



Australian Government
Australian Transport Safety Bureau

A safety analysis of remotely piloted aircraft systems

A rapid growth and safety implications for traditional aviation

Second edition

January 2012 to June 2017



Research

ATSB Transport Safety Report

Aviation Research

AR-2017-016a

Final – 9 August 2017

Publishing information

Published by: Australian Transport Safety Bureau
Postal address: PO Box 967, Civic Square ACT 2608
Office: 62 Northbourne Avenue Canberra, Australian Capital Territory 2601
Telephone: 1800 020 616, from overseas +61 2 6257 4150 (24 hours)
Accident and incident notification: 1800 011 034 (24 hours)
Facsimile: 02 6247 3117, from overseas +61 2 6247 3117
Email: atsbinfo@atsb.gov.au
Internet: www.atsb.gov.au

© Commonwealth of Australia 2017



Ownership of intellectual property rights in this publication

Unless otherwise noted, copyright (and any other intellectual property rights, if any) in this publication is owned by the Commonwealth of Australia.

Creative Commons licence

With the exception of the Coat of Arms, ATSB logo, and photos and graphics in which a third party holds copyright, this publication is licensed under a Creative Commons Attribution 3.0 Australia licence.

Creative Commons Attribution 3.0 Australia Licence is a standard form license agreement that allows you to copy, distribute, transmit and adapt this publication provided that you attribute the work.

The ATSB's preference is that you attribute this publication (and any material sourced from it) using the following wording: *Source:* Australian Transport Safety Bureau

Copyright in material obtained from other agencies, private individuals or organisations, belongs to those agencies, individuals or organisations. Where you want to use their material you will need to contact them directly.

Addendum

Page	Change	Date

Note for second edition

Since the publication of the ATSB report *A safety analysis of remotely piloted aircraft systems 2012 to 2016* ([AR-2017-016](#)) in March 2017, the ATSB has observed a significant change in the trend of reported occurrences involving Remotely Piloted Aircraft Systems (RPAS). **Contrary to the previous report, our most current forecasts predict the total number of RPAS occurrences reported to the ATSB in 2017 to be comparable to 2016.** Further, the recent publication of a joint report by the UK Department for Transport, Military Aviation Authority and the British Airline Pilots' Association has provided additional information regarding the consequences of a collision between RPAS and manned aircraft.

Due to this new information and the lack of data present in the public arena, the ATSB opted to publish a new edition of the report detailing our current understanding of the implications to transport safety associated of RPAS activity in Australia. **Data presented in this edition is current to the end of June 2017.**

Safety summary

Why the ATSB did this research

The growth in the number of remotely piloted aircraft systems (RPAS) in Australia is increasing rapidly. This presents an emerging and insufficiently understood transport safety risk.

The ATSB aims through this report to present data and analysis to further understanding of the implications for transport safety associated with the continual growth of RPAS activity in Australia.

What the ATSB found

Although accurate assessments of the number of RPAS in Australia is not possible, using proxy data, it is clear that the number of RPAS in Australia is growing rapidly each year. Compared to 2016, there will be a possible doubling in the number of systems in Australia by the end of 2017.

In association with the level of growth, the number of RPAS-related safety occurrences reported to the ATSB increased rapidly during the 2012 to 2016 period. However, the first half of 2017 saw significantly fewer occurrences than predicted given the previous data. Current forecasts—incorporating data up to the end of June 2017—predict the number of RPAS occurrences reported to the ATSB in 2017 to be comparable to 2016.

Over half of all occurrences from January 2012 to June 2017 involved near encounters with manned aircraft, almost three-quarters occurred between January 2016 and June 2017. Most occur in capital cities, Sydney in particular, and above 1,000 ft above mean sea level (AMSL).

To date, there have been no reported collisions between RPAS and manned aircraft in Australia.

The next most common type of occurrence involved collisions with terrain, almost half of which results from a loss of control of the RPAS.

The consequences of collisions between RPAS and manned aircraft are not yet fully understood. World-wide, there have been five known collisions. Three of these resulted in no damage beyond scratches. However, one collision with a sport bi-plane in the United States in 2010 resulted in a crushed wing. Fortunately, the aircraft landed safely. Less fortunately, a Grob G 109B motor glider had a wing broken by an RPAS collision in 1997 in Germany, resulting in fatal injury to the two people on board.

Due to the rarity of actual collisions, there is limited data from which to draw conclusions regarding the possible outcomes. Laboratory testing and mathematical models produced by various agencies have been used in conjunction with abundant aircraft birdstrike data in an attempt to assess the probable consequences of a collision.

RPAS collisions with high capacity air transport aircraft can be expected to lead to an engine ingestion in about eight per cent of strikes. The proportion of ingestions expected to cause engine damage and engine shutdown will be higher than for bird ingestion (20 per cent of ingestions).

RPAS have the potential to damage a general aviation aircraft's flight surfaces (wings and tail), which could result in a loss of control. Furthermore, a collision with a general aviation aircraft's windscreen poses a high risk of penetration.

A collision with a helicopter's windscreen poses a similar penetration risk. Any impact on a helicopter's tail rotor could cause catastrophic failure of the rotor.

Safety message

The operation of remotely piloted aircraft is an emerging risk to transport safety that requires close monitoring as the popularity of these aircraft continue to rapidly grow.

Contents

Executive Summary	1
Ownership	1
Near encounters	1
Terrain collisions	1
Consequence risk of a collision with a manned aircraft	2
Analysis of RPAS ownership.....	4
CASA registered RPAS certificate holders	4
Google trends	5
Analysis of RPAS safety occurrences.....	7
Interference with manned aircraft (near encounters)	9
Terrain collisions	17
Consequence analysis of RPAS collisions with other aircraft	25
Probable strike locations	26
Possible damage	28
Possible airframe damage	29
Possible engine damage	33
Conclusions	35
Australian Transport Safety Bureau	36
Purpose of safety investigations	36
Developing safety action	36

Executive summary

Ownership

The number of remotely piloted aircraft systems (RPAS) is growing rapidly in Australia. At the end of June 2017, there were around 1,050 CASA registered RPAS certificate holders in Australia. However, as not all RPAS require CASA certificates, the total number of RPAS in Australia is unknown.

Forecasts, based on the growth of CASA certified operators and Google trends shopping data as proxies for real total numbers, indicate that the number of RPAS in Australia is likely to double by the end of 2017 compared to 2016 numbers. Assuming the probability of an RPAS-related safety occurrence is relative to the number of RPAS, this suggests a significant increase in the expected number of occurrences by the end of 2017. This increase was not observed in the first half of 2017. Current forecasts predict the total number of RPAS-related occurrences in 2017 to be comparable to 2016.

Near encounters

Over 60 per cent of the 242 occurrences recorded since January 2012 involved near encounters with manned aircraft. Near encounters occur when an RPAS interrupts or is sighted in the proximity of another aircraft. Occurrences only include those encounters where the aircraft had to manoeuvre (or would have manoeuvred if there was more opportunity) to maintain a safe distance from the remotely piloted aircraft.

Almost three-quarters of all reported RPAS near encounters with other aircraft between January 2012 and June 2017 (154 occurrences), occurred since January 2016 (114 occurrences). However, current (until 30 June 2017) statistical models forecast the total number of near encounters in 2017 are likely to be comparable to 2016.

To date, there have been no reported collisions between RPAS and manned aircraft in Australia.

Almost half of all reported near encounters involved high capacity air transport aircraft.

Most occurrences happened in the main capital cities, with Sydney accounting for 40 per cent of all near encounters.

The altitude of the RPAS was known in around 85 per cent of reported near encounters. The majority of these took place above 1,000 ft above mean sea level (AMSL), with about half between 1,000 ft and 2,000 ft. Around 21 per cent were above 5,000 ft. As RPAS are almost never identified for these occurrences, the ATSB does not know if they were certified RPAS, model aircraft, or toys. Given the heights (mostly above 1,000 ft), locations (mostly urban areas), and over-representation of weekends for reported near encounters, it is likely the majority of RPAS involved were not being used commercially (e.g. for aerial photography).

The standard operating conditions for uncertified RPAS in Civil Aviation Safety Regulation Part 101 include visual line of sight, less than 400 ft, outside of controlled airspace and 5 km away from aerodrome boundaries and in non-populated areas. As most reported near encounters occurred outside of these conditions, it appears that the operators of these RPAS were either unaware or were unconcerned about these rules.

Terrain collisions

The second most common type of RPAS-related occurrence involved collisions with terrain, accounting for 64 occurrences between January 2012 and June 2017, 47 of which occurred since January 2016.

Around 40 per cent of the RPAS involved in terrain collisions reported to the ATSB, had a mass above 7.5 kg and a quarter were between 2.75 and 3.65 kg. Three RPAS terrain collisions had an aircraft mass above 25 kg. About 19 per cent were below 2 kg, however this may be related to a lower reporting rate by operators of these very small aircraft to the ATSB.

Only around 45 per cent of terrain collisions were near a capital city. About one-third of terrain collisions were in urban environments, including the heavier remotely piloted aircraft (average mass 6.8 kg).

Where known, terrain collisions were most commonly associated with a loss of control (about 42 per cent), a bird striking the RPAS (about 11 per cent), or an engine failure or malfunction (11 per cent).

Consequence risk of a collision with a manned aircraft

While the exposure risk to manned aircraft is increasing, the consequence risk for a collision with an RPAS is unclear.

Although there have been no mid-air collisions in Australia involving RPAS reported to the ATSB, world-wide, there have been five known collisions and one suspected collision. Three of these resulted in no damage beyond scratches, including the suspected collision with an Airbus A320 at Heathrow Airport in April 2016. However, one collision with a sport bi-plane in the US in 2010 resulted in a crushed wing. Fortunately, the aircraft landed safely. Less fortunately, a Grob G 109B motor glider had a wing broken by an RPAS collision in 1997 in Germany, resulting in fatal injury to the two people on board.

Due to the rarity of actual collisions, and limited actual testing, mathematical models have been used to predict damage expected from collisions with RPAS. These are informed by abundant birdstrike data with about 2,000 birdstrikes recorded in Australia for 2015.

ATSB birdstrike analyses shows that 7.7 per cent of high capacity aircraft birdstrikes result in engine ingestions (20 per cent of which led to engine damage), with smaller aircraft having lower ingestion rates.

Aircraft damage from birdstrike analysis shows engines are most likely to be damaged in high capacity aircraft, followed by wings. For low capacity air transport aircraft, wings are most likely to be damaged, and to a much lesser extent, engines and propellers. For general aviation aircraft, again damage to wings is most likely, and to a much lesser extent, windscreens.

It should be noted that while only 6 per cent of high capacity aircraft birdstrikes result in damage, 25 per cent of birdstrikes to general aviation aircraft result in damage. This is a result of more fragile parts in general aviation aircraft including wings and windscreens.

As remotely piloted aircraft are rigid and generally heavier than most birds, the overall proportion of collisions resulting in aircraft damage is expected to be higher than for birdstrikes, and the distribution of damage across an airframe will probably also differ.

Recent laboratory testing and computational modelling by the UK Department for Transport and Military Aviation Authority (DFT/MAA) found that air transport-standard aeroplane windscreens could withstand an RPAS collision at typical landing/approach speeds. At higher speeds, complete structural failure of the windscreen was found to be possible upon impact with a 4 kg quadcopter, but not with a 1.2 kg quadcopter.

For general aviation aircraft, the DFT/MAA study found that even a 400 g quadcopter (the lightest RPAS tested) could penetrate non-birdstrike certified helicopter windscreens at speeds well below their expected cruise. General aviation aircraft without birdstrike certified windscreens were therefore also found to be at risk. The study also highlighted the risk posed to helicopter tail rotors. The invariably high impact speed resulted in critical damage to the rotor, even when struck with the lightest, 400 g quadcopter.

Without more information, it is difficult to thoroughly assess the risk of occurrence and the severity of the outcome for an RPAS collision. However, some observations based on the current literature and the ATSB analysis include:

- While research has been done looking at birdstrikes, and collisions with rocket and satellite debris, there is still much uncertainty regarding the consequences of a collision between an RPAS and an air transport aircraft. Although the probability is likely to be low, RPAS components could conceivably penetrate the wing or fuselage of an air transport aircraft.
- Engine ingestion in high capacity air transport aircraft (mostly with large turbofan engines) can be expected for about eight per cent of RPAS collisions based on birdstrike data. The proportion of RPAS ingestions expected to cause engine damage and engine shutdown will be higher than for bird ingestion. However, loss of a single engine should have minimal consequence to the safety of the aircraft.
- RPAS collisions with a general aviation aircraft's windscreen poses a high risk of penetration. The risk is considerably lower for an air transport aircraft, as the energy required to penetrate these windscreens necessitates a heavy RPAS and cruising speed/altitude.
- RPAS have the potential to damage a general aviation aircraft's flight surfaces (wings and tail), and helicopter tail rotors, which could result in a loss of control.
- For a single engine (general aviation) aircraft, an engine ingestion could cause an engine failure, requiring a forced landing. However, the probability of ingestion is very low due to small engine intakes. It would be more common for the propeller to contact the RPAS, which could cause some propeller damage resulting in a precautionary or forced landing.

Analysis of RPAS ownership

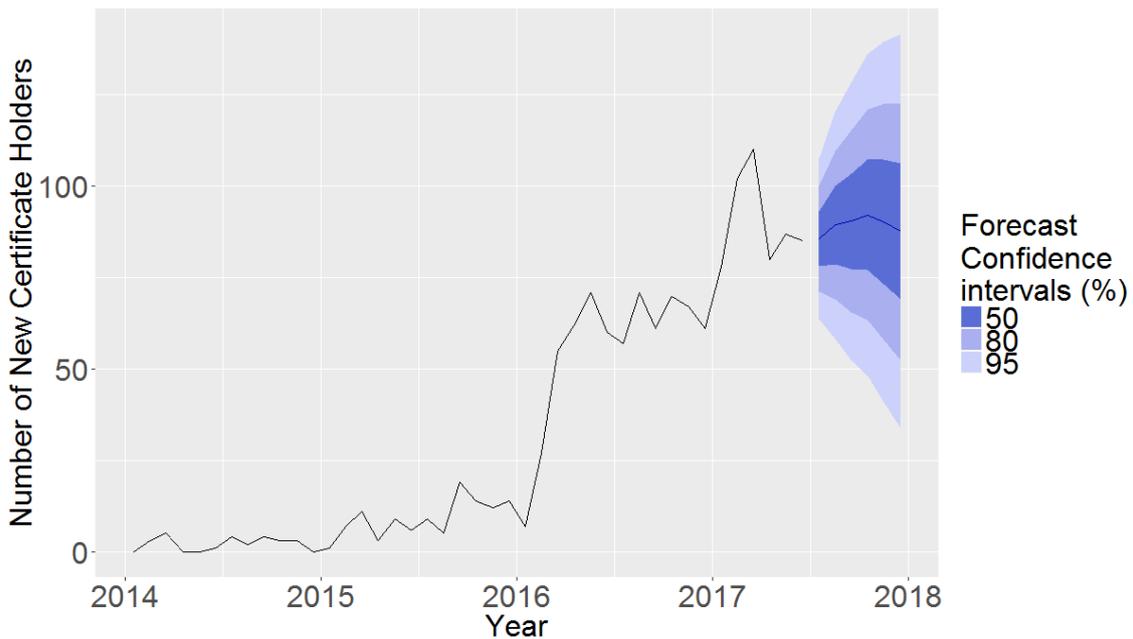
The number of remotely piloted aircraft systems (RPAS) is growing rapidly in Australia. The total number of RPAS in Australia is unknown as not all RPAS require Civil Aviation Safety Authority (CASA) certificates. At the end of June 2017, the CASA website showed there were around 1,050 registered RPAS certificate holders in Australia.

There are currently no records of the number of RPAS hours flown in Australia as there are for other aircraft types (recorded by the Bureau of Infrastructure, Transport and Regional Economics).

CASA registered RPAS certificate holders

CASA registered RPAS operators likely comprise only a proportion of the total RPAS operators in Australia. However, the growth in their number is probably a good indicator of the general growth of RPAS in Australia (Figure 1).

