Frequency of ADS-B Equipped Manned Aircraft Observed by the OpenSky Network

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Identify Manned Aircraft Intruders

Objective: Identify types of manned aircraft that a sUAS may encounter, particularly at low altitudes below 1200 or 500 feet AGL

- The low altitude airspace needs to be characterized and modeled to quantify airborne collision risk
- Airborne collision risk is dependent on the size and speed of encountered aircraft
  - Encounter models based on speed and dynamics of aircraft
  - New encounter models use aircraft type as a surrogate for size
- Characterizing the type and size of low altitude aircraft can inform surveillance requirements and the simulations to estimate the likelihood of a collision
- Leveraging crowdsourced ADS-B reports, aircraft registries, and open datasets to identify low altitude aircraft

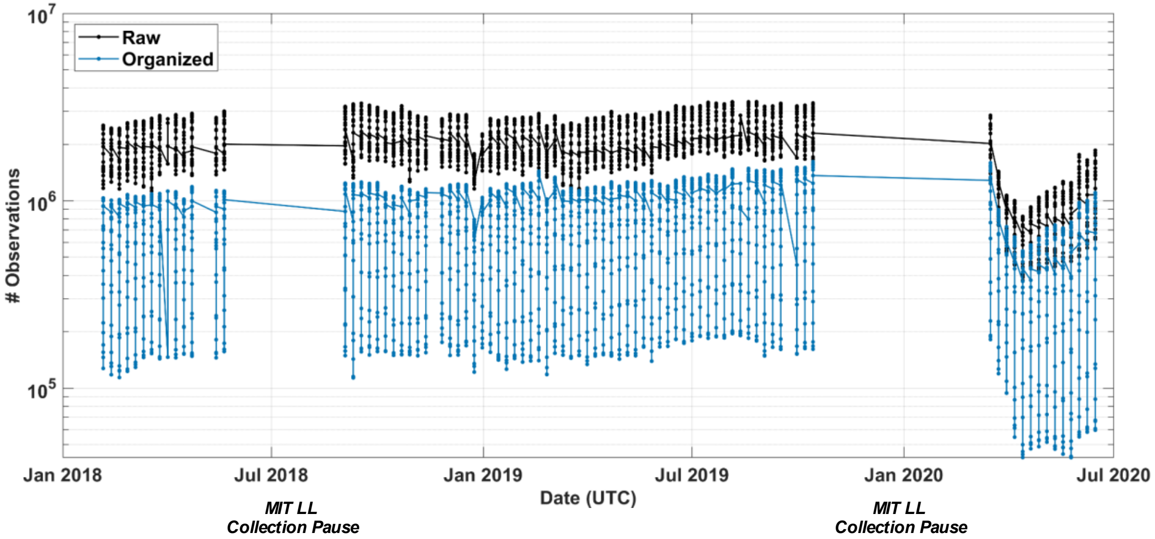
AGL – Above Ground Level

- **Overview**
- **Data Source and Processing**
- **Distributions Given Airspace Class and Altitude Layer**
- **Distributions Given Aircraft Seats**
- **Summary**

