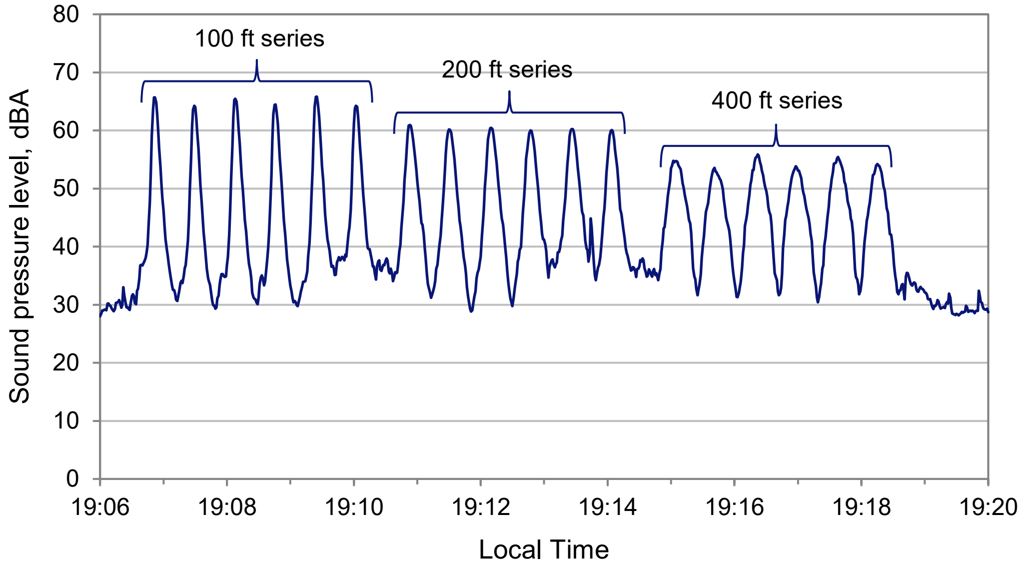


C21 As previously noted, GPS flight data for the drones flown in the Cranfield tests were not made available by the drone operators. This meant it was not possible to verify the extent of any differences between the target heights and the actual heights flown by each vehicle. Details of actual ground speeds are also not known.

C22 Following completion of the tests, inspection of the measured noise profiles for the Parrot ANAFI, DJI Mavic 2 Pro and DJI FPV revealed a relatively wide variation in the measured noise level between successive overflights for each drone (indicating that inconsistent heights and/or speeds had been flown during each pass). Measurements for these aircraft were therefore considered to be unreliable. Further noise analysis for the DJI Matrice 210 was also not possible due to a paucity of measurements.

C23 However the measured noise profiles for both DJI M300 drones, the DJI Inspire 1 V2 and the DJI Mavic Air were relatively consistent across each series of overflights, providing confidence that the drones had been flown consistently at the target altitudes. By way of example Figure C6 shows the overflight noise time history plot for one of the DJI M300s, clearly illustrating three distinct groups of noise event profiles (for each series of flyover heights). The overflight data for these drones were considered reliable enough for further analysis.

Figure C6 DJI M300 overflight noise level time history (IGP mic)



C24 Overflight measurements for the first DJI M300 drone are summarised in Tables C11 and C12 for the IGP microphone and 1.2 m microphone, respectively. Tables C13 and C14 present the equivalent measurement results for the second DJI M300 drone. Tables C15 and C16 present the overflights results for the DJI Inspire 1 V2. Tables C17 and C18 present the overflights results for the DJI Mavic Air. In each table, the mean noise levels for the 200 ft series of overflights are also shown for comparison.

Table C11 DJI M300 overflights (drone 1), Inverted Ground Plane microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	19:06:48	19:06:57	65.7	71.4
2	100	19:07:25	19:07:34	64.2	70.0
3	100	19:08:04	19:08:13	65.5	71.2
4	100	19:08:42	19:08:51	64.5	70.2
5	100	19:09:21	19:09:30	65.8	71.4
6	100	19:09:58	19:10:07	64.3	70.2
7	200	19:10:47	19:11:01	61.0	68.6
8	200	19:11:25	19:11:38	60.2	67.9
9	200	19:12:04	19:12:18	60.4	68.5
10	200	19:12:41	19:12:55	60.0	67.9
11	200	19:13:20	19:13:34	60.2	68.4
12	200	19:13:58	19:14:11	60.1	67.7
13	400	19:14:54	19:15:17	54.8	65.3
14	400	19:15:31	19:15:54	53.5	63.7
15	400	19:16:12	19:16:34	55.9	65.6
16	400	19:16:47	19:17:12	53.8	64.1
17	400	19:17:28	19:17:50	55.4	65.5
18	400	19:18:04	19:18:26	54.2	64.2
Mean (200 ft overflight)		-	-	60.3	68.2
Std. Dev		-	-	0.3	0.4
90% CI		-	-	0.3	0.3