Figure 1: Number of new CASA registered RPAS certificate holders per month (Jan 2014–Jun 2017). The blue regions are the 50th, 80th and 95th per cent confidence intervals for the forecast (up to Dec 2017) calculated using an ARIMA model^{1,2}



Source: CASA Register (www.casa.gov.au)

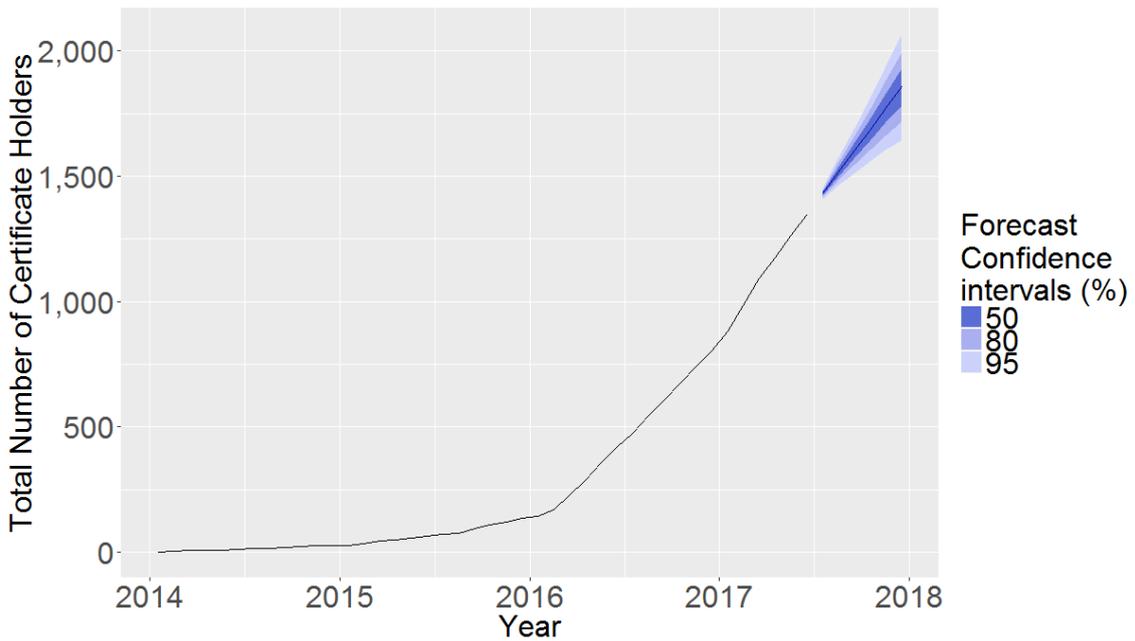
The cumulative effect of this level of growth in the number of new CASA RPAS certificate holders, assuming the operators still maintain ownership of their aircraft, leads to a more than doubling in total RPAS certificate holders at the end of 2017 compared to 2016 (Figure 2).

¹ Rob Hyndman (2016). *forecast: Forecasting Functions for Time Series and Linear Models*

² Plot created using the 'ggplot2' package in R:

Wickham, H. 2009, *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York.

Figure 2: Total number of CASA registered RPAS certificate holders (Jan 2014–Jun 2017). The blue regions are the 50th, 80th and 95th per cent confidence intervals for the forecasts (up to Dec 2017) calculated using an ARIMA model ^{1,2}

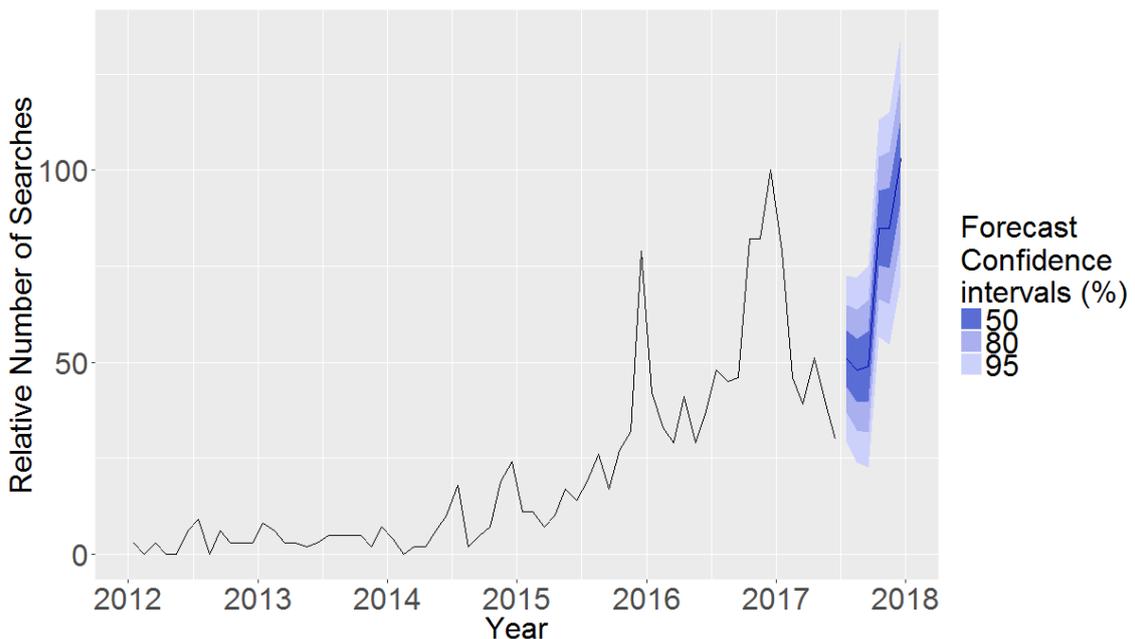


Source: CASA Register (www.casa.gov.au)

Google trends

Another good resource to estimate the growth of RPAS in Australia is Google trends. This tool was used to retrieve the number of people searching for RPAS (and several other pseudonyms) on the Google shopping site within Australia (Figure 3). Although this does not equate to the number of people who purchased an RPAS, it is a reasonable indicator of the number of people interested in purchasing an RPAS.

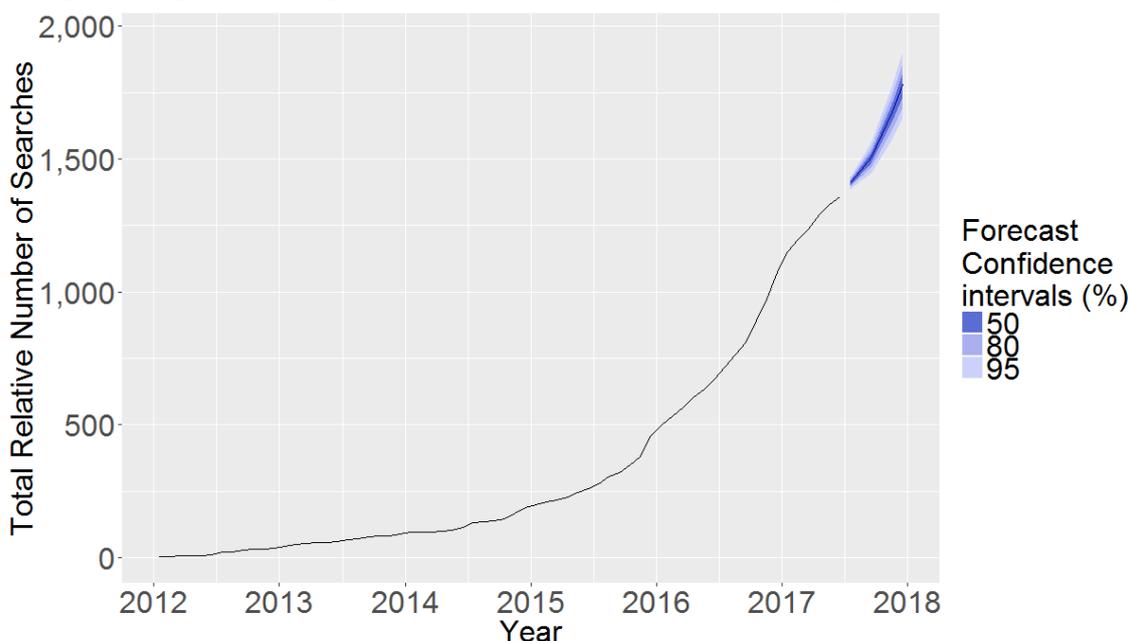
Figure 3: Number of Google shopping RPAS searches (Jan 2012–Jun 2017) normalised to 100 at peak demand (Dec 2016). The blue regions are the 50th, 80th and 95th per cent confidence intervals for the forecasts (up to Dec 2017) calculated using an ARIMA model ^{1,2}



Source: Google Trends (www.google.com.au/trends/)

Peaks in the number of searches can be seen in December each year. Similar to the number of CASA RPAS certificate holders, it can be seen that demand has increased significantly in 2016. Figure 4 shows the cumulative effect—assuming a constant proportion of people searching online then purchase an RPAS, showing an expected exponential growth in the number of RPAS in Australia.

Figure 4: Total number of Google shopping RPAS searches in Australia (Jan 2012–Jun 2017) normalised to 100 at peak demand (Dec 2016). The blue regions are the 50th, 80th and 95th per cent confidence intervals for the forecasts (up to Dec 2017) calculated using the weighted average of ARIMA and Exponential smoothing state space models^{1,2}



Source: Google Trends (www.google.com.au/trends/)

Unlike data from the CASA register, the growth in number of searches has significantly decreased over the last six months. The total relative number of searches in the first half of 2017 was only 35 per cent greater than the first half of 2016, with the total for 2017 expected to be around 65 per cent greater than 2016—this is almost half of the previous year’s growth rate. Non-commercial growth in RPAS in Australia has possibly begun to level-off compared to rapid growth of previous years. However, the uncertainty in the forecast is high, as seen by the size of the confidence interval. Due to this, the forecasts are considered indicative only and are not intended to be accurate predictions of the growth of RPAS in Australia.³

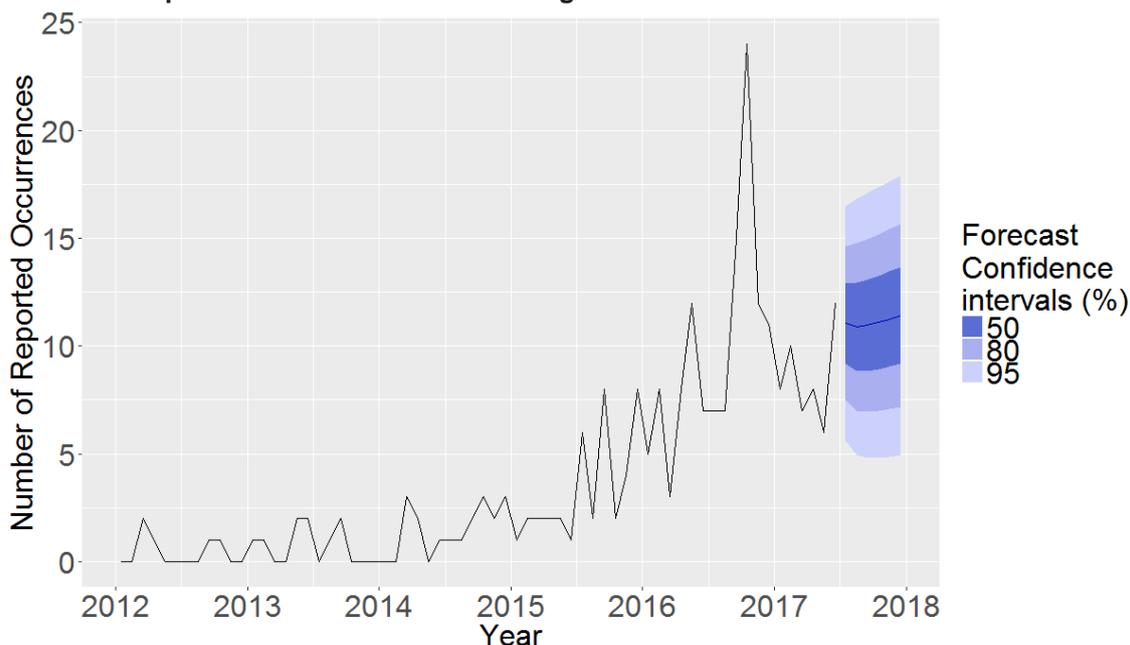
³ There are three main sources of uncertainty underlying all the forecasts presented:

- Uncertainty in the data: The main contributors are the inherent noise in the data and reporting issues such as under/over reporting and misclassification.
- Uncertainty in the models: This uncertainty comes from the choice of model used and how accurately it generalises the data.
- Uncertainty in external factors: Regulatory changes, changes in consumer activity and new laws or increased enforcement can all affect the accuracy of the forecast.

Analysis of RPAS safety occurrences

The number of RPAS occurrences reported to the ATSB has grown significantly from January 2012 to June 2017, with a significant increase from mid-2015 through to end-2016 (Figure 5). Safety occurrences are incidents and accidents either involving an RPAS, or a near encounter between an RPAS and a manned aircraft.

Figure 5: All occurrences involving an RPAS reported to the ATSB (Jan 2012–Jun 2017). The blue regions are the 50th, 80th and 95th per cent confidence intervals for the forecasts—up to Dec 2017—calculated using an ARIMA model^{1,2}



Source: ATSB occurrence database

The number of reported RPAS occurrences (51 occurrences) in the first half of 2017 was about 20 per cent more than the first half of 2016 (43 occurrences).

The model forecasts the total number of occurrences reported to the ATSB in 2017 to be comparable with 2016 figures. Due to the high level of uncertainty underlying the forecast it is not intended to be an accurate prediction of future RPAS occurrences.

The historical peak in RPAS occurrences was in October 2016, which was almost double that of any other month. This is possibly the result of a change in the rate of reporting. October 2016 was the first full month when the new Civil Aviation Safety Regulation Part 101.F was introduced (coming into force on 29 September 2016), which would have increased awareness of RPAS occurrences.

Table 1 displays the correlation between the number of reported RPAS occurrences, the total number of CASA registered RPAS certificate holders and the total number of Google shopping RPAS searches. It shows that there is strong positive correlation between the CASA and Google data, but a less strong but still positive correlation between the occurrence data and the other two data sets.

Table 1: Correlation between the number of reported RPAS occurrences, the total number of new CASA registered RPAS certificate holders (Jan 2014– Jun 2017) and the total number of Google shopping RPAS searches (Jan 2012–Jun 2017)⁴

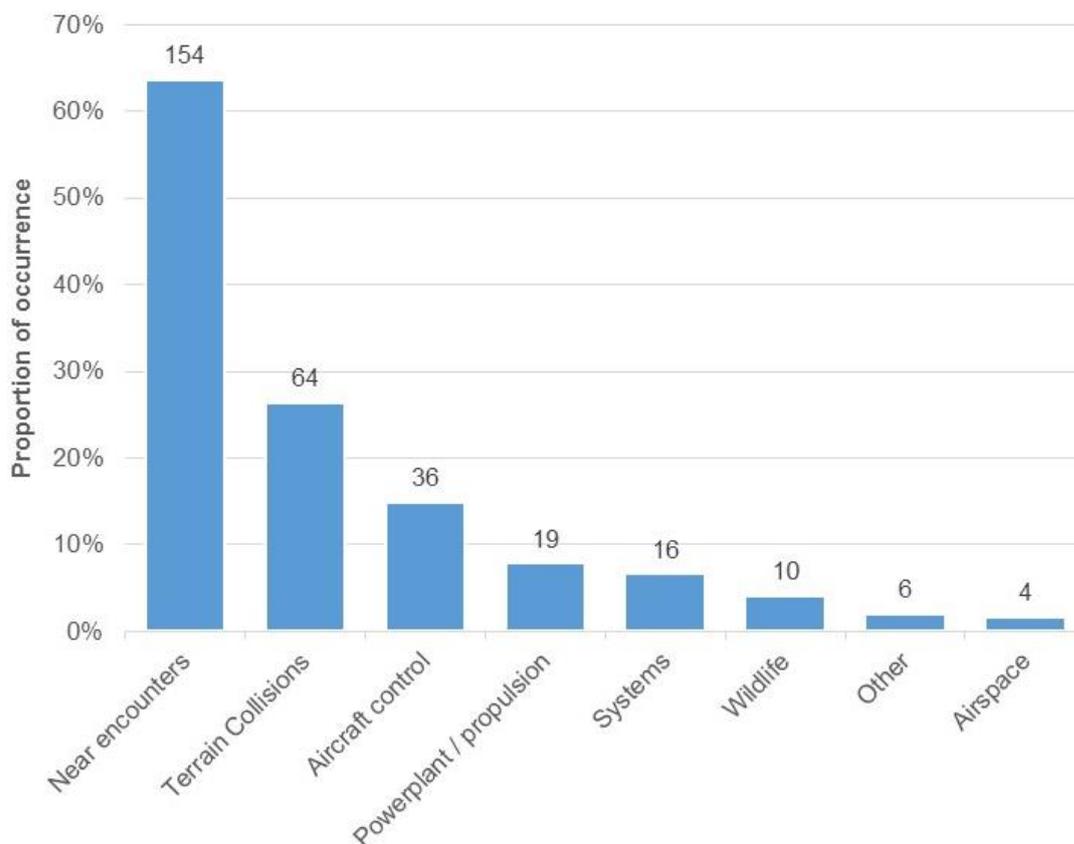
	Reported Occurrences	CASA Register	Google Trends
Reported Occurrences	1.00	0.64	0.78
CASA Register	0.64	1.00	0.98
Google Trends	0.78	0.98	1.00

Between January 2012 and June 2017, 242 RPAS-related occurrences (59 accidents, 16 serious incidents or near accidents, and 167 incidents) were reported to the ATSB.