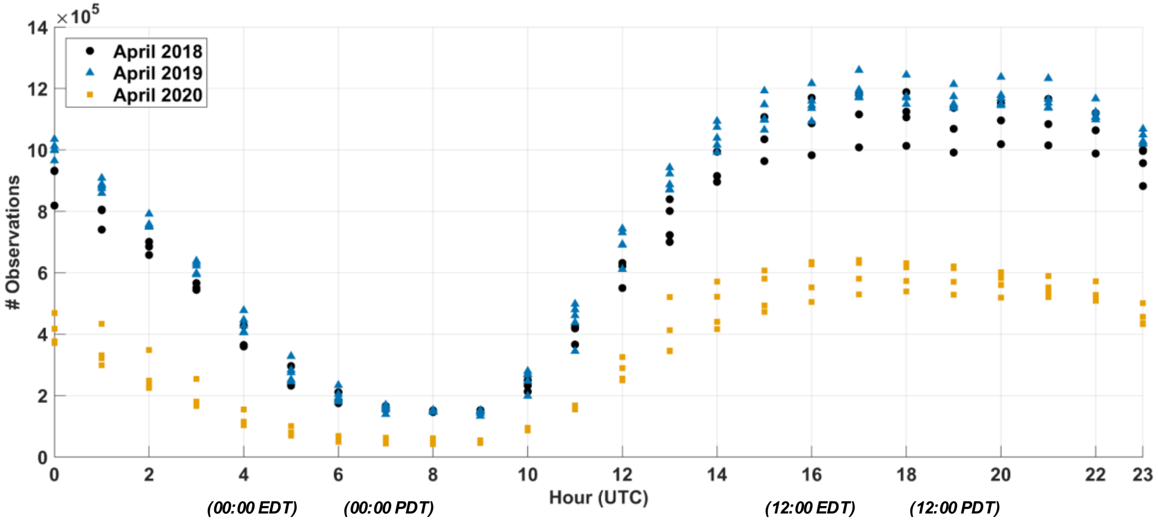
Data Source: OpenSky Network

- **Community-based receiver network which continuously collects air traffic surveillance**
  - **Archives raw data and makes it accessible to researchers**
  - **Eight trillion+ ADS-B and Mode S messages collected from more than 1000 global sensors**
  - **40 million+ daily worldwide ADS-B messages**

MIT LL Collected Data Available for Processing



Example Temporal Distribution



ADS-B – Automatic Dependent Surveillance-Broadcast

M. Schäfer, M. Strohmeier, V. Lenders, I. Martinovic and M. Wilhelm, "Bringing Up OpenSky: A Large-scale ADS-B Sensor Network for Research," in 13th IEEE/ACM International Symposium on Information Processing in Sensor Networks (IPSN), Berlin, 2014.
M. Schäfer, M. Strohmeier, M. Smith, M. Fuchs, V. Lenders and I. Martinovic, "OpenSky Report 2018: Assessing the Integrity of Crowdsourced Mode S and ADS-B Data," in 37th AIAA/IEEE Digital Avionics Systems Conference (DASC), London, 2018.

Downloading the Raw Data

- The OpenSky Network weekly makes easily accessible the abstracted raw data from the previous Monday (UTC) with observations at least 10 seconds apart
- Only the last 10-15 Mondays are made the easily most accessible
- MIT LL has aggregated data on the LLSC since 2018, but not continuously
- Raw data available in hourly segments, although no guarantee all 24 hours of a day were made available

89 Mondays Processed

2018-02-05	2018-04-23	2018-10-22	2019-01-07	2019-03-18	2019-06-03	2019-08-12	2020-03-16	2020-05-25
2018-02-12	2018-05-14	2018-10-29	2019-01-14	2019-03-25	2019-06-10	2019-08-19	2020-03-23	2020-06-01
2018-02-19	2018-05-21	2018-11-05	2019-01-21	2019-04-01	2019-06-17	2019-08-26	2020-03-30	2020-06-08
2018-02-26	2018-09-03	2018-11-12	2019-01-28	2019-04-08	2019-06-24	2019-09-02	2020-04-06	2020-06-15
2018-03-05	2018-09-10	2018-11-26	2019-02-04	2019-04-15	2019-07-01	2019-09-09	2020-04-13	2020-06-22
2018-03-12	2018-09-17	2018-12-03	2019-02-11	2019-04-22	2019-07-08	2019-09-16	2020-04-20	2020-06-29
2018-03-19	2018-09-24	2018-12-10	2019-02-18	2019-04-29	2019-07-15	2019-09-30	2020-04-27	2020-07-06
2018-03-26	2018-10-01	2018-12-17	2019-02-25	2019-05-06	2019-07-22	2019-10-07	2020-05-04	2020-07-13
2018-04-02	2018-10-08	2018-12-24	2019-03-04	2019-05-13	2019-07-29	2019-10-14	2020-05-11	
2018-04-09	2018-10-15	2018-12-31	2019-03-11	2019-05-20	2019-08-05		2020-05-18	
2018-04-16								

Source: https://opensky-network.org/datasets/states/
MIT LL – MIT Lincoln Laboratory
LLSC – Lincoln Laboratory Supercomputing Center

Analysis Scope

- Analysis scoped based on administrative boundaries and altitude
  - Only considered observations over the United States, Puerto Rico, and Virgin Islands
  - Limited observations to altitudes below 18,000 feet AGL and MSL
- Considered barometric and geometric altitudes and data from 2018 and 2019
  - No statistical difference between barometric and geometric altitude-based results
  - No statistical difference between years
  - Presented results focus on processed barometric altitude from 2019
- Identify aircraft type using the ICAO24 address
  - Use registries from multiple civil aviation authorities*
  - Leverage registries from multiple years

Analyzed 380,000+ flight hours below 18,000 feet MSL with 52,000+ flight hours at altitudes of 50 – 1,200 feet AGL

