UK Civil Aviation Authority

Review of noise measurements from UAS and AAM aircraft

CAP 3076

Published by the Civil Aviation Authority 2025

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First published March 2025

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The latest version of this document is available in electronic format at: www.caa.co.uk/CAP3076

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Chapter 1

Introduction

1.1 Consideration and assessment of the potential environmental impacts resulting from an airspace change proposal is a necessary part of the CAA's decision-making process, and also enables those who are affected by a proposed airspace change to better understand the impacts of the different design options being considered.

1.2 In order to achieve this, the CAA requires change sponsors to provide an environmental assessment that evolves through the various stages of the airspace change process, which are detailed in CAP 1616i, Environmental Assessment Requirements and Guidance for Airspace Change Proposals. However, detailed noise data is not readily available for Unmanned Aircraft Systems (UAS or 'drones') or advanced air mobility (AAM or 'air taxis'). In addition, there are currently no formal calculation methods to model noise specifically from electrically-powered UAS or AAM operations.

1.3 To bridge the knowledge gap, an initial research review was undertaken on noise emissions of lightweight drones (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), the results of which were published in 2023 in CAP 2506, Noise measurements from eVTOL aircraft: A review of available data.

1.4 This report provides an update to CAP 2506 with the aim of further understanding noise from emerging technology aircraft. Chapters 2 to 11 provide a succinct review of additional research papers and reports on outdoor noise emissions of selected UAS and AAM aircraft, presented in alphabetical order by manufacturer, with a focus on the measurement and quantification of noise in terms of conventional A-weighted noise metrics. Included in this review are several environmental assessments conducted by the US Federal Aviation Administration (FAA) to assess the noise impacts from proposed drone operations at specific locations across a number of US states.[1]

[1] Under the US National Environmental Policy Act (NEPA), the FAA is required to consider the environmental impacts of its actions in any decision making related to flight operations in the National Airspace System (NAS). https://www.faa.gov/uas/advanced_operations/nepa_and_drones

1.5 Over the past few years, voluntary guidance on the measurement of noise from UAS aircraft has been developed separately by EASA and ISO.[2,3] EASA has also published Environmental Protection Technical Specifications (EPTS) applicable to VTOL-capable aircraft (VCA), which are intended to cover certain air taxi designs.[4] In the US, the FAA has made available noise certification standards that apply to individual model unmanned aircraft or drones.[5] It should be noted, however, that none of the data reviewed in this report is claimed to meet these guidelines or standards.

1.6 Chapter 12 provides a summary of overflight data covered in this review and in CAP 2506, with a focus on overall L_{ASmax} sound pressure levels for vehicles at a reference height of 400 ft (120 m).

1.7 A list of terms and abbreviations is provided in Appendix A. References are provided in Appendix B. Further details of a CAA UAS noise measurement study conducted in 2023 are provided in Appendices C and D.[6]

1.8 Finally, it is widely recognised that noise from multi-rotor UAS and AAM aircraft may be perceived as more annoying compared to conventional aeroplanes and helicopters. CAP 2505 and CAP 2962, published respectively in 2023 and 2024, provide an overview of the current state of knowledge concerning the impacts of noise from emerging technology aircraft, including the extent to which sound quality metrics such as loudness, sharpness, roughness, tonality and fluctuation strength influence the prediction of annoyance. While a comprehensive review of sound quality metrics was beyond the scope of these reports, interested readers may refer to the appendix of NT ACOU 111 for an introduction to the subject or consult Fastl and Zwicker (2007) for more detailed information.

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[2] Guidelines on Noise Measurement of Unmanned Aircraft Systems Lighter than 600 kg Operating in the Specific Category (Low and Medium Risk), EASA, 12 June 2023. https://www.easa.europa.eu/en/downloads/137139/en

[3] BS ISO 5305:2024 Noise measurements for UAS (unmanned aircraft systems) https://standardsdevelopment.bsigroup.com/projects/2020-02487

[4] https://www.easa.europa.eu/en/newsroom-and-events/press-releases/easa-consolidates-its-leading-role-setting-standards-and-limits

[5] Noise Certification of UAS/AAM using Rules of Particular Applicability, Federal Aviation Administration https://www.faa.gov/about/office_org/headquarters_offices/apl/aee/noise/uas_noise_certification

[6] Chapter 5 also provides a brief overview of the CAA study.

Chapter 2
DroneUp PRISM V2

2.1 In November 2024 the US FAA published its Final Environmental Assessment to assess a proposed commercial drone delivery service by DroneUp, LLC in Dallas–Fort Worth, Texas. The aircraft covered by the proposal is DroneUp's PRISM V2, a multirotor design with eight propellers mounted on four arms. The PRISM V2 weighs 24.9 kg (55 lbs), including its maximum payload of 4.5 kg (10 lbs). After arriving at a delivery site, the PRISM V2 drone hovers in place at about 80 ft above ground level and lowers the package by a retractable line.

2.2 As part of the environmental assessment, noise measurements of the PRISM V2 were collected in February 2024 by noise consultant HMMH in accordance with the FAA's proposed package delivery noise measurement protocol, which includes measurements at multiple distances along three axes under track, lateral to, and behind the point from which the drone takes off, lands, and delivers a payload (Hobbs et al., 2024). The FAA protocol also specifies that microphones should be positioned 5 ft above the ground with diaphragms orientated for grazing incidence.

2.3 Each measurement axis for the PRISM V2 assessment included six sound level meters positioned from 16 ft out to 800 ft from the hub and delivery points and from 0 ft out to 800 ft for en route overflights. Measurements of hover noise were also conducted as part of the noise assessment although results were not reported.

2.4 Table 1 presents the consolidated average measured Sound Exposure Levels (SELs) reported in the FAA's environmental assessment for the combined take-off and landing phases, for lateral distances up to 100 ft. The test flight profile included a vertical ascent to 200 ft, a lateral traverse away from the take-off point, and then a return for landing following the same flight path as take-off but in reverse. The averaged results consist of nine valid passes for under track, three valid passes for lateral and one valid pass for behind. The variation in numbers of valid flight passes was due to weather condition constraints during the measurements.

Table 1 Average measured take-off/landing SEL levels for the PRISM V2 (FAA 2024a)

Distance from take-off and landing (ft)	SEL (dBA)
16	93.9
50	87.5
100	83.8

2.5 Table 2 presents the consolidated average measured SELs reported for the delivery phase.[7] The delivery profile included a lateral traverse at a height of 200 ft to the test delivery location. The aircraft would then descend to between 80-120 ft and hover (for approximately one minute) while lowering the package to the ground using a winch before retracting the line, ascending vertically to 200 ft and traversing laterally away from the delivery point. The averaged results consist of 10 valid passes for under track, one valid pass for lateral and three valid passes for behind.

Table 2 Average measured delivery SEL levels for the PRISM V2 (FAA 2024a)

Distance from delivery (ft)	SEL (dBA)
16	91.0
50	88.9
100	86.4

2.6 Table 3 presents the average measured overflight SELs at a height of 200 ft for lateral distances up to 100 ft (each comprising of at least six individual measurements). Beyond a lateral measurement distance of 100 ft, the environmental assessment noted there was insufficient signal-to-noise ratio to reliably determine SEL.

[7] Beyond a lateral distance of 100 ft, the average measured SELs were reported to be less consistent along the three different track axes and have therefore not been included in Tables 1 and 2.

