DOT/FAA/TC-19/43

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Technology Assessment to Improve Operations Counts at Non-Towered Airports

November 2019

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-19/43		

4. Title and Subtitle	5. Report Date
TECHNOLOGY ASSESSMENT TO IMPROVE OPERATIONS COUNTS AT NON-TOWERED AIRPORTS	November 2019
	6. Performing Organization Code
7. Author(s) John H. Mott, Chuyang Yang, Brandon Hardin, Steven Zehr, Darcy M. Bullock, Jack R. Bell	8. Performing Organization Report No.
9. Performing Organization Name and Address Purdue University 610 Purdue Mall West Lafayette, IN 47907	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 12-C-GA-PU-061
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Airport Planning and Environmental Division (APP-400) 800 Independence Avenue SW Washington, DC 20591	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code APP-400

15. Supplementary Notes

The FAA Airport Safety Technology Research & Development Section PM was Mr. Jonathan Torres. Primary staff contact in APP-400 is Michael Lawrance.

16. Abstract

Accurate airport operations counts are important for determining appropriate funding allocations for airport development and improvement. However, fewer than 270 of the 2941 non-primary airports in the United States have air traffic control personnel who are available to count airport operations. Existing counting methods, such as automatic acoustic counters, are not viable long-term solutions because of the expense and inconvenience of deploying the devices on a large scale.

The Federal Aviation Administration (FAA) Planning and Environmental Division tasked the FAA Airport Technology Research and Development Branch with the evaluation of aircraft transponder technology to accurately register operations counts at non-towered airports. The evaluation was conducted Purdue University through the FAA Partnership to Enhance General Aviation Safety, Accessibility and Sustainability Center of Excellence. This report documents the research conducted at four Indiana airports to validate a cost-effective counting technology based on a technique that uses signal strength obtained from aircraft transponders to register the occurrence of aircraft operations at non-towered airports. This report also presents and validates a barometric calibration method, which is used to improve the accuracy of operations counts.

Data collectors were installed at Purdue University Airport, Terre Haute Regional Airport, Indianapolis Executive Airport, and Warsaw Municipal Airport, providing over 150 million transponder records during the data collection period. Operations counts estimates were compared to Air Traffic Activity Data System counts where available, resulting in monthly error rates ranging from -8.7% to 8.3% and long-term error rates ranging from -3.1% to 3.0% over time periods ranging from 31 days to 398 days. These results suggest that this implementation of the transponder signal-counting technology is an accurate and cost-effective way to count non-towered airport operations. Improvements and testing of this technology are being undertaken.

17. Key Words	18. Distribution Statement
Transponder, Aircraft operations, Counting, ADS-B, Mode C, Mode S, Extended squitter, Non-towered	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	34	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

This research was funded by the Federal Aviation Administration (FAA) Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS) Center of Excellence. The preproduction prototype was provided by Bluemac Transportation Data Systems, LLC. The financial value of that equipment and associated engineering support by Bluemac was used to meet the required FAA cost share contribution for PEGASAS projects awarded to Purdue University. The authors have no financial interest in Bluemac Transportation Data Systems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AAC	Automated acoustic counter
ACRP	Airport Cooperative Research Program
ADS-B	Automatic dependent surveillance-broadcast
AGL	Above ground level
ATADS	Air Traffic Activity Data System
ATC	Air traffic control
ES	Extended squitter
FAA	Federal Aviation Administration
GA	General aviation
GPS	Global positioning system
″Hg	Inches of Mercury
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronic Engineers
IFPTO	Instrument flight plans to total operations
KASW	Warsaw Municipal Airport
KHUF	Terre Haute Regional Airport
KLAF	Purdue University Airport
KTYQ	Indianapolis Executive Airport
nm	Nautical mile
OPBA	Operations per based aircraft
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility and Sustainability
SS	Short squitter
S/TC	Security/trail camera
TPA	Traffic pattern altitude
U.S.	United States
VID	Video image detection

EXECUTIVE SUMMARY

Accurate airport operations counts are important for determining appropriate funding allocations for airport development and improvement. However, fewer than 270 of the 2941 non-primary airports in the United States have air traffic control personnel who are available to count airport operations. Existing counting methods, such as automatic acoustic counters, are not viable long-term solutions because of the expense and inconvenience of deploying the devices on a large scale.

This report validates a cost-effective counting technology based on a technique that uses signal strength obtained from aircraft transponders to register the occurrence of aircraft operations at non-towered airports. Over 150 million transponder records were collected from two different versions of the system, which were installed at four Indiana airports: Purdue University Airport, Terre Haute Regional Airport, Indianapolis Executive Airport, and Warsaw Municipal Airport. The operations counts calculated from these records were compared with those obtained from the Federal Aviation Administration air traffic activity data system database, which contains official operations data reported by airports with air traffic control towers.

This report also presents and validates a barometric calibration method, which was used to improve the accuracy of operations counts. The Version I device used a Raspberry Pi® platform and produced monthly error rates ranging from -10.2% to +7.6%. The Version II device consisted of the preproduction commercialized system and resulted in long-term error rates ranging from -3.1% to 3.0% over time periods that ranged from 31 days to 398 days. Shorter-duration monthly error for the Version II platform rates ranged from -8.7% to 8.3%.

The test results suggest that this preproduction implementation of the transponder signal-counting technology is an accurate and cost-effective way to count non-towered airport operations. Improvement and testing of this technology are ongoing.

1. INTRODUCTION

Accurate operations counts are critical for determining funding allocation for national airports. Such counts are also important for facilitating a thorough understanding of the national airspace system. According to the 2019-2023 National Plan of Integrated Airport Systems report, the Federal Aviation Administration (FAA) annually spends approximately $2.5 billion in Airport Improvement Program funding at 2941 non-primary airports (FAA, 2018). At airports with air traffic control (ATC) towers, controllers manually record aircraft operations; however, fewer than 270 of those non-primary airports have ATC personnel (Airport Cooperative Research Program, 2015). Therefore, operations counts are more difficult to obtain at non-towered airports due to an absence of full-time personnel. An accurate counting technology is reasonably expected to estimate airport operations with an absolute error rate of less than 10% based on data aggregated over 60 days or more. Consequently, several estimation methods and counting technologies have been developed in an effort to derive accurate total aircraft operations counts.

