Protecting the Future:

Trials and Simulation of Downwash and Outwash for Helicopters and Powered Lift Aircraft

CAP 3075

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Introduction

This publication summarises a project to gather real-world data of downwash and outwash at helicopter operating sites. Its aim is to inform United Kingdom Civil Aviation Authority (CAA) knowledge of downwash and outwash, as used in publications like CAP 1264.[1]

The work also addresses the Verification and Validation (V&V) called for in CAP 2576, exploring possible downwash and outwash effects on eVTOL aircraft.[2]

The work reported is part of a process of creating a physics-based understanding of downwash and outwash. Currently a view of downwash and outwash as a 'wind' is often found in published material. Anyone who stands near a hovering helicopter instantly knows that it is not the case. The air is very turbulent, unlike any strong wind. Understanding the physics of this turbulence is essential to understanding the risks of downwash and outwash.

Tools to enable this new understanding have been trialled and are proposed for wider use. Physics-based modelling should inform current and future operations of powered-lift aircraft to make them safer and to enable rapid innovation.

The focus of this report is on building knowledge that can be quickly assimilated and acted on.

The work in this report was carried out by the CAA's Flight Operations department using internal CAA funds, supported by two contractors, Sophrodyne Aerospace and Snowdonia Aerospace.

It was enabled by the kind co-operation of Silverstone Helicopters, Bristow Helicopters and Fire Safety Training.

The material and views presented are those of the CAA. This report does not constitute regulation and does not form a definitive view of the subject matter at this time. It is intended to be used as part of wider discussions between regulators, operators and innovators engaged in the safe, rapid development of vertical flight operations.

[1] Civil Aviation Authority Publication 1264 (CAP 1264) Standards for Helicopter Landing Areas at Hospitals, April 2024, https://www.caa.co.uk/our-work/publications/documents/content/cap1264/, accessed 20th March 2025

[2] Civil Aviation Authority Publication 2576 (CAP 2576) Understanding the downwash/outwash characteristics of eVTOL aircraft, October 2023, https://www.caa.co.uk/our-work/publications/documents/content/cap2576/, accessed 20th March 2025

Project Overview

Why we did it

In 2003 CAA publication CAP 2576, *Understanding the Downwash/Outwash Characteristics of eVTOL Aircraft*, examined the physics of the complex airflows caused by powered-lift aircraft. As part of that work several issues, where a physics-based approach could help, were recognised:

- There is a fundamental need to protect third parties on the ground from air that is pushed down and out by a hovering aircraft. The risks from these airflows were tragically illustrated by a fatal accident at Derriford Hospital in the United Kingdom in 2022.
- Current safety needs for downwash and outwash are based on simple approaches such as downwash safety zones. For example, CAP 1264 specifies safety zones for helicopter operations in terms of safety circles based on weight/disc loading.
- The Air Accident Investigations Branch (AAIB) report into the Derriford accident[3] indicated that the presence of ground obstacles may alter downwash and outwash patterns.
- Training manuals and guides from regulators, manufacturers and operators often show downwash and outwash as a form of wind, relatively steady in form (see Figure 1). This view fails to show the transitory aspects of downwash and, in particular, the very different physics of outwash, which is not simply downwash that has 'turned a corner' (see Figure 2).
- Operators flying into congested or busy helipads may not be able to judge safety distances for downwash and outwash as their mental models are based on the view of a relatively steady 'wind' that forms a circular pattern.

The real-world tests and simulations shown in this report reveal airflows under helicopters may be more complex than experience, and some current publications, assume.

The modelling of downwash and outwash physics in CAP 2576 forms the basis of the verification and validation work reported in this new publication, CAP 3075 *Protecting the Future: Trials and Simulation of Downwash and Outwash for Helicopters and Powered Lift Aircraft*.

We wanted to see if the vortex-dominated, transitory flows shown in simulations in CAP 2576 (Figure 2) matched real-world experience and data.

[3] Air Accident Investigation Branch, Aircraft Accident Report AAR 2/2023 - Sikorsky S-92A, G-MCGY, 2nd November 2023, available at https://www.gov.uk/aaib-reports/aircraft-accident-report-aar-2-slash-2023-sikorsky-s-92a-g-mcgy accessed 20th March 2025

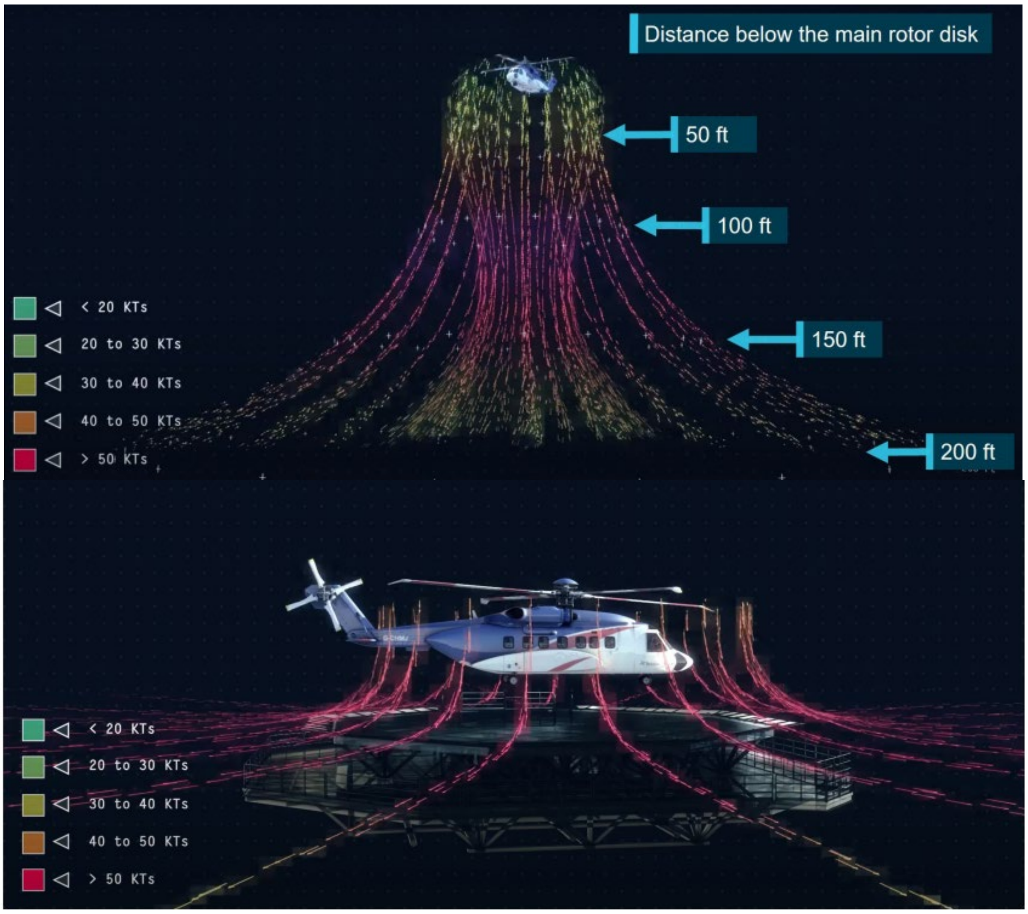

Figure 1. Stills from a safety training video showing airflow under a Sikorsky S92 helicopter as steady, 'wind-like', flows. Source 'Helicopter Downdraft Danger', BP video available at https://youtu.be/09bvuYRKwwc accessed 20th March 2025.

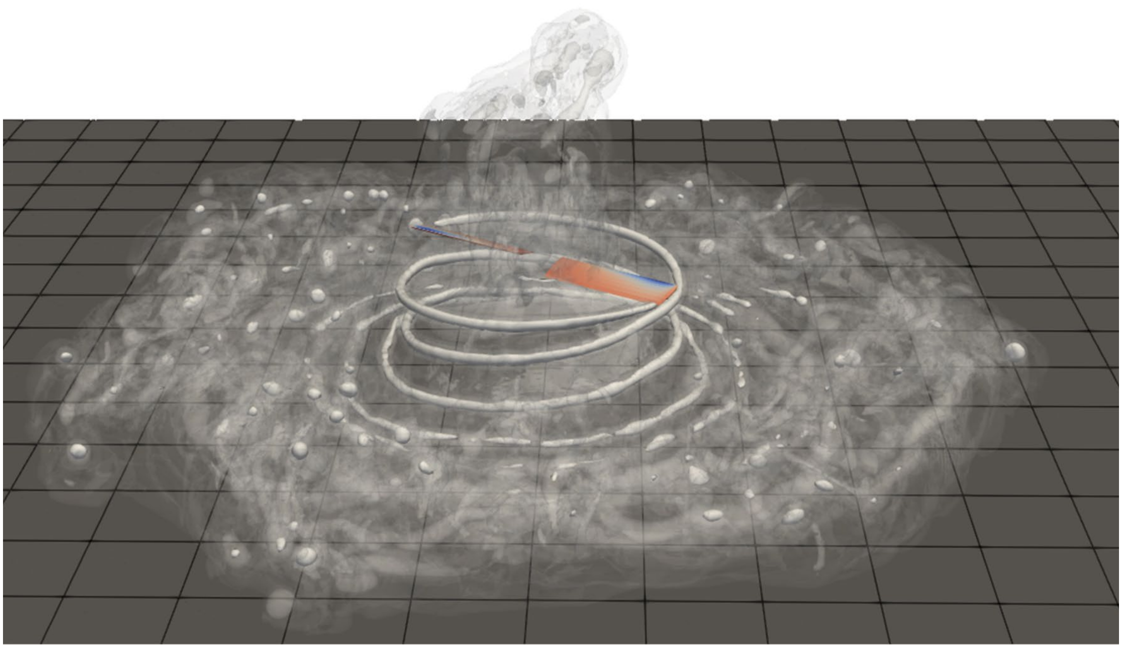

Figure 2. Modelling from CAP 2576 showing a physics-based view of airflow under a rotor.

What we did

The attempt to match simulations to real-world data was carried out in a project called Research Assessment of Transitory Helicopter Downwash (RATHD). The initial focus of RATHD was the AAIB's Safety Recommendation 2023-029, taken from their report on the Derriford accident:

> "It is recommended that the UK Civil Aviation Authority, in conjunction with the Onshore Safety Leadership Group and the relevant NHS organisations in the UK, develop and promulgate enhanced risk management guidance for hospital helicopter landing sites, and provide information on the range and use of potential mitigations for the protection of uninvolved persons from helicopter downwash."