Table 3 Average measured overflight SEL levels for the PRISM V2 (FAA 2024a)

Aircraft configuration	Air speed (kts)	Height (ft)	0 ft SEL (dBA)	50 ft SEL (dBA)	100 ft SEL (dBA)
Maximum weight (24.9 kg)	23.3	200	76.1	76.0	75.1
Empty weight (20.4 kg)	23.3	200	74.3	74.8	74.1

Chapter 3
Flytrex FTX-M600P

3.1 In November 2022 the US FAA published its Final Environmental Assessment for Causey Aviation Unmanned, Inc. to conduct unmanned aircraft commercial package delivery operations across four separate locations in North Carolina. The aircraft included in the proposal is the Flytrex FTX-M600P, which is a six-motor multicopter drone. The FTX-M600P has a maximum take-off weight of 15.1 kg (33.4 lbs), including a maximum payload of 3 kg (6.6 lbs).

3.2 After taking off from a distribution centre, the FTX-M600P will typically cruise at a height of 230 ft and airspeed of 29 kts to the delivery point. During the delivery phase, the aircraft descends vertically to a height of 82 ft and then hovers while the package is lowered to the ground by a retractable tether.

3.3 In support of the environmental assessment, noise measurements were recorded for hover and en route overflight conditions and the results reported in an FAA Memorandum attached to the main document. All measured noise data were corrected by subtraction of 6 dB to account for assumed pressure-doubling by the microphone ground boards.[8,9] However, noise levels for take-off, delivery and landing phases were modelled rather than measured for the assessment. The modelled results, which were based on the FTX-M600P hover measurements, are not reviewed in this report.

3.4 For the hover condition, measurements were made while the aircraft was hovering 50 ft above a ring of eight microphones mounted on ground boards, with each recording lasting for 30 seconds. The average sound pressure level was then calculated at each microphone over four separate recordings and normalised to a distance of 70.7 ft assuming spherical spreading.[10] The final reported hover results are shown in Table 4.

[8] The sound pressure close to a large, acoustically reflective surface is twice the corresponding free-field sound pressure and the measured sound pressure level is 6 dB greater than the free-field sound pressure level.

[9] Information on the orientation and placement of the microphones on the ground boards is not specified in the FAA report.

[10] Based on the hover height of 50 ft and the reference (normalised) distance of 70.7 ft, it is inferred the hover measurements were obtained at a lateral angle of 45 degrees relative to the ground, although this is not specified in the FAA report. However, the report does state an assumption that the FTX M600P drone is an omnidirectional sound source, meaning that the same sound levels would have been measured at any point on the surface of a sphere centred on the drone.

Table 4 Average sound pressure level for the FTX-M600P while hovering (FAA 2022a)

Aircraft configuration	Distance (ft)	Sound Pressure Level (dBA)
Maximum weight (15.1 kg)	70.7	64.9
Empty weight (12.1 kg)	70.7	63.1

3.5 For the overflight phase, the FTX-M600P drone was measured flying at a cruise speed of 29 kts and an average height of 216 ft directly above a microphone mounted on a ground board. Measurements were made at maximum weight and empty weight under both upwind and downwind conditions.[11] The average measured Sound Exposure Level (SEL) at each weight is shown in Table 5.

Table 5 Average measured SEL overflight levels for the FTX-M600P (FAA 2022a)

Aircraft configuration	Ground speed (kts)	Height (ft)	SEL (dBA)
Maximum weight (15.1 kg)	29	216	66.4
Empty weight (12.1 kg)	29	216	62.8

[11] Overflight sample sizes are not reported in the Flytrex noise assessment.

Chapter 4
Joby Aviation JAS4-2

4.1 In summer 2021 NASA partnered with Joby Aviation to undertake noise measurements of the Joby JAS4-2 preproduction prototype air taxi at Joby's electric flight base in California. The Joby JAS4-2 is an all-electric design with six tilting propellers, capable of vertical take-off and landing with a maximum take-off weight of 4,200 lbs (1,905 kg).

4.2 Detailed analysis of the measurement data was reported by NASA, which included the presentation of noise contours and an analysis of frequency and directivity under different operating conditions (Pascioni et al., 2022).

4.3 In a separate paper published in 2022, which is the focus of this review, Joby Aviation published a comparison of overflight noise levels between the remotely-piloted Joby aircraft and similar conventional aircraft (Bain et al., 2022).[12] The report authors commented that the types of aircraft available for the tests "were restricted by the desire to have all aircraft available on the same day and location to get a direct one-to-one comparison with as little environmental variability as possible."

4.4 Each aircraft in the Joby study was flown once over the noise instrumentation in level flight at a height of 1,500 ft and airspeed of approximately 100 kts (51 m/s) with the exception of the Joby aircraft, which was also tested at 95 kts (49 m/s) to assess the speed sensitivity. The report states that the Joby aircraft was flown near its maximum gross weight, although the actual test weight is not specified.[13]

4.5 The measurement system for the Joby flyover tests comprised of pre-polarised pressure condenser microphones placed at ground level which were subject to pressure doubling.[14] The authors state that results were subsequently corrected for free field conditions; it is assumed by subtraction of 6 dB from the measured levels, although this is not made explicit in the report.

[12] The conventional aircraft included two propeller-driven fixed-wing aeroplanes (Cirrus SR22 and Beechcraft Baron 55) and three helicopters (Leonardo AW109, Bell 206 and Robinson R44).

[13] The report's authors noted that none of the aircraft was flown at its maximum gross weight or a high speed that would be representative of a certification test.

[14] Information on the orientation and placement of the ground microphones is not specified in the report.

4.6 The maximum measured overflight noise levels (L_{ASmax}) reported for the Joby aircraft are shown in Table 6.[15]

Table 6 Measured overflight L_{ASmax} levels for the Joby JAS4-2 (Bain et al., 2022)

Airspeed (kts)	Height (ft)	L_{ASmax} (dB)
95	1,500	45
100	1,500	46

15 Although not shown in Table 6, the measured overflight L_{ASmax} levels for the conventional aircraft were more than 10 dB higher than the measured levels for the Joby aircraft.

Chapter 5

Malloy Aeronautics T150

5.1 In June 2023 the UK CAA in collaboration with the University of Salford, Eagle Eye Innovations and Sierra Nevada Corporation Mission Systems UK conducted a field study in South Scarle, Nottinghamshire to measure the noise from a Malloy Aeronautics T150 cargo multicopter. This chapter provides a brief overview of the study, with further details provided in Appendix C.

5.2 The T150 is a 61 kg quadcopter with coaxial contra-rotating propellers capable of carrying up to 68 kg payload. The T150 is significantly heavier than the drones measured previously by the CAA.

5.3 The CAA's noise instrumentation for the T150 study consisted of a single ground plane microphone positioned directly underneath the test flight path, with the microphone lying flat on a 40 cm diameter circular ground plate. A second microphone was mounted on a tripod approximately four metres from the ground plane microphone, in line with the flight path, with the microphone diaphragm positioned 1.2 m above ground level.

5.4 Measurements of overflight noise with no payload installed were conducted at nominal heights above ground level of 25 m and 50 m and ground speeds of 5 m/s and 15 m/s, the latter intending to represent typical 'slow' and 'fast' operations, respectively. Additional 25 m overflight measurements were conducted at 15 m/s with an installed payload of 40 kg, giving a total vehicle mass of 101 kg.