1.1 BACKGROUND

The Airport Cooperative Research Program (ACRP) Report 129 (2015) summarized three methods of estimating annual operations at airports. These estimation methods included multiplying based aircraft by an estimated number of operations per based aircraft (OPBA), applying a ratio of FAA instrument flight plans to total operations (IFPTO), and using a sample extrapolation method to estimate annual operations counts. Since no official personnel are responsible for counting aircraft operations at all times when the non-towered airports are open, OPBA and IFPTO methods were not recommended for estimating annual operations at these airports because of a lack of consistent OPBA and IFPTO figures at small, non-towered airports nationally. However, an extrapolation of sample data to estimate annual operations counts was recommended (ACRP, 2015). Existing counting technologies that are used to collect sample aircraft operations at airports were summarized by Ford and Shirack (ACRP, 2015, Appendix) and ACRP (2015). These technologies included automated acoustic counters (AAC), sound-level meter acoustic counters (SMAC), security/trail cameras (S/TC), video image detection (VID), and automatic dependent surveillance-broadcast (ADS-B) transponder receiver technology. According to test results provided by Bahler, Kranig, and Minge (1998) in a highway traffic counting environment, the accuracy of AAC was impacted by low-temperatures and other factors, so that the relative accuracy is roughly 15%. Using S/TC to count aircraft is labor intensive because images must be tallied manually. VID is the most expensive option for counting aircraft operations; in ACRP (2015), Muia and Johnson reported that the lease cost was $36,000 for two cameras and one ADS-B receiver over the 7-month period of their evaluation of the technology.

McNamara, Mott, and Bullock (2016) developed a technology that can be used for counting operations with extended Mode S aircraft transponder signals, which contain global positioning system (GPS)-derived aircraft position information and can be received with a 1090 MHz software-defined radio platform in conjunction with a single-board reduced instruction set computer and Linux® operating system. This technology is cost-effective (less than $100 per unit for an experimental model) compared with acoustic counters (around $4800 per unit) or VID, so it can be deployed on a large scale over a long period of time (table 1) (McNamara et al., 2016).

Table 1. Basic Accuracy and Cost Information for Existing Counting Technologies

Counting Technology[1]	Test Airport	Reported Percentage Error	Cost Per Unit[2]
Sound-Level Meter Acoustic Counter (Portable acoustic counter)	Purdue University Airport	5% to 99%	$4,800
	Indianapolis Executive Airport	8% to 48%	
Security/Trail Camera (Portable camera with infrared night vision)	Purdue University Airport	54% to 100%	$1,000
	Indianapolis Executive Airport	0% to 43%	
Stationary VID with ADS-B Transponder Receiver (stationary)[3]	Indianapolis Executive Airport	10% to 17%	$36,000

[1]All data in this table were retrieved from ACRP Report 129 (ACRP, 2015).
[2]The costs are represented as paid for the equipment tested in (ACRP, 2015), and do not include any installation time (except for the leased VID equipment) or data retrieval time.
[3]The costs decrease to $31,000 without the ADS-B receiver. This is a lease cost and will vary from airport to airport depending on the airport layout.

In the United States (U.S.) in calendar year 2017, the total general aviation (GA) fleet size was 211,757 (Bureau of Transportation Statistics, 2019). As of July 1, 2019, the number of ADS-B-equipped GA aircraft was 64,959 (FAA, 2019). It is safe to assume that the GA fleet size as of July 1, 2019 is virtually unchanged from 2017. Hence, the proportion of Mode S Extended Squitter (ES)-equipped aircraft of the U.S. GA fleet is approximately 30.6%. However, note that operations per aircraft are not evenly distributed across the GA fleet; the majority of actual operations are generated by a subset of the entire GA fleet. The proportion of the fleet that conducts most operations is also the most likely to be equipped with ADS-B, since those aircraft will need regular access to A, B, and C airspace. So, when referring to fleet equipage alone, the operationally weighted proportion of the fleet with ADS-B is thought to be substantially higher than suggested.

Mode A and Mode C transponders operate in identification-only, pulse amplitude-modulated modes that transmit a four-digit octal code to the ground-based interrogating station. Mode C includes barometric altitude information; Mode A does not (Mott, 2018a). Aircraft equipped with Mode C transponders are interrogated by secondary surveillance antennas, which have a rotational period of approximately 4.8 seconds. Mode S signals differ from both Mode A and Mode C in that they are pulse position-modulated and contain altitude information and a 24-bit data stream, which is a combination of parity information and an International Civil Action Organization (ICAO)-issued code used to identify the aircraft. In the U.S., there is a unique, one-to-one correspondence between this ICAO code and the FAA aircraft registration code. Mode S ES replies (transmitted periodically without interrogation) contain a 56-bit data field used for transmitting both altitude and position information (Mott, 2018b). The ES reply is capable of carrying more data than the basic Mode S short squitter (SS) version. For appropriately equipped aircraft, Mode S ES data is transmitted without interrogation at a nominal rate of one record every 5 seconds when airborne and every 10 seconds when on the ground.

Such transponder signals are easily obtained in a passive manner by inexpensive ground-based receivers, and the data from the signals can be stored to provide the researcher with the ability to derive a rich range of related operational metrics. While Mode S ES data is very useful in determining aircraft position relative to a particular runway, the aircraft fleet penetration of Mode S ES transponders, as noted previously, is only about 7%, despite an FAA requirement that most domestic aircraft be equipped with either Mode S ES or universal access transceiver (UAT) ADS-B transponders by January 1, 2020 (Mott, 2018a). In contrast, because the combined penetration of Mode S SS and Mode C is about 81%, it is important to find opportunities to use this data (neither of which contain GPS-derived aircraft position information) to estimate airport operations counts.