Figure 6 shows the proportion of all reported RPAS occurrences for the various types of occurrences they are involved in. The occurrences shown in Figure 6 mostly involve (in order):

- RPAS near encounters with manned aircraft (64%)
- collisions with terrain (26%)
- aircraft control issues (15%).

Figure 6: Occurrence types associated with occurrences reported to the ATSB involving RPAS (Jan 2012–Jun 2017). Multiple occurrence types can be associated with the same occurrence



Source: ATSB occurrence database

⁴ Values in the table are the Pearson product-moment correlation coefficient. Values near '1' indicate positive linear correlation between data sets. That is, as one data set increases, the other increases linearly. Values near '0' indicate no linear correlation between data sets. Values near '-1' are negatively linearly correlated. That is, as one data set increases the other decreases linearly.

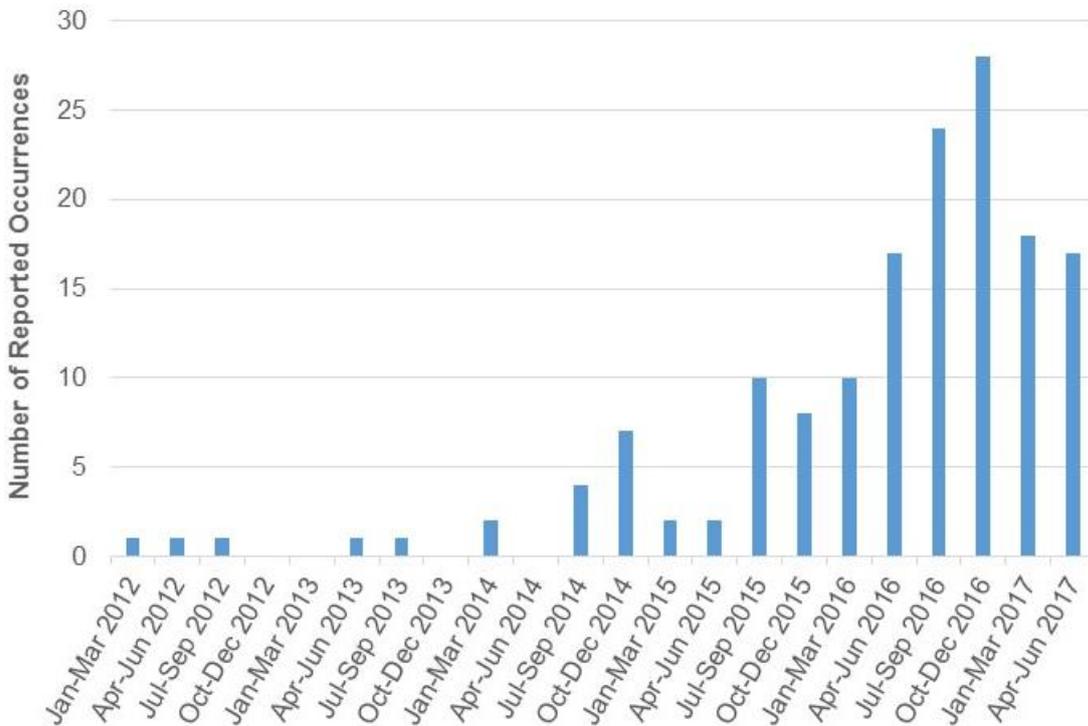
Interference with manned aircraft (near encounters)

Interference with manned aircraft from an RPAS (near encounters) is where an RPAS interrupts or is sighted in the proximity of another aircraft. Occurrences only include those encounters where the aircraft had to manoeuvre (or would have manoeuvred if there was more opportunity) to maintain a safe separation, or there was an unsafe situation, or when avoidance action would have been appropriate.

Almost three-quarters of near encounters with an RPAS reported to the ATSB occurred since the start of 2016. However, the first half of 2017 saw a decline compared to the previous 6 months but was still 30 per cent higher compared to the first half of 2016 (Figure 7).

To date, there have been no collisions reported between RPAS and manned aircraft in Australia. There were 152 near encounter incidents and two serious incidents reported to the ATSB between January 2012 and June 2017.

Figure 7: Near encounters with manned aircraft involving an RPAS reported to the ATSB (Jan 2012–Jun 2017)

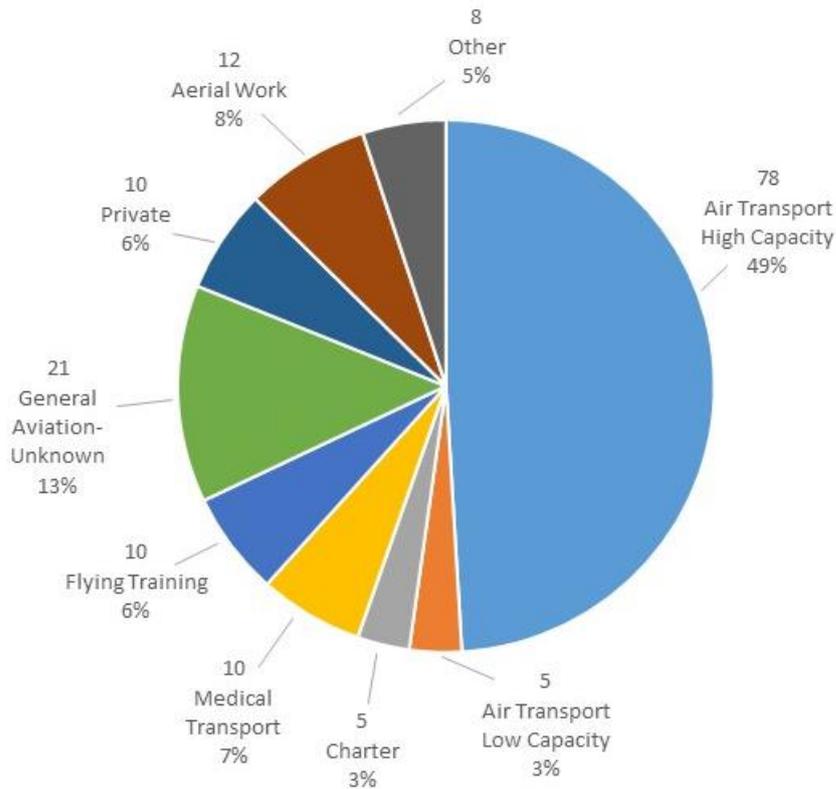


Source: ATSB occurrence database

The forecasts predict the number of near encounters reported to the ATSB in 2017 to be comparable to 2016. Due to the level of uncertainty underlying these forecasts, they are indicative of an increase only and are not intended to be accurate predictions of future RPAS near encounters.

In almost half (49 per cent) of all near encounters, the other aircraft was a high capacity air transport aircraft (Figure 8). The most affected aircraft was the Boeing 737 (around 16 per cent of all encounters) followed by the Airbus A320 (around 13 per cent).

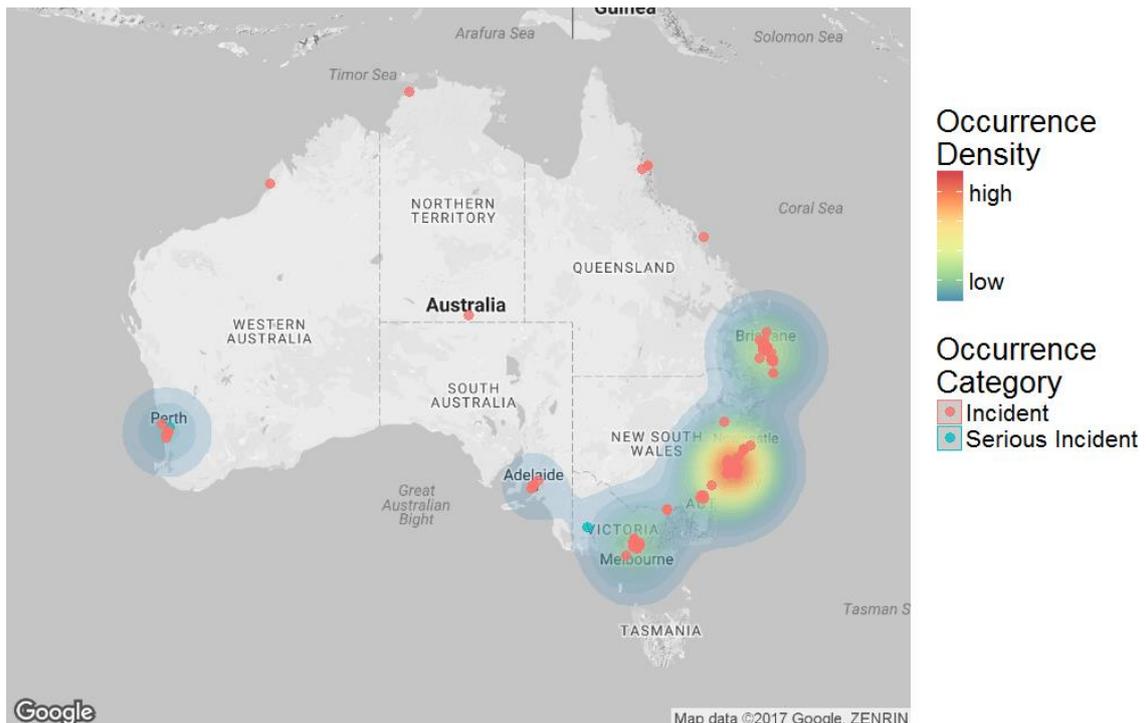
Figure 8: Operation types of the manned aircraft involved in near encounters



Source: ATSB occurrence database

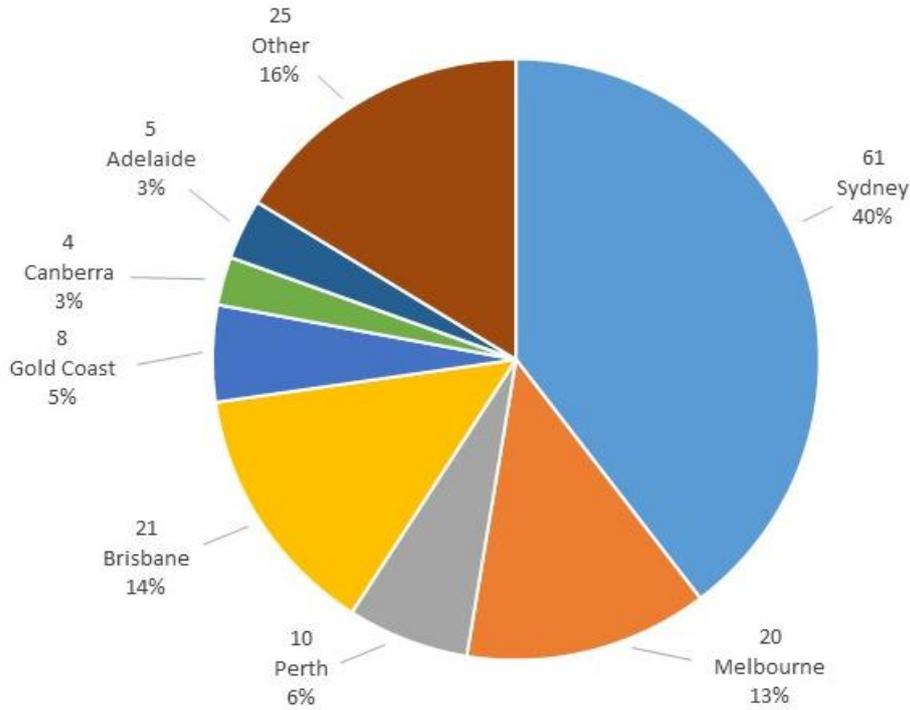
Figure 10 also shows that five capital cities (Sydney, Melbourne, Brisbane, Perth, Adelaide and Canberra), and the Gold Coast, account for over 80 per cent of near encounters with RPAS. The Gold Coast was the only significant non-capital city airport in terms of frequency.

Figure 9: Heat map of reported location of RPAS near encounters and occurrence category around Australia (Jan 2012–Jun 2017)



Source: Google maps

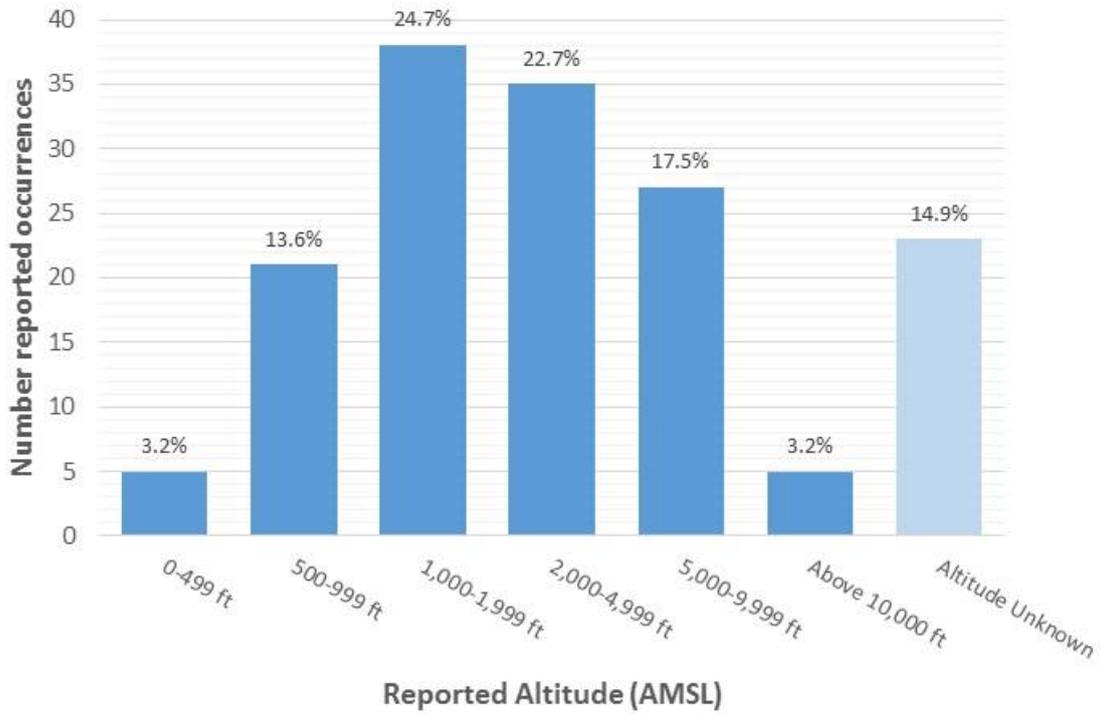
Figure 10: Proportion of aircraft near encounters involving an RPAS at significant locations around Australia (Jan 2012–Jun 2017)



Source: ATSB occurrence database

Figure 11 shows the reported altitude of RPAS involved in near encounters. Most encounters were above 1,000 ft above mean sea level (AMSL). Five encounters were above 10,000 ft. Very few (less than 4 per cent of encounters with a known altitude) were under 500 ft.