5.5 Table 7 summarises the average measured L_{ASmax} noise levels recorded using the CAA ground plane microphone. Table 8 provides the corresponding average measured L_{ASmax} noise levels from the 1.2 m microphone.

Table 7 Average measured overflight L_{ASmax} levels for the T150; ground mic

Aircraft mass (kg)	Ground speed (m/s)	Height (m)	L_{ASmax} (dB)
61	5	25	79.4
61	15	25	78.2
61	5	50	73.5
61	15	50	73.8
101	15	25	87.0

Table 8 Average measured overflight L_{ASmax} levels for the T150; 1.2 m mic

Aircraft mass (kg)	Ground speed (m/s)	Height (m)	L_{ASmax} (dB)
61	5	25	76.4
61	15	25	75.0
61	5	50	70.3
61	15	50	70.7
101	15	25	83.7

Chapter 6
Matternet M2

6.1 In March 2023 the US FAA published its Final Environmental Assessment for UPS Flight Forward, Inc. to conduct drone package delivery operations in Columbus, Ohio. The aircraft included in the proposal is the Matternet M2, which is a four-motor multicopter drone. The M2 has a maximum take-off weight of 13.2 kg (29.1 lbs), including a maximum payload of 2 kg (4.4 lbs).

6.2 In support of the environmental assessment, noise measurements were recorded for hover and en route overflight conditions and the results reported in an FAA Memorandum attached to the main document. However, noise levels for take-off, delivery and landing phases were modelled (based on the M2 hover measurements) and have not been reviewed for this report.

6.3 For the hover condition, measurements were first made while the aircraft was hovering 16.5 ft above ground level using two microphones positioned 4 ft above ground and 20 ft laterally at 0 degrees and 90 degrees relative to the aircraft. The aircraft was then rotated by 180 degrees to measure noise levels at the 180 and 270 degree positions in order to cover the four cardinal directions. All recordings lasted approximately 30 seconds.

6.4 The average sound pressure level at each microphone was then normalised to a distance of 70.7 ft assuming spherical spreading and the four results averaged to generate the overall hover result shown in Table 9.

Table 9 Average sound pressure level for the M2 while hovering (FAA 2023a)

Aircraft configuration	Distance (ft)	Sound Pressure Level (dBA)
Maximum weight (13.2 kg)	70.7	65.3

6.5 For the overflight phase, the M2 drone was measured in level flight at its maximum weight and empty weight above a single microphone. The measured Sound Exposure Level (SEL) for each overflight was then normalised to a reference airspeed of 35.1 kts and reference height of 250 ft.[16] Results are shown in Table 10.

Table 10 Measured SEL overflight levels for the M2 (FAA 2023a)

Aircraft configuration	Reference air speed (kts)	Reference height (ft)	SEL (dBA)
Maximum weight (13.2 kg)	35.1	250	67.8
Empty weight (11.2 kg)	35.1	250	65.3

[16] Adjustments for off-reference heights and speeds were made using 12.5 $\log_{10}$ and 10 $\log_{10}$ relationships, respectively. Overflight sample sizes are not reported in the M2 noise assessment.

Chapter 7
Prime Air MK27-2/MK30

7.1 In September 2024 the US FAA published its Final Supplemental Environmental Assessment for Amazon Prime Air (Prime Air) to conduct commercial drone package delivery operations from the Prime Air Drone Delivery Center located in College Station, Texas.

7.2 While Prime Air's existing drone package delivery operations were being performed using its MK27-2 drone, the supplemental assessment was issued to evaluate any potential incremental environmental impacts resulting from the addition of the next generation MK30 drone variant into Prime Air's fleet.

7.3 The MK27-2 and MK30 are both multi-rotor designs consisting of six propellers, with the ability to take off and land vertically and transition to wing borne flight for the en route (overflight) phase. The maximum take-off weights for the MK27-2 and MK30 drones are 91.5 lbs (41.5 kg) and 83.2 lbs (37.8 kg), respectively, both of which include a maximum package weight of about 5 pounds (2.2 kg).

7.4 The delivery procedure for the Prime Air aircraft includes a vertical descent from the overflight height (typically between 160-180 ft above ground level) to a height of 13 ft. At this point the aircraft then hovers for approximately two seconds while the package is dropped before climbing vertically back to the cruise height and returning to the take-off/landing point.

7.5 Included in the FAA's environmental assessment were details of two noise measurement studies of the Prime Air aircraft. The first study was conducted in April 2022 to measure take-off, landing, delivery and overflight noise levels for the MK27-2 in support of initial Prime Air operations. The second noise study, which is the focus of this review, was undertaken by Prime Air in February 2024 to compare the noise exposure between the MK27-2 and MK30. The purpose of these tests was to demonstrate that the newer MK30 variant was quieter than the MK27-2. This could then enable the use of the previously approved MK27-2 noise data for future NEPA assessments of MK30 drone operations.[17]

7.6 Six pairs of back-to-back flights were flown for the comparative tests, with each pair including one MK27-2 flight and one MK30 flight. Three pairs were flown to collect noise data for take-off and landing and three were flown to collect overflight data.

[17] National Environmental Policy Act (NEPA). https://www.epa.gov/nepa/what-national-environmental-policy-act

7.7 For take-off and landing, measurements were collected 10 m laterally from the take-off/landing pad and at three additional locations positioned at 26.7 m, 43.3 m and 60 m. For overflight noise, measurements were collected at four distances beginning directly under track and extending laterally outward at 20 m, 40 m and 60 m from the main flight path. All microphones were positioned 5 ft above the ground.

7.8 It was noted in the Prime Air report that some of the results were not usable due to noise interference and were excluded from the analysis. This generally applied to measurements at the two outer most measurement locations. For the overflight measurements however, only two pairs of flights yielded valid noise data directly under the flight path.

7.9 In addition, overflight heights are not directly reported in the Prime Air comparative noise report. Instead the aircraft heights are provided in chart form, which indicate that the height of each vehicle over the microphones was not consistent for each pair of overflights. The aircraft heights also appeared to vary between about 34 to 40 m above ground level across all overflights at the time of L_{ASmax}.

7.10 Tables 11 and 12 summarise the average measured take-off L_{ASmax} and SEL levels for each aircraft at the two innermost measurement locations (10 m and 26.7 m laterally) where valid data were available for all three pairs of flights. Tables 13 and 14 present corresponding noise results for landing. In all cases, average noise levels for the MK30 are at least 5 dB lower than for the MK27-2.

Table 11 Average measured take-off L_{ASmax} levels for the MK27-2 and MK30 (FAA 2024b)

Aircraft	10 m L_{ASmax} (dB)	26.7 m L_{ASmax} (dB)
MK27-2	85.4	75.3
MK30	79.1	69.7

Table 12 Average measured take-off SEL levels for the MK27-2 and MK30 (FAA 2024b)

Aircraft	10 m SEL (dBA)	26.7 m SEL (dBA)
MK27-2	92.8	84.6
MK30	85.3	78.3

Table 13 Average measured landing L_{ASmax} levels for the MK27-2 and MK30 (FAA 2024b)

Aircraft	10 m L_{ASmax} (dB)	26.7 m L_{ASmax} (dB)
MK27-2	81.4	73.5
MK30	76.0	67.4

Table 14 Average measured landing SEL levels for the MK27-2 and MK30 (FAA 2024b)

Aircraft	10 m SEL (dBA)	26.7 m SEL (dBA)
MK27-2	92.9	86.0
MK30	87.2	80.5

7.11 As noted previously, only two pairs of flights yielded valid overflight noise data directly under the flight path at the 0 m lateral position. There is also some uncertainty regarding aircraft test heights, which varied between overflights based on estimates obtained from line graphs shown in the Prime Air noise report. For the purposes of this current review, and based on noise levels reported for the MK27-2 and MK30 at the estimated test heights, corresponding estimates of the average overflight L_{ASmax} noise level at a reference height of 400 ft are provided in Table 15 (based on spherical spreading).