Mott (2018b) developed an aircraft distance estimation method based on Mode S SS and Mode C transponder signal strength by employing a self-calibrating adaptive digital filter. A methodology to extend the Mode S ES operations counting technology to include the use of the Mode S SS and Mode C data, thereby including a large portion of the GA fleet in the samples available for counting, was developed by Mott, McNamara, and Bullock (2016; 2017).

1.2 OBJECTIVE

One objective of this research effort was to validate Mott and Bullock's methodology for counting non-towered airport operations. Another objective was to test the preproduction prototype of the receiver/data collection device, consisting of a low-cost receiver, self-calibrating signal-processing algorithm. Finally, a third objective was to test an estimation technique providing greater accuracy than that associated with traditional acoustic counters (figure 1). Note this proposed technology does not have the ability to classify operations as touch and goes, nor does the Air Traffic Activity Data System (ATADS) data classify operations as such.

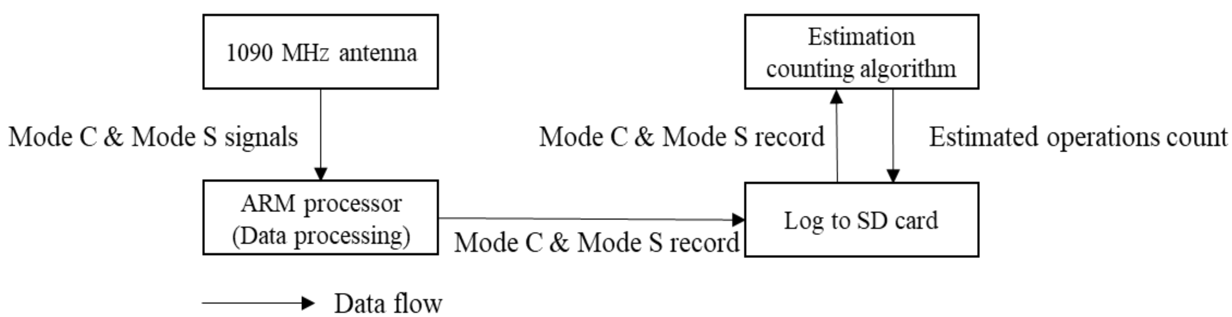
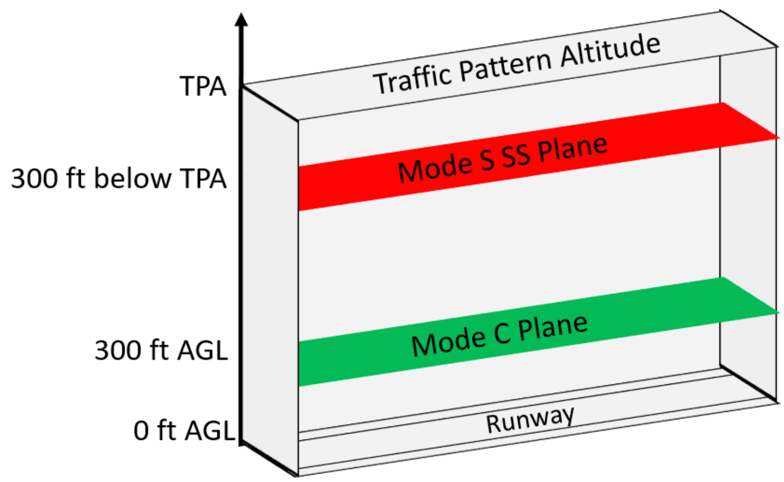


Figure 1. Preproduction Prototype (Version II)

2. TEST SETUP

2.1 COUNT REGISTRATION PROCESS

Altitude information can be obtained from most received transponder signals, with the exception of Mode A, which, as noted, are less common. Because Mode C and Mode S SS responses do not contain position or heading information, aircraft position must be estimated from the strength of the received transponder signal. Once an appropriate threshold detection level has been determined, the distance for a particular aircraft may be measured. Consecutive transponder records with decreasing distances and altitudes below that of the airport traffic pattern suggest that the related aircraft is executing a landing, while records with increasing distances and altitudes suggest that the associated aircraft is engaged in a takeoff (figure 2).



AGL = Above ground level
TPA = Traffic pattern altitude

Figure 2. Threshold Altitudes Used in Operations Counts Registration (Mott, 2018b)

Mott (2018a) described the heuristics for recording airport operations using received transponder records. For Mode S ES operations, an air-to-ground or ground-to-air transition between contiguous entries is identified. These entries must be separated by greater than 10 seconds (to eliminate erroneous transitions due to bounced landings) and less than 90 seconds (to account for what is likely a separate operation). If the aircraft is within 35 degrees of the runway heading, as determined from the transponder record, an operation is registered.