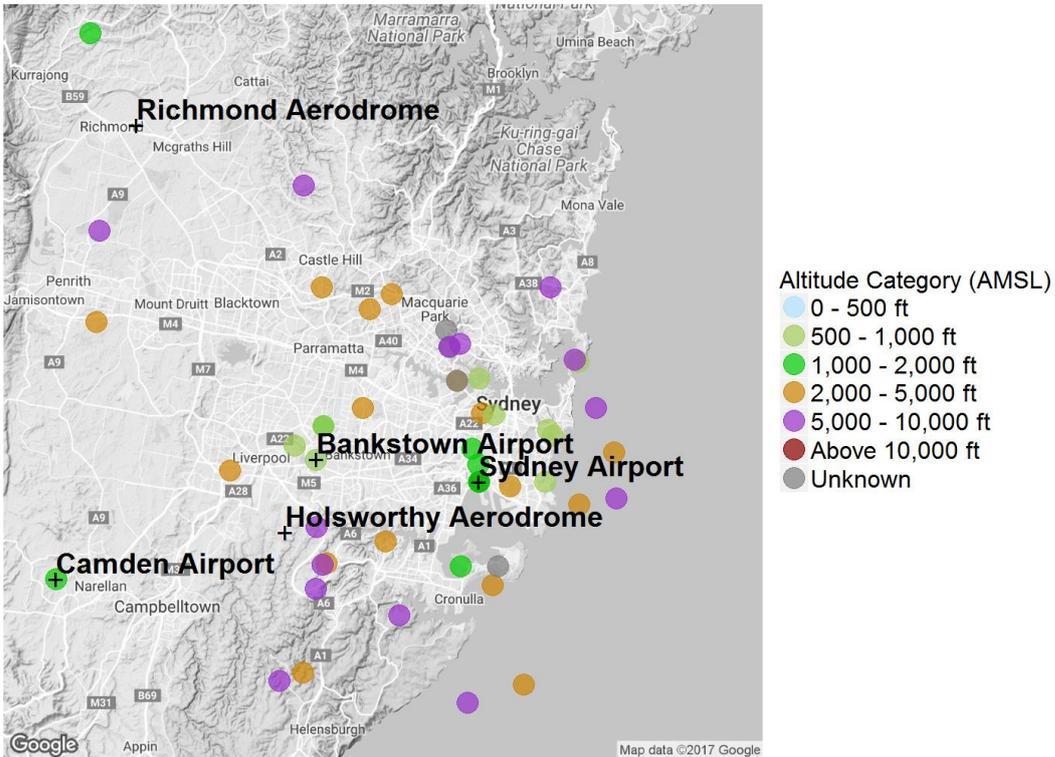
Figure 11: Reported altitude of RPAS involved in a near encounter with manned aircraft occurrences (Jan 2012– Jun 2017). When RPAS altitude is unknown other aircraft altitude is used



Source: ATSB occurrence database

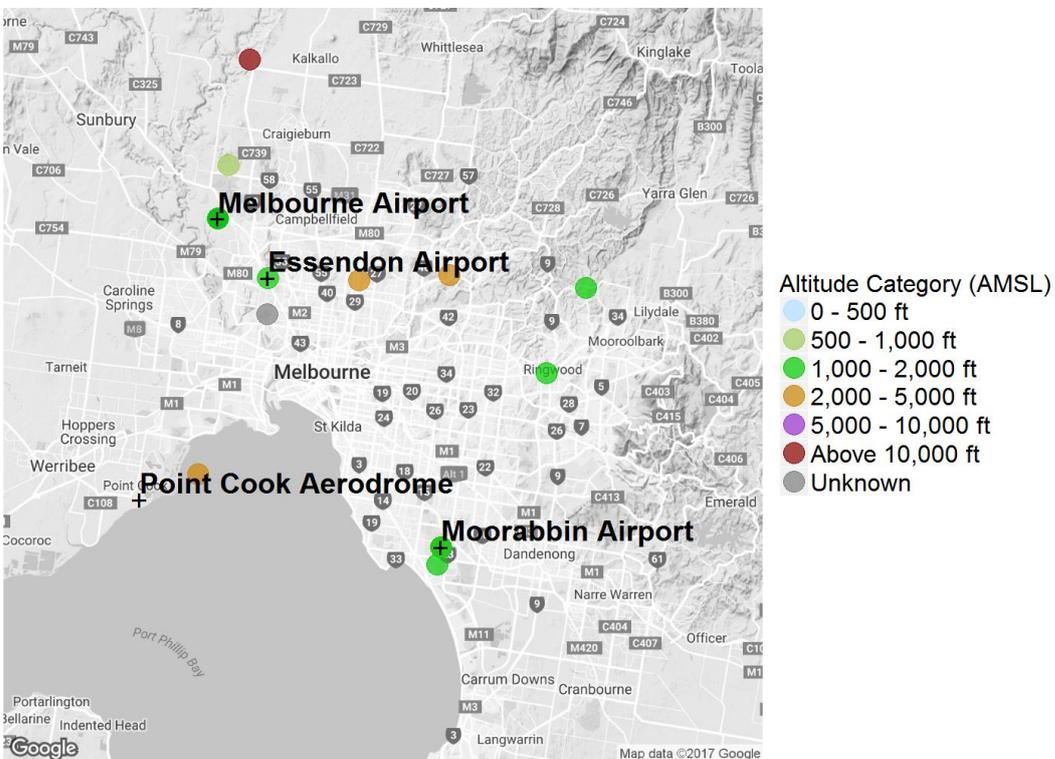
Figure 12 to Figure 14 display RPAS near encounters with aircraft around significant Australian locations. The estimated altitude is also displayed.

Figure 12: Locations, including relevant altitude categories, of reported RPAS near encounters around Sydney (Jan 2012–Jun 2017)⁵



Source: Google maps

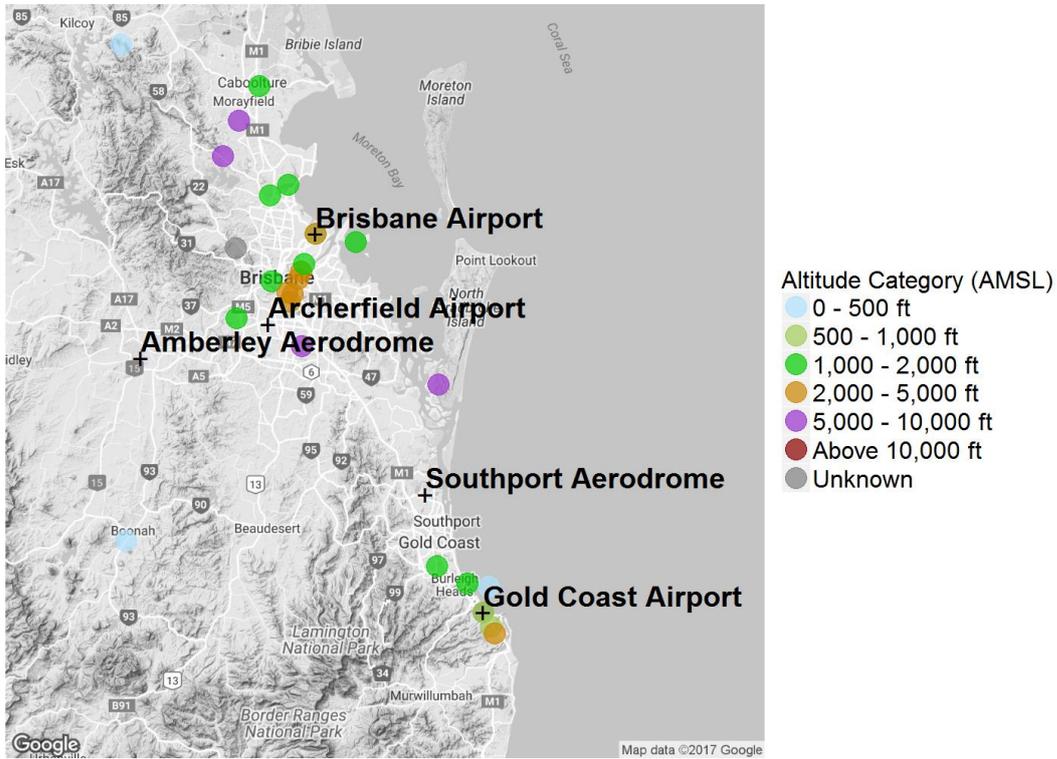
Figure 13: Locations, including relevant altitude categories, of reported RPAS near encounters around Melbourne (Jan 2012–Jun 2017)



Source: Google maps

⁵ When there is more than one occurrence at the same geographical point in these maps (Figure 12, Figure 13, Figure 14), they are only displayed as one point.

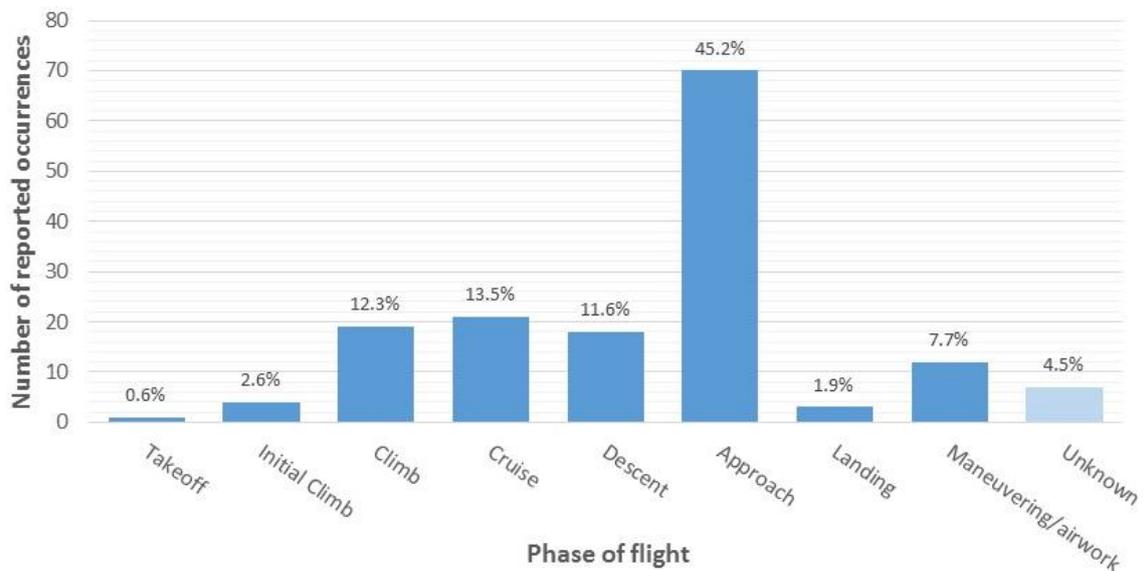
Figure 14: Locations, including relevant altitude categories, of reported RPAS near encounters around Brisbane/Gold Coast (Jan 2012–Jun 2017)



Source: Google maps

Over 45 per cent of near encounters occurred when the affected manned aircraft was on the approach phase of flight. A lower proportion involved aircraft climbing after take-off (nearly 15 per cent were in the initial climb or climb phases). Nearly 14 per cent involved manned aircraft during the cruise. Where the operation type was known (12 occurrences), all manoeuvring/airwork occurrences were within general aviation with four within the aerial work sub-operation type (Figure 15).

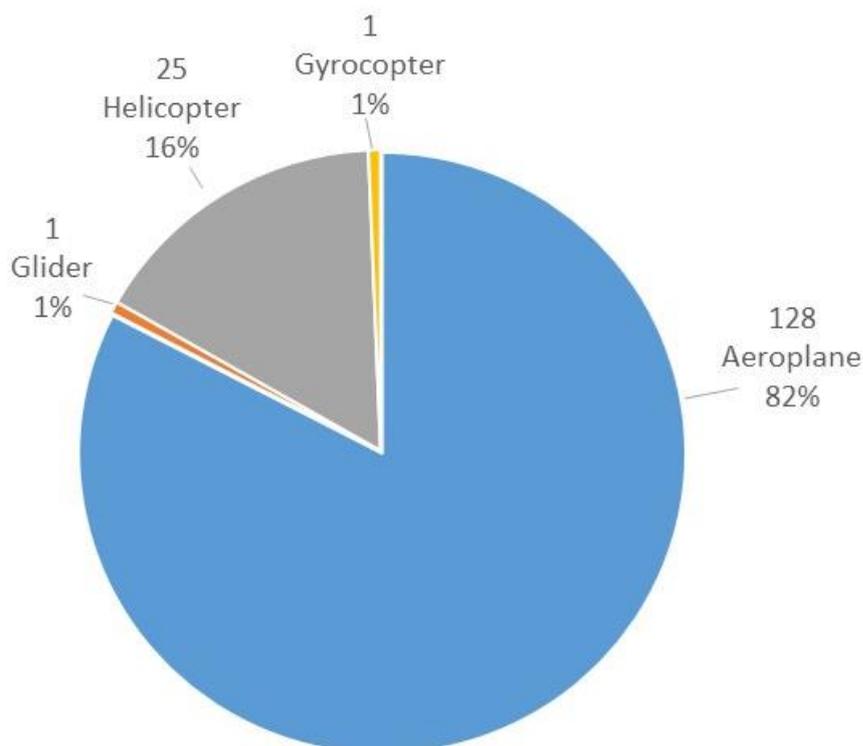
Figure 15: Affected aircraft's phase of flight at time of an RPAS near encounter (Jan 2012–Jun 2017)



Source: ATSB occurrence database

The majority of aircraft affected were aeroplanes (Figure 16). However, although helicopters made up around 13 per cent of the flying hours of all manned aircraft types⁶ (2010-2014),⁷ they were involved in 16 per cent of RPAS near encounters. This implies helicopters are slightly more likely to be involved in a reported RPAS encounter, per flight hour, than aeroplanes. However, there is a high level of uncertainty surrounding the calculation of aircraft type, primarily due to the low count and possible reporting issues (as helicopter pilots may have more opportunity to observe an RPAS than the aeroplane pilot due to the relatively slower speed).

Figure 16: Proportion of aircraft type effected by an RPAS near encounter (Jan 2012– Jun 2017)



Source: ATSB occurrence database

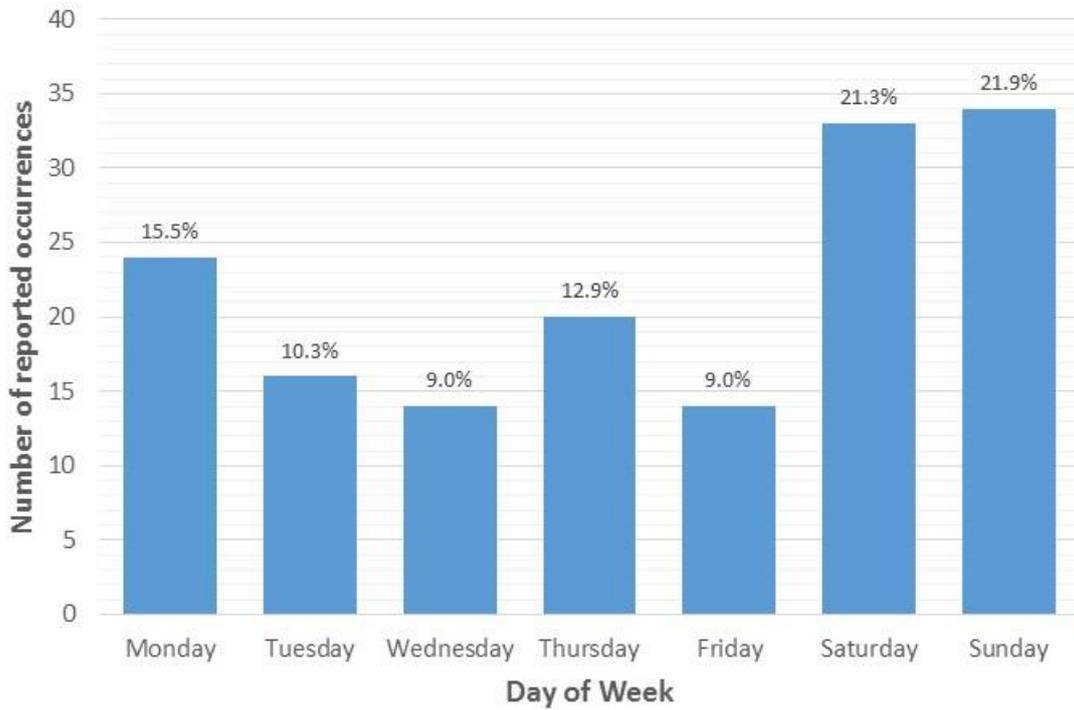
The majority of near encounters have no detail concerning the RPAS model, operation type or operator.