Table 15 Average measured overflight L_{ASmax} levels for the MK27-2 and MK30 at a reference height of 400 ft (FAA 2024b)

Aircraft	L_{ASmax}, dB
MK27-2	49.4
MK30	48.5

Chapter 8
Tarot X8

8.1 Konzel and Greenwood published a study undertaken by Pennsylvania State University in 2022 to assess the repeatability of flyover noise measurements of a Tarot X8 multicopter. The Tarot X8 has eight rotors and a maximum take-off weight of 7.9 kg (17.4 lbs) that includes a payload of about 2.0 kg (4.5 lbs). The aircraft was selected for the study on the basis that it was representative of platforms used for package delivery.

8.2 The measurement system consisted of a lateral array of 12 inverted ground plane microphones set up in accordance with recommended guidance described in SAE (2007). Two additional tripod-mounted microphones were also used to collect data, with the microphone diaphragms positioned at the standard height of 1.2 m (4 ft) above ground and collocated with two of the ground plane microphones (one located directly under the test flight path and the other at a lateral location). Noise levels from the ground plane microphones were adjusted by the report authors to free-field conditions by subtracting 6 dB.

8.3 SELs were calculated across the microphone array for repeated overflights at heights of 50 ft, 100 ft and 200 ft and vehicle speeds of 10 mph and 20 mph in both upwind and downwind conditions. The authors noted that the variability in the vehicle’s flight state during a run may have a smaller effect on the variation of noise level than changes in noise caused by changes in atmospheric conditions.

8.4 Table 16 summarises the average measured overflight SELs reported for the two centreline ground plane microphones deployed in the study (identified as M3 and M8 in the paper), covering vehicle speeds of 10 mph and 20 mph at a height of 50 ft.[18] The report, however, does not state whether these results relate to the aircraft’s minimum or maximum weight.

Table 16 Measured SEL overflight levels for the Tarot X8 (Konzel and Greenwood 2022)

Speed (mph)	Height (ft)	M3 SEL (dBA)	M8 SEL (dBA)
10	50	67.5	67.2
20	50	65.2	65.0

[18] Equivalent results for the 100 ft and 200 ft test cases are not reported in the paper.

Chapter 9
Volocopter VC-2X

9.1 In 2024 Clero et al. published results of a noise measurement campaign undertaken in March 2022 at Pontoise Aerodrome, close to Paris, by the acoustical laboratories of Bruitparif, ONERA, RATP and the STAC (Technical Service of Civil Aviation of the French DGAC). The aim of the study was to characterise the sound from the Volocopter VC-2X air taxi demonstrator aircraft in various flight conditions covering hover, overflight, take-off and approach.

9.2 The VC-2X is an all-electric design with 18 non-tilting rotors, capable of vertical take-off and landing with a maximum take-off weight of 450 kg. The VC-2X is being used as a technology demonstrator for the larger VoloCity aircraft (intended to be Volocopter's first production aircraft), since it features the same design but at a smaller scale.

9.3 The measurement system consisted of a lateral array of nine inverted ground plane microphones set up in accordance with Appendix 6 of ICAO Annex 16, Volume 1.[19] The microphones were positioned from 0 m out to 300 m, perpendicular to the main flight path. Their locations were defined to measure noise directivity approximately every 10° from 0 to 80° with respect to vertical at a test height of 50 m. Noise levels from the ground plane microphones were adjusted by the report authors to free-field conditions by subtracting 6 dB.

9.4 Tests were conducted with the aircraft flying in both directions along the flight path in order to measure the noise radiated from both sides. The report authors commented that flight direction did not have any impact on the sound pressure levels, confirming the symmetry of the noise radiated by the aircraft.[20] The authors also noted that each phase of flight was measured several times, except take-off and approach which were only measured twice and were therefore not covered in the paper.

9.5 An additional vertical microphone array was also deployed for the tests, with five microphones distributed between 2 m and 10 m above ground level. Measurements from the vertical array are not discussed in the paper but are intended to provide data which could be used for studying annoyance.

[19] The same inverted ground plane microphone setup is described in SAE ARP4055.

[20] It was noted however that maximum noise directivity during overflight occurred at about 20° from the vertical.

9.6 The paper focuses on results from two flight phases: hover at a height of 7 m and overflight at a height of 50 m at 27 kts. A conclusion of the study was that sound pressure levels at those aircraft heights quickly decrease with lateral distance on the ground, falling below 65 dBA at 50 m distance while in hover and below 65 dBA at 80 m distance during overflight.

9.7 Tabular results of overall A-weighted sound pressure levels are not provided in the report. Instead, A-weighted measurements are provided in chart form. For the purposes of this review, and based on sound pressure levels for a single flight plotted graphically over time in the report, an overflight L_{ASmax} level of 76 dB is estimated for the VC-2X when flying at a height of 50 m (Table 17).

Table 17 Measured overflight L_{ASmax} level for the Volocopter VC-2X (Clero et al., 2024)

Airspeed (kts)	**Height (m)**	**L_{ASmax} (dB)**
27	50	76

Chapter 10
Wing Hummingbird

10.1 In November 2023 the US FAA published its Final Environmental Assessment for Wing Aviation, LLC (Wing) to conduct drone package delivery operations in the Dallas–Fort Worth, Texas. The main aircraft covered by the proposal is the Wing Hummingbird 7000W-B, a hybrid fixed-wing design with multiple propellers used for vertical flight and separate propellers used for forward flight. However, noise measurement data from the previous 7000W-A model was used as a “conservative” noise surrogate for the FAA assessment.

10.2 The 7000W-A weighs 6.8 kg (15 lbs), including a maximum package weight of 1.5 kg (3.3 lbs). Typical operations consist of a vertical departure to a cruising height of between 150 to 250 ft at which point the aircraft transitions to horizontal flight. Once at the delivery location, the aircraft transitions to hover mode and descends to approximately 23 ft to deliver the package by a retractable line.

10.3 In support of the environmental assessment, overflight and hover noise measurements for the 7000W-A aircraft were provided in a separate report by noise consultants HMMH[21] that was attached to the main FAA document. However, details of the noise instrumentation and microphone mounting arrangement used in the noise tests are not described in the report.

10.4 Overflight noise measurements of the 7000W-A were taken at heights of 100 ft and 200 ft both with and without a payload.[22] Results are summarised for L_{ASmax} and SEL in Tables 18 and 19, respectively. Details of sample sizes are not provided in the FAA document although the report states that multiple passes were conducted.

[21] https://hmmh.com/

[22] It is assumed that maximum (L_{ASmax}) noise levels were measured using Slow time weighting although this is not mentioned in the HMMH report.