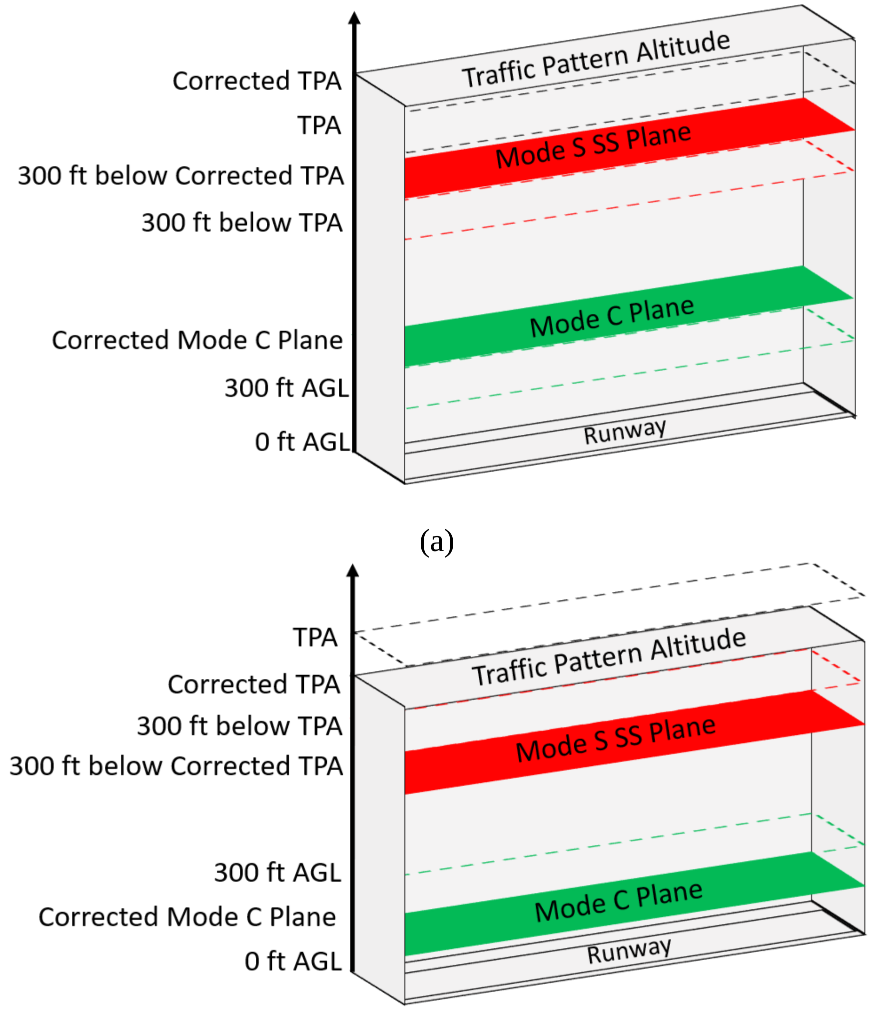
Accurate estimation of aircraft distances is necessary for Mode C and Basic Mode S operations, as those two modes do not contain encoded position information. To estimate the distance between aircraft and receiver unit, a data vector consisting of eight signal strength values from the transponder receiver is collected and filtered using a combined digital adaptive first-order, low-pass Butterworth filter and Rayleigh maximum likelihood estimator. The filter coefficient is adjusted using distances computed from the known positions of aircraft equipped with Mode S ES transponders.

For a Mode C operation, consecutive transmissions must be separated by a distance of less than 1.1 nautical miles (nm) and times of between 18 and 90 seconds; these conditions allow discrimination between possible multiple Mode C aircraft using the assumption that the maximum airspeed in Class D airspace is not exceeded. If the Mode C aircraft is registered as descending below a 300-foot horizontal plane above the airport elevation, the operation is recorded.

Basic Mode S operations counts involve ensuring three conditions: the aircraft must be within 2 nm of the receiver, the aircraft must be 300 feet below the pattern altitude with either consecutive increases or decreases in altitude, and more than 90 seconds must occur since the last operation of the aircraft.

Atmosphere pressure is one of the basic factors related to aerodynamics, and measurements thereof utilizing various flight instruments provide important information to pilots. The pressure altimeter is one of the most important flight instruments onboard an aircraft. Since air is a substance having mass, the force it exerts is equal in all directions, and its effect on bodies is called pressure. Atmospheric pressure varies primarily with altitude and temperature (FAA, 2008).

Since, from a climatological perspective, atmospheric pressure in general varies seasonally, that variation has an effect upon the pressure-sensitive aircraft barometer. This variation affects the original heuristics of operations registration proposed by Mott et al. (2016). When local atmospheric pressure is higher than 29.92 inches of mercury (″Hg), an aircraft altimeter will cause the aircraft's transponder altitude encoder to transmit an updated aircraft altitude which is relatively lower than the altitude based on the standard pressure datum of 29.92 ″Hg, while a relatively higher altitude will be transmitted when local atmospheric pressure is below 29.92 ″Hg (FAA, 2008). If the corresponding threshold altitude is not adjusted based on the local atmospheric pressure, the updated altitudes will cause over-counting or under-counting of operations at these airports. Hence, two calibration models were developed to eliminate the impacts of pressure variation upon the related operations counts (figure 3).



AGL = Above ground level
TPA = Traffic pattern altitude

(b)

Figure 3. Calibrated Runway Bounding Cuboid: (a) Calibration Based on Local Atmospheric Pressure Below 29.92 ″Hg and (b) Calibration Based on Local Atmospheric Pressure Above 29.92 ″Hg (Mott et al., 2016)

2.2 EXPERIMENTAL DATA COLLECTION INFRASTRUCTURE

To fully test and validate the estimation methods and counting technology, field deployments of Version I (the initial experimental transponder signal receiver and processing system) and Version II (the preproduction prototype of the commercial version of the signal-counting technology) devices were conducted at four Indiana airports over extended periods. During Version I and Version II data collection, more than 150 million transponder records were examined. These deployments were conducted at Purdue University Airport (KLAF), Terre Haute Regional Airport (KHUF), Indianapolis Executive Airport (KTYQ), and Warsaw Municipal Airport (KASW). Among these airports, KLAF and KHUF have FAA ATC towers; KTYQ and KASW are non-towered airports. To test a variety of deployment types with the data collectors, each airport deployment was unique in setup. This variation in deployments served to verify the data collector operations at multiple altitudes and positions relative to the airport runway. The data collection sites are presented in figures 4 through 7.