A research plan, centred on assessing whether the presence of transitory features in downwash and outwash patterns exist, was developed and approved for internal CAA funding under their Safety Research Programme. The objective was to seek data and knowledge that could inform any actions to meet Safety Recommendation 2023-029.

The RATHD research proposed to trial a simple method for the measurement of transitory downwash and outwash flows. Philosophically RATHD is an extension of the simple techniques used by NASA to assess and compare downwash and outwash from rotorcraft and fan-driven tilt-wing aircraft from the 1960s[4].

It was hoped that if the method worked it might also allow a connection to be drawn between the idealised, digital methods shown in CAP 2576 and the wider data available from NASA and other organisations that have undertaken extensive real-world testing over decades.

The first step of the RATHD fieldwork was the purchase of portable, off-the-shelf anemometers to measure the airflow velocities around hovering helicopters.

The research programme was broken down into the following tasks:

1. Procurement of test equipment, owned by the CAA.
2. Development of a downwash measurement plan for operating sites.
3. Measurement visits by CAA staff to capture data during helicopter operations.
4. Data used for verification and validation of simulation software in CAP 2576.

As the work progressed it became clear that tools could also be developed for wider use. These could rapidly disseminate verified and validated knowledge of downwash and

[4] O'Bryan, T.C., NASA Technical Note D-977 An Investigation of the Effect of Downwash from a VTOL Aircraft and a Helicopter in the Ground Environment, NASA Langley Research Center, 1961, available at https://ntrs.nasa.gov/citations/20040008178 accessed 20th March 2025

outwash more widely across the aviation sector (Figure 3). This included the potential to use extensive historic data as a source to further refine digital models.

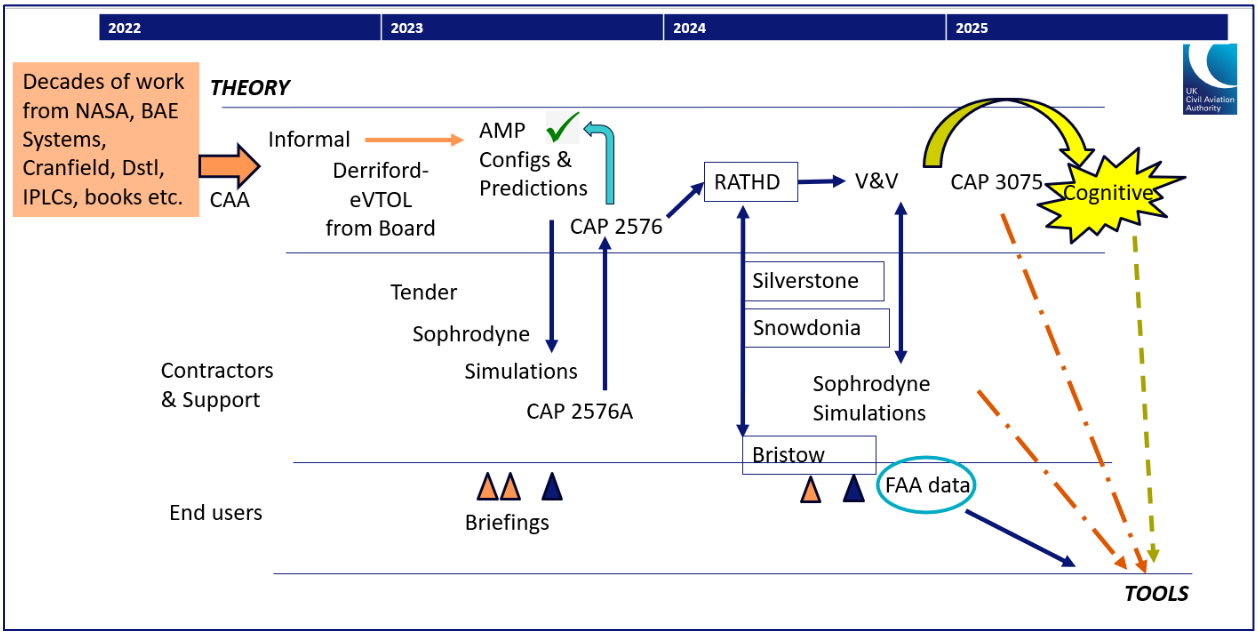

Figure 3. Overview of the RATHD project. As well as the Verification and Validation of the work in CAP 2576 the project also drew on emerging data published by industry and the Federal Aviation Administration. The findings of RATHD allowed the development of tools to be developed, all informed by the decades of publicly available data from the National Aeronautics and Space Administration (NASA), industry, academia, the UK Defence Science and Technology Laboratory (Dstl) and its predecessor organisations, and four decades of International Powered Lift Conferences (IPLC) technical meetings run by the American Institute of Aeronautics and Astronautics, American Helicopter Society/Vertical Flight Society, Society of Automotive Engineers and the Royal Aeronautical Society.

What we found

The equipment budget for RATHD was limited so a trade-off was made between resources available for data gathering and those for analysis. This determined that rather than taking precise readings with sophisticated equipment an approach where less precise helicopter airflow data could be statistically adjusted might work. It was also thought this approach would allow methods that could more easily be applied in daily flight operations.

A. Silverstone trial

We decided to carry out a trial at Silverstone in July 2024 in order to test the utility of the equipment and the viability of the data gathering method. We were not looking for precision. Instead, this was a trial of the practicality of the methods of RATHD.

During the annual Formula 1 Grand Prix Silverstone is the busiest heliport in the world, with movements happening as often as every ten seconds. A familiarisation in 2023 had shown this could provide a good location to measure airflows around single and multiple helicopters, ground crew and buildings.

With the kind assistance of Silverstone Helicopters, we were able to access a number of test locations, shown in Figure 4.

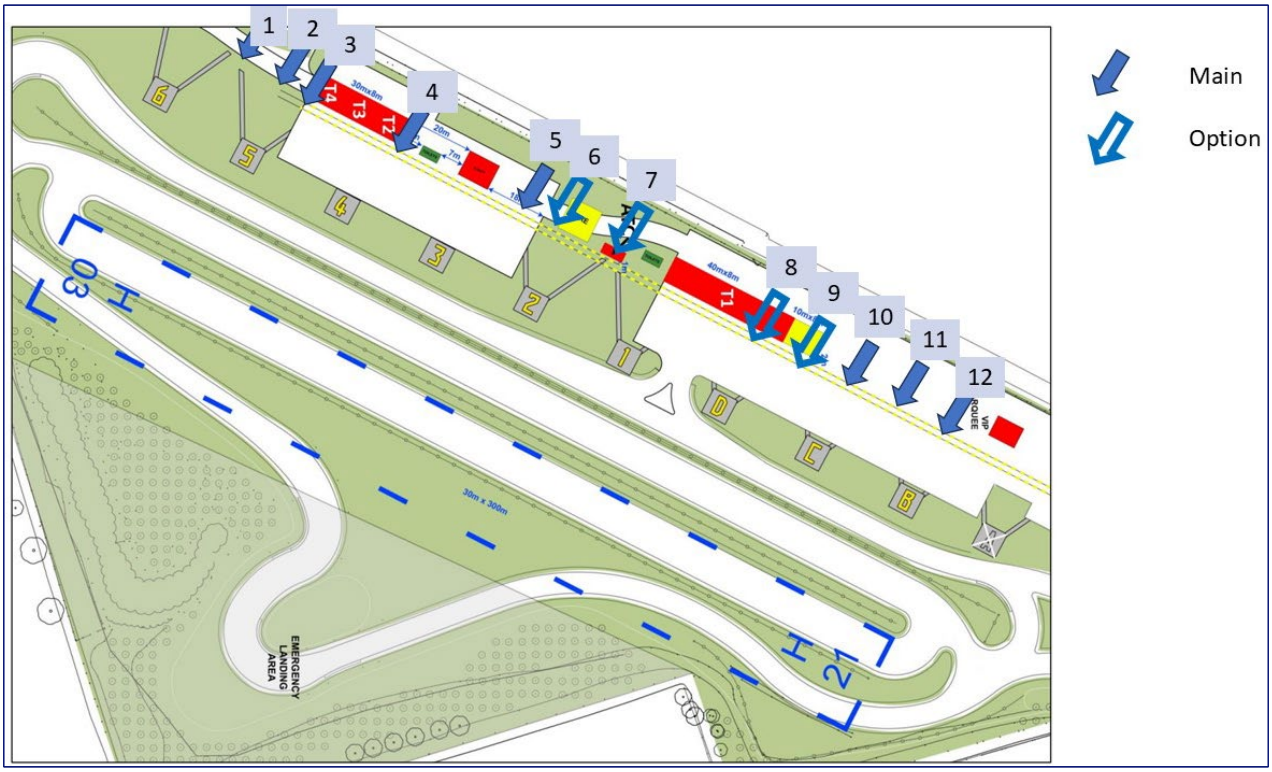

Figure 4. A map of the heliport at Silverstone and the test locations used to measure outwash from the helipads. The main test locations were where most data were gathered.

The helicopter testing at Silverstone gave some surprising insights, as well as data. Performing the tests with sensors that we held in our hands, rather than remote sensor arrays, meant we experienced downwash and outwash as a person on the ground does. We found outwash has both a physical effect and a cognitive one. Simple tasks like reading out numbers become much harder when you are immersed in high-speed air. The CAA test team had long-term aviation personnel in it who had experience of jet blast, yet outwash was clearly a different phenomenon, particularly the turbulence of the airflow.

The data gathered also held surprises. We used two types of anemometers. Pocket wind meters, often used by drone operators to assess ambient winds, were one. We found that these produced a very wide and varied set of numbers, even when two wind meter sensors were held in almost the same location near the same helicopter. It appears that as these anemometers are driven by a small spinning fan the time taken to ‘spool up’, and down, as wind gusts passed through them made it virtually impossible to establish a clear maximum outwash speed. The transient gusts felt were too rapid for the fan to keep up. It was decided to use the pocket wind meter sensors only to establish background, natural wind speeds, not to establish peak gust velocities.

For all measurements we took a series of three readings at three separate heights for each sensor. At any one time up to three small teams of CAA personnel took the measurements, using up to six sensors. This was driven by a desire to obtain sufficient data points to allow the use of statistical analysis.