Table 18 Average measured overflight L_{ASmax} levels for the 7000W-A (FAA 2023b)

Aircraft configuration	Air speed (kts)	Height (ft)	L_{ASmax} (dB)
Empty weight (5.3 kg)	70	100	63
Maximum weight (6.8 kg)	56	100	64
Empty weight (5.3 kg)	70	200	59
Maximum weight (6.8 kg)	56	200	60

Table 19 Average measured overflight SEL levels for the 7000W-A (FAA 2023b)

Aircraft configuration	Air speed (kts)	Height (ft)	SEL (dBA)
Empty weight (5.3 kg)	70	100	66
Maximum weight (6.8 kg)	56	100	67
Empty weight (5.3 kg)	70	200	63
Maximum weight (6.8 kg)	56	200	64

10.5 For the hover condition, multiple noise measurements were made at a lateral distance of 20 ft with the aircraft hovering at a height of 20 ft above ground level and the results averaged to give the overall result shown in Table 20.

Table 20 Average measured L_{ASmax} levels for the 7000W-A while hovering (FAA 2023b)

Aircraft configuration	Height (ft)	L_{ASmax} (dB)
Maximum weight (6.8 kg)	20	73

Chapter 11
Zipline Sparrow

11.1 In February 2022 the US FAA published its Final Environmental Assessment for Zipline International Inc. to conduct drone package delivery operations in Kannapolis, North Carolina and the surrounding area. The aircraft included in the proposal is the Zipline Sparrow, which is a fixed-wing design powered by two electric motors and has a maximum take-off weight of 21 kg (46 lbs), including a payload of 1.8 kg (3.9 lbs).

11.2 The aircraft is launched by a catapult system and then climbs to a cruise height of between 130 to 400 ft. Once at the delivery location, packages are released through payload doors from a height of about 60 ft using a small parachute. The aircraft then returns to the launch area for retrieval via a capture line.

11.3 In support of the environmental assessment, noise measurements were recorded by Zipline for each phase of the aircraft's flight (launch, delivery, and recovery). The results from the Zipline tests are summarised in a separate noise assessment report by noise consultants HMMH[23] that was attached to the main FAA document. The HMMH report notes that the documentation provided by Zipline did not fully describe the noise measurement setup. In some cases, the distances between the microphone and the aircraft had to be estimated by HMMH based on the geometry described in Zipline's measurement narrative. The HMMH report also notes that while the Zipline dataset provided multiple samples in some cases, the more conservative noise sample was used for analysis by HMMH.

11.4 Table 21 shows the measured SEL and L_{Amax} levels reported for the delivery phase of Zipline's operation.[24] The noise levels reported for the launch and recovery phases of the Zipline operation are considered less relevant for this review and are not shown.

Table 21 Measured delivery noise levels for the Zipline Sparrow (FAA 2022b)

Delivery speed (kts)	Height (ft)	SEL (dBA)	L_{ASmax} (dB)
45	60	68.1	66.5

[23] https://hmmh.com/

[24] It is assumed that maximum (L_{ASmax}) noise levels were measured using Slow time weighting, although this is not mentioned in the HMMH report. The delivery speed of 45 kts is estimated based on the middle of the ranges reported by Zipline.

Chapter 12

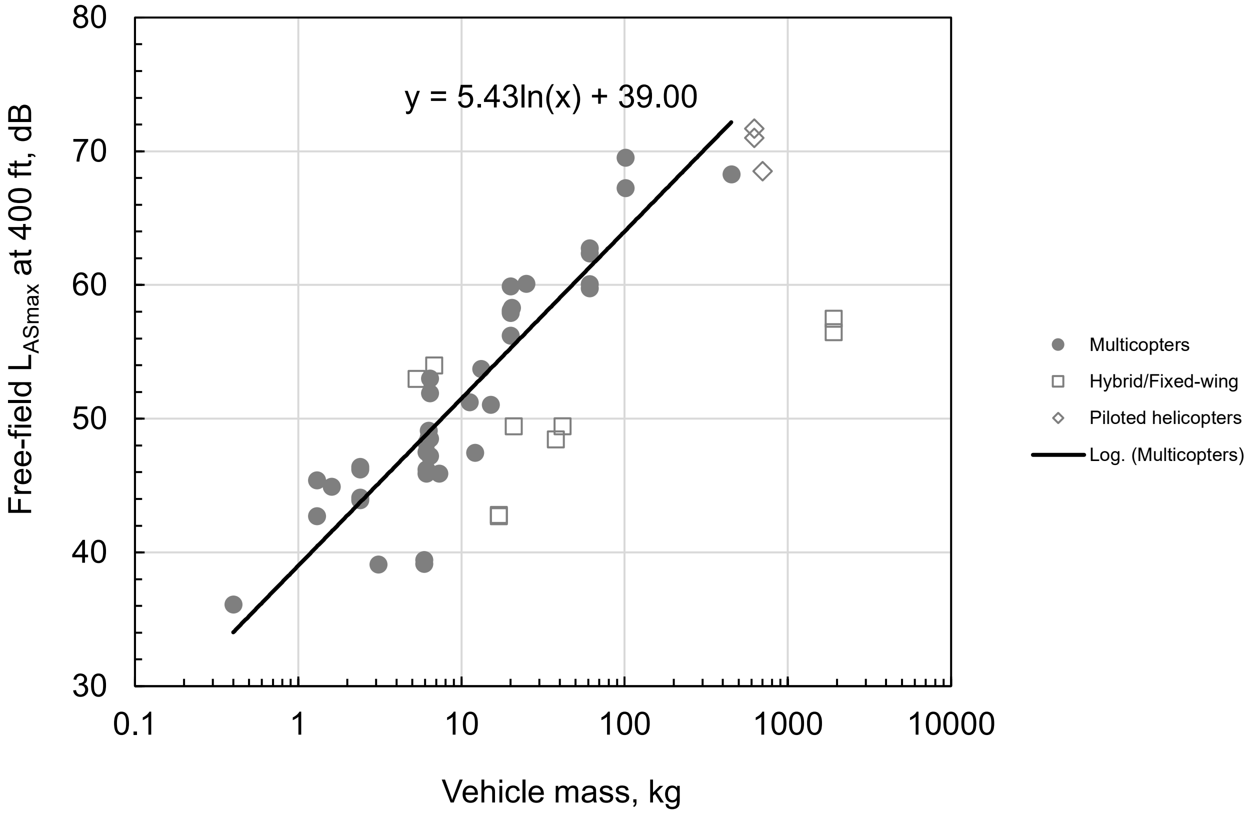
Variation of UAS/AAM noise level by mass at a reference height of 400 ft

12.1 Figure 1 provides a summary of overflight L_{ASmax} noise levels for the range of UAS and AAM aircraft covered in this report and in CAP 2506. The results show a general trend of increasing noise level with increasing vehicle mass.

12.2 The results in Figure 1 are based on measurements recorded for each aircraft, normalised to a reference distance of 400 ft assuming spherical spreading. Where noise measurement data were recorded for more than one flyover height, data for the highest test height were used in order to minimise adjustment errors. Where applicable, noise measurements from microphones mounted on ground plates have been adjusted to equivalent free-field conditions by subtracting 6 dB (to account for assumed pressure-doubling).

12.3 For most aircraft noise events, SEL values are numerically greater than L_{ASmax}, typically by around 10 dB. For cases where only SEL data were available, measured SELs were adjusted to an equivalent L_{ASmax} on this basis. However, it is noted that in practice there may be significant numerical variation between SEL and L_{ASmax} depending on aircraft speed and height. Because of these uncertainties, the L_{ASmax} data shown in Figure 1 should be considered approximate.