The day of the week (Figure 17) and time of day (Figure 18) when an RPAS near encounter happened may be an indicator of the type of operator flying the RPAS. More than two-thirds of these occurrences happened between the hours of 1000 and 1600, over half of which occurred on weekends. The probability that an occurrence was on a given weekend day (over 20 per cent) was almost double that of a given weekday (approximately 11 per cent). Wednesdays and Fridays had the lowest percentage of RPAS near encounters at around 9 per cent. The higher proportion of encounters on weekends suggests these were mostly not commercial operations.

⁶ The Bureau of Infrastructure, Transport and Regional Economics (BITRE) collect and compile this activity data from reports submitted by airlines, and from other aircraft operators through the General Aviation Activity Survey.

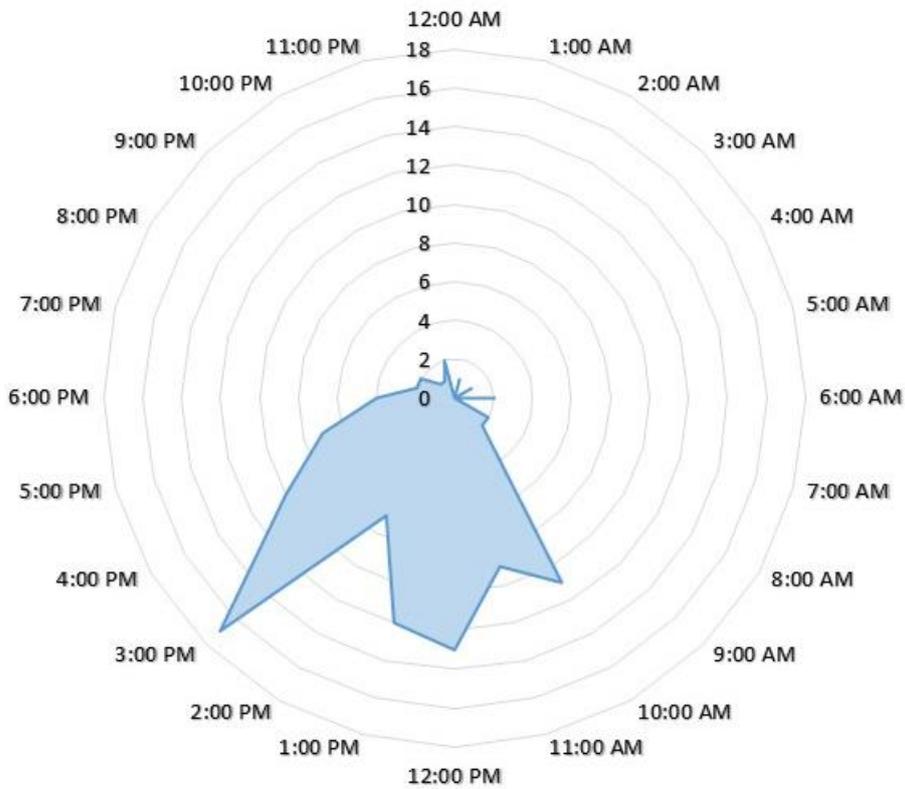
⁷ 2014 was the last year that aircraft type activity data was available from BITRE for all operation types.

Figure 17: Day of week when an RPAS near encounter occurred (Jan 2012–Jun 2017)



Source: ATSB occurrence database

Figure 18: Twenty four-hour clock displaying the number of reported RPAS interference with manned aircraft occurrences for each hour of the day (Jan 2012–Jun 2016)



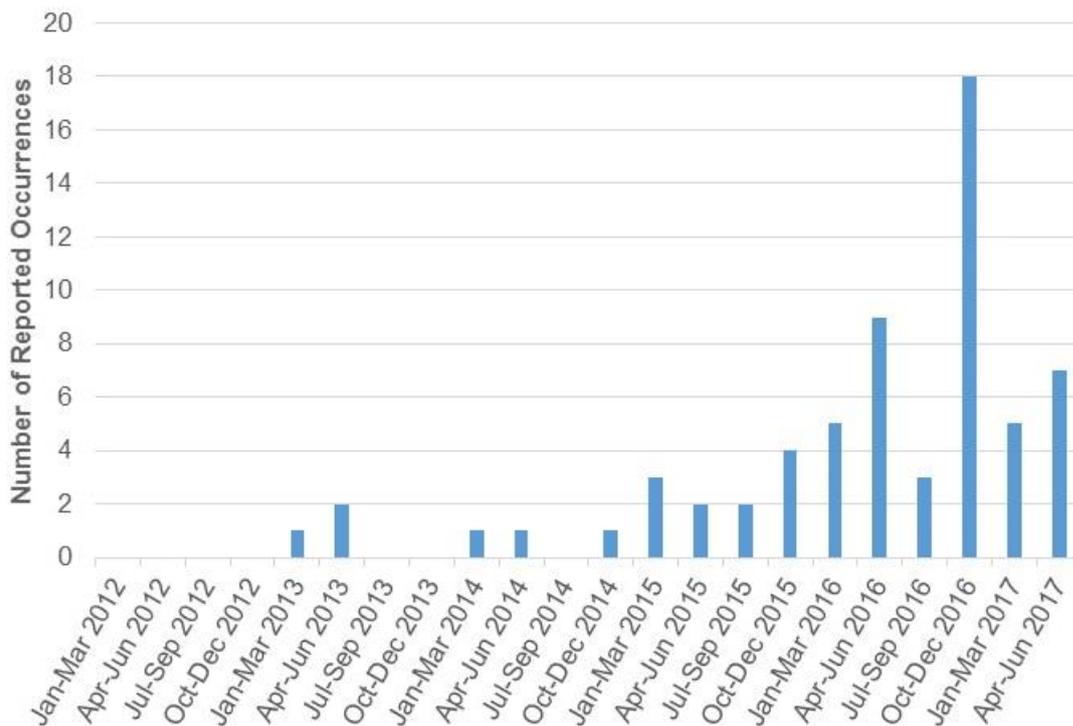
Source: ATSB occurrence database

Terrain collisions

There were 47 terrain collisions involving an RPAS reported to the ATSB between January 2016 and June 2017, while only 17 were reported in the previous four years. The majority (about 84 per cent) of all reported RPAS terrain collisions were accidents (where the aircraft was either destroyed or significantly damaged), and 13 per cent were serious incidents (almost an accident).

Figure 19 shows the number of terrain collisions involving an RPAS reported to the ATSB is steadily increasing.

Figure 19: Terrain collisions involving an RPAS reported to the ATSB (Jan 2012–Jun 2017)



Source: ATSB occurrence database

Forecast predict the total number of terrain collisions involving an RPAS reported to the ATSB by in 2017 to be comparable to 2016. Due to the level of uncertainty underlying these forecasts, they are indicative only and are not intended to be accurate predictions of future RPAS occurrences.

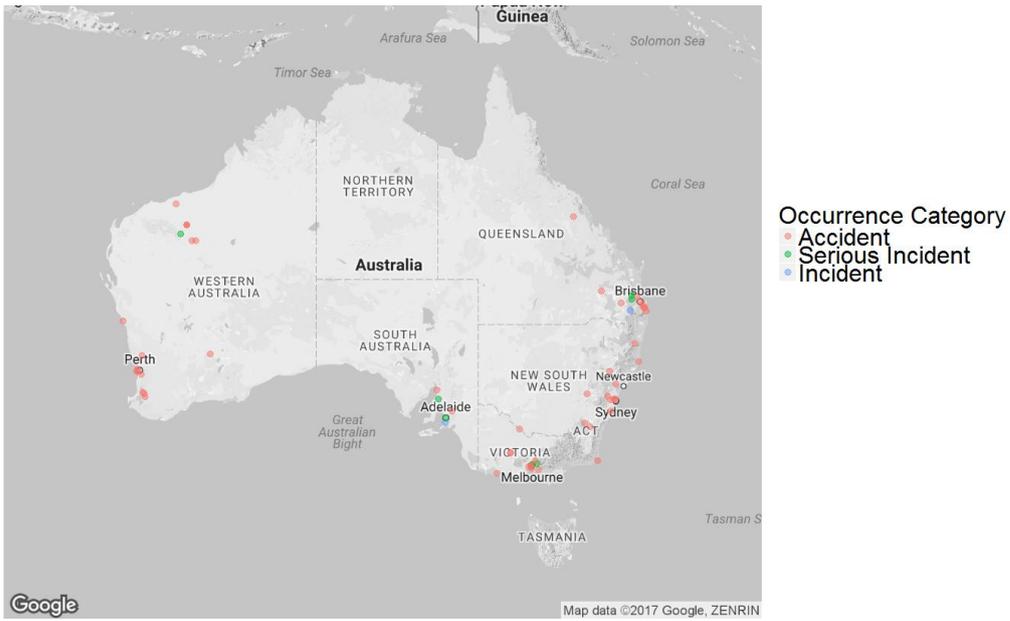
Case Study: Collision with terrain near Geraldton Aerodrome on 7 April 2014

In 2014, a race participant received minor injuries while competing in a triathlon in Geraldton, WA, from collision with an RPAS that was filming the race. The collision occurred after the remote pilot lost control of the aircraft (ATSB occurrence 201402113).

Almost half of reported RPAS terrain collisions were in the main population centres (Figure 20 to Figure 21). Further, around one-third of occurrences were in built-up areas.⁸ Melbourne and the Brisbane/Gold Coast area had a disproportionate number of terrain collisions for their population sizes compared to other Australian cities. However, due to the low number of terrain collisions, a large variability in the reported data between locations would be expected.

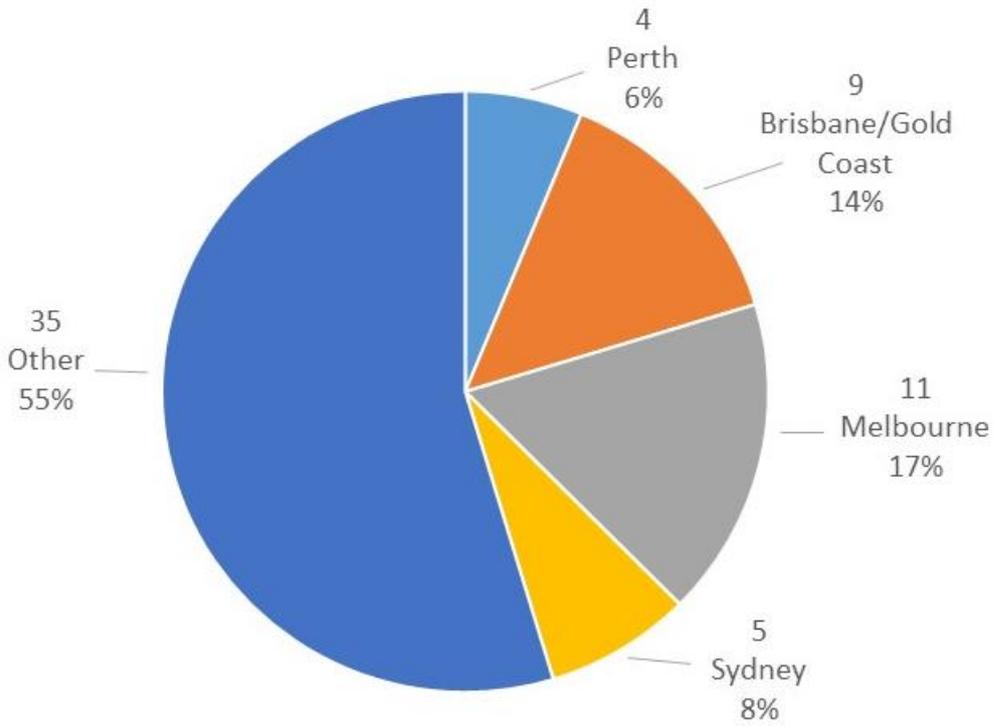
⁸ Built-up areas were determined at those where the terrain collision locations had a several house within one kilometre.

Figure 20: Locations of reported RPAS terrain collisions (Jan 2012–Jun 2017)



Source: Google maps

Figure 21: Proportion of collisions with terrain involving an RPAS at significant locations around Australia (Jan 2012–Jun 2017)



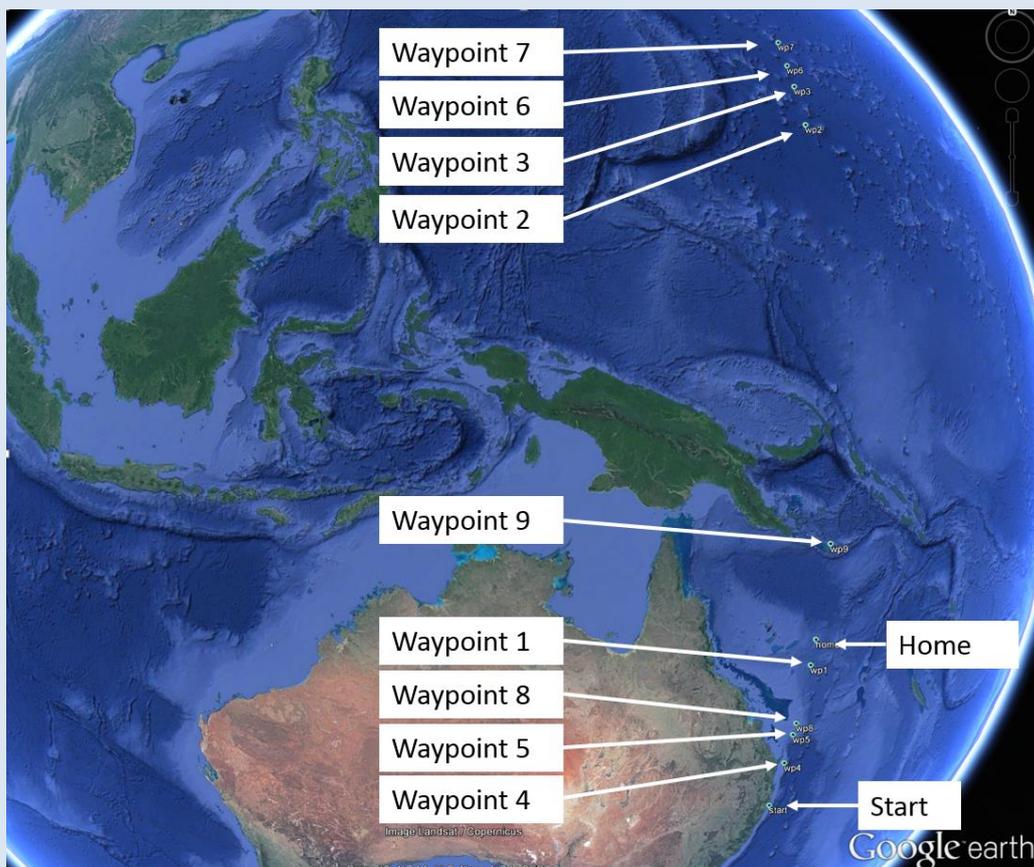
Source: ATSB occurrence database

Case Study: Loss of control involving remotely piloted aircraft Pulse Aerospace Vapor 55, UAV0734, 4 km NE of Ballina/Byron Gateway Airport, NSW, on 28 September 2016

A Pulse Aerospace Vapor 55 remotely piloted aircraft was operating a test flight at Lighthouse Beach, Ballina, NSW. After flying using manual inputs from the pilot for about 7 minutes, the data-link signal was lost. Thirty seconds later, the aircraft entered the 'home' flight mode, and commenced tracking to the programmed home position at an altitude of 154 ft. However, rather than tracking where the pilot expected, the aircraft headed NNE of the start position. In the home flight mode, the aircraft did not respond to the control inputs made by the remote pilot, and the pilot subsequently lost sight of it. The aircraft was not found despite an extensive search.