While the pocket wind meter sensors proved less useful than had been hoped, the second type of anemometer used, hand-held hot wire sensors, were able to obtain reproducible results at each of the three heights. Cross-checking between two hot wire anemometers was shown to work. Sampling at a rate of 0.8 seconds was chosen in order to allow ‘eyeball’ estimates of the rate of change of gusts and a chance for colleagues to write down the recordings. A simple method of recording the maximum figure within each five second window (i.e the largest of six numbers shown in that timeframe) was used, with the anemometers also recording the maximum figure in their built-in memory. At each of the three heights three readings would be taken when time permitted, e.g. when a helicopter was waiting for tower clearance while hovering over a pad location.

An example of the data gathered is shown in Table 1. This is for an Agusta 109 helicopter taking off from Silverstone Pad B. It was in the hover with its tail facing Team 1, located at test location 12. There was no helicopter at the adjacent pad. A second team were located at test location 11, i.e. at around 30 degrees from the helicopter’s tail (see Figure 4).

We had not aimed for precision, but some trends are discernible in Table 1. The location around the helicopter’s axis appears to matter. With one exception, Team 1, aligned on the nose-to-tail axis, experienced higher velocities at similar conditions.

It can readily be seen that there are no constant velocities at any sensor height.

Sensor Height	Team 1	Team 1	Team 1	Team 2	Team 2	Team 2
Low (50cm)	16.2	22.0	25.5	10.6	9.3	9.8
Mid (150cm)	23.5	12.9	13.9	13.7	6.2	12.9
High (250cm)	6.6	26.9	25.7	14.7	12.6	17.9

Table 1. Example helicopter max outwash velocities in statute miles per hour from Agusta 109 hovering at Silverstone, 7 July 2024. Sensors are both hot wire anemometers.

The expectation of a boundary layer effect with the low sensors, as described in the literature, does not appear in the data.

This may have been caused by the lowest sensor height still being above the boundary layer. The effects of a safety barrier between the test teams and the helicopter (see Figure 5) were also considered, although the sensors were held very close to the gaps in the barrier. We tried to stay clear of the water tanks securing the barrier, but it will clearly cause some deflected flows at the lower reading heights.

Figure 5. Helicopters operating at Silverstone, showing safety barriers.

Data from many other helicopter landings showed similar trends amidst the initially random scattering of numbers. However, of much greater interest was the physiological experience of the tests. Many of the team experienced being both physically and cognitively overwhelmed by the outwash, making the task much harder to perform than expected.

Using the hot wire anemometers each would require a team of two, one person holding the anemometer sensor in one hand and the display unit in the other, while their colleague wrote down the readings called out to them. This is an exceptionally simple task in principle, but its achievement took considerable effort.

As one might expect the strength of the outwash field posed problems for the person holding a clipboard to write down the numbers, blowing the clipboard around. For all team members however the constant buffeting from the outwash posed a challenge to also hold the sensor, and themselves, steady, while small stones and grit were also thrown up. Ear and eye protection helped keep people safe, but communication was made difficult from the rotor, engine and outwash noise.

More noticeable was a very odd effect where the person reading the numbers would turn to shout them to their colleague, and in that moment would forget them. It was essential to use both verbal and visual cross-checking of the sensor display and the written record, and to 'call back' numbers between team members, to be certain the data was right.

This cognitive difficulty was surprising and hindered the entire trial.

In addition, a heavy shower of rain provided an interesting visualisation of the outwash flows over the tarmac, with clear 'waves' shown moving out radially from the helicopters. These matched the physical feeling of the unsteady airflow.

It was also noted that the marshalling staff of the heliport sometimes had to hold on to the safety barrier to stay upright, and often turned their bodies and faces away from hovering helicopters.

B. Sikorsky S92 Test

With the experience from the Silverstone trial a more detailed test was planned to be carried out in more controlled circumstances.

With the support of one of the RATHD contractors, Snowdowia Aerospace, a plan was created to hover a helicopter at their airfield at Llanbedr in North Wales and to take a series of measurements at precisely marked locations with the helicopter hovering at fixed heights.

An approach was made by the CAA to Bristow Helicopters to provide a Sikorsky S92 from their search and rescue fleet for the test. This was to be provided at no cost, something that was greatly appreciated by the CAA. This would also allow a test to be undertaken with the type of helicopter involved in the accident at Derriford. Although no blame was attributed to the helicopter or crew at Derriford, having the same model of aircraft could allow an improved understanding of the physics involved in support of the AAIB's Safety Recommendation 2023-029. We feel this is a very good example of industry co-operating with a regulator to benefit safety.

Unfortunately, the first attempt at Llanbedr was called off at the last minute due to the search and rescue crew having a real emergency to respond to. Despite this, Bristow extended an invitation to their base at Caernarfon where a small CAA team could wait for a suitable time for a test. This reduced the chances of a call-out leading to further disruption. This visit to Caernarfon happened a few weeks after the initial attempt at Llanbedr.

Being based at the S92 operating base allowed a pre-flight inspection of the aircraft and a chance for a pre-flight briefing. As part of the test preparation the CAA team had reflected on their experience with physical and cognitive effects at Silverstone and the test plan had been adjusted accordingly. On discussion with the Bristow team one of them confirmed that they had also experienced cognitive challenges when winch paramedics were trying to fasten harnesses in a downwash flow. A task that is relatively simple (though vital for rescuing people) fastening harnesses is practised hundreds of times in the hangar but is much harder when buffeted by airflow.

Discussions also revealed that the winch operators spend much time looking at the flow patterns formed by downwash on the sea and that crews had learned that downwash patterns were irregular around the aircraft, being worse near the tail rotor. This knowledge was used to shape their approach path and hovering patterns when rescuing people.

The test itself was supported by Fire Safety Training staff based at Caernarfon Airport, who took the CAA team to the test site and took photographs. Again, we would like to extend our thanks for this help, freely provided, which enabled the trial to go ahead.

The test plan was for the helicopter to hover at two heights, 65 feet and 6.5 feet, as measured by radar altimeter to the bottom of the undercarriage wheels. The S92 would hold position over a clear area of tarmac while the CAA team approached along a grass verge looking for a strong outwash field. They would then take measurements at the two helicopter hovering heights, assisted by a member of the Bristow crew that the helicopter dropped off before hovering. They would provide a communication link and precise geolocation data.

The test plan enabled CAA staff to fall backwards onto the grass if blown over, while being able to measure an outwash field that had passed over a clear area of tarmac (Figure 6).

Figure 6. Caernarfon Airport test location, 13 September 2024.

The test, as flown, allowed the helicopter to face into wind and the CAA test team to locate themselves directly in front of the aircraft nose, with ambient wind coming directly from behind. A curious feature was that after the helicopter initially hovered, after dropping off their crew member, there was virtually no outwash despite the proximity of a hovering helicopter weighing 24,000 pounds. This position was about 45 degrees from the aircraft nose, and it was only by walking around to stand directly in front of the aircraft's nose that a strong outwash was found. Figure 7 shows the first location, with no significant downwash, while Figure 8 shows the CAA test team located by the aircraft nose, with the much stronger airflow shown by their postures.

Figure 7. CAA test team and Bristow support crew member at the initial test point, experiencing minimal outwash. Image Copyright: Alan Hughes / Fire Safety Training.

Figure 8. The CAA test team immersed in a strong outwash field when stood directly in front of the S92 nose. Image Copyright: Alan Hughes / Fire Safety Training.

Once again the turbulence of the outwash field led to both physical and cognitive disturbance. Two of the CAA team had been present at Silverstone while the third had not, but he was briefed on the expected difficulties.

This experience and briefing allowed a more assured data collection although, as the notes show, it was not easy.

At the 65 foot hover height the notes record:

> “Very ‘buffety’ and needed effort to stay in position’.

For the 6.5 foot hover the notes are:

> “At this height right on limit to stand up – had to keep stepping back and lean down to write”.

A full set of planned hot wire anemometer readings were recorded, as well as ambient wind which was cross-checked with the airport control tower. Pocket wind meter anemometers were also used as a cross-check in the test, but once again proved very variable in output and had readings clearly at odds with the physically experienced strength of the outwash.

C. Simulation

The primary purpose of the test at Caernarfon was to obtain data in test conditions that could then be simulated. The contractor used for the simulation was Sophrodyne Aerospace, the same contractor who had carried out the modelling in CAP 2576. It was this modelling that we wanted to verify and validate, a primary aim of the RATHD project.

The contractor was not given any data from the test at Caernarfon, only the test conditions, as shown in Figure 9.

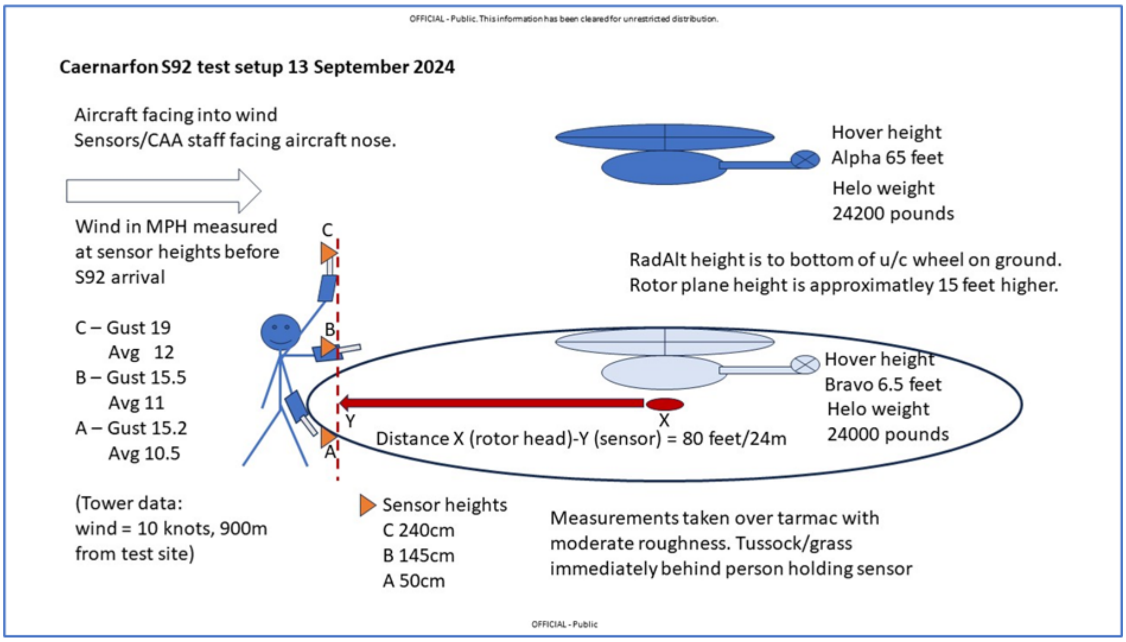

Figure 9. Test conditions given to Sophrodyne Aerospace to be simulated.