AGL – Above Ground Level
MSL – Mean Sea Level
* Annual registries from United States, Canadian, Dutch, and Irish civil aviation authorities

- Overview
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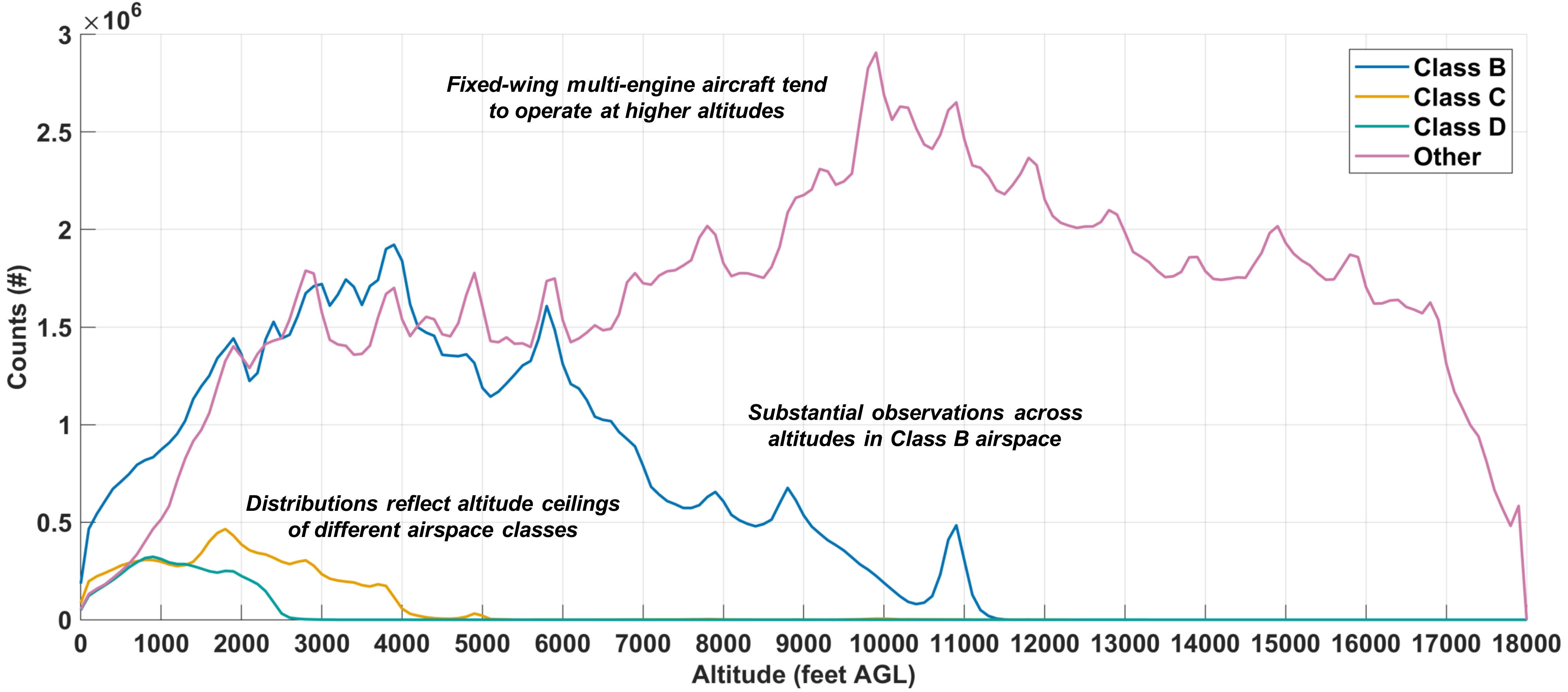
- Distributions Given Airspace Class and Altitude Layer
- Distributions Given Aircraft Seats
- Summary

Airspace Class and Altitude Layer

- Airspace class discretized into four categories: Class B, Class C, Class D, Other
  - Same discretization as MIT LL uncorrelated encounter models*
  - Other includes controlled Class E and uncontrolled Class G airspaces
- Altitude reports discretized into 100 feet intervals
  - Smaller interval than used by MIT LL encounter models*
  - Assessed barometric and geometric altitude, although results agnostic to altitude source
- Analysis an aggregation of altitude reports across the entire time window
  - No conclusions can be drawn about the distribution at a specific location
  - Initial networks of previous MIT LL encounter models have a similar constraint