The investigation found that during the pre-flight programming, the south-eastern point used to georeference the image on the ground control station map was selected to a northern hemisphere latitude. This resulted in incorrect waypoints and home position for the mission. When the data-link signal to the ground control station was lost, the aircraft commenced tracking to the programmed home position, which was in the Coral Sea Islands about 1,200 km north of the start position.

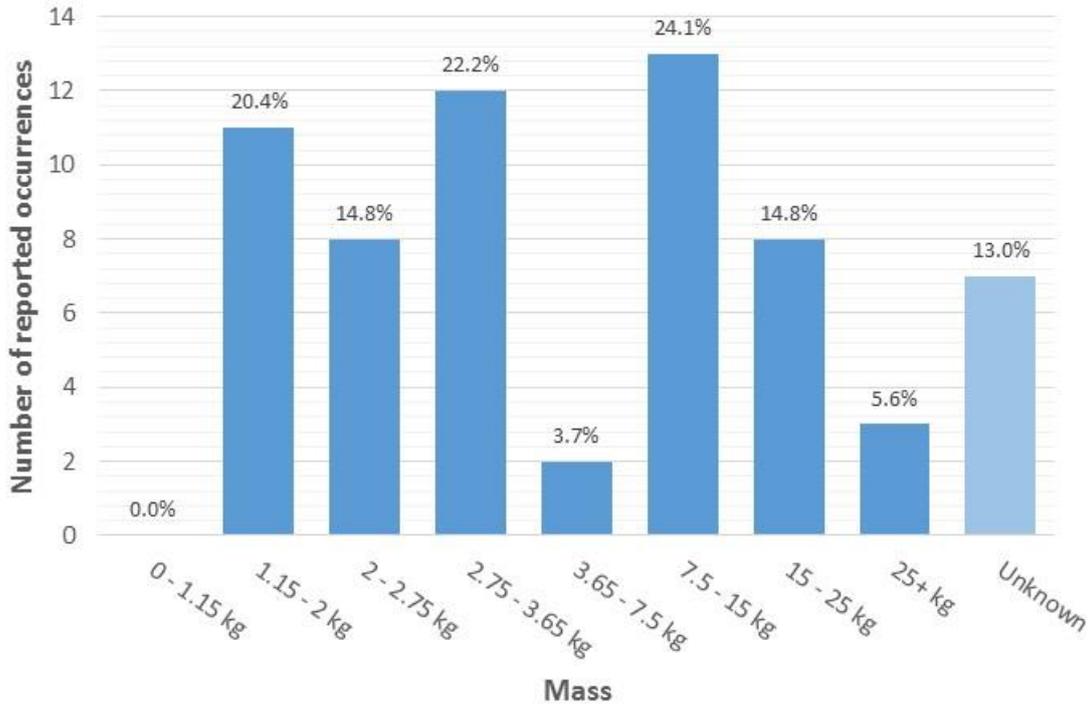
([ATSB investigation AO-2016-128](#)).



Location of waypoints programmed in the ground control station pre-flight from AO-2016-128. Source: Google Earth annotated by ATSB

The majority of terrain collisions reported to the ATSB had detail concerning the RPAS involved. Figure 22 displays the mass of the RPA where information regarding the model was reported. The average mass was 11.6 (± 5.6) kg. The most common mass was 2.9 kg (around 19 per cent of occurrences).

Figure 22: Mass of RPA involved in terrain collisions reported to the ATSB (Jan 2012–Jun 2017)⁹



Source: ATSB occurrence database

The average mass from an RPAS involved in a terrain collision in a built-up location (6.8 kg) was less than that for remote locations (14.8 kg). However, the most common mass was 2.9 kg for both built-up and remote locations.

⁹ The mass categories were chosen to overlap with those used for bird mass outlined in US Federal Aviation Regulation (FAR) 33.76, also those used in the Civil Aviation Safety Regulation Part 101 and other categories were used to split the data more evenly.

Case Study: Collision with terrain involving Lockheed Martin Stalker XE, Avoca Race Track, Victoria, on 25 October 2016

Following a normal take-off involving bungee launch procedures, the Lockheed Martin Stalker XE tracked and climbed to two pre-programmed waypoints. About 20 seconds into the flight, however, the aircraft entered an uncontrolled descent from about 225 ft above ground level, and collided with the ground. The aircraft sustained substantial damage.

After the accident, the aircraft’s negative main power cable was found to have separated from its pin in the connector. Due to the total loss of electrical power, the aircraft was unable to maintain normal flight or conduct a safe glide landing, therefore collided with the ground.

As a result of this occurrence, the aircraft manufacturer has advised the ATSB that all battery connectors are being replaced and sacrificial pigtailed are being added to the connectors, to be replaced after a number of connections. In addition, the aircraft battery circuitry is being modified to prevent arcing during connection and disconnection. ([ATSB investigation AO-2016-141](#)).

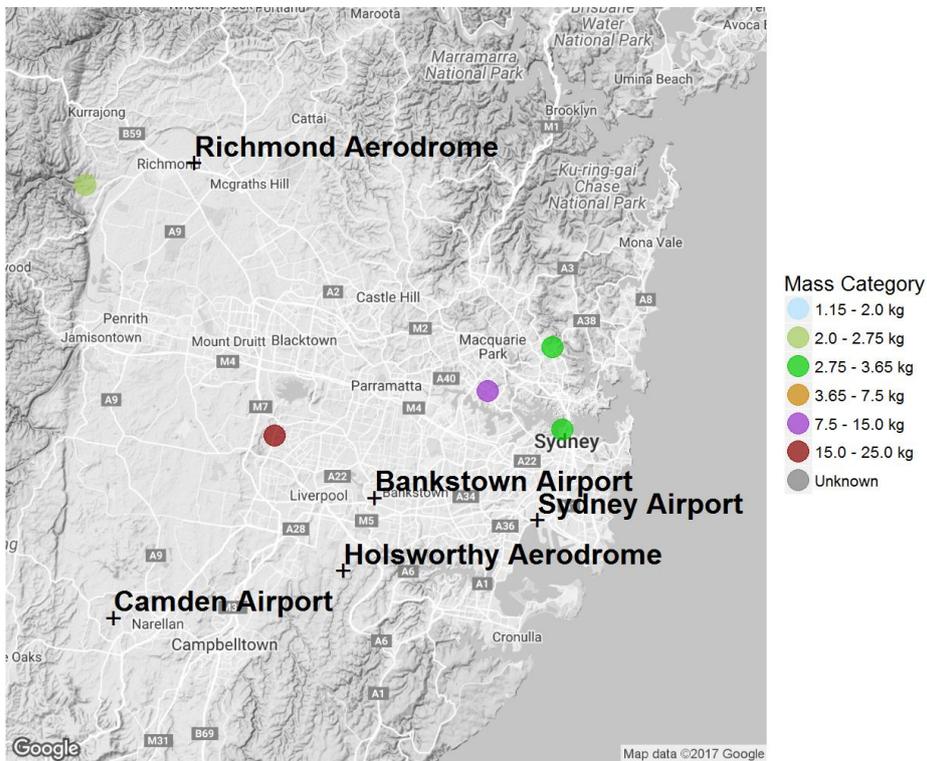


Lockheed Martin Stalker XE remotely piloted aircraft from AO-2016-041. Source: RPAS operator

The most common associated occurrence type involved in terrain collisions was a loss of control (around 42 per cent). Approximately 11 per cent involved a bird striking the RPAS, and another 11 per cent involved engine failure or malfunction of the RPAS.

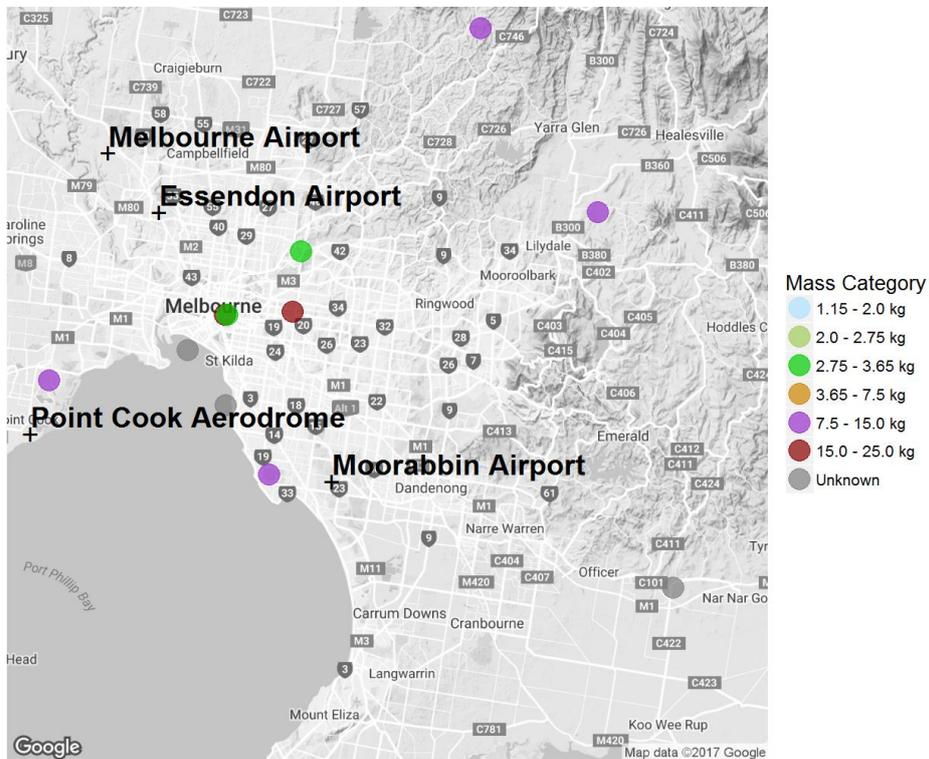
Figure 23 to Figure 25 show RPAS terrain collisions around significant locations including the mass categories.

Figure 23: Locations, including relevant mass categories, of RPAS terrain collision occurrences around Sydney (Jan 2012–Jun 2017)



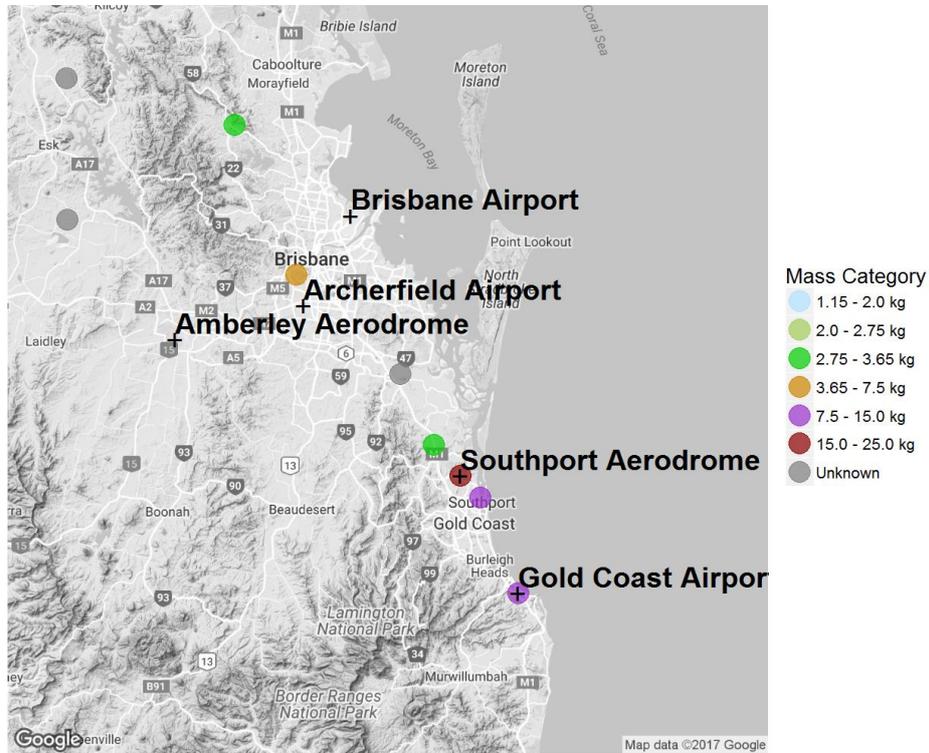
Source: Google maps

Figure 24: Locations, including relevant mass categories, of RPAS terrain collision occurrences around Melbourne (Jan 2012–Jun 2017)



Source: Google maps

Figure 25: Locations, including relevant mass categories, of RPAS terrain collision around Brisbane/Gold Coast (Jan 2012–Jun 2017)



Source: Google maps

Case Study: Loss of operator control involving an Aeronavics SkyJib 8 remotely piloted aircraft near the Melbourne Cricket Ground, Melbourne, Vic. on 29 March 2015

The RPAS was operating as part of the media coverage of the International Cricket Council World Cup Final at the Melbourne Cricket Ground. About 2 minutes into the flight, with the Aeronavics SkyJib 8 RPAS over the northern roof of Hisense Arena, the operating crew lost control of the aircraft. The crew commenced alternate recovery procedures, but were unable to re-establish control. The aircraft ultimately collided with terrain just to the south of Rod Laver Arena. There were no injuries to people on the ground, and no damage to other property, but the aircraft and associated equipment were substantially damaged

Radio frequency interference was the most likely cause of the accident. The volume of radio frequency traffic at the time of the accident was probably substantial, and perhaps sufficient to override RPAS control signals under the prevailing conditions. ([ATSB investigation AO-2015-035](#)).



Aeronavics SkyJib 8 remotely piloted aircraft from AO-2015-035. Source: RPAS operator

Consequence analysis of RPAS collisions with other aircraft

Although there have been no reported mid-air collisions between an RPAS and a manned aircraft in Australia, the outcome of such an occurrence is not well understood. A recently published (October 2016) European Aviation Safety Authority (EASA) report from their ‘Drone Collision’ Task Force¹⁰ documented all known RPAS strikes in Europe and USA to date, summarised in Table 2. As the table shows, only five confirmed strikes have occurred, with one resulting in fatal injuries and a destroyed aircraft (in Germany), and one causing serious damage to the aircraft (in USA). In the fatal accident, the aircraft in question was a motor glider, which was struck on the wing by a radio-controlled aeroplane, causing an in-flight break-up. The serious damage accident involved a sport bi-plane, which struck a model aeroplane resulting in a crushed wing. Fortunately, the aircraft landed safely.

In addition to those five occurrences, a high profile suspected RPAS collision occurred on 17 April 2016 when an A320 reportedly struck what was believed to be an RPAS during landing at Heathrow Airport, UK. However, subsequent inspections revealed no damage to the aircraft, and there was insufficient evidence to confirm the presence of an RPAS.¹¹ Another suspected collision occurred on 5 January 2017 near Tete, Mozambique.¹² While on approach, the crew of a Boeing 737 reported hearing a crash. Inspection upon landing revealed several deep gashes in the radome on the aircraft’s nose. While RPAS had been reportedly operating around the aerodrome, Mozambique’s Civil Aviation Authority (ICAM) concluded the radome most likely failed as a result of a structural failure caused by air flow pressure.¹³

Table 2: List of known mid-air collisions with RPAS in Europe and USA

Date	Airspace type	Altitude in ft	A/C type	Aircraft Registration	Drone type	Aircraft Damage	Comments
30/08/2015	Unknown	2500	Grumman AA-1	N3LY	Unknown	None	RPAS struck undercarriage
30/04/2015	Controlled airspace	700	Robin DR 400-180	F-GSBM	SAS Wildthing	Scraping on wing	Type of airspace unknown - final approach - exact altitude not available
05/04/2015	G	630	Pioneer 300	G-OPFA	Valenta Ray X, S037996	Scuffing and scraping (GBP 1 400)	Uncontrolled airspace
14/08/2010	Controlled airspace	50	Shpakow SA 750	N28KT	AJ Slick model airplane	Lower left wing crushed aft to the main spar	Video
03/08/1997		<650	Grob G 109B		Dingo	Destroyed	2 fatalities

Source: European Aviation Safety Agency

Given the relatively small number of reported collisions involving RPAS and other aircraft, methods other than direct observation must be used in order to best assess the risk posed by RPAS to manned aircraft.