Sophrodyne use a proprietary computer code to run their Vorticity Transport Model (VTM). Unlike other, Reynolds Averaged Navier Stokes (RANS), computer codes that lose the ‘swirliness’ of vortices in the air as they move away from a simulated air vehicle, Sophrodyne’s VTM approach retains the vortex structures as they move out into a large volume of air.

The task they were given was to simulate the two test conditions using a simple helicopter-like digital model developed as part of CAP 2576. This had been intended to support a taxonomy of powered-lift aircraft simulations, allowing connections to be drawn between each of them and cross-verification of results. This would be possible as they were all based on the same physics models run in the VTM code. Figure 10 shows this taxonomy.

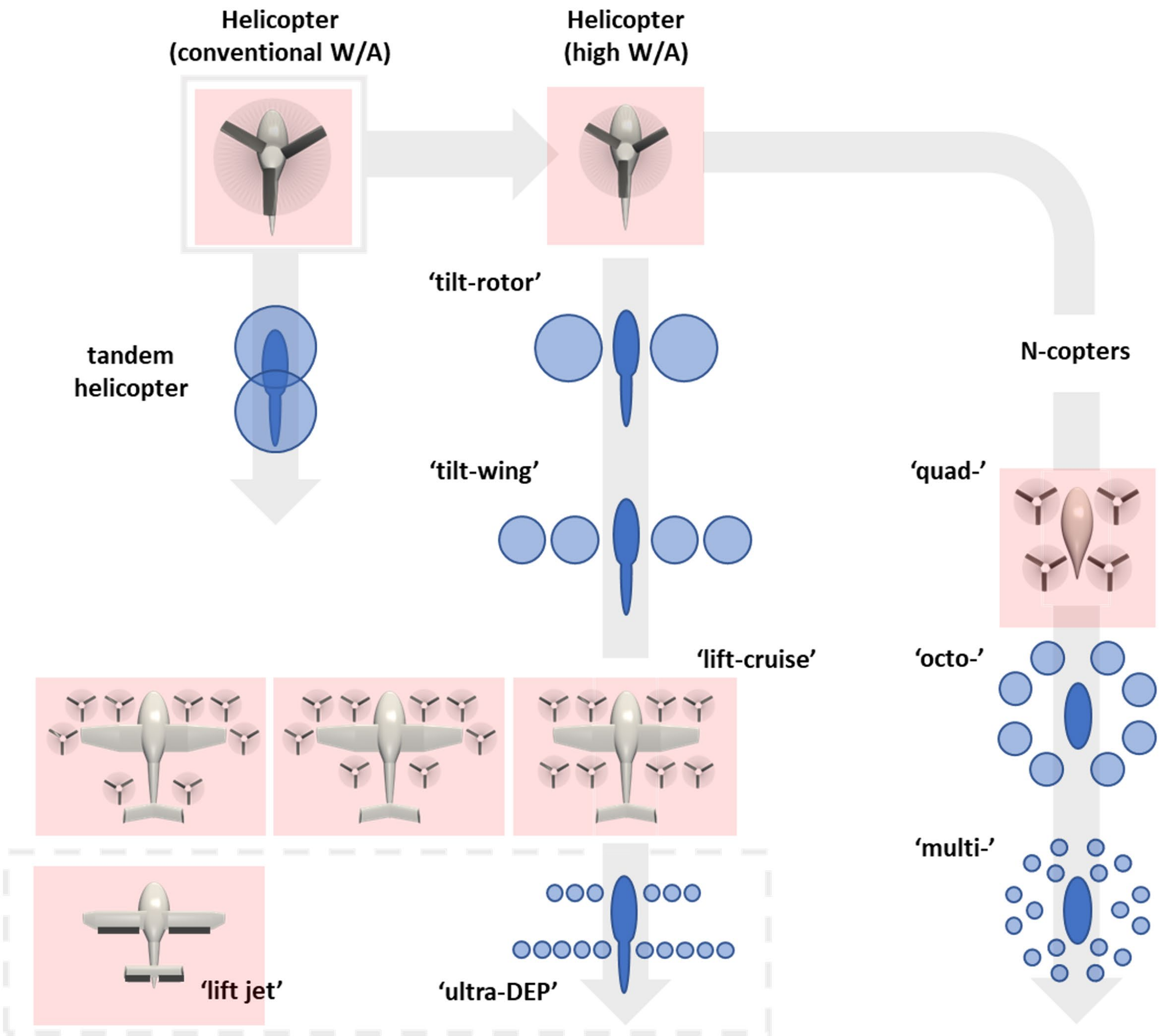

Figure 10. Powered-lift aircraft taxonomy from CAA publication CAP 2576 showing a simple helicopter-like aircraft with a rigid rotor at top left.

As there were no flying eVTOL aircraft in the United Kingdom when the tests were carried out it was assumed that if the physics of the VTM simulations could be verified using a helicopter. This would serve as an initial verification of the VTM code, with later tests and wider data hopefully adding data to build the taxonomy more robustly.

The contracted task for Sophrodyne was to model four scenarios:

Cases:

1. *Scale CAP 2576 helicopter (conventional disc loading only) to S92 weights and simulate Alpha and Bravo hovering positions.*
2. *'Best effort' model of S92 to simulate Alpha and Bravo hovering positions. Best effort can include a simple rotor modification to case 1 above (e.g. 4 rotors with aspect ratio of S92).*

Required outputs:

Data points from simulations giving peak outwash velocities for the three sensor heights (A, B, C) and test location (point Y) used in physical tests for cases 1 and 2 above.

One aspect of Sophrodyne's VTM code is that it allows for many additional air vehicles and many different test conditions to be modelled. It is a tool that allows for 'playing with the physics'. This also allowed Sophrodyne to not just model the simple helicopter but also the Sikorsky S92 as well, using open-source data to generate its external lines. This allowed a 'best effort' that was much more refined than the CAA had expected within the limited budget.

Sophrodyne's two modelled air vehicles were names AMP-Heavy, the scaled CAP 2576 simple helicopter with an eVTOL-like rigid rotor, and SIK-92, the open-source digital S92.

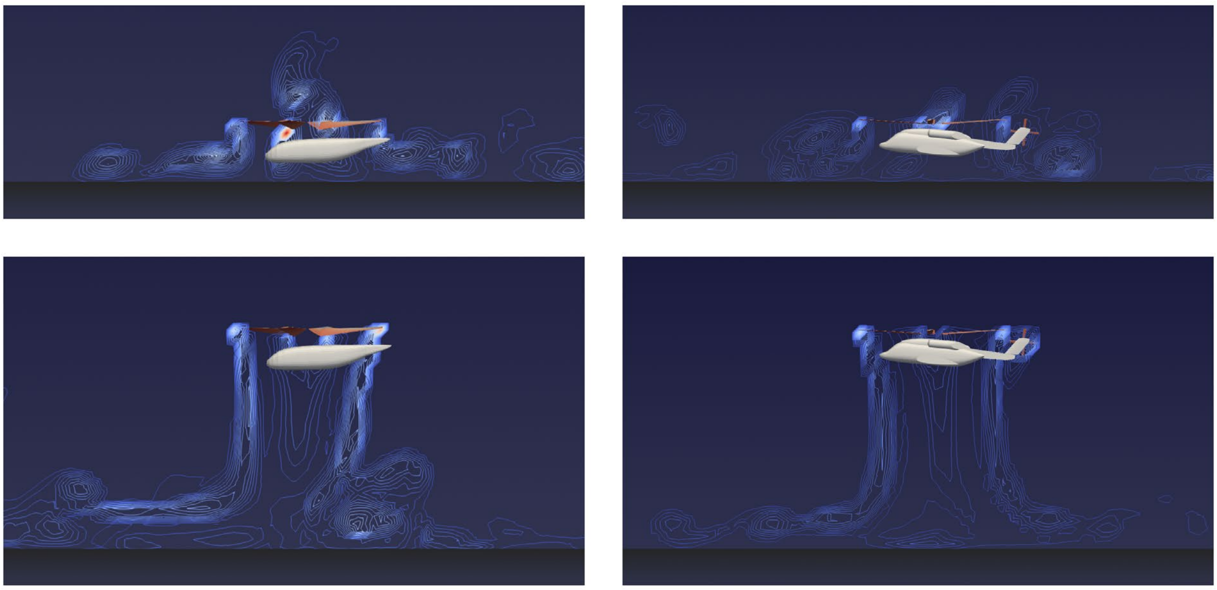

Figure 11. AMP-Heavy and SIK 92 models (not to scale) at the two test conditions from Caernarfon. Images Copyright Sophrodyne Aerospace.

It is immediately apparent from Figure 11 that the two digital aircraft models have different downwash and outwash patterns, shown in light blue, despite having exactly the same weight and disc loading.

A fundamental difference is that AMP-Heavy, being a derivative of the Air Mobility Platforms (AMPs) used to test eVTOL configurations in CAP 2576, has a rigid rotor. SIK-92 has a fully articulated rotor head as on a real Sikorsky S92, and also has fully representative aircraft attitude, a tail rotor and many other realistic details.

The outwash pattern of the SIK-92 is clearly more structured than the rigid rotor AMP-Heavy. This is probably a result of its articulated head. This difference from AMP-Heavy may have significance when reading across helicopter test data on downwash and outwash to eVTOL configurations, which tend to have multiple rigid propellors or rotors.

Raw data from Sophrodyne's simulations of the two aircraft at the two hover heights evaluated at Caernarfon are shown in Appendix A. These show that the outwash velocities at the test location are highly transient, with velocities between very high and negative (i.e. gusts arriving from behind the observer).

Initial attempts at validating the visualisations and data centred on using Weibull analysis to draw out matching data points between the simulations and the real-world test results. These showed good agreement but did not capture the fundamental physical properties of the vortex-dominated flow that lies at the heart of Sophrodyne's VTM modelling, and as experienced during the tests.

What was wanted was a clearer visualisation of the flow physics that was driving the data points and the overall profile of the outwash velocities at the location of the test observer.