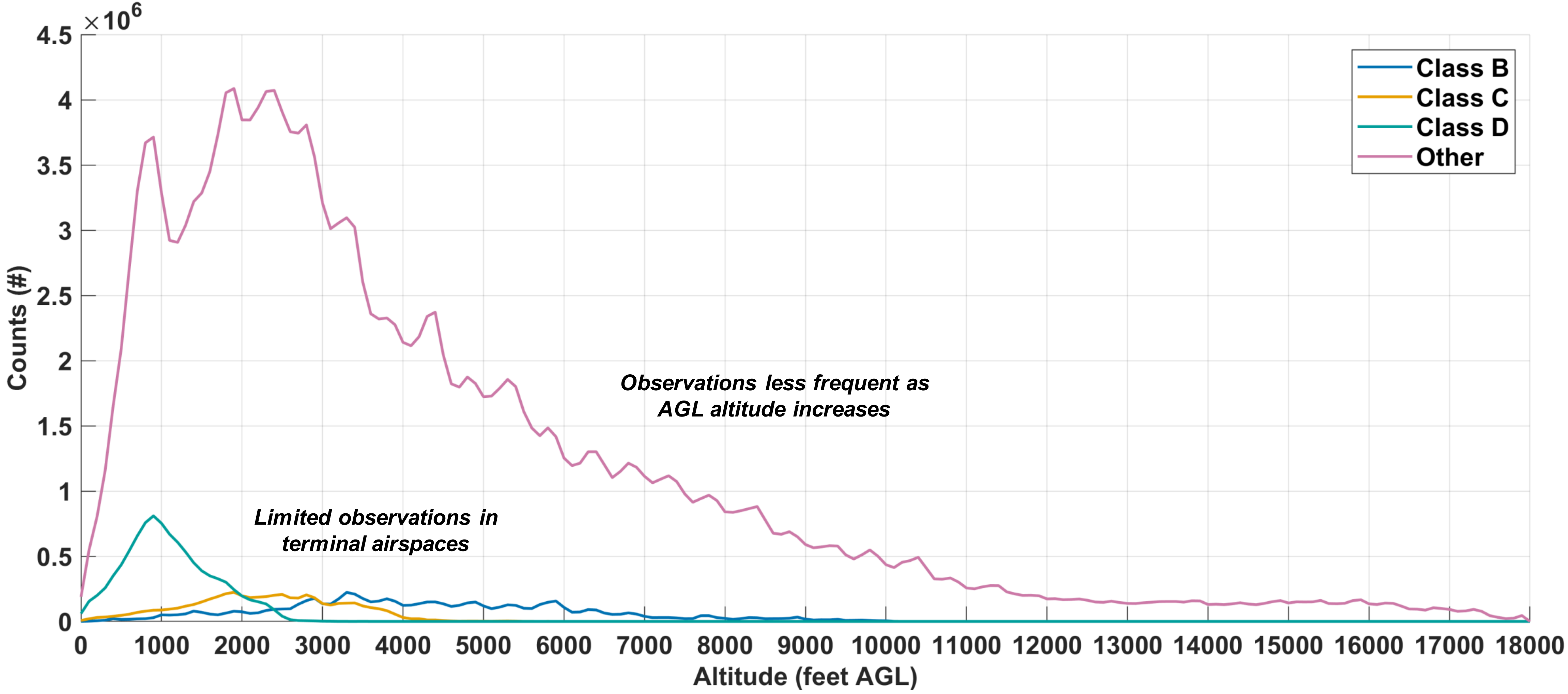
* em-model-manned-bayes v1.2 (http://doi.org/10.5281/zenodo.4048719)

ADS-B Equipped Fixed-Wing Multi-Engine
Processed Barometric Altitude Reports in 2019