Figure 1 Variation of UAS/AAM noise level by mass at a reference height of 400 ft



Where:

y = L_{ASmax}, dB

x = vehicle mass, kg

Chapter 13
Conclusions

13.1 A review of up-to-date literature on outdoor noise emissions from a range of UAS and AAM aircraft has been undertaken, with a focus on overall L_{ASmax} sound pressure levels for vehicles at a reference height of 400 ft. The outcome of the review is the provision of suitable data to support further development of a CAA noise modelling capability for UAS operations.

13.2 It is envisaged that airspace change sponsors will, where necessary, be able to refer to the data summarised in Chapter 12 of this report when assessing noise impacts from their UAS/AAM activities.

APPENDIX A

Glossary of Terms and 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.
eVTOL	electric Vertical Take-off and Landing. An electric propulsion aircraft capable of vertical take-off and landing.
FAA	Federal Aviation Administration (US)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IGP	Inverted Ground Plane (microphone)
kts (or knots)	Nautical miles per hour
L_{ASmax}	The maximum sound level measured during an aircraft event (using frequency weighting A and time weighting S). Often abbreviated to L_{Amax} or L_{max}.
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	Time weighting is used to describe how quickly a sound level meter reacts to changes in sound pressure. There are two commonly used time weightings for environmental noise measurement, Fast (F) and Slow (S). For aviation noise it is standard practice to use Slow 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 UAS noise measurement study, 2023

Introduction

C1 On 14 June 2023 the UK CAA in collaboration with the University of Salford[25], Eagle Eye Innovations[26] and Sierra Nevada Corporation Mission Systems UK[27] conducted a field study in South Scarle, Nottinghamshire to measure the noise from a Malloy Aeronautics[28] T150 cargo multicopter.

C2 The T150 is a 61 kg quadcopter with coaxial contra-rotating propellers capable of carrying up to 68 kg payload, see Figure C1. The T150 is significantly heavier than the UAS vehicles measured previously by the CAA.

Figure C1 Malloy T150 with additional payload installed

C3 Noise measurements for the South Scarle study were recorded using instrumentation provided separately by the CAA and the University of Salford. This appendix summarises the results of overflight noise measurements obtained using the CAA's instrumentation. However, initial lateral directivity results from the University of Salford's noise instrumentation are provided for information.

[25] https://hub.salford.ac.uk/sirc-acoustics/

[26] https://eeinnovationsltd.com/

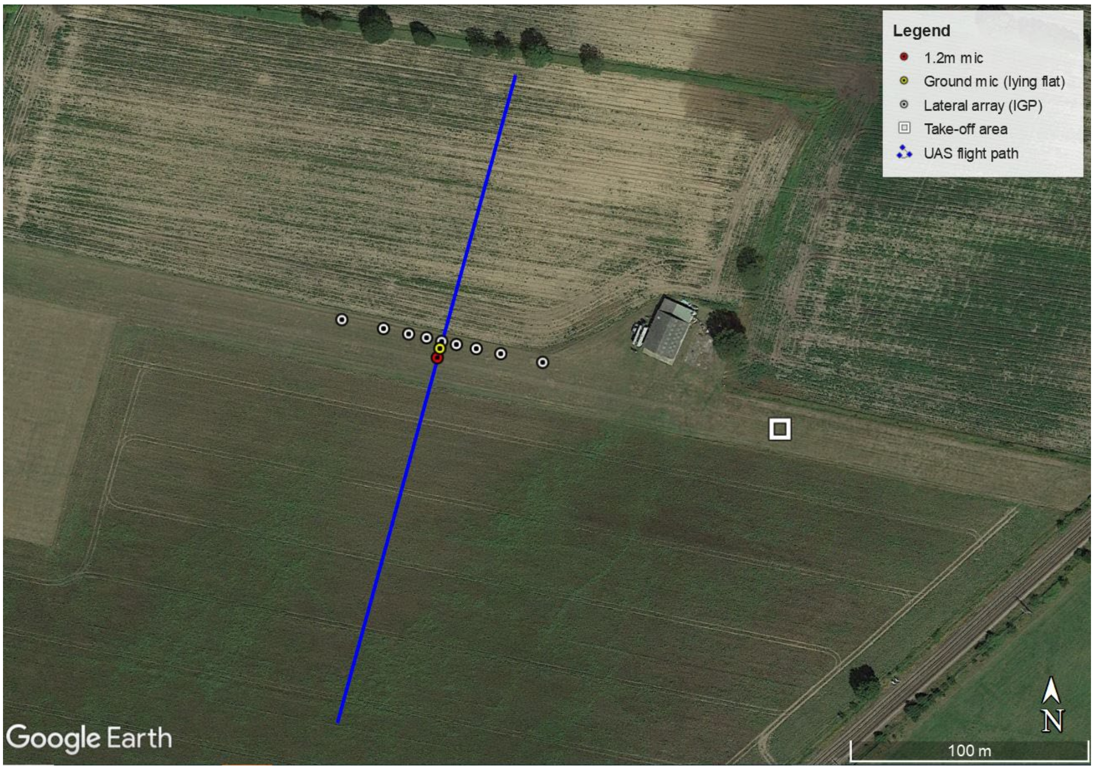
[27] https://www.sncmsuk.com/

[28] https://www.malloyaeronautics.com/t150.html

Methodology

C4 The field study took place on a privately operated farm strip (grass runway) in South Scarle, Nottinghamshire. Figure C2 illustrates the layout of the site in relation to the UAS test flight path and noise instrumentation.

Figure C2 Overview of the South Scarle test site



C5 For operational reasons it was not possible to extend the UAS flight track an equal distance to the north and south of the noise instrumentation. Consequently, the northern segment of the flight track was approximately 40 m shorter than the southern segment.

C6 Weather conditions on the day were dry and sunny with an average temperature of approximately 23°C. A north-easterly wind with an average speed of approximately 5 m/s was measured at the site over the duration of the tests.[29]

C7 Noise measurements were made using the following microphone configurations:

i) A lateral array of nine Inverted Ground Plane (IGP) microphones supplied by the University of Salford, arranged perpendicular to the UAS flight path with a central microphone directly underneath and four microphones extending 43.3 m either side of the flight path. The IGP microphones were installed on 40 cm diameter circular ground plates and positioned to provide noise measurements

[29] Measured 4 m above ground.

at 15-degree intervals, up to a lateral angle of 60 degrees (from normal to the ground) for a reference height of 25 m above the central microphone.[30]