This was produced in the form of a number of videos that showed clearly the dynamic nature of the airflow and the resulting velocities. The striking thing about the videos was that they captured not only the physics of the flow but also the physical experience of being immersed in an outwash flow. The visualisations allow direct apprehension of the visceral experience of outwash as well as matching data points. The full videos are available at https://sophrodyne-aerospace.com/resources/

Figure 12 shows a still from one of the videos. The SIK-92 is producing outwash that flows over the observation point, shown by a digital mannequin with a 'rake' of sensor positions on a red line, at 1-foot intervals up to 10 feet. At each of these heights a velocity is produced over an extended period of time, up to 200 rotor revolutions. This allowed the simulation to show a fully formed flow field over a large volume of air with all vortical structures retained.

The still image in Figure 12 shows one such vortical structure at the point of the observer. It can be seen that gust strengths of over 50 knots have been modelled, with velocities decreasing with height. At 10 feet there is a small flow reversal, with flow back towards the helicopter. It is also of note that there is an airflow structure rising above the rotor.

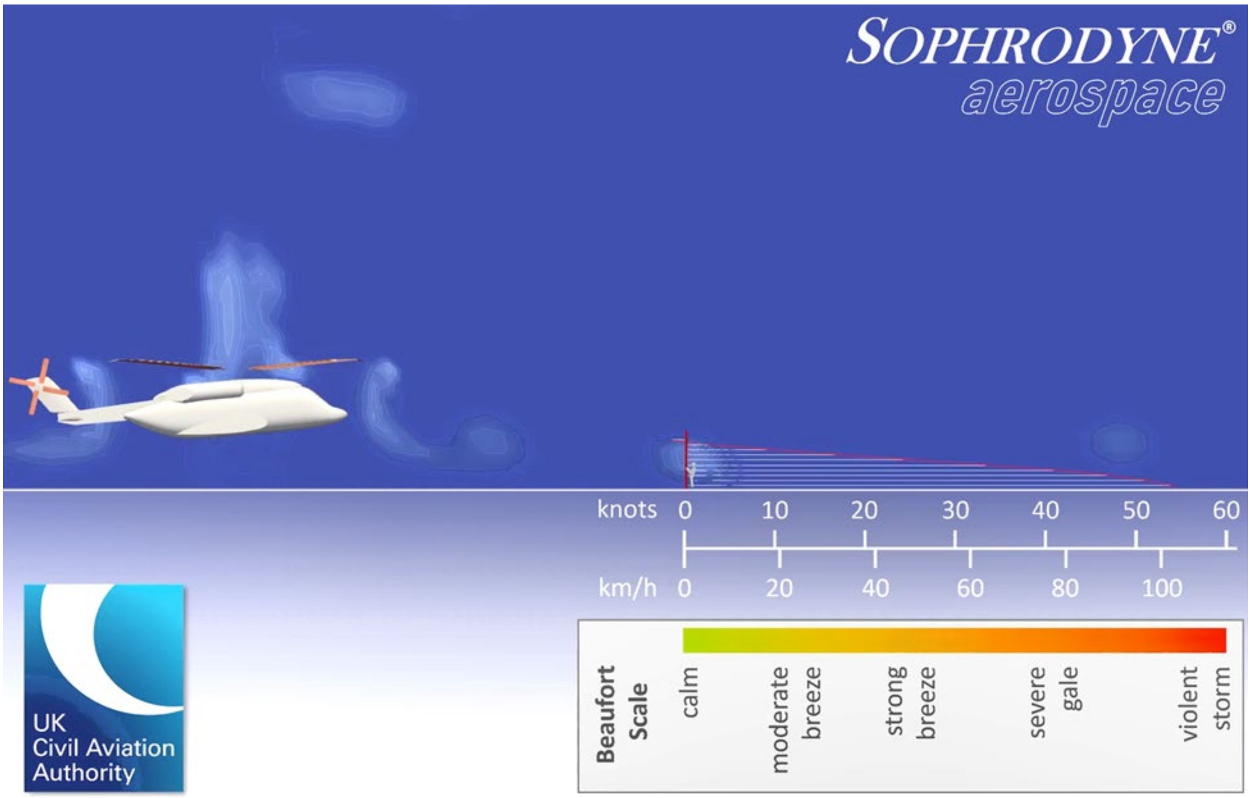

Figure 12. Simulation of SIK-92 helicopter repeating observed conditions from the Caernarfon test. The observer at the centre has a vortical flow structure striking them.

Velocities of around 50 knots are the highest generated by the simulation for anything other than the most fleeting of moments at the heights used in the actual tests (up to ca. 8 feet), as will be clearly seen by watching the videos.

Table 2 shows comparable data for the test condition shown in Figure 12, i.e. 6.5 feet hover and highest measured velocities. Three sets of measurements were made, with the highest velocity in each of three five second windows recorded.

Height	1st set - Knots	2nd set - Knots	3rd set - Knots
7.9 feet	28.3	20.9	28.2
4.8 feet	36.8	36.0	39.9
1.6 feet	43.1	47.4	46.8

Table 2. Three sets of test measurements from Caernarfon matching the conditions shown in Figure 12.

It can be seen that the absolute figures closely match those in the simulation, while the profile of the flow velocities, with velocities declining with height, match those generated in the simulation by a vortical airflow structure striking an observer, as shown in Figure 12.

While performing the real-world test it was physically very apparent that the lowest hover height generated the strongest outwash velocities, and also the most destabilising flows for the observer, with the highest velocities giving a feeling of being ‘punched’ by the air.

The rapid transients that caused this feeling included moments of almost still air as well as unsteadiness driven by airflow from behind, acting to push the observer, who was braced, leaning into the assumed prevailing airflow out from the helicopter as shown in Figure 8.

This reversal of the airflow was also shown by the simulations from Sophrodyne. Figure 13 shows this, with the airflow direction and magnitude again shown by the red line above the observer.

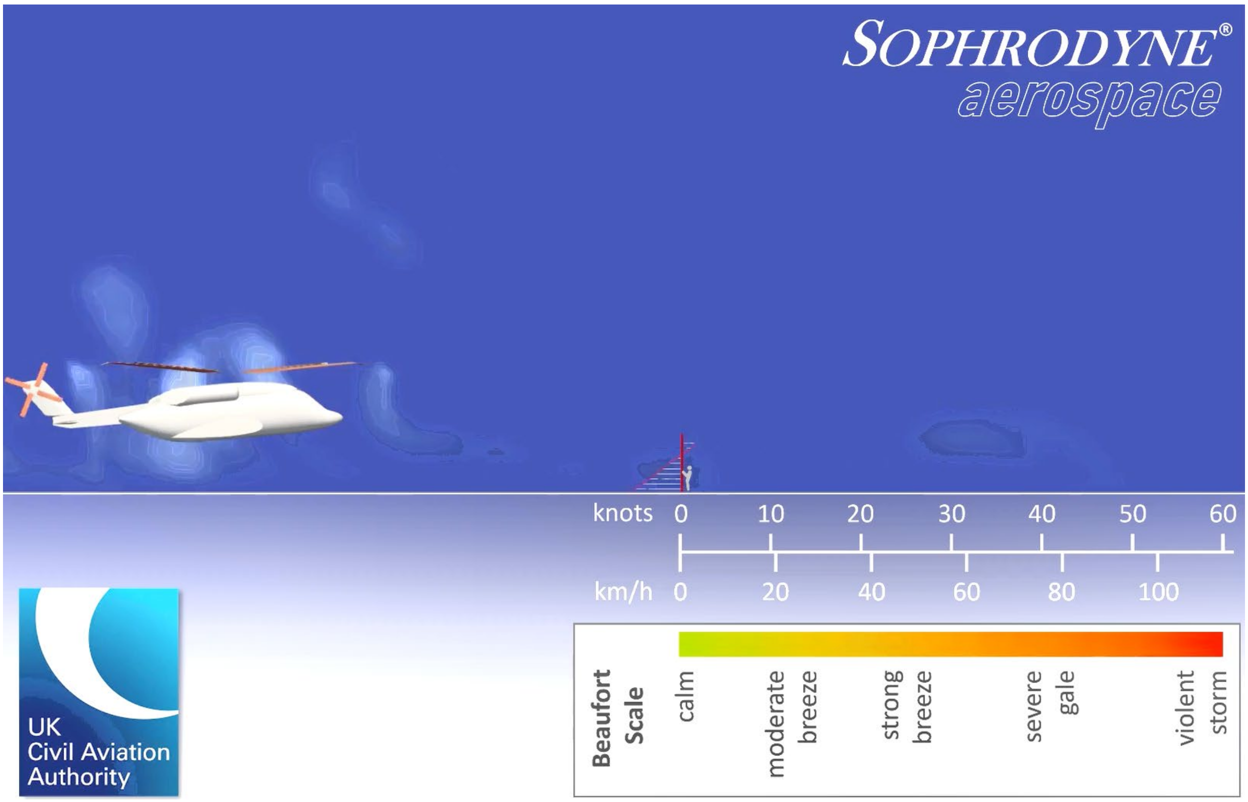

Figure 13. Transient flow reversal shown by simulation.

It was difficult to capture these reversals with the hot wire anemometers as the sensor heads are directional and were oriented to capture flow coming from the direction of the helicopter, not going towards it. However, this would explain some fleeting ‘0’ airspeed readings as well as the rapid rise and fall of the airflow velocities seen on the sensor screen units. However as noted above, the physical sensations felt at the observation point fully accorded with these flow reversals.

Once again, the real-world situation is best understood by watching the simulation videos.

Similarly, different perspectives used in some videos help understand the physics of the airflow as experienced at the test point. While Figures 12 and 13 show a vertical ‘slice’ from the side, similar conditions are shown in three dimensions in Figures 14 and 15.