Table C12 DJI M300 overflights (drone 1), 1.2 m microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	19:06:49	19:06:59	59.8	65.7
2	100	19:07:26	19:07:36	58.5	64.5
3	100	19:08:05	19:08:15	59.5	65.6
4	100	19:08:43	19:08:52	58.8	64.7
5	100	19:09:22	19:09:32	59.9	65.8
6	100	19:09:59	19:10:09	58.6	64.8
7	200	19:10:49	19:11:03	55.3	62.9
8	200	19:11:25	19:11:40	54.2	62.3
9	200	19:12:05	19:12:20	54.8	62.8
10	200	19:12:42	19:12:57	54.2	62.5
11	200	19:13:21	19:13:36	54.6	62.7
12	200	19:13:58	19:14:13	54.0	62.1
13	400	19:14:55	19:15:20	49.3	59.6
14	400	19:15:32	19:15:59	48.5	58.7
15	400	19:16:13	19:16:36	50.6	59.9
16	400	19:16:48	19:17:14	48.3	58.7
17	400	19:17:29	19:17:53	49.7	60.0
18	400	19:18:05	19:18:29	48.4	58.7
Mean (200 ft overflight)		-	-	54.5	62.6
Std. Dev		-	-	0.5	0.3
90% CI		-	-	0.4	0.3

Table C13 DJI M300 overflights (drone 2), Inverted Ground Plane microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	19:31:02	19:31:11	67.1	72.8
2	100	19:31:40	19:31:49	64.9	70.8
3	100	19:32:19	19:32:28	66.7	72.4
4	100	19:32:56	19:33:05	65.0	70.8
5	100	19:33:35	19:33:44	66.9	72.5
6	100	19:34:12	19:34:22	65.1	70.9
7	200	19:35:02	19:35:15	62.0	69.7
8	200	19:35:38	19:35:52	60.2	68.2
9	200	19:36:18	19:36:31	62.0	69.7
10	200	19:36:55	19:37:08	60.5	68.3
11	200	19:37:34	19:37:48	61.9	69.7
12	200	19:38:12	19:38:25	60.4	68.2
13	400	19:39:06	19:39:31	56.3	66.7
14	400	19:39:45	19:40:08	53.9	64.4
15	400	19:40:25	19:40:47	56.3	66.4
16	400	19:41:01	19:41:24	54.1	64.5
17	400	19:41:41	19:42:03	55.8	66.1
18	400	19:42:18	19:42:41	54.5	64.7
Mean (200 ft overflight)		-	-	61.2	69.0
Std. Dev		-	-	0.9	0.8
90% CI		-	-	0.7	0.7

Table C14 DJI M300 overflights (drone 2), 1.2 m microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	19:31:04	19:31:13	61.1	66.9
2	100	19:31:41	19:31:50	59.1	65.2
3	100	19:32:20	19:32:29	60.6	66.6
4	100	19:32:57	19:33:07	59.2	65.2
5	100	19:33:36	19:33:46	60.9	66.7
6	100	19:34:13	19:34:23	59.4	65.4
7	200	19:35:03	19:35:17	56.2	63.9
8	200	19:35:39	19:35:54	54.3	62.5
9	200	19:36:19	19:36:33	56.1	63.9
10	200	19:36:56	19:37:10	54.7	62.6
11	200	19:37:36	19:37:49	56.1	63.8
12	200	19:38:12	19:38:27	54.6	62.6
13	400	19:39:10	19:39:33	50.9	60.8
14	400	19:39:45	19:40:11	48.5	59.0
15	400	19:40:26	19:40:49	50.8	60.6
16	400	19:41:02	19:41:27	48.6	59.1
17	400	19:41:42	19:42:05	50.4	60.4
18	400	19:42:18	19:42:44	48.6	59.3
Mean (200 ft overflight)		-	-	55.3	63.2
Std. Dev		-	-	0.9	0.7
90% CI		-	-	0.7	0.6

Table C15 DJI Inspire 1 V2 overflights, Inverted Ground Plane microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	19:54:29	19:54:38	57.3	61.9
2	100	19:55:10	19:55:20	57.1	62.9
3	100	19:55:54	19:56:04	55.3	61.2
4	100	19:56:38	19:56:48	54.7	60.5
5	100	19:57:22	19:57:31	55.3	61.5
6	100	19:58:04	19:58:15	53.8	60.2
7	200	19:58:57	19:59:10	52.3	59.5
8	200	19:59:37	19:59:54	50.4	59.2
9	200	20:00:21	20:00:36	51.0	58.4
10	200	20:01:04	20:01:19	51.7	59.6
11	200	20:01:47	20:02:03	51.4	59.2
12	200	20:02:28	20:02:45	49.9	58.8
Mean (200 ft overflight)		-	-	51.1	59.1
Std. Dev		-	-	0.9	0.4
90% CI		-	-	0.7	0.4