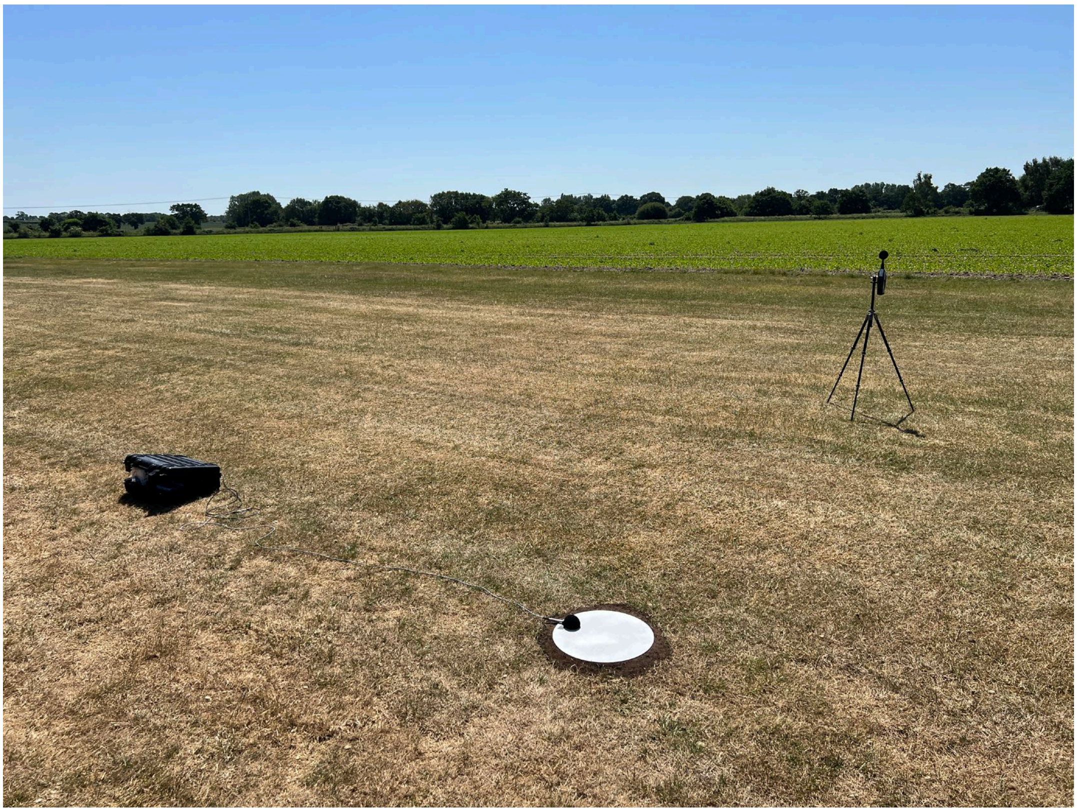
ii) A single ground plane microphone supplied by the CAA, positioned directly underneath the UAS flight path, approximately three metres from the University of Salford's central microphone. In contrast to the inverted mounting arrangement of the microphones in the lateral array, the CAA's ground plane microphone was installed with the microphone lying flat on a 40 cm diameter circular ground plate to facilitate a future comparison of noise measurements acquired using different microphone mounting arrangements.

iii) A single tripod-mounted microphone supplied by the CAA, with the microphone diaphragm positioned at the standard height of 1.2 m above ground and directly underneath the UAS flight path, approximately four metres from the CAA's ground plane microphone. Again, the 1.2 m microphone was deployed to provide a comparison of the different microphone mounting arrangements.

C8 The microphone used in the CAA ground plane set-up was a Brüel & Kjær 4192L pressure response microphone connected to a Brüel & Kjær 2250 sound level analyser. The instrumentation used for the 1.2 m microphone installation was a Brüel & Kjær 2250L sound level analyser fitted with a standard Brüel & Kjær 4950 freefield microphone. Figure C3 shows details of the CAA microphone installations. Sound level calibration checks were conducted at the start and end of the measurement study using a Brüel & Kjær 4231 sound calibrator.

[30] The microphone configuration was selected to conform with guidance presented in ISO 5305:2024 - Noise measurements for UAS (unmanned aircraft systems).

Figure C3 CAA ground plane and 1.2 m microphone installations



C9 The test flights were flown using pre-programmed waypoints. The T150 was fitted with an on-board Global Navigation Satellite System (GNSS) receiver based on Real-Time Kinematic positioning (RTK) which provides enhanced positional accuracy compared to a standard Global Positioning System (GPS) receiver.

C10 The overflight tests involved a series of alternate overflights, passing backwards and forwards along the same ground track over the noise monitoring equipment. Limited noise tests were also undertaken for take-off/landing and hover conditions using the Salford microphone array but are not covered in this report.

C11 Measurements of overflight noise with no payload installed were conducted at nominal heights of 25 m and 50 m and ground speeds of 5 m/s and 15 m/s, the latter intending to represent typical 'slow' and 'fast' UAS operations, respectively.[31] Additional 25 m overflight measurements were conducted at 15 m/s with an installed payload of 40 kg, giving a total vehicle mass of 101 kg.

C12 Spatial positioning data from the vehicle's on-board GNSS receiver were provided by the operator after the tests were completed to confirm the actual heights and ground speeds flown. With the exception of one test procedure (25 m overflight at 15 m/s, with no payload) for which only four overflight runs

[31] According to the manufacturer, the maximum cruise speed of the T150 is 31 m/s.

were completed, at least six valid measurements were recorded for each test series.

C13 Maximum sound pressure levels (L_{ASmax}), using frequency weighting 'A' and time weighting 'S' (slow) were obtained for each overflight, along with Sound Exposure Levels (SEL). The duration of each noise event was defined by the '10 dB-down' points of the event L_{ASmax} time-history.

C14 Table C1 summarises the average measured L_{ASmax} noise levels recorded using the CAA ground microphone. Table C2 provides the corresponding average measured L_{ASmax} noise levels from the 1.2 m microphone. Measurement results for individual overflight runs are provided in Appendix D.

Table C1 Average measured overflight L_{ASmax} levels for the T150; ground mic

Aircraft mass (kg)	**Valid runs**	**Ground speed (m/s)**	**Height (m)**	**L_{ASmax} (dB)**	**Std. Dev.**	**90% CI**
61	7	5	25	79.4	0.9	0.7
61	4	15	25	78.2	0.8	0.9
61	6	5	50	73.5	0.5	0.4
61	6	15	50	73.8	0.7	0.6
101	6	15	25	87.0	0.7	0.6

Table C2 Average measured overflight L_{ASmax} levels for the T150; 1.2 m mic

Aircraft mass (kg)	**Valid runs**	**Ground speed (m/s)**	**Height (m)**	**L_{ASmax} (dB)**	**Std. Dev.**	**90% CI**
61	7	5	25	76.4	0.8	0.6
61	4	15	25	75.0	0.9	1.1
61	6	5	50	70.3	0.3	0.2
61	6	15	50	70.7	1.0	0.8
101	6	15	25	83.7	0.7	0.6

C15 Table C3 provides initial average lateral directivity results for the T150 measured at the time of L_{AFmax} by the University of Salford's lateral microphone array.[32] Results are shown for both flyover speeds and have been back-propagated to a reference distance of 2 m. These initial results indicate that the overall A-weighted noise level for the T150 varies by less than 1.5 dB within a lateral angle of +/- 60 degrees.

Table C3 T150 L_{AFmax} lateral noise directivity (back-propagation radius: 2 m)

Lateral angle (deg)	L_{AFmax} **(dB) at 5 m/s**	L_{AFmax} **(dB) at 15 m/s**
-60	96.4	94.7
-45	96.9	94.9
-30	97.2	94.9
-15	97.3	95.0
0	97.7	95.4
15	97.8	95.3
30	97.8	95.1
45	97.4	94.7
60	96.9	94.3

General observations

C16 Noise level variability between individual runs was generally low, with 90 percent confidence intervals no greater than 1 dB L_{ASmax} in nearly all cases.

C17 Measured sound pressure levels obtained from a ground plane microphone will normally be 6 dB higher than equivalent free-field levels.[33] For this study, the average L_{ASmax} difference between the CAA ground plane and 1.2 m microphone measurements was approximately 3 dB, indicating the presence of ground reflections at the 1.2 m microphone, which was as expected.