These images show where vortex-driven airflow with higher velocities are found at particular moments, shown as lighter patches on the ground and near the observer

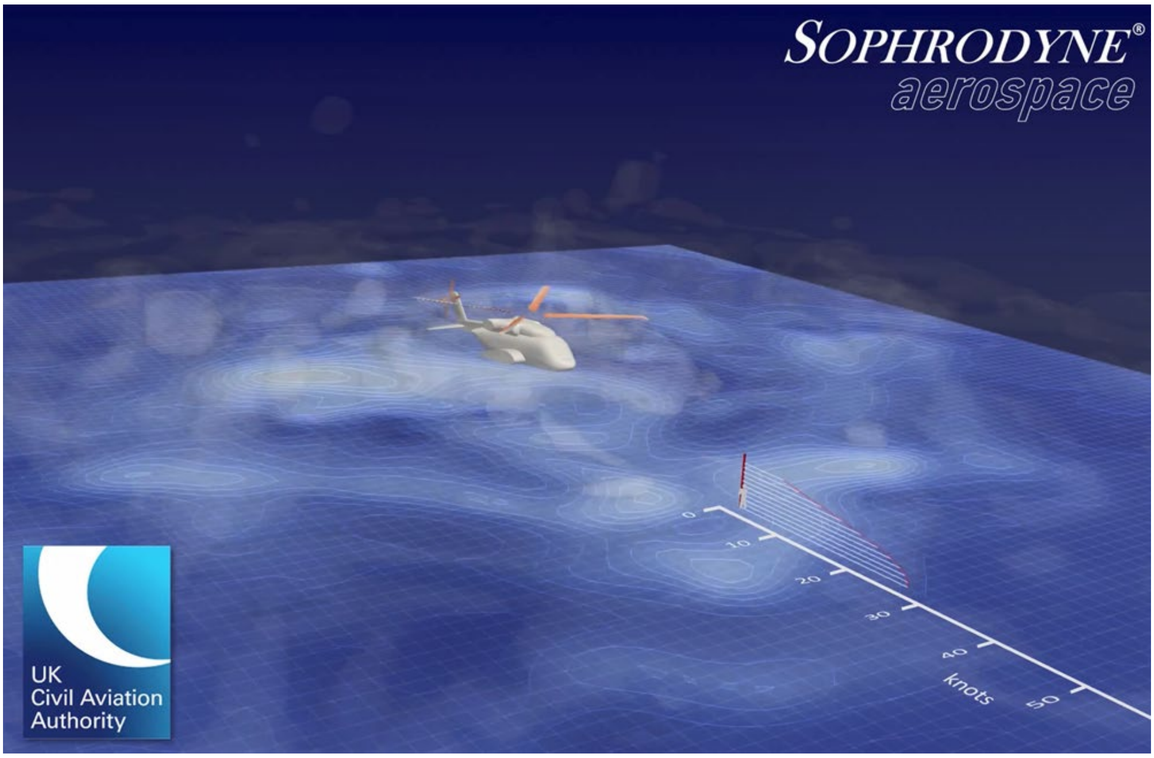

Figure 14. Three-dimensional view of a simulation showing airflow velocities and patches of vorticity in the airflow.

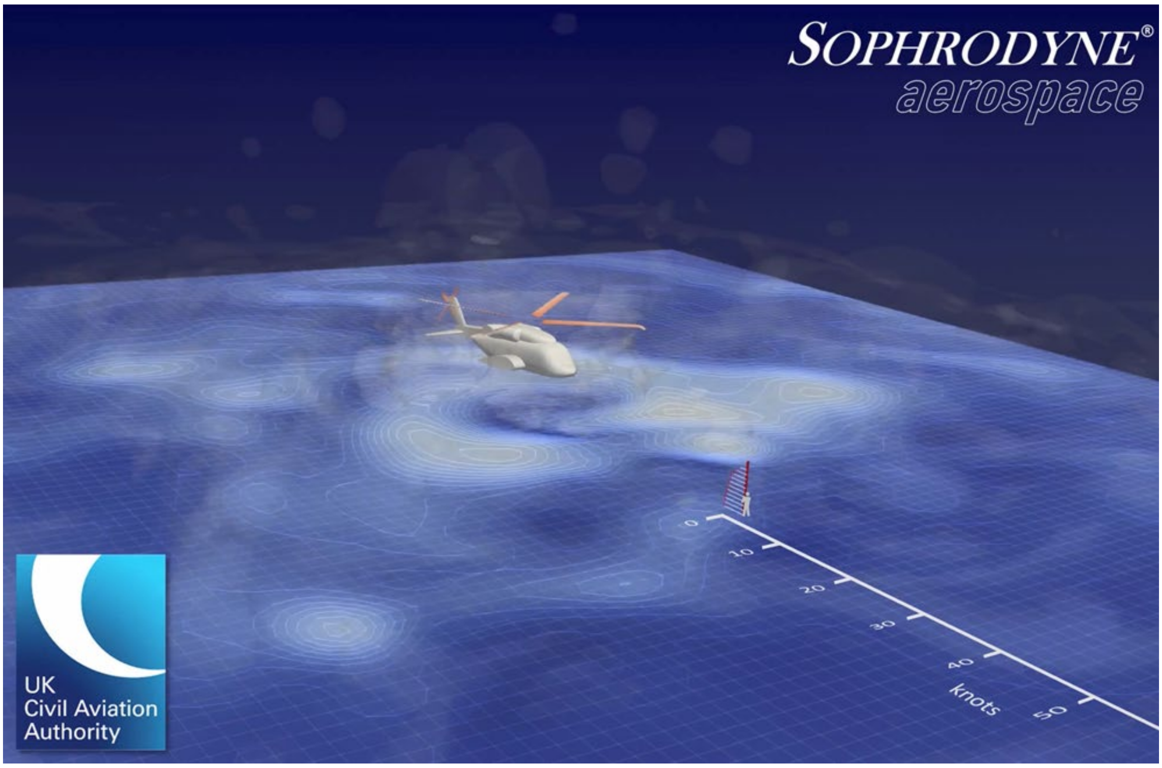

Figure 15. Three-dimensional view of a simulation showing airflow velocities and patches of vorticity in the airflow during a flow reversal.

The videos of the simulation were clearly a powerful tool. They not only matched our data but also allowed a direct understanding of the physics and the flow conditions under the S92 aircraft as experienced by people on the ground.

This ability to 'see the air' shows the complexity of the flows, their highly transient nature and allows a better understanding of what causes people, and objects, on the ground to become unsteady and to be moved by the airflow. It is not simply the strength of the wind, but rather its transient, turbulent, 'swirly' nature, driven by vorticity.

FAA data

During the course of the RATHD project additional data became available from Federal Aviation Administration work measuring downwash and outwash velocities of three eVTOL aircraft[5]. These appear to broadly agree with the predictions made in CAP 2576.

Using much more sophisticated test equipment, but with a test approach that was planned using computer modelling that the FAA report admits did not produce the expected results, the FAA work shows that high and transient velocities can be expected from the downwash and outwash of eVTOL aircraft.

The significance of the maximum velocities measured is hard to gauge without access to the raw recorded data. With measurements taken at 100 Hz and 40 Hz it is possible that peak velocities are too short to affect humans over the 2-5 Hz band identified as significant as part of the CAA RATHD project (see the Discussion section below).

It would be of great value to analyse the FAA data to show results over 0.2 to 0.5 second intervals, and to model it using the Vorticity Transport Model at the test conditions used. The existence of the Air Mobility Platform digital models used in CAP 2576 should make this easier than an ab initio exercise.

Such activities would allow a robust database of real world and simulated helicopter and eVTOL data to be made comparable and available to operators of such air vehicles, as well as to allow a fuller appreciation of risks and mitigations of downwash and outwash.

[5] Maria J. Muia, PhD;, Joshua Stanley; Todd Anderson; David Hall; Zachary Shuman; Jan Goericke; Jagdeep Batther; Zoren Habana; Chengjin He; and Hossein Saberi; Electric Vertical Takeoff and Landing (eVTOL) Downwash and Outwash Surveys, Report number: DOT/FAA/TC-24/42, December 2024, available at https://www.airporttech.tc.faa.gov/Products/Airport-Pavement-Papers-Publications/Airport-Pavement-Detail/electric-vertical-takeoff-and-landing-evtol-downwash-and-outwash-surveys accessed 20th March 2025

Discussion

During the RATHD project two surprises were thrown up:

1. That statistical approaches, such as Weibull analysis, used in the initial treatment of the data gathered in the Silverstone trial and Caernarfon test, is of less use in understanding the physics than direct visualisations of the flow.
2. That the physical effects of outwash on people on the ground include a cognitive effect, as already partly described.

For the first surprise it became apparent the use of visual presentation in the form of videos was far more useful than tables of data in understanding the physics of downwash and outwash, as described in the previous section.

For the second surprise, an attempt was made to quantify the cognitive effects of the transitory flows shown by the modelling and experienced in the tests.

There is an academic and professional literature that focuses on the maximum wind strength that can 'upset' a person. Differences in age and physical capacity are often factored into these models which sometimes represent an idealised human subject. Typical of these are the PAXman model, based on a trained US Marine infantryman.

All these models appear to share an assumption that the combination of the right personal characteristics matched to a maximum windspeed will allow some form of 'safety rating' that would allow safe outwash windspeeds to be determined.

The RATHD work has indicated that it is not a maximum windspeed that may matter but also the rate of change, the transient conditions, in outwash velocities driven by vorticity. These transient conditions also cause unsteadiness for people on the ground. A search of the literature revealed that there was another model that showed the effects of this transient rate of change, rather than maximum 'wind speed', in terms of a relationship between the frequency of gusts and their strength, i.e. the rate of change experienced.

Higher frequency gusts can allow higher peak airflow velocities to be tolerated, as shown in Figure 16.[6]

[6] S.C. Jordan , T. Johnson , M. Sterling, C.J. Baker; Evaluating and modelling the response of an individual to a sudden change in wind speed; Building and Environment 43 (2008) 1521–1534

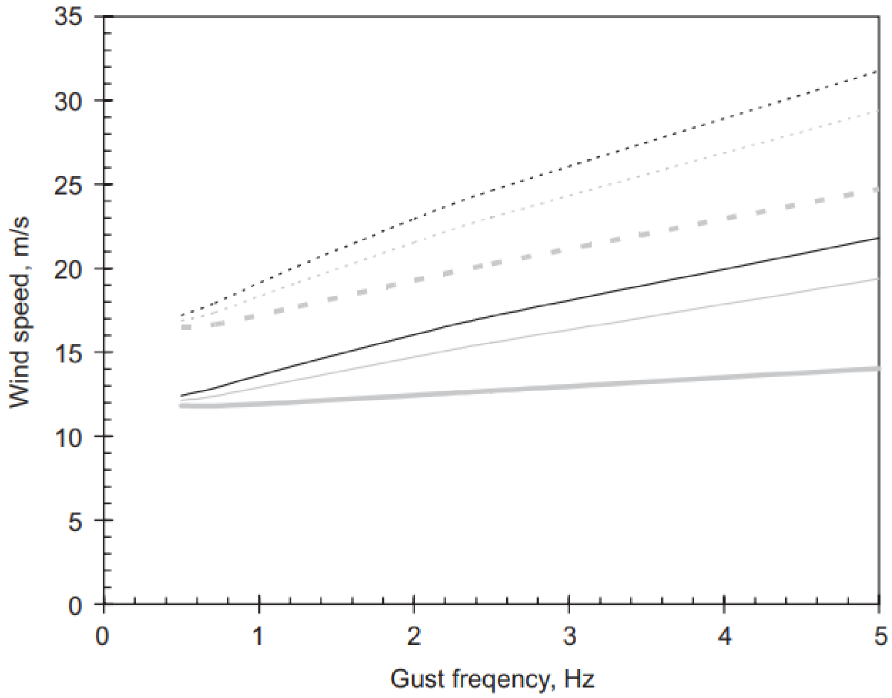

Figure 16. Gusts predicted to cause a loss of balance for a 50th percentile height/weight man facing the wind (dashed lines) and 50th percentile female child (solid lines). Source Jordan et al, 2008.