AGL – Above Ground Level

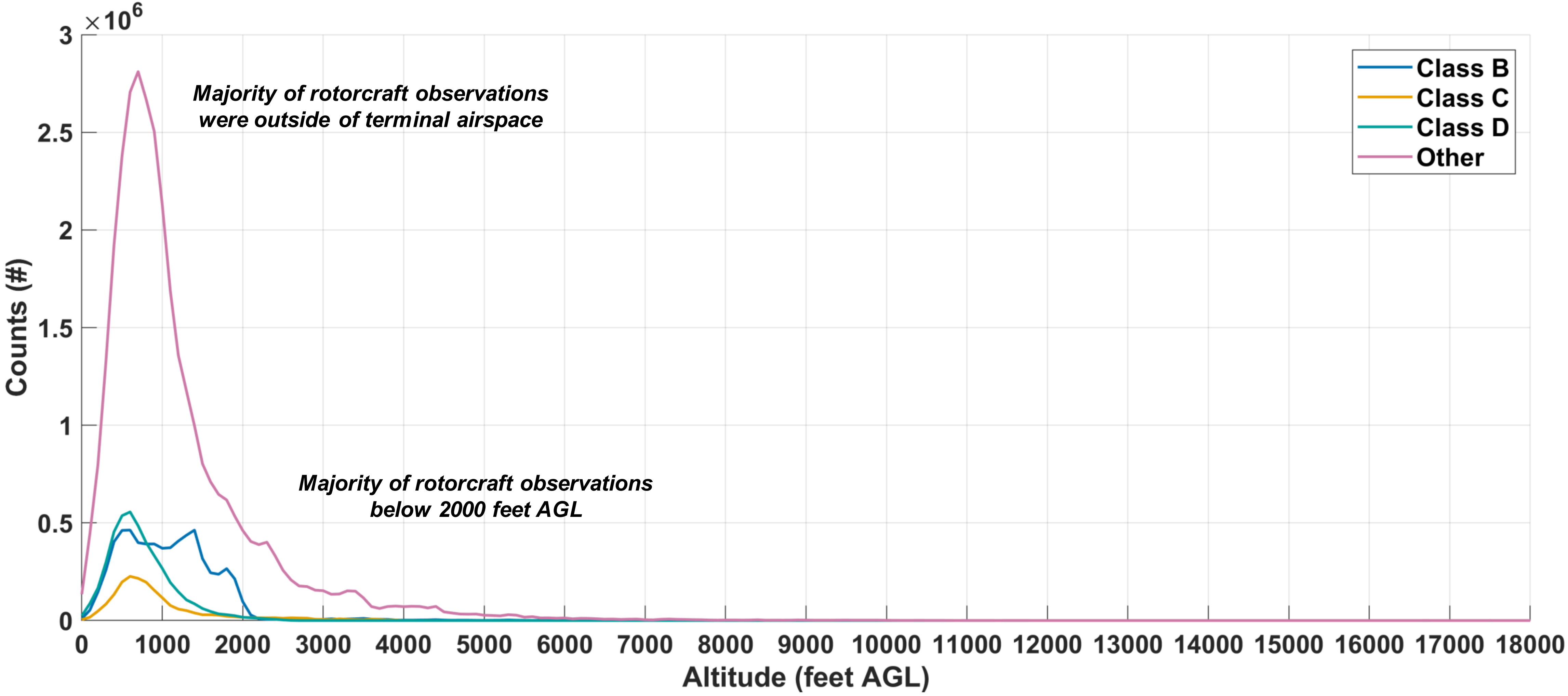
ADS-B Equipped Fixed-Wing Single Engine
Processed Barometric Altitude Reports in 2019



AGL – Above Ground Level

ADS-B Equipped Rotorcraft

Processed Barometric Altitude Reports in 2019



AGL – Above Ground Level

Discussion on Airspace Class and Altitude Layer

- Altitude distribution is strongly dependent on aircraft type

- All aircraft types have sufficient observations below 500 feet AGL
  - Majority of rotorcraft observed below 3000 feet AGL
  - Fixed-wing single engine rarely observed in controlled terminal airspace
  - Fixed-wing multi-engine have the most relative observations in Class B airspace

- Analysis indicates that, across the aggregate, smaller UAS can expect to encounter all three different manned aircraft types at low altitudes

- This analysis did not consider the size of the aircraft potentially encountered
  - Fixed-wing multi-engine can vary in size by over a hundred feet
  - Speeds and behaviors of aircraft vary based on airspace and altitude

- Overview
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Aircraft Size Frequency Analysis
Organized by Number of Seats, Not Individual Aircraft Models

- **Aircraft size can be identify by correlating an aircraft‘s ICAO 24-bit address with aircraft registries to find aircraft manufacturer and model**
  - Reduce number of unknown aircraft by using annual registries from United States, Canada, Ireland, and the Netherlands
  - Calculate average number of seats across all instances of the same aircraft model
- **Aircraft registries have good quality control on aircraft type and number of seats, but aggregating aircraft manufacturer and aircraft models is challenging**
  - Inconsistent data or similar variants: *“Cessna 172” vs. “Textron C172” vs. Cessna 172s*
  - Natural language processing techniques applied to improve aircraft registries
  - Further registry processing can be improved as future work
- **Distribution of size is more important than relative frequency between different models**
  - Aircraft size tends to increases with the quantity of seats
  - Probability of detecting an aircraft is dependent upon the aircraft’s size
  - Selecting aircraft for flight tests is easier based on seats, than seeking specific aircraft