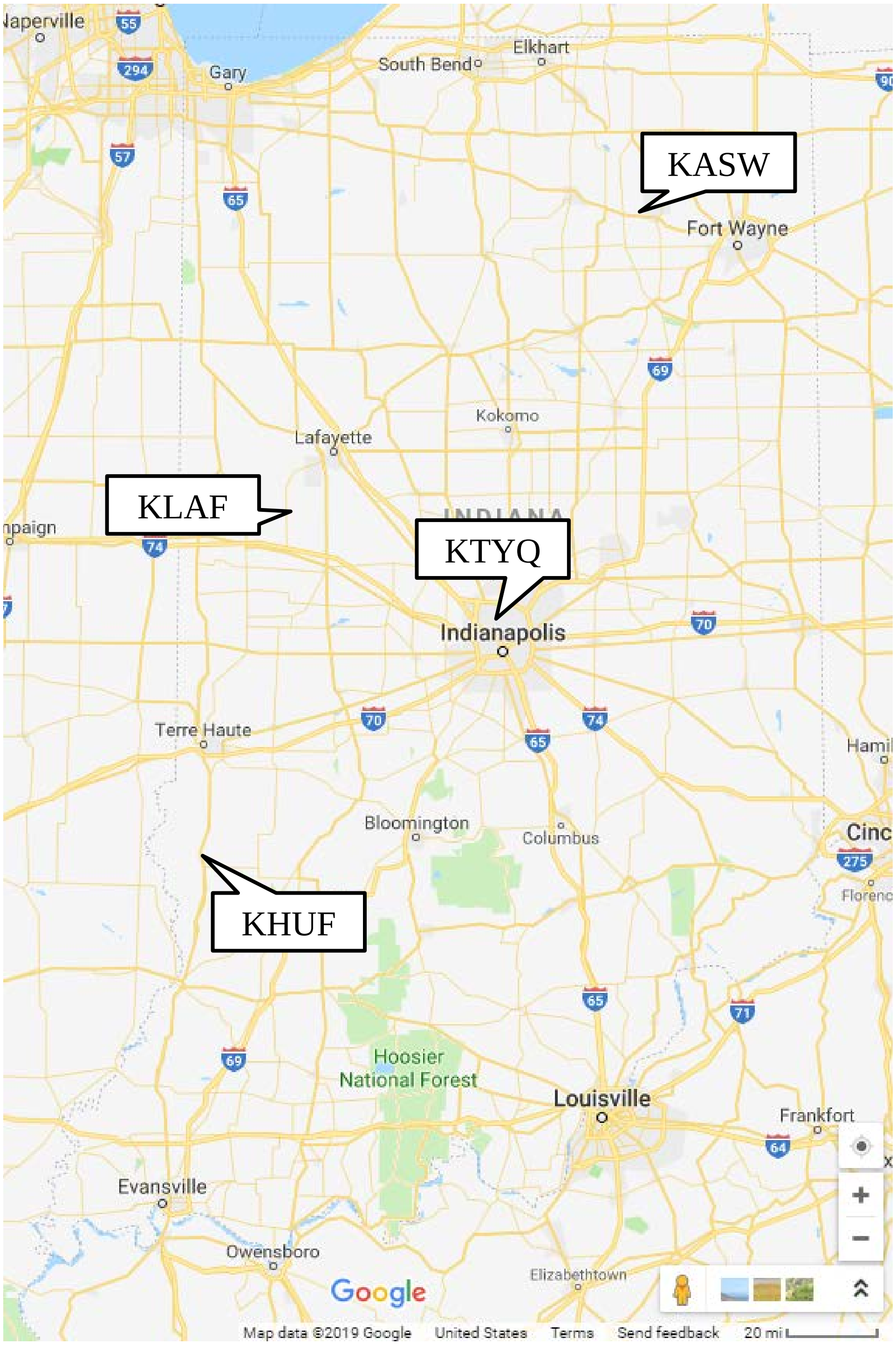
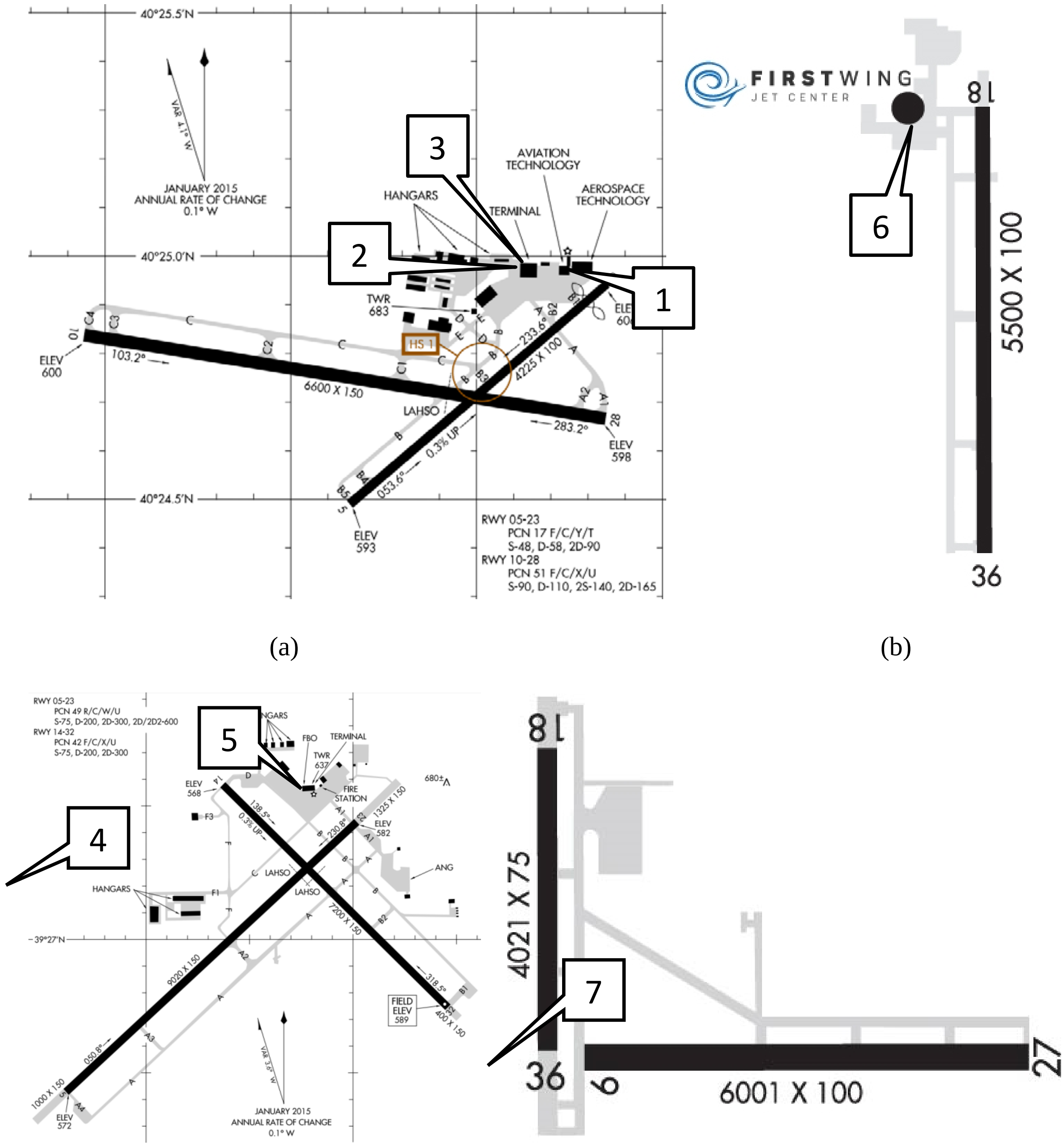