The work in Jordan et al (2008) shows that a sudden 'step change' in wind strength, caused by a gust with a duration of about 0.2-0.5 seconds (2-5 Hertz) can be enough to blow a person over. Additional factors complicate the calculation, such as orientation of the person to the gust direction (e.g. a person's feet tend to stabilise them more against gusts from behind) but the main factor appears to be the speed of response of the human nervous system to stabilise against the acceleration imparted by the gust.

This provoked some consideration of whether the cognitive problems experienced during the RATHD work are directly related to instability and could be similarly quantified. Although clearly post hoc, an attempt was made to use the Bedford scale that is used to assess the cognitive loading of piloting tasks.[7]

The Bedford scale is shown in Figure 17. It is used by many flight test organisations, including NASA, who note that for critical tasks a rating of 3 or less is desired, while for non-critical tasks a rating of 6 or less is desirable.

[7] A.H. Roscoe; Assessing pilot workload in flight. In: Conference Proceedings No.373. Flight Test Techniques, AGARD, Paris (1984)

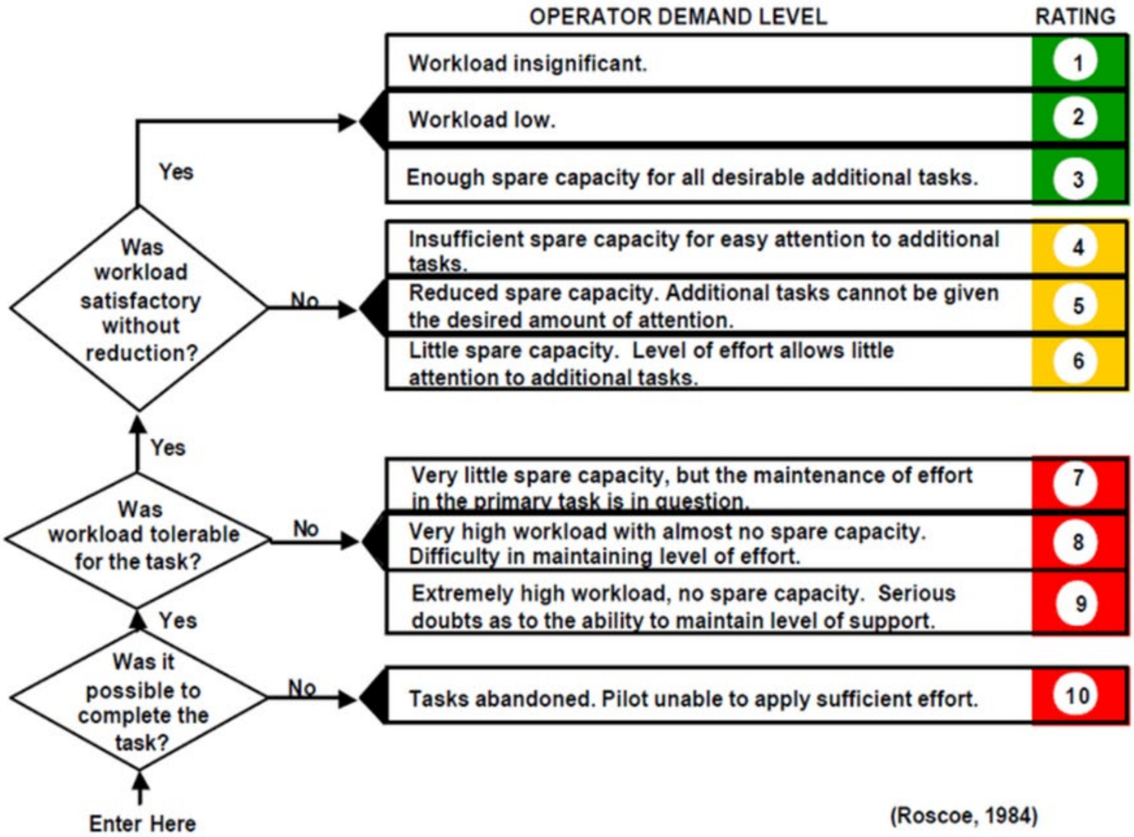

Figure 17. The Bedford Scale

The CAA staff involved in the Silverstone and Caernarfon trial and test were asked to rate the difficulties found using the Bedford scale for both physical and cognitive tasks. It is of note that the tasks carried out, standing upright while holding a small sensor at arm's length and reading a number off a screen and writing it down on paper, are very simple, at worst perhaps level 3 on the Bedford scale, and more likely between levels 1 and 2.

The results obtained indicate the effect of outwash on human performance of these tasks are shown in Tables 3 and 4.

Person	**Physical**	**Cognitive**
A	7	8
B	7	5
C	6	5
D - On own (with assist)	3 (3)	9-10 (6)
E (task lead)	6	7

Table 3. Bedford ratings for CAA staff at Silverstone trial

Person	Physical	Cognitive
D (stood behind)	3	5 both cases
E (task lead)	8 (at 2m) – 6 (20m)	5 both cases
F (writing only)	6 (at 2m hover) 4 (at 20m hover)	5-6

Table 4. Bedford ratings for CAA staff at Caernarfon test

The CAA team were all male, in good health, and several had extensive exposure to aviation environments as pilots, airport ground staff and military personnel.

The results are stark. It should be re-emphasised that this is post hoc analysis and that a properly run assessment of a Bedford rating would require prior briefing and training and controlled recording of data. However, the strength of the findings shown in Tables 3 and 4 indicate the potential cognitive effects of outwash on humans.

One notable feature of these effects was a form of short-term memory loss where, in the time between looking at a number on the screen and writing it down, it would be forgotten. This happened with individuals and between team members such that a process of constant checking was required. This may have significance in safety management where, for example, warning signs or verbal instructions need to be assimilated or acted on when in an outwash or downwash flow field.

The Bedford ratings do show some possible trends. Experience from the Silverstone trial allowed a briefing before the Caernarfon test, and this may explain the reduction in cognitive load for persons D and E who were at both events, despite the later Caernarfon event imposing a higher physical rating.

This may indicate that while physical ratings are ultimately a product of the physics of the airflow – people and objects will be overcome by sufficient force - the cognitive rating may be amenable to training to reduce risks.

Clearly this post hoc Bedford rating exercise serves only to highlight the physical and cognitive issues of performing a task for individuals. When combined with the work looking at the strength and frequency of gusts required to blow a person over shown by Jordan et al (2008) it starts to present the challenge for assessing third party and other ground risks from outwash as more complex than a simple maximum wind speed approach.

The transitory nature of the airflow may mean lower-than-expected airflow velocities may pose greater than expected risks.

Next Steps

As the RATHD work progressed it became clear that it was generating insights that could turn what had been theoretical knowledge into more readily useful tools. Although not the purpose of the RATHD project, it appears that some of these tools could be made widely useful with only limited additional effort, a focus of ongoing CAA work:

1. Sophrodyne's modelling has shown a powerful visual way to help train people on the ground about what to expect from downwash and outwash. By showing the complex physics and the transient airflows, as well as quantifying the maximum velocities and rates of change that could be experienced, videos of this nature can replace the simpler view of downwash and outwash as a wind described earlier in the report. A moving picture 'paints 10,000 words' and may offer a real boost to communicating vital safety information with something as dynamic and variable as downwash and outwash.

2. It may be possible to harness the data in old reports to support further modelling in place of more 'real world' testing. This would allow a rapid extension of verification and validation of the VTM model as well as other computational methods. A short trial was undertaken of artificial intelligence to see what was possible. This consisted of an initial attempt to develop prompts for ChatGPT, Microsoft Copilot and Grok3, based on large language models (LLMs). These showed that existing LLMs were reasonably good at identifying the issues and risks generated by downwash and outwash but were unreliable and inconsistent in possible mitigations or understanding the underlying physics.

   A second attempt, using material that the CAA was able to get copyright clearance on, explored a small, bespoke artificial intelligence model dubbed 'VertAI'. Using the LangChain software framework PDF reports were 'chunked' (i.e. broken into 500-word sections). It was found that to generate realistic outputs the text and data chunks required considerable context to be added to generate useful outputs, but it is possible. An exercise at scaling the content of 'VertAI' may allow a more efficient process to generate data.

3. A better understanding of the cognitive effects of downwash and outwash could be found using a structured trial of their effects with the Bedford rating scale. This could use experienced and trained ground and air crews in a near-repeat of the Caernarfon trial to obtain proper data. Allied with modelling of human responses on the ground and in the cockpit, this could allow a rating of the aerodynamic effects of downwash and outwash on human responses. In addition, wider regulatory, academic and other research organisations could explore the wider causes of the possible cognitive effect.

Summary

This report has shown that a simple approach provides a limited verification and validation of the simulations and modelling of helicopters and of the eVTOL aircraft explored in CAP 2576.

While the limited data appeared to match well, of more significance was the ability to match digital simulations with the visceral experience of people exposed to a downwash and outwash flow field. This ability to show the physics that drives human responses is a potentially powerful new approach to understanding the safety risks of downwash and outwash, as well as in identifying new ways to address them.

Model visualisation of airflows may help prepare and train people on the ground to respond safely to outwash and downwash. By understanding the physics and seeing the airflows it is hoped that the potential risks presented by the previous, simplified, view of outwash and downwash as a 'linear wind' can be avoided. The complex, transient and vortex-dominated flow needs to be properly understood to ensure safe flight operations.

The identification of a previously unreported cognitive effect of downwash and outwash, and a method by which to gauge it, may also allow future risks to be avoided well before flight operations begin. This should allow increased safety by eliminating unexpected surprises for operators in the high-volume, growth generating end of the innovation process, as well as helping to develop mitigations to improve current operations.