ADS-B Equipped Fixed-Wing Multi-Engine

83%+ had greater than 10 seats and subject to a TCAS mandate*

Beechcraft King Air

DHC-6 Twin Otter

Boeing 787

	Year	Altimeter	? Seats	[1,10] Seats	[11,31] Seats	[32, ∞] Seats
≤ 18,000 ft AGL	2018	Barometric	6.9×10^{7} (0.3%)	5.1×10^{9} (21.9%)	3.9×10^{9} (17.0%)	1.4×10^{10} (60.7%)
	2018	Geometric	6.9×10^{7} (0.3%)	5.0×10^{9} (21.9%)	3.9×10^{9} (17.0%)	1.4×10^{10} (60.7%)
	2019	Barometric	1.2×10^{8} (0.3%)	7.3×10^{9} (17.5%)	6.2×10^{9} (14.9%)	2.8×10^{10} (67.2%)
	2019	Geometric	1.2×10^{8} (0.3%)	7.3×10^{9} (17.6%)	6.2×10^{9} (14.9%)	2.8×10^{10} (67.2%)
≤ 1200 ft AGL	2018	Barometric	1.2×10^{7} (1.0%)	2.6×10^{8} (22.6%)	1.9×10^{8} (16.7%)	7.0×10^{8} (59.6%)
	2018	Geometric	9.7×10^{6} (0.9%)	2.5×10^{8} (22.4%)	1.8×10^{8} (16.5%)	6.8×10^{8} (60.3%)
	2019	Barometric	1.2×10^{7} (0.6%)	3.6×10^{8} (18.7%)	3.0×10^{8} (15.3%)	1.2×10^{9} (65.4%)
	2019	Geometric	1.1×10^{7} (0.6%)	3.5×10^{8} (18.6%)	2.8×10^{8} (15.0%)	1.2×10^{9} (65.8%)

*** 14 CFR § 135.180**
Percentages organized by row

ADS-B Equipped Fixed-Wing Single Engine

Majority had 6 or less seats

Cirrus SR20

Quest Kodiak

Cessna 208

	Year	Altimeter	? Seats	[1,6] Seats	[7,10] Seats	[11, ∞] Seats
≤ 18,000 ft AGL	2018	Barometric	6.3×10^{7} (0.5%)	1.1×10^{10} (86.8%)	6.2×10^{8} (4.8%)	1.0×10^{9} (7.9%)
	2018	Geometric	6.3×10^{7} (0.5%)	1.1×10^{10} (86.9%)	6.2×10^{8} (4.8%)	1.0×10^{9} (7.8%)
	2019	Barometric	2.3×10^{8} (1.0%)	1.9×10^{10} (84.9%)	1.1×10^{9} (5.2%)	2.0×10^{9} (8.9%)
	2019	Geometric	2.3×10^{8} (1.0%)	1.9×10^{10} (85.0%)	1.1×10^{9} (5.2%)	2.0×10^{9} (8.8%)
≤ 1200 ft AGL	2018	Barometric	1.8×10^{7} (0.9%)	1.9×10^{9} (95.1%)	4.4×10^{7} (2.2%)	3.5×10^{7} (1.8%)
	2018	Geometric	1.7×10^{7} (0.9%)	1.8×10^{9} (95.3%)	4.1×10^{7} (2.1%)	3.1×10^{7} (1.7%)
	2019	Barometric	6.6×10^{7}(1.8%)	3.2×10^{9} (91.6%)	1.3×10^{8} (3.9%)	9.9×10^{7} (2.7%)
	2019	Geometric	6.5×10^{7} (1.9%)	3.2×10^{9} (91.6%)	1.3×10^{8} (3.9%)	9.2×10^{7} (2.6%)