Figure 4. Data Collection Sites Across Indiana



(c)

(d)

Figure 5. Airport Diagrams of Data Collection Sites (with location numbers as callouts):
(a) KLAF, (b) KTYQ, (c) KHUF, and (d) KASW

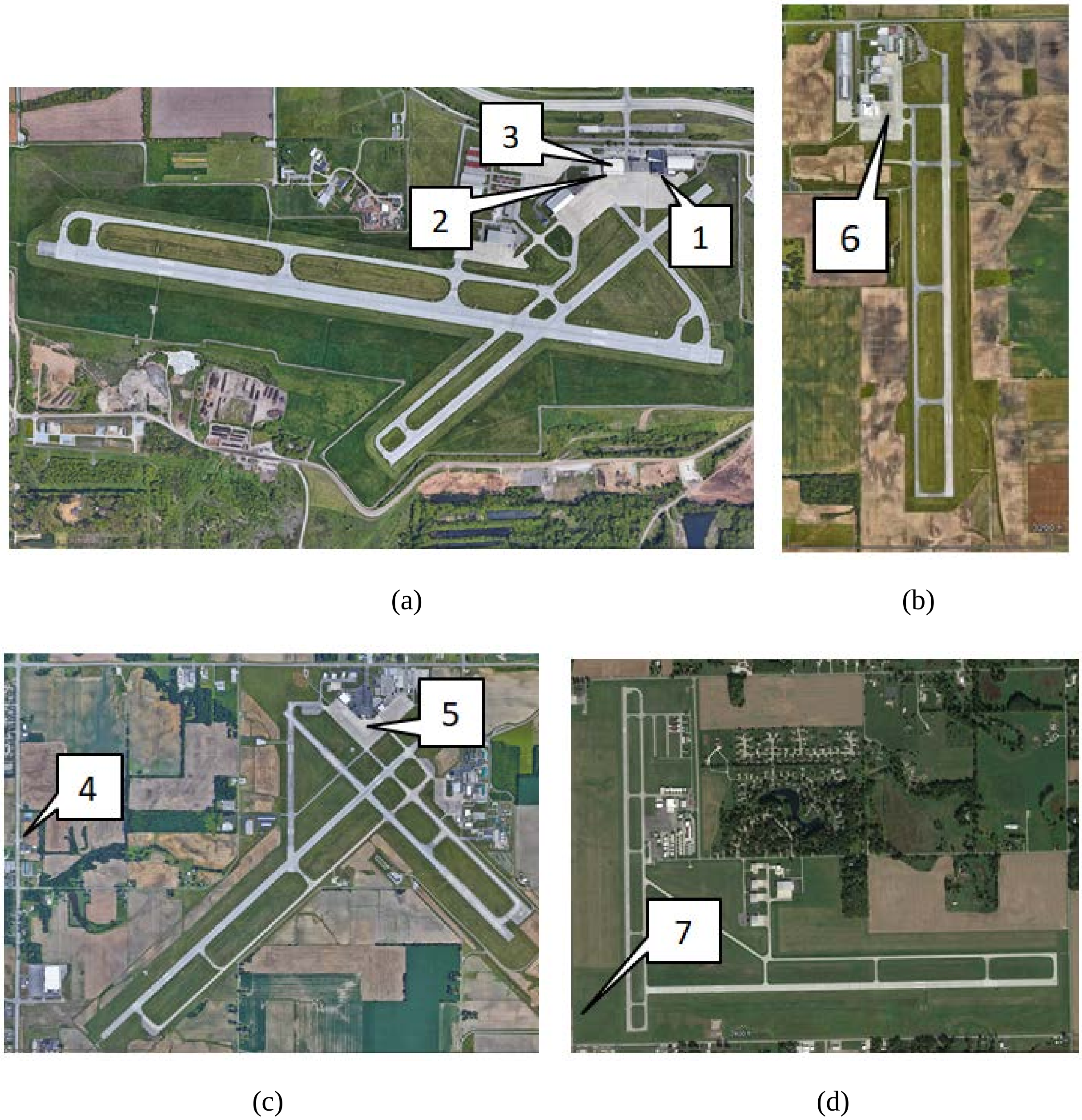


Figure 6. Aerial Photographs of Data Collection Sites (with location numbers as callouts):
(a) KLAF, (b) KTYQ, (c) KHUF, and (d) KASW