By changing our view of outwash and downwash, to capture its true physical form, we can show how it connects to human responses to protect future flight operations and all people engaged with them, including third parties. Figure 18 highlights this view.

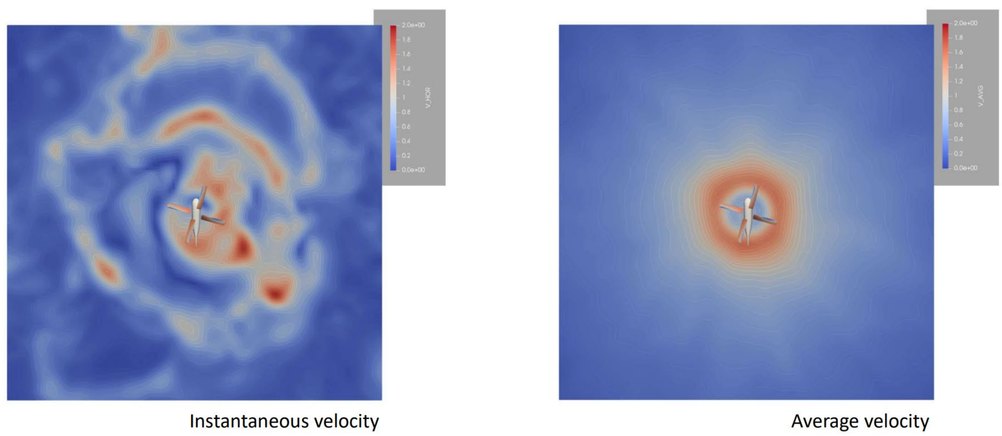

Figure 18. A physics-based view of outwash (left) shows its messiness and transience, in contrast to the time-averaged view of a 'doughnut' of air forming a circle that may understate the dangers. Image Copyright Sophrodyne Aerospace.

Appendix A

Raw Simulation Data

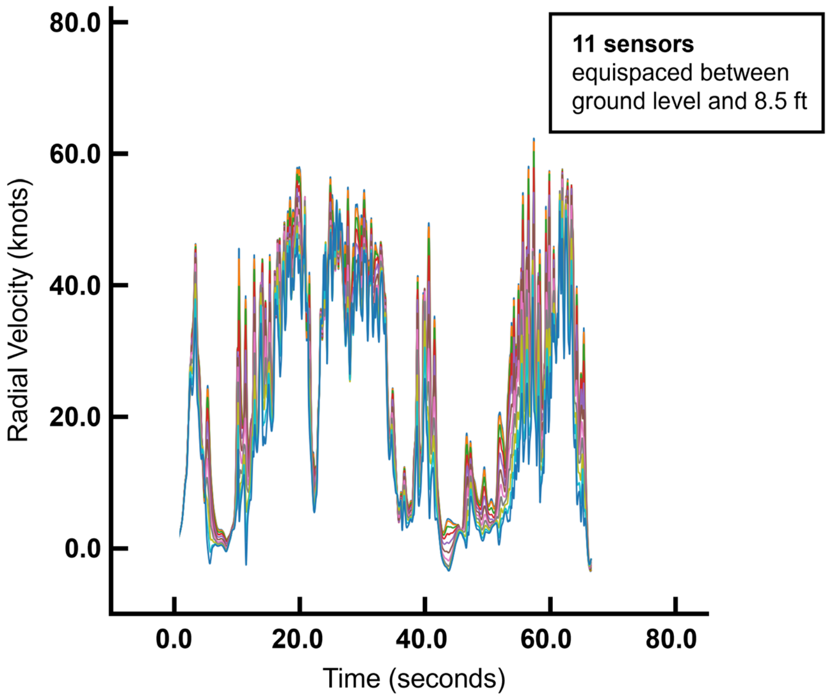

Figure A1. AMP-Heavy simulation data at flight condition Alpha (65 feet hover)

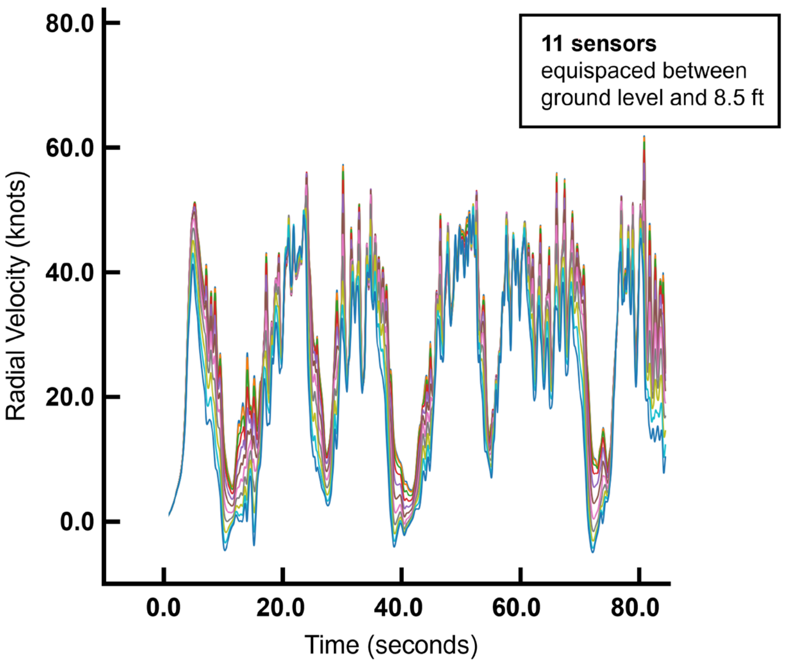

Figure A2. SIK-92 simulation data at flight condition Alpha (65 feet hover)

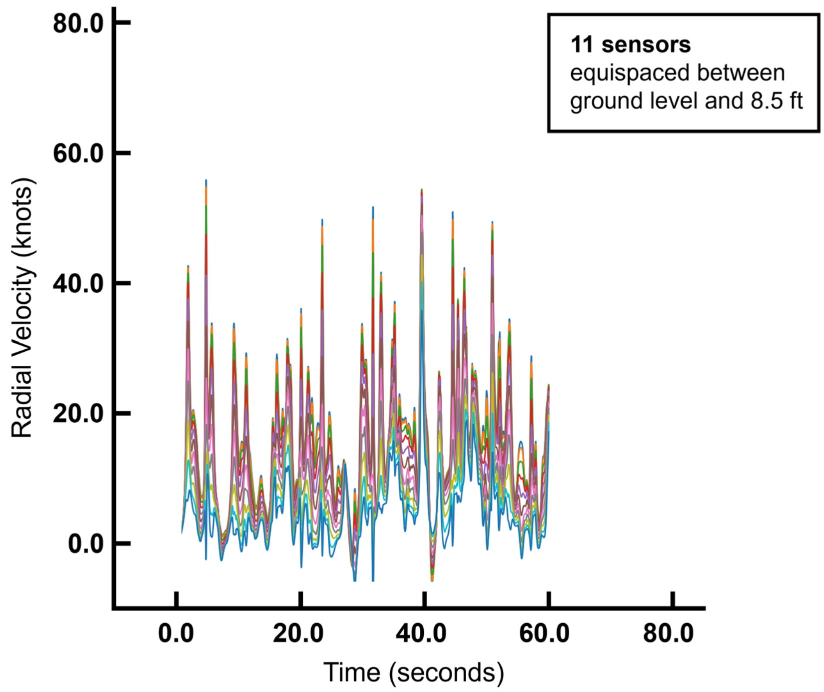

Figure A3. AMP-Heavy simulation data at flight condition Bravo (6.5 feet hover)

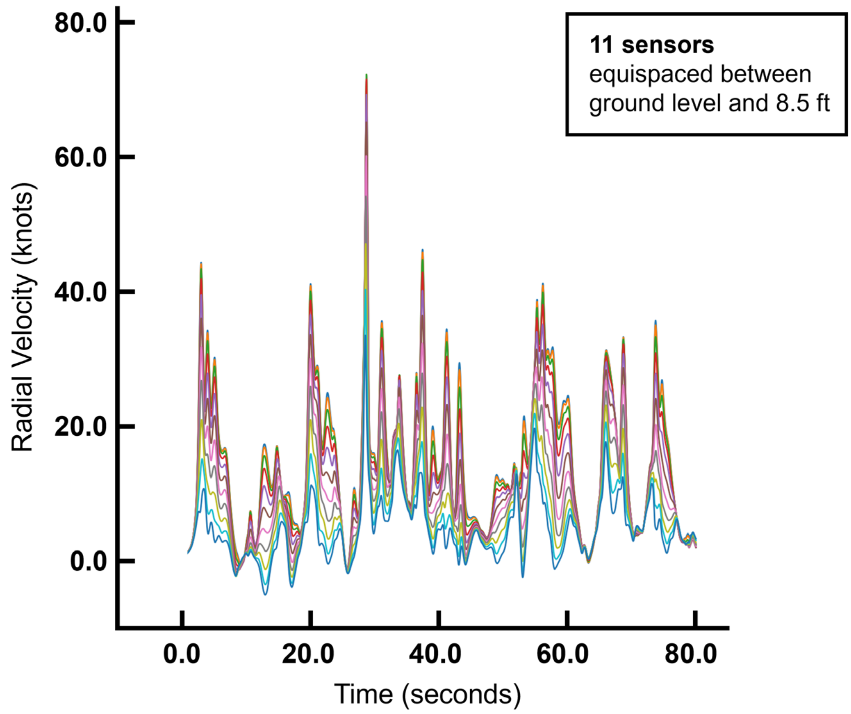

Figure A4. SIK-92 simulation data at flight condition Bravo (6.5 feet hover)

Appendix B

Abbreviations used in CAP 3075

- AMP – Air Mobility Platform
- CAA – Civil Aviation Authority
- CFD – Computational fluid dynamics
- Dstl – Defence Science and Technology Laboratory
- eVTOL – Electric vertical take-off and landing
- FAA – Federal Aviation Administration
- Hz – Hertz
- IPLC – International Powered Lift Conference
- LLM – Large Language Model
- NASA – National Aeronautics and Space Administration
- RANS – Reynolds Averaged Navier Stokes
- RATHD – Research Assessment of Transitory Helicopter Downwash
- RPAS – Remotely Piloted Air System
- VTOL – Vertical take-off and landing
- VTM – Vorticity Transport Model
- V&V – Verification and validation