Percentages organized by row

ADS-B Equipped Rotorcraft

Majority of had 5, 6, 7, or 8 seats

Robinson R44

Bell 429

Airbus H175

	Year	Altimeter	? Seats	[1,4] Seats	[5,8] Seats	[9, ∞] Seats
≤ 18,000 ft AGL	2018	Barometric	3.5×10^7 (1.4%)	5.3×10^8 (21.9%)	1.5×10^9 (63.0%)	3.3×10^8 (13.6%)
	2018	Geometric	3.5×10^7 (1.4%)	5.3×10^8 (21.9%)	1.5×10^9 (62.9%)	3.3×10^8 (13.7%)
	2019	Barometric	8.5×10^7 (1.8%)	7.3×10^8 (15.9%)	3.2×10^9 (70.4%)	5.4×10^8 (11.9%)
	2019	Geometric	8.5×10^7 (1.8%)	7.4×10^8 (16.0%)	3.2×10^9 (70.3%)	5.5×10^8 (11.9%)
≤ 1200 ft AGL	2018	Barometric	1.3×10^7 (0.8%)	4.4×10^8 (25.3%)	1.1×10^9 (62.6%)	1.9×10^8 (11.3%)
	2018	Geometric	1.2×10^7 (0.7%)	4.4×10^8 (25.7%)	1.0×10^9 (62.4%)	1.9×10^8 (11.3%)
	2019	Barometric	3.3×10^7(1.0%)	6.3×10^8 (19.7%)	2.2×10^9 (69.5%)	3.1×10^8 (9.8%)
	2019	Geometric	3.3×10^7 (1.0%)	6.4×10^8 (19.7%)	2.2×10^9 (69.7%)	3.1×10^8 (8.8%)

Percentages organized by row

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Most Observed ADS-B Equipped Aircraft in 2019

≤ 18,000 feet AGL and All Airspace Classes

Type	Manufacturer	Model	# Seats (Mean)	Flight Hours (≤ 18,000 ft AGL)	Flight Hours (≤ 1200 ft AGL)
Fixed-Wing Multi-Engine	Boeing	737	164	12,485	657
Fixed-Wing Multi-Engine	Embraer	ERJ-170	86	11,646	563
Fixed-Wing Multi-Engine	Airbus	A320	198	8,223	406
Fixed-Wing Multi-Engine	Airbus	A321	304	7,578	332
Fixed-Wing Multi-Engine	Bombardier	CL-600	54	7,175	285
Fixed-Wing Multi-Engine	Airbus	A319	161	6,027	318
Fixed-Wing Single Engine	Cessna	172s	4	4,488	1,012
Fixed-Wing Multi-Engine	Embraer	EMB-145LR	55	4,239	122
Fixed-Wing Multi-Engine	Bombardier	DHC-8	59	3,682	196
Fixed-Wing Single Engine	Cessna	172r	4	2,683	616

Across all altitudes, majority of observed aircraft were fixed-wing multi-engine

Most Observed Low Altitude ADS-B Equipped Aircraft in 2019
≤ 1200 feet AGL and All Airspace Classes

Type	Manufacturer	Model	# Seats (Mean)	Flight Hours (≤ 18,000 ft AGL)	Flight Hours (≤ 1200 ft AGL)
Fixed-Wing Single Engine	Cessna	172s	4	4,488	1,012
Rotorcraft	Airbus	AS-350b3	7	970	814
Rotorcraft	All American	AS-350b2	6	850	669
Fixed-Wing Multi-Engine	Boeing	737	164	12,485	657
Fixed-Wing Single Engine	Cessna	172n	4	2,465	630
Fixed-Wing Single Engine	Cessna	172r	4	2,683	616
Fixed-Wing Single Engine	Beech	172s	4	2,637	602
Rotorcraft	All American	AS-350b3	6	724	574
Fixed-Wing Multi-Engine	Embraer	ERJ-170	86	11,646	563
Fixed-Wing Single Engine	Blue Diamond	DA20-C1	2	1,957	548

Majority of observed ADS-B equipped aircraft at low altitudes had 7 or less seats

Discussion on Distributions Based on Seats

Negligible variation in results between altitude source and year

- Similar distributions between comparing all altitude reports and just at low altitude.
- Observations of fixed-wing single engine skewed to six seats or less at low altitudes
  - Assumes non-transponding aircraft at low altitudes will also generally have six or less seats
  - Size of fixed-wing single engine and rotorcraft at low altitudes may be independent of transponder equipage
- Cessna 172 fixed-wing single engine variants were some of the most observed ADS-B equipped aircraft
- Results can inform simulations based on aircraft size
  - Supports an extension of J.W. Andrews on air-to-air visual acquisition*
  - Enables weighting simulations based on aircraft size and subsequent probability of detection

Distributions inform the size of ADS-B equipped aircraft encountered at low altitudes

Andrews, J. W., Air-To-Air Visual Acquisition Performance with TCAS II, Project Report ATC-130, MIT Lincoln Laboratory, Lexington, MA, 1984.
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- Overview
- Data Source and Processing
- Distributions Given Airspace Class and Altitude Layer
- Distributions Given Generalized Operational Regions
- Distributions Given Aircraft Seats
- Summary