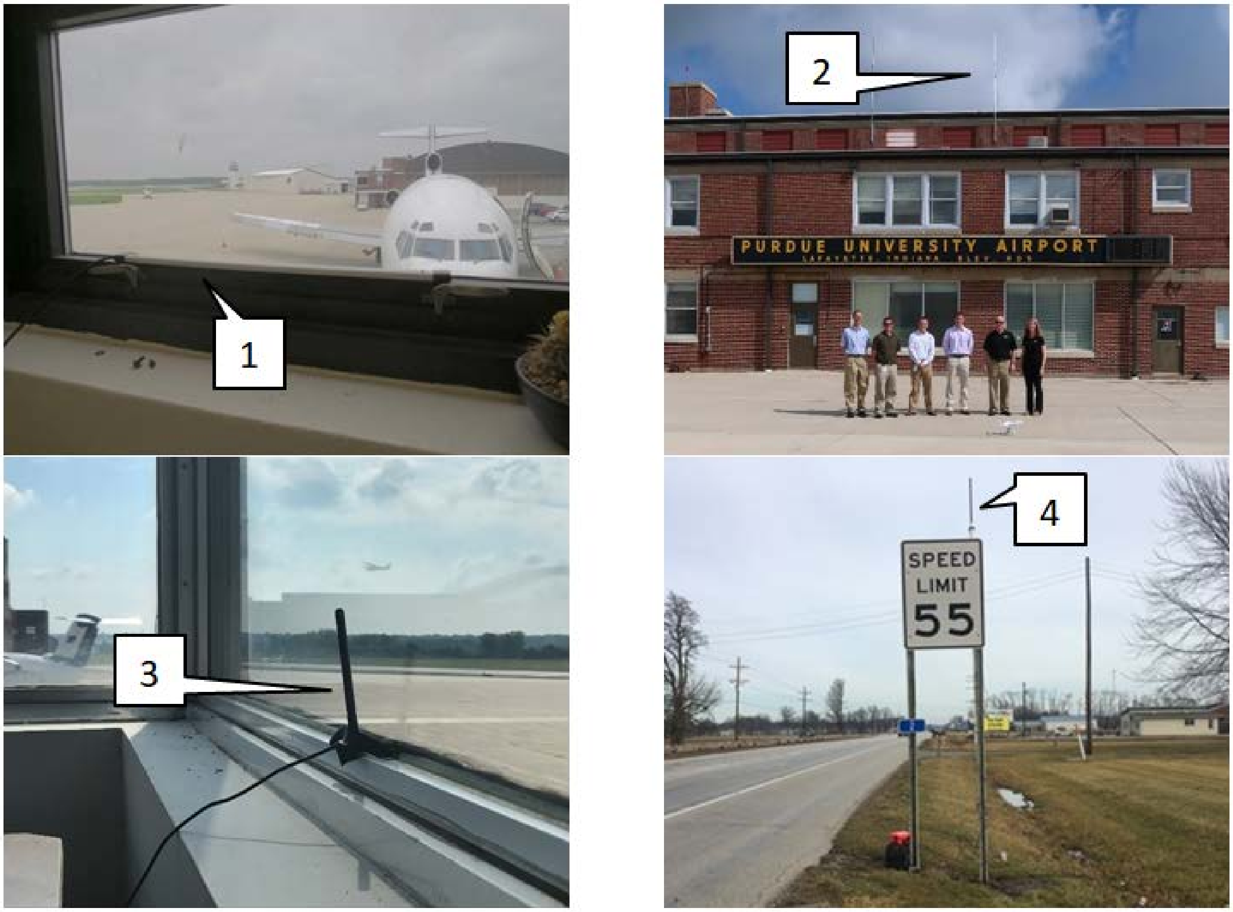


Figure 7. Close-up Views of Several Antenna Deployment Locations
(Locations 1-3 are at KLAF, and Location 4 is at KHUF. KLAF Location 3 is Version II device.)

The Version I device (figure 8) is the experimental version of the transponder data collection system created by McNamara et al. (2016). The signal-processing platform included a Raspberry Pi single-board computer, a software-defined radio, custom scripts written for the project, and dump1090, an open-source script running on the Raspberry Pi and utilized to capture aircraft transponder signals (Sanfilippo & Robb, 2018). An R script was written by the authors to preprocess the signal records and output a .csv data file, as suggested by (Comitz & Kersch, 2016). Version I devices were deployed at two locations at KLAF for varying deployment windows and near KHUF for an 8-day deployment window. At KLAF Location 1, an indoor antenna was placed in an office window facing southwest, and over 1,000,000 transponder signal records were obtained from this deployment over a period of 60 days. At KLAF Location 2, a pole-mounted omnidirectional antenna was installed on the rooftop of the terminal building at KLAF. Over 15,000,000 transponder records were logged from KLAF Location 2 over 180 days. Finally, approximately 400,000 records were received by a Version I installation at KHUF Location 4 over a span of 8 days. The antenna locations for these deployments are displayed in figure 7. The data from Version I was collected to validate the accuracy of the methods utilized to process the transponder signals and register the operations counts, as developed by Mott (2018a). The authors then tested the counting performance of the Version II device.

Figure 8. Version I Device With Antenna

Version II is a preproduction prototype of the Blueavion f1 device manufactured by Bluemac Transportation Data Systems and released on July 23, 2018. This device was developed from the Version I device and features a low-cost transponder data collection system in a solar-powered, self-contained unit. The device provides considerable flexibility regarding installation locations and a self-calibrating, signal-processing algorithm. The Version II device is shown in figure 7 (KLAF Location 3), and figures 9 and 10.

(a)

(b)

Figure 9. Field Deployments of (a) Pole-Mounted Device at KHUF and (b) Stand-Alone Device at KTYQ

(a)

(b)

Figure 10. Field Deployments Located at (a) KHUF and (b) KTYQ

The Version II device was deployed at KLAF, KHUF, KTYQ, and KASW. At KLAF Location 3, a Version II device in conjunction with an indoor antenna was installed in an office window facing southwest on December 1, 2017. Over 94,800,000 transponder records from Version II were logged at this site over a period of 398 days. At KHUF Location 5, a pole-mounted, solar-powered Version II device was located on the rooftop of the terminal building, facing south. About 19,200,000 transponder records were obtained at KHUF Location 5 over a period of 252 days. At KTYQ Location 6, a Version II unit was installed outdoors near a warehouse facing southeast on June 26, 2018. Over 41,900,000 transponder data records were recorded as of May 31, 2019 at this location. Over 1,000,000 transponder data were obtained from Version II unit at KASW Location 7 from January 26, 2019 to May 31, 2019. These data were used to validate the accuracy of the device, with additional data collected on an ongoing basis to continue the validation process over an extended period of time.

A summary of the collected data records from Version II devices is presented in table 2.