¹⁰ European Aviation Safety Agency, 2016, ‘Drone Collision’ Task Force, Final Report. EASA, October 2016

¹¹ The Guardian, 2016, *Heathrow plane strike ‘not a drone incident’*, 28 April 2016, viewed on 24 February 2017, <https://www.theguardian.com/technology/2016/apr/28/heathrow-ba-plane-strike-not-a-drone-incident>.

¹² USA Today, 2017, *African airline reports drone collision with passenger jet*, 6 January 2017, viewed on 9 January 2016, <http://www.usatoday.com/story/news/2017/01/06/african-airline-reports-drone-collision-passenger-jet/96237622/>.

¹³ ‘Incident: LAM B737 at Tete on Jan 5th 2017, radome structural failure’, in Aviation Herald. 10 January 2015, viewed on 1 February 2017, <http://avherald.com/h?article=4a319157&opt=0>.

Birdstrikes are currently the most appropriate comparison to RPAS collisions, and a rich dataset exists in Australian aviation.¹⁴ However, they are not completely analogous, and it is important to understand the limitations in the comparison. Firstly, some species of birds will flock, whereas RPAS are generally a single unit controlled by a single pilot. Birds are also less predictable and prone to startling. According to the most recent damage models, the physical behaviour of a bird upon impact with an aircraft is best described as an incompressible fluid.¹⁵ An RPAS, on the other hand, would be better modelled by several connected, solid parts, depending on its construction. These differences must be kept in mind when using birdstrike data to assess the potential outcomes of RPAS collisions.

A recent UK study was commissioned by the Department for Transport (DFT), the Military Aviation Authority (MAA) and the British Airline Pilots' Association¹⁶. This study involved laboratory testing with actual aircraft and RPAS components, which helped to calibrate and validate a computational model for a collision between an RPAS and an air transport aeroplane windscreen, a helicopter windscreen, and a helicopter tail rotor. The simulations were then used to assess the possible outcomes of a mid-air collision between an RPAS and an aircraft.

The study found that the damage caused depended heavily on which part of the RPAS impacted first, as well as the specific materials involved. For example, a metal motor impacting an aircraft was found to cause much more damage than the same motor covered by a thin plastic sheath. Results from the different impact scenarios are detailed in the *Possible damage* section below. Studies sanctioned by the US Federal Aviation Administration (FAA) investigated the likelihood and outcomes of airframe penetration by solid debris, which were assumed to be non-deformable. Equation 1 shows a penetration equation developed by the FAA (also known as the FAA V_{50} equation, or ballistic limit equation).

Equation 1: The ballistic limit equation developed by the FAA¹⁷

$$V_{50} = \sqrt{\frac{2 \cdot L \cdot G_d \cdot t^2}{m \cdot \cos^2 \theta}}$$

This equation describes the velocity, V_{50} (in m/s) at which an item of debris has a 50 per cent probability of penetrating a target, where:

- L = presented area perimeter of the debris (small L for a smaller impact area) [m]
- G_d = dynamic shear modulus (empirically determined constant based on target material) [Pa]
- t = target thickness [m]
- m = mass of debris [kg]
- θ = obliquity of impact (0° is an impact orthogonal to the surface).

The FAA penetration equation has been used by other agencies to assess the potential risks posed to aircraft by debris. The Range Commanders Council released a study examining the risks of falling satellite debris using the FAA penetration equation.¹⁸ This is a valuable resource for assessing the similar risks posed by RPAS, but dissimilarities must be kept in mind when analysing their findings, such as the difference in trajectory between satellite debris and an RPAS, as well as the differences in size and velocity. Probable strike locations

¹⁴ ATSB, 2017, *Australian aviation wildlife strike statistics: 2006 – 2015* (Report AR-2016-063). <http://www.atsb.gov.au/publications/2016/ar-2016-063/>

¹⁵ Vignjevic, R. Orłowski, M. De Vuyst, T. Campbell, J.C., 2013, A parametric study of bird strike on engine blades. *International Journal of Impact Engineering*, vol 60, 2013, pp. 44-57.

¹⁶ Department for Transport, Military Aviation Authority, 2017, *Small Remotely Piloted Aircraft Systems (Drones) Mid-Air Collision Study*.

¹⁷ Lundin, S.J., 2002, *Engine Debris Fuselage Penetration Testing Phase II* FAA, September 2002, viewed on 1 December 2016, <http://www.tc.faa.gov/its/worldpac/techrpt/AR01-27-2.pdf>.

¹⁸ Range Commanders Council, 2007, *Common Risk Criteria Standards for National Test Ranges: Supplement*.

Birdstrike occurrences can be used to help predict the areas of aircraft that are most likely to be involved in a collision with RPAS. While birdstrike records in Australia are kept for commercial passenger transport and general aviation, the details of strike location are only provided if damage to the aircraft is detected. The exception is engine ingestion events, where all occurrences are recorded. Table 3 provides the number of bird ingestion events, per operation type, over the 10 years 2006 to 2015.

Table 3: Number of bird ingestions by operation type, 2006 - 2015

Operation Type	Engine ingestion	Number of birdstrikes	Per cent of birdstrikes
High capacity air transport	1 engine	713	7.7%
	2 engines	7	
Low capacity air transport	1 engine	97	3.9%
	2 engines	2	
General Aviation	1 engine	24	1.5%

Source: ATSB, 2017, Australian aviation wildlife strike statistics: 2006 – 2015 (Report AR-2016-063).

The majority of birdstrike occurrences in general, and ingestions in particular, involve high capacity transport operations. This is due in part to the large number of commercial flights, but it is also a function of the size and type of the engines in question. The turbofan engines commonly used in high capacity air transport have a large intake relative to the aircraft’s frontal area, and their effective area is increased by additional suction. Conversely, a conventional single-piston engine aircraft has a small intake relative to the aircraft size, and no additional suction. The variability in engine size is the reason the percentage of strikes resulting in ingestion is greater for high capacity air transport compared with general aviation (Table 3, right column). If the difference in behaviour between birds and RPAS can be neglected, then these percentages should be a reasonable approximation of the proportion of RPAS collisions that will result in engine ingestion.

Table 4 shows the number of birdstrikes that resulted in damage, as well as the part damaged and the associated operation type. In high capacity air transport, the engine is the most frequently damaged component. This is probably due to the size of the engines relative to the aircraft’s frontal cross sectional area. Additionally, the relatively strong parts like the wings, fuselage, and windscreen on jet aircraft are less susceptible to damage. In low capacity transport and general aviation, the wings (and helicopter rotors) are the most common region damaged.

Table 4: Number of birdstrikes by part damaged and operation type over the 2006 - 2015 period

Part damaged	High capacity air transport	Low capacity air transport	General aviation
Wing/Rotor	106	112	190
Engine	145	44	10
Nose	49	23	15
Propeller	28	35	24
Other	23	30	30
Landing Gear	25	11	12
Windscreen	10	9	30
Lights	24	12	7
Tail	15	9	18
Fuselage	17	8	9

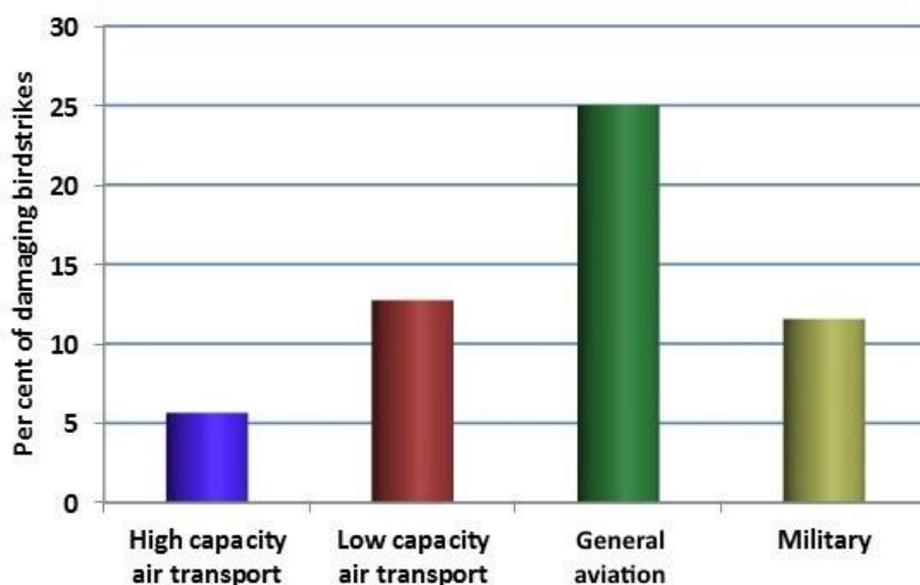
Source: ATSB, 2017, Australian aviation wildlife strike statistics: 2006 – 2015 (Report AR-2016-063).

This data represents a strong starting point to predict damage from RPAS collisions. However, given the different physical composition of RPAS, the distribution of damage across an airframe will change for an RPAS collision, as RPAS are more rigid, and generally heavier than most birds. For example, there are more incidents involving damaged wings in general aviation than there are

in high capacity air transport, despite there being more than five times the number of birdstrikes in the latter category. This is the result of a more fragile wing in general aviation aircraft. RPAS may be more likely to damage the stronger wings in high capacity air transport aircraft, which would result in wings becoming more represented in the total number RPAS strikes resulting in damage. Out of 720 engine bird ingestions in high capacity air transport (Table 3), 145 resulted in damage to the engine (Table 4). Once again, due to the added weight and rigidity, this proportion will likely increase for RPAS collisions.

Figure 26 shows that general aviation aircraft, in general, are more likely to sustain damage following a birdstrike than air transport category aircraft. The overall proportion of RPAS collisions resulting in aircraft damage is expected to increase from the recorded birdstrike values shown in Figure 26. The following section discusses this in more detail.

Figure 26: Proportion of birdstrikes resulting in damage in each operation type over the 2006 - 2015 period



Source: ATSB, 2017, Australian aviation wildlife strike statistics: 2006 – 2015 (Report AR-2016-063).

Possible damage

The physical composition and resulting behaviour on impact of RPAS is significantly different to that of a bird. However, even between different remotely piloted systems, there is substantial variation. Table 5 displays the smallest and largest commercially available RPAS, by weight, which have been involved in Australian aviation occurrences. For comparison, the widely popular DJI Phantom 4 is listed as well.

Table 5: Specifications for RPAS involved in Australian aviation occurrences

Name:	Sensefly eBee	DJI Phantom 4	Pulse Aerospace Vapor 55
Weight:	0.69 kg	1.38 kg	25.0 kg (MTOW) ¹⁹
Type:	Fixed wing	Quadcopter	Helicopter



As is evident from the table above, the size and composition of RPAS varies significantly. However, generally speaking, most RPAS can be described as a collection of common components built into a comparatively light airframe. The airframe is generally made of expanded polystyrene or a rigid polymer, which is often fibre-reinforced. The elements common to many RPAS are: motors, batteries, cameras, and propeller blades. Upon impact with an aircraft, the RPAS airframe will provide relatively low resistance, as will most propeller blades and rotors. As such, the behaviour of an RPAS colliding with an aircraft can be simply modelled as multiple solid objects striking in close proximity to one another. These objects will of course vary in size and weight. For reference, the battery (generally the heaviest component) on the Vapor 55 weighs up to 10 kg, while the DJI Phantom 4 battery weighs 0.46 kg.

Possible airframe damage

EASA’s ‘Drone Collision’ Task Force report utilised the knowledge of various stakeholders from within the aviation industry (aircraft manufacturers, RPAS manufacturers, regulators, and safety agencies) in an effort to assess the threat posed by RPAS collisions. As stated in the report, there are obvious limitations for a study such as this. Stakeholders with a wide range of technical expertise used their own judgment when assessing threats. In addition, each stakeholder might have a different idea on the appropriate damage classifications and what is considered ‘likely’. The limited number of stakeholder responses also limits the value of this data. When discussing the possible severity impact, this report frequently referred to the kinetic energy involved (based solely on the mass and speed of the colliding bodies). However, the reality is much more complex. The rigidity, angle of incidence, and orientation of components can all have substantial effects on the outcome of an impact. This is discussed in more detail below.

With respect to large manned aeroplanes, the ‘Drone Collision’ Task Force report identified impact to the following areas of manned aircraft as posing the most risk:

- fuselage areas above and below windscreens
- engines
- tailplane/wing leading edges and flaps
- nose/radomes/antennas
- windscreens
- propellers.

Consensus from the report determined that ‘large’ RPAS (3.5 kg) generally pose a threat to commercial air transport aircraft at any altitude. However, ‘medium’ RPAS (1.5 kg) were considered less likely to pose a threat at lower altitudes (under 10,000 ft) due to slower aircraft speeds. The risk was assessed to be lower because commercial aircraft are certified to withstand

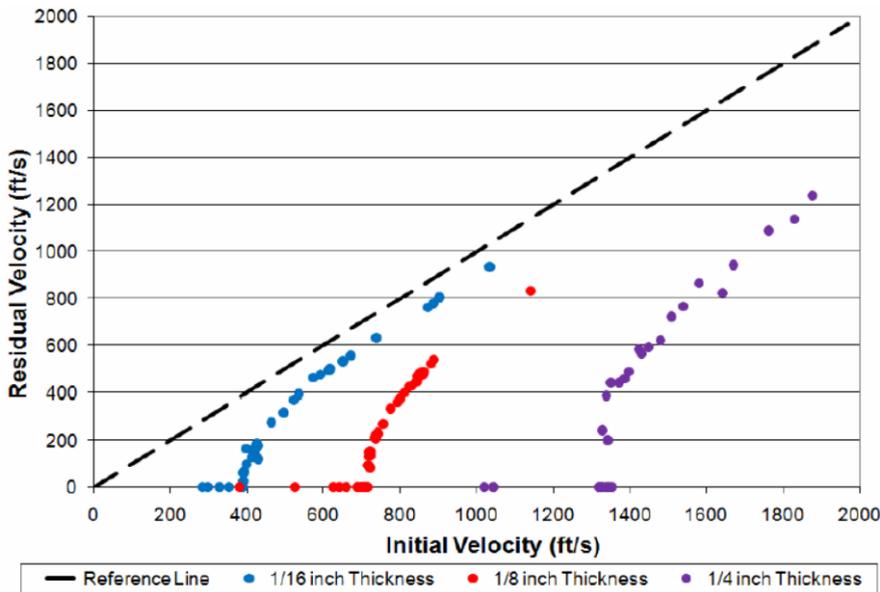
¹⁹ Maximum take-off weight.

a bird of equivalent mass. However, this is not a completely valid comparison because the impact behaviour of RPAS (and RPAS components) will be significantly different to a bird.

Based on laboratory testing and computational modelling, the DFT/MAA study found that air transport-standard aeroplane windscreens could withstand an RPAS collision at typical landing/approach speeds. At higher speeds, complete structural failure of the windscreen was found to be possible upon impact with a 4 kg quadcopter, but not with a 1.2 kg quadcopter.

Figure 27 illustrates impact test results from an FAA-sponsored study investigating aircraft vulnerability to falling rocket/satellite debris.²⁰ A good approximation for the ballistic limit (V_{50} as described in the FAA equation), is the point at which the impact velocity is high enough for some residual velocity to result. That is, when the projectile has penetrated the target.

Figure 27: Impact testing involving a 0.5 inch steel sphere striking aluminium plates of different thicknesses.



Source: Monash University/CASA

A collaborative report between Monash University and the Civil Aviation Safety Authority (CASA) used this methodology for a theoretical study on the possibility of aircraft penetration by RPAS components.²¹ Table 6 lists the components that were used in the study, which were based off actual RPAS parts.