Summary

- The continuing integration of unmanned aircraft systems operations into the NAS requires development of regulations and technology to maintain safety
- To support development and evaluation of UAS DAA systems, the low altitude airspace needs to be characterized and modeled
- Airborne collision risk is dependent on the size and speed of encountered aircraft
- Observations of ADS-B equipped aircraft by the OpenSky Network were analyzed based on three different factors
  - Airspace class and altitude layer
  - Number of seats on the aircraft
- Results inform aircraft types used in DAA simulations and testing

Thank You!

Questions?

Feedback?

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Most Observed ADS-B Equipped Aircraft in 2019

Fixed-Wing Multi-Engine

Ranking	Manufacturer	Model	# Seats	Flight Hours (All)	Flight Hours (Low)
1	Boeing	737	164	12,485	657
2	Embraer	ERJ-170	86	11,646	563
3	Airbus	A320	198	8,223	406
4	Airbus	A321	304	7,578	332
5	Airbus	A319	161	6,027	318
6	Bombardier	CL-600	54	7,175	285
7	Bombardier	DHC-8	59	3,682	196
8	New Piper	PA-44	4	1,536	162
9	Embraer	EMB-145LR	55	4,239	122
10	Boeing	757	190	2,592	113
11	Bombardier	BD-100	8	1,472	83
12	Embraer	ERJ-190	24	2,061	81
13	Boeing	717	100	1,838	71
14	Embraer	EMB-505	9	1,291	70
15	Boeing	777	439	1,354	69
16	Embraer	EMB-135KL	37	1,762	68
17	Boeing	767	237	1,473	65
18	Embraer	EMB-145XR	55	2,024	59
19	McDonnell Douglas	MD-88	142	1,515	29
20	Cessna	402c	10	1,253	27

#1: Boeing 737

#8: Piper PA-44 Seminole

Most Observed ADS-B Equipped Aircraft in 2019
Fixed-Wing Single Engine

Ranking	Manufacturer	Model	# Seats	Flight Hours (All)	Flight Hours (Low)
1	Cessna	172s	4	4,488	1,012
2	Cessna	172n	4	2,465	630
3	Cessna	172r	4	2,683	616
4	Beechcraft*	172s	4	2,637	602
5	Blue Diamond	DA20-C1	2	1,957	548
6	Cessna	152	2	1,638	472
7	Cessna	172m	4	1,473	376
8	New Piper	PA-28	4	1,798	354
9	Cessna	172p	4	1,585	306
10	Blue Diamond	DA40	5	1,349	239
11	Aero Design	SR-20	4	1,444	228
12	Cessna	182t	4	617	79
13	Aero Design	SR-22t	5	1,288	70
14	Aero Design	SR-22	4	1,096	55
15	Cessna	208b	12	2,133	48
16	*Homekit*	*Homekit*	11	1,156	44
17	*Homekit*	*Homekit*	12	1,162	40
18	Cessna	T206h	6	622	36
19	Beechcraft	A36	6	673	25
20	New Piper	PA-46	6	572	14

#1: Cessna 172 Skyhawk

#5: Blue Diamond DA20-C1

* Likely NLP error

Most Observed ADS-B Equipped Aircraft in 2019

Rotorcraft

Ranking	Manufacturer	Model	# Seats	Flight Hours (All)	Flight Hours (Low)
1	Airbus	AS-350b3	7	970	814
2	All American	AS-350b2	6	850	669
3	All American	AS-350b3	6	724	574
4	BHI Helicopters	R-44	4	656	544
5	Bell	407	8	855	541
6	All American	EC-130	7	934	467
7	Bell	206b	5	459	427
8	Airbus	EC-130	8	917	407
9	Bell	369ff	4	413	407
10	All American	EC-120b	5	330	316
11	All American	AS-350b2	7	377	276
12	Bell	206L4	7	353	258
13	BHI Helicopters	R-22 Beta	2	299	254
14	Bell	429	9	324	220
15	Bell	407	7	264	191
16	All American	AS-350b3	7	255	176
17	Eurocopter	MBBK-117	8	270	170
18	Eurocopter	EC-135p2	7	292	157
19	BHI Helicopters	R-66	5	166	127
20	Bell	206L3	7	193	67

#1: Eurocopter AS350
(Now Airbus Helicopters H125)

#14: Bell 429

Imagery Sources

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