Table C16 DJI Inspire 1 V2 overflights, 1.2 m microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	19:54:29	19:54:41	51.4	57.3
2	100	19:55:11	19:55:21	53.5	59.8
3	100	19:55:56	19:56:06	51.6	57.7
4	100	19:56:39	19:56:50	48.9	56.0
5	100	19:57:23	19:57:33	51.6	58.0
6	100	19:58:05	19:58:17	49.3	56.1
7	200	19:58:57	19:59:12	48.6	55.8
8	200	19:59:36	19:59:58	45.2	54.9
9	200	20:00:21	20:00:39	46.5	54.9
10	200	20:01:01	20:01:22	46.6	55.5
11	200	20:01:47	20:02:05	47.1	55.6
12	200	20:02:28	20:02:46	45.7	54.5
Mean (200 ft overflight)		-	-	46.6	55.2
Std. Dev		-	-	1.2	0.5
90% CI		-	-	1.0	0.4

Table C17 DJI Mavic Air overflights, Inverted Ground Plane microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	20:16:08	20:16:23	51.5	59.4
2	100	20:17:06	20:17:18	51.6	58.9
3	100	20:18:06	20:18:20	53.5	61.3
4	100	20:19:04	20:19:14	52.8	59.3
5	100	20:20:00	20:20:14	53.5	61.4
6	100	20:20:58	20:21:08	52.7	59.3
7	200	20:22:01	20:22:24	48.2	58.4
8	200	20:23:00	20:23:16	47.9	56.7
9	200	20:23:55	20:24:17	47.9	58.1
10	200	20:24:53	20:25:09	48.3	56.9
Mean (200 ft overflight)		-	-	48.1	57.5
Std. Dev		-	-	0.2	0.8
90% CI		-	-	0.2	0.7

Table C18 DJI Mavic Air overflights, 1.2 m microphone

Run Number	Nominal height, ft	Event Start	Event End	L_{ASmax}, dB	SEL, dB
1	100	20:16:09	20:16:24	47.7	55.7
2	100	20:17:05	20:17:19	47.4	54.7
3	100	20:18:06	20:18:23	47.5	56.2
4	100	20:19:04	20:19:16	47.4	54.2
5	100	20:20:00	20:20:17	47.5	56.1
6	100	20:20:58	20:21:10	47.5	54.4
7	200	20:21:57	20:22:27	42.4	53.7
8	200	20:22:57	20:23:25	42.7	52.7
9	200	20:23:52	20:24:20	42.1	53.5
10	200	20:24:51	20:25:12	42.7	52.0
Mean (200 ft overflight)		-	-	42.5	53.0
Std. Dev		-	-	0.3	0.8
90% CI		-	-	0.3	0.6

General observations

C25 The Newbury test site was a remote location and used a diesel generator for power, including UAS battery charging. Due to noise interference the generator had to be switched off during test-runs, impeding battery charging and causing slight delay to some flight tests.

C26 During post-processing of the Newbury test data it was observed that the hybrid fixed-wing aircraft had been programmed to fly at 200 ft above ground level by following the local terrain height. Because the land surrounding the test site was gently undulating, this meant the fixed-wing aircraft was not in perfect level flight whist overflying the monitoring equipment. Although any effect on the measured noise levels is expected to be minimal, a requirement to fly at a fixed and level height above any noise monitoring equipment would need to be made clearer to drone operators in any future tests.

C27 Noise level variability between passes was very low with 90% confidence intervals no greater than 0.5 dB L_{ASmax} in several cases.

C28 The difference between the ground-plane and 1.2 m measurements in some cases is less than 6 dB, indicating the presence of ground reflections at the 1.2 m microphone.

C29 The average wind speed during the Cranfield tests (1-2 m/s) was slightly lower than the average wind speed at Newbury (3-4 m/s). It is noted that the average overflight noise levels of the two DJI M300 drones measured at Cranfield fall towards the lower end of the range of average noise levels obtained under separate tailwind and headwind conditions at Newbury (Tables C3 to C6 and Tables C11 to C14).

C30 Comparison of the average take-off and landing measurements (L_{ASmax}) for the DJI M300 and the hybrid fixed-wing at Newbury indicates that take-off noise levels were approximately 4 dB quieter than on landing for both aircraft.

C31 Due to spherical spreading, and ignoring the influence of atmospheric absorption, the sound pressure level from a noise source will typically reduce by 6 dB for each doubling of distance.

C32 It was noted however that the average decay rates observed for the drones in both studies do not always appear to follow the expected -6 dB spherical spreading relationship, see for example Table C19 which summarises the data measured at Cranfield[35]. A similar phenomenon can also be observed in the data

[35] As previously noted, GPS flight data for the drones flown in the Cranfield tests were not made available by the drone operators. However the analysis in Table C19 assumes each drone was flown consistently at the target altitude.

reported by Senzig, D A et al (2018) for the DJI Phantom 3 (see Chapter 3). The reason(s) for these differences are not yet understood.

Table C19 Mean measured L_{ASmax} decay rates for Cranfield drones (IGP mic), dB

Change in aircraft height, ft	DJI M300 (1)	DJI M300 (2)	DJI Inspire 1 V2	DJI Mavic Air
100 to 200	-4.7	-4.8	-4.5	-4.5
200 to 400	-5.7	-6.0	N/A	N/A

References

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APPENDIX D

Variation of eVTOL noise level by mass at a reference height of 400 ft

Figure D1 Variation of eVTOL noise level by mass at a reference height of 400 ft