Table 6: Dimensions and weights of RPAS components used by Monash University/CASA

	Item	Model	Geometry	Dimensions [mm]	Weight [g]
Quad-copter (small)	Motor A	NX-4006-530kv	Cylinder	D=45, L=12	67
	Battery A	--	Block	25x50x65	160
	Camera A	GoPro Hero 2	Block	42x60x30	190
Quad-copter (big)	Motor B	Turnigy Multistar 4830-480Kv	Cylinder	D=47, L=33	154
	Battery B	--	Block	45x45x138	583
	Camera B	Canon EOS 7D	Block	148x110x74	820
Single-engine	Motor C	Turnigy CA120-70 (100cc eq)	Cylinder	D=118, L=120	2730

Source: Monash University/CASA

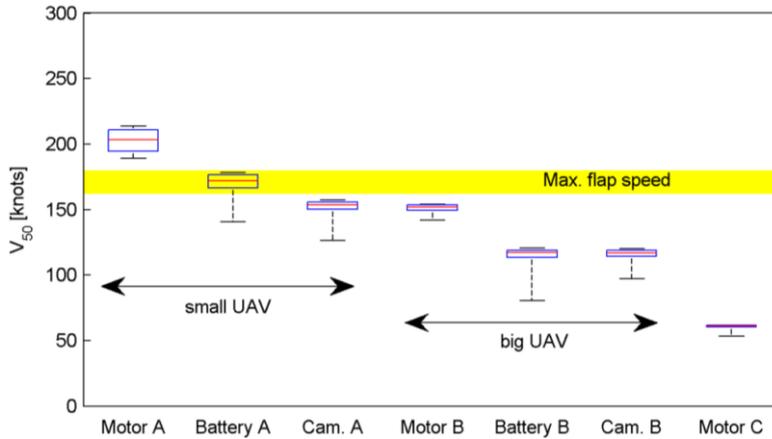
²⁰ Wilde, P.D. 2014, *Impact Testing and Improvements in Aircraft Vulnerability Modelling for Range Safety*. 20 October, 2014.

²¹ Monash University 2013 *Potential damage assessment of a mid-air collision with a small UAV*. CASA, 12 June 2013.

The Monash/CASA study calculated the ballistic limit for these components, based on the FAA V_{50} equation (Equation 1).

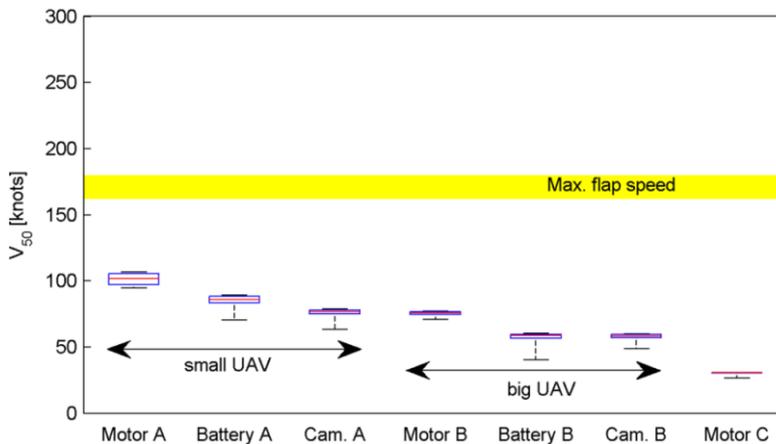
The study assumed the fuselage and wings to be modelled as 1/8 inch and 1/16 inch aluminium plates, and treated the impact as perpendicular ($\theta = 0^\circ$). The shear modulus, G_d , was assumed to be 276 MPa in accordance with the FAA-sponsored study. Boxplots in Figure 28 and Figure 29 illustrate the ballistic limit for the different components as well as the maximum flap speeds of a Boeing 737-400 and 747-400 (162 kt and 180 kt, respectively). Uncertainty in the values is the result of changes in the projected area of the perimeter of the debris (L in the equation).

Figure 28: Ballistic limits of drone components impacting 1/8 inch thick aluminium



Source: Monash University/CASA

Figure 29: Ballistic limits of drone components impacting 1/16 inch thick aluminium



Source: Monash University/CASA

As the figures show, all components are expected to penetrate 1/16 inch thick aluminium at an impact speed lower than speeds reasonably expected by a commercial air transport aircraft on take-off or landing. All components except for the small quadcopter motor are predicted to penetrate 1/8 inch thick aluminium under the same conditions.

Before any conclusions are drawn based on the findings of the Monash/CASA study, it is important to note the limitations created by several critical assumptions:

- An obliquity of 0° is not a realistic assumption for most RPAS collisions. Given the relatively low velocity of an RPAS with respect to a high capacity aeroplane, particularly a Boeing 737 or 747, it can be reasonably assumed that the impact will occur on one of the front-facing surfaces of the aeroplane, such as the nose, or wing leading edge. As an aerodynamic requirement, all of these surfaces are swept, so almost any head-on collision will be a glancing blow. In the worst-case scenario, such as an RPAS striking the exact point of the wing's

leading edge, the obliquity may be 0°, but the thickness of the skin will be higher in this area for the sake of wing strength. The curve of the leading edge also adds geometric strength, which will assist in resisting debris penetration, whereas the FAA ballistic limit equation assumes a flat surface.

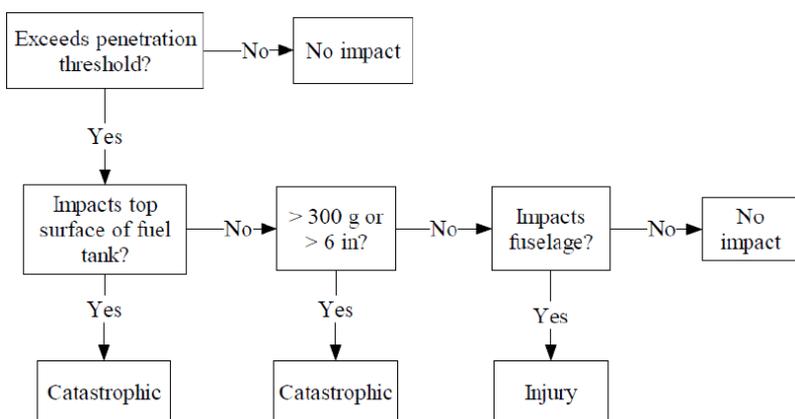
- The equation assumes a perfectly rigid projectile. In the FAA-sanctioned study, the impact test results shown in Figure 27 served to validate the ballistic limit equation. The results fitted well with the equation because the elastic modulus of the steel projectile is substantially higher than that of the aluminium target, so the rigid assumption is valid. In the case of RPAS components, the rigidity of the projectile is questionable (although it will be far more rigid than a bird). A lithium-ion battery for example, will generally consist of several materials including aluminium, lithium, copper, graphite, and an electrolyte paste. Relative to an aluminium skin, the rigidity of a battery will depend heavily on its construction, geometry, and its orientation at impact. A motor is more likely act as a rigid body due to its components, but it could still fragment on impact.
- Assumptions of an aluminium skin are oversimplified/outdated. The materials used in the skin of a modern commercial air transport aircraft are diverse. Even general aviation airframes are now including more composite materials in their design. Unfortunately, composite materials, particularly fibre metal laminates such as Glare, are too complex to be modelled by something as simplistic as the ballistic limit equation. The non-linearity of composite material properties means the dynamic shear modulus term, G_d , would likely need to be expressed as a function of both strain and strain rate at the very least. Finite element modelling of impact for a particular material configuration would probably be more practical than developing a universal equation.

These assumptions will tend to over-predict the probability of penetration. On the other hand, the calculated V_{50} values were much lower than the expected impact velocities. Therefore, the probability of penetration into the wing and fuselage of a commercial air transport aircraft cannot be ruled out. However, it is unlikely to occur as often as implied by the Monash/CASA study.

Figure 30 is a flow chart from a working paper produced by the International Civil Aviation Organization discussing the aircraft hazards of launch/re-entry operations.²² The chart is a summarised analysis of consequences should penetration occur, based on current aircraft vulnerability models. The analysis assumes the debris is falling at terminal velocity, since it was created for falling satellite/rocket debris. It is clearly conservative with regard to the possible consequences of an item penetrating the aircraft. A fuel tank rupture, or even penetration of an object in excess of 300 grams will not necessarily result in a catastrophic outcome. Furthermore, debris falling at terminal velocity will have more energy (relative to mass) than an RPAS. Consequently, penetration of RPAS components will generally (but not necessarily) result in less adverse consequences.

²² Smiley, G. 2015 Launch/Reentry Operation Aircraft Hazard Areas. Presented at the 26th Separation and Airspace Safety Panel Meeting. May 2015.

Figure 30: Analysis of penetration consequences from falling satellite/rocket debris



Source: International Civil Aviation Organization

Aside from penetration events, RPAS strikes could cause loss of control due to damaged flight surfaces, such as the wings or tailplane. In 2008, a Cessna Citation collided with terrain in the United States following a birdstrike.²³ The subsequent investigation found the accident was due to damage to the wing structure caused by one or more of the birds. The strike altered the aerofoil’s aerodynamic profile enough to cause a loss of control, even though no penetration of the airframe was observed. This is one such example of a catastrophic outcome from a strike on the airframe without penetration. An RPAS collision is more likely to damage flight surfaces due to the higher potential mass and comparatively rigid components.

With regard to general aviation operations, the study produced by the Range Commanders Council identified penetration of the windscreen and subsequent pilot incapacitation as a high risk in the event of falling satellite/rocket debris. There are numerous examples of birds penetrating the windscreen of general aviation aircraft and incapacitating the pilot. It is therefore obvious that RPAS collisions could result in similarly adverse outcomes. The DFT/MAA study came to similar conclusions, finding that even a 400 g quadcopter (the lightest RPAS tested) could penetrate non-birdstrike certified helicopter windscreens at speeds well below their expected cruise. General aviation aircraft without birdstrike certified windscreens were therefore also found to be at risk.

In the EASA ‘Drone Collision’ Task Force report, stakeholders expressed significant concern for the outcome of an RPAS strike on general aviation category aircraft. Commuter-type general aviation aircraft in Europe are only certified to withstand a birdstrike of less than 0.91 kg, and only on the windscreen. Most RPAS weigh more than this and are of significantly higher density, so the chance of penetration through the fuselage or windscreen is high. The empennage was also considered by stakeholders to be a high-risk strike location. DFT/MAA testing and simulation found that birdstrike certified helicopter windscreens (certified to withstand 1 kg birdstrikes) were much more resistant than non-birdstrike certified windscreens, but could still be penetrated at speeds approaching the aircraft’s cruise.

DFT/MAA computational modelling also highlighted the risk posed to helicopter tail rotors. The invariably high impact speed resulted in critical damage to the rotor, even when struck with the lightest, 400 g quadcopter.

Possible engine damage

For single engine aircraft, ingestion of an RPAS could have catastrophic consequences. With regard to reported birdstrikes in Australia over the last 10 years, 41 per cent of general aviation engine ingestions resulted in damage. This value is expected to increase with regard to RPAS strikes. As mentioned in the previous section, the proportion of birdstrikes resulting in ingestion for

²³ National Transportation Safety Board, 2009 *Crash of Cessna 500, N113SH, Following an In-Flight Collision with Large Birds*, Oklahoma City, Oklahoma, 4 March 2008.

general aviation operations is quite low (1.5%). While the consequence of an RPAS ingestion could be an engine failure, given that no RPAS strikes have yet been reported in Australia, the probability of a RPAS ingestion during general aviation operations is extremely low at present.

Within the general aviation category, birdstrikes on propellers are much more likely than engine ingestions, but propeller birdstrikes do not always result in damage. RPAS are more likely to damage propellers in the event of a collision, so the risk they pose to single engine aircraft is definitely worth considering. Impact with a propeller could cause enough damage to result in a precautionary or forced landing.

The proportion of birdstrikes resulting in engine ingestion increases for larger aircraft, while the likelihood of damage is reduced. A similar proportion of RPAS are expected to be ingested (approximately 7.7% of collisions for high capacity, based on Table 3), but the outcome of ingestion is still uncertain. For single bird ingestions, FAA regulations require turbine engines with a throat area in excess of 3.90 m² to be able to ingest a bird of up to 3.65 kg without any adverse effects²⁴ (such as more than 50 per cent power loss immediately after the strike). Any bird weighing more than 3.65 kg is beyond the certification standards of any current turbofan engine. Ignoring the fact that even lighter RPAS could cause more damage due to their rigid components, there are already many RPAS in operation that weigh far in excess of 3.65 kg.

For twin-engine aircraft, the consequence of an engine shutdown due to RPAS ingestion is expected to be relatively minor. Certified commercial aircraft are required to be able to continue safe flight in the event of a single engine shutdown. Only a tiny percentage of birdstrikes have resulted in ingestion into two engines, and this percentage is expected to be smaller still for RPAS, given that they are less likely to operate in groups.

Given that twin-engine aircraft are not likely to experience a double engine RPAS ingestion, the largest risk posed by RPAS ingestion during commercial passenger transport activities is the possibility of an uncontained engine failure. While turbofan engines are certified to contain a thrown blade or ingested bird (under 3.65 kg), an uncontained engine failure cannot be ruled out in the event of ingestion of a large RPAS. Further research is required in order to assess the risks of such an occurrence. However, it is worth remembering that an uncontained engine failure rarely results in a catastrophic outcome.

²⁴ Electronic Code of Federal Regulations – 33.76: Bird Ingestion, in US Government Publishing Office. December 2016, viewed on 1 December 2016, www.ecfr.gov/cgi-bin/text-idx?SID=e41faf7af7c74e01eb8769152998fd6f&mc=true&node=se14.1.33_176&rgn=div8

Conclusions

The number of reported RPAS-related safety occurrences increased significantly in 2016 compared to previous years. Contrary to previous assessments, this appears to have levelled-off significantly until mid-2017, with the total number of occurrences forecasted to be similar to 2016 numbers. However, due to the inherent uncertainties of these forecasts—uncertainty in the data, forecast model choice and changes in external factors (e.g. regulations)—they should only be used as indicative of future numbers.

The limited number of incidents to date means the consequence risk for a collision with an RPAS is unclear. Laboratory testing, mathematical modelling, and birdstrike data suggest RPAS operations could pose a significant risk to general aviation in the future, but collisions with high capacity transport aircraft are less likely to result in catastrophic outcomes.

Close monitoring of RPAS-related safety occurrences is required in the coming months and years.

Australian Transport Safety Bureau

The Australian Transport Safety Bureau (ATSB) is an independent Commonwealth Government statutory agency. The ATSB is governed by a Commission and is entirely separate from transport regulators, policy makers and service providers. The ATSB's function is to improve safety and public confidence in the aviation, marine and rail modes of transport through excellence in: independent investigation of transport accidents and other safety occurrences; safety data recording, analysis and research; fostering safety awareness, knowledge and action.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to operations involving the travelling public.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

Purpose of safety investigations

The object of a safety investigation is to identify and reduce safety-related risk. ATSB investigations determine and communicate the factors related to the transport safety matter being investigated.

It is not a function of the ATSB to apportion blame or determine liability. At the same time, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

Developing safety action

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to initiate proactive safety action that addresses safety issues. Nevertheless, the ATSB may use its power to make a formal safety recommendation either during or at the end of an investigation, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation.

When safety recommendations are issued, they focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on a preferred method of corrective action. As with equivalent overseas organisations, the ATSB has no power to enforce the implementation of its recommendations. It is a matter for the body to which an ATSB recommendation is directed to assess the costs and benefits of any particular means of addressing a safety issue.

When the ATSB issues a safety recommendation to a person, organisation or agency, they must provide a written response within 90 days. That response must indicate whether they accept the recommendation, any reasons for not accepting part or all of the recommendation, and details of any proposed safety action to give effect to the recommendation.

The ATSB can also issue safety advisory notices suggesting that an organisation or an industry sector consider a safety issue and take action where it believes it appropriate. There is no requirement for a formal response to an advisory notice, although the ATSB will publish any response it receives.

Australian Transport Safety Bureau

Enquiries 1800 020 616

Notifications 1800 011 034

REPCON 1800 011 034

Web www.atsb.gov.au

Twitter @ATSBinfo

Email atsbinfo@atsb.gov.au

Research

ATSB Transport Safety Report Aviation Research

A safety analysis of remotely piloted aircraft systems
A rapid growth and safety implications for traditional aviation
January 2012 to June 2016

AR-2017-016a - Second edition
Final – 9 August 2017