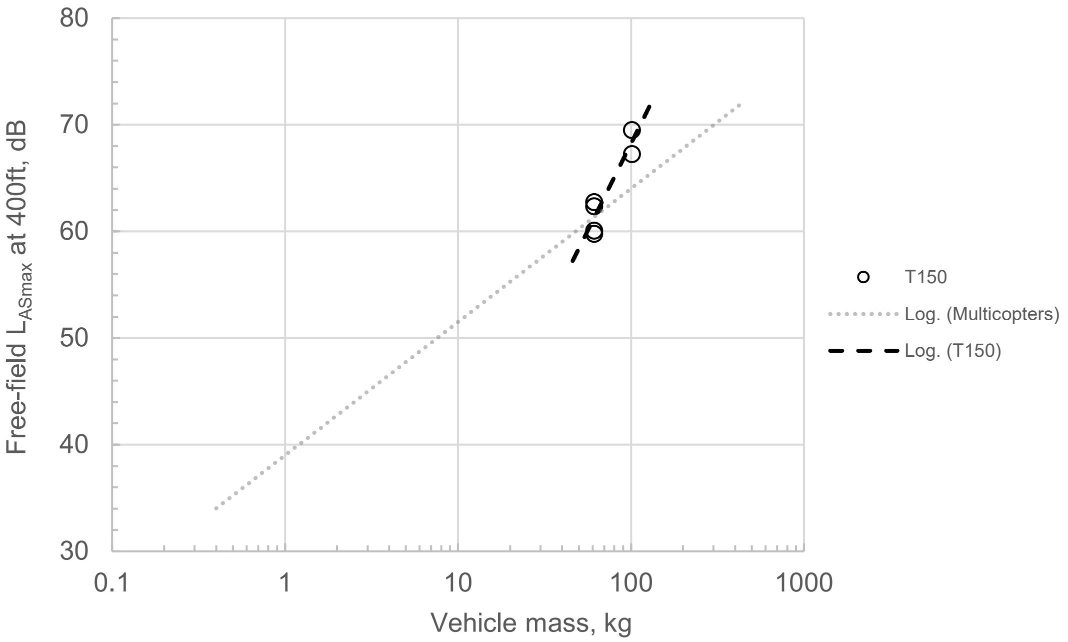
[32] Negative and positive lateral angles correspond to the port and starboard side of the vehicle, respectively.

[33] 'Free-field' is used to describe an ideal sound measurement environment where there are no reflections from nearby surfaces.

C18 The average measured L_{ASmax} results for the slow (5 m/s) and fast (15 m/s) T150 overflights without payload were generally comparable at both test heights.[34] However, for the 25 m runs, the slow overflights were slightly noisier in terms of L_{ASmax} (by about 1 to 1.5 dB, on average) whereas for the 50 m runs, the fast overflights were slightly noisier (by about 0.5 dB). This finding may not be significant however, given the smaller sample size for the 25 m overflight runs at 15 m/s. It is also noted that the ground speeds tested for this study were well below the T150's specified maximum cruise speed of 31 m/s.

C19 The average measured L_{ASmax} for the 25 m T150 overflight at 15 m/s with 40 kg payload was measured approximately 9 dB higher than the equivalent run without a payload. An increase of 5 dB would generally be perceived as a clearly noticeable change by most people and an increase of 10 dB would be perceived as twice as loud. The trend of noise versus mass is also much steeper than the trendline across different multicopter vehicles (Figure C4).

Figure C4 Trend of noise versus mass for the T150 compared with the trendline across different vehicles



C20 For the 15 m/s overflight runs, the shorter segment of the ground track to the north of the noise instrumentation meant that when the T150 was flying northwards, it typically began to decelerate a few seconds before the 10 dB-down point had been reached, particularly for the 50 m overflights.

[34] However, SEL differences between the slow and fast runs were significantly larger than for L_{ASmax}, with SELs for the slow runs being approximately 4-5 dB higher than for the fast runs. This finding is unsurprising since SEL also accounts for the duration of a noise event.

Likewise, when flying in the opposite direction at 15 m/s, the T150 was still accelerating to cruising speed during the initial few seconds of the event time history. For the majority of noise events, the ground speed remained above 10 m/s during these acceleration/deceleration phases and the effect on the overall SEL measurements is expected to be minimal. The 5 m/s overflight runs were not affected in the same way.

APPENDIX D

Measured T150 noise levels for individual runs

Table D1 Measured T150 noise levels (25 m overflight, 5 m/s, 60 kg mass); ground mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	18	79.8	89.0
2	S	Aborted run	-	-
3	N	19	79.6	89.0
4	S	25	77.6	87.8
5	N	19	80.0	89.3
6	S	21	78.6	88.6
7	N	19	80.1	89.4
8	S	20	80.0	89.4

Table D2 Measured T150 noise levels (25 m overflight, 15 m/s, 60 kg mass); ground mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	9	79.3	84.4
2	S	9	77.8	83.3
3	N	9	77.8	83.4
4	S	9	77.7	83.2

Table D3 Measured T150 noise levels (50 m overflight, 5 m/s, 60 kg mass); ground mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	32	73.6	85.3
2	S	35	72.9	84.0
3	N	36	73.3	85.2
4	S	35	74.3	85.2
5	N	34	73.4	85.2
6	S	32	73.7	85.0

Table D4 Measured T150 noise levels (50 m overflight, 15 m/s, 60 kg mass); ground mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	12	74.4	81.5
2	S	13	73.4	80.9
3	N	11	74.7	81.8
4	S	14	72.9	80.7
5	N	12	74.3	81.2
6	S	13	73.4	80.7

Table D5 Measured T150 noise levels (25 m overflight, 15 m/s, 101 kg mass); ground mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	9	86.3	92.2
2	S	9	87.9	92.9
3	N	8	87.7	93.0
4	S	9	86.4	91.7
5	N	8	86.3	92.0
6	S	9	87.1	92.5

Table D6 Measured T150 noise levels (25 m overflight, 5 m/s, 60 kg mass); 1.2m mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	18	76.9	85.7
2	S	Aborted run	-	-
3	N	18	76.9	85.6
4	S	23	74.8	84.5
5	N	19	76.7	85.8
6	S	20	75.8	85.2
7	N	19	76.7	86.0
8	S	19	76.8	85.9

Table D7 Measured T150 noise levels (25 m overflight, 15 m/s, 60 kg mass); 1.2m mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	8	76.4	81.4
2	S	9	74.6	80.1
3	N	8	74.4	79.9
4	S	9	74.7	80.0

Table D8 Measured T150 noise levels (50 m overflight, 5 m/s, 60 kg mass); 1.2m mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	33	70.4	82.0
2	S	31	70.1	80.7
3	N	36	70.0	81.7
4	S	35	70.5	81.8
5	N	34	70.2	81.9
6	S	30	70.8	81.7

Table D9 Measured T150 noise levels (50 m overflight, 15 m/s, 60 kg mass); 1.2m mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	12	71.4	78.1
2	S	13	70.0	77.2
3	N	11	72.0	78.7
4	S	14	69.6	77.1
5	N	11	71.5	78.1
6	S	14	69.9	77.1

Table D10 Measured T150 noise levels (25 m overflight, 15 m/s, 101 kg mass); 1.2m mic

Run No.	Direction	Event duration, s	L_{ASmax} (dB)	SEL (dBA)
1	N	9	83.3	88.9
2	S	9	83.9	89.3
3	N	8	84.9	89.8
4	S	9	83.1	88.4
5	N	9	83.1	88.7
6	S	9	83.8	89.0