Table 2. Overview of Collected Records on Version II Device

Date		KLAF Location 3		KHUF Location 5		KTYQ Location 6		KASW Location 7	
		Days of Data	Records	Days of Data	Records	Days of Data	Records	Days of Data	Records
2017	December	31	7,097,987						
2018	January	29	5,275,764						
	February	15	2,771,959						
	March	31	7,172,442						
	April	30	6,917,008	3	121,803				
	May	19	4,433,784	15	703,666				
	June	30	6,869,755	27	1,933,406	5	648,575		
	July	31	8,305,333	28	2,061,482	28	4,043,985		
	August	19	5,197,437	28	2,120,459	28	4,195,261		
	September	30	9,874,545	30	2,130,392	30	4,459,357		
	October	31	8,361,933	21	1,754,258	29	4,686,334		
	November	30	6,474,439	0	0	0	0	0	0
	December	25	4,477,726	0	0	0	0	0	0
2019	January	4	494,902	20	998,527	20	3,501,622	6	139,434
	February	0	0	2	58,977	25	4,020,308	28	272,702
	March	13	3,725,331	20	2,302,829	28	5,564,424	28	252,919
	April	18	5,019,875	27	2,521,544	27	4,861,930	30	267,476
	May	12	2,350,698	31	3,090,322	28	5,979,531	28	150,846
Total		398	94,820,918	252	19,797,665	248	41,961,327	120	1,083,377

3. RESULTS

An analysis of Version I records from the KLAF Location 1 installation over a 60-day period indicated an overall percentage error of slightly less than 1% between this data and the FAA ATADS data. At KLAF Location 2 over a 30-day period, the model produced a 10.2% undercount compared with the ATADS counts, with the absolute percentage error decreasing as the data collection period increased. Additional Version I data from KLAF Location 2 over a 90-day period was tested; the resulting error rate was 1.7%. Finally, at KHUF Location 4 over an 8-day period, the percentage error was approximately 3.4% (table 3)

Table 3. Version I Test Results

Location	Time Period	ATADS	Estimated Counts	Net Error	Percentage Error
KLAF Location 1	30 days 04/01/2016-04/30/2016	7,877	8,480	603	7.6
KLAF Location 1	60 days 04/01/2016-05/30/2016	14,271	14,404	133	0.9
KLAF Location 2	30 days 09/12/2016-10/11/2016	12,177	10,937	-1,240	-10.2
KLAF Location 2	180 days 09/12/2016-03/10/2017	52,750	51,577	-1,173	-2.2
KLAF Location 2	90 days 12/01/2017-02/28/2018	21,368	21,742	374	1.7[1]
KHUF Location 4	8 days 01/22/2017-01/29/2017	722	698	-24	-3.4

[1]It is always possible to select particular data points where behavior of individual subsets is not representative of the aggregate case. This was discussed by Mott (2018b).

Based on the validated estimation methods and counting technology, the authors deployed Version II at KLAF, KHUF, KTYQ, and KASW to examine the performance of these devices. The overall results from these deployments are provided in table 4. At KLAF Location 3 over a 398-day period, the model resulted in a 0.6% overcount as compared to the FAA ATADS counts. As the data collection period ranged from 31 days to 106 days, the error rate ranged from a 3.1% undercount to a 0.8% overcount. The error rate at KHUF (Location 5) over a 252-day period was 3.3%. The comparisons between full monthly estimated counts and ATADS at KLAF and KHUF are listed in tables 5 and 6 with monthly percentage errors ranging from -8.7% to -8.3%.

Table 4. Version II Test Results

Location	Time Period	ATADS	Barometric Calibration Counts	Net Error	Percentage Error
KLAF Location 3	31 days 12/01/2017-12/31/2017	6,157	6,207	50	0.8[1]
KLAF Location 3	106 days 12/01/2017-01/29/2018[2] 02/14/2018-03/31/2018	24,310	23,568	-742	-3.1
KLAF Location 3	398 days 12/01/2017-01/29/2018[2] 02/14/2018-05/08/2018[2] 05/21/2018-08/16/2018[2] 08/29/2018-12/05/2018[2] 12/12/2018-01/04/2019[2] 03/19/2019-04/11/2019[3] 04/14/2019-04/20/2019[2] 05/01/2019-05/06/2019[2] 05/22/2019-05/27/2019	120,345	121,963	1,618	1.3
KHUF Location 5	252 days 04/28/2018-05/05/2018[2] 05/22/2018-06/17/2018[3] 06/21/2018-07/17/2018[3] 07/21/2018-08/24/2018[3] 08/28/2018-10/21/2018[2] 01/12/2019-02/02/2019[2] 03/12/2019-04/20/2019[3] 04/24/2019-05/31/2019	43,194	41,767	-1,427	-3.3
KTYQ Location 6	248 days 06/26/2018-07/17/2018[3] 07/21/2018-08/24/2018[3] 08/28/2018-10/29/2018[2] 01/12/2019-02/05/2019[3] 02/09/2019-03/08/2019[3] 03/12/2019-04/02/2019[3] 04/06/2019-04/30/2019[3] 05/04/2019-05/31/2019	N/A[4]	72,344	N/A[4]	N/A[4]
KASW Location 7	120 days 01/25/2019-03/16/2019[3] 03/20/2019-04/30/2019[3] 05/04/2019-05/31/2019	N/A[4]	9,465	N/A[4]	N/A[4]

[1]It is always possible to select particular data points where behavior of individual subsets is not representative of the aggregate case. This was discussed by Mott (2018b).
[2]Testing break due to updating of the collection units.
[3]Testing break due to shut down for data retrieval.
[4]ATADS data was unavailable at KTYQ and KASW due to lack of an ATC facility.

Table 5. Overview of Monthly Processed Operations Counts From Version II and ATADS at KLAF Location 3

Date		KLAF Location 3			
		Days of Data	ATADS	Barometric Calibration Counts	Percent Difference
2017	December	31	6,157	6,207	0.8
2018	January	29	4,598	4,389	-4.5
	February	15	4,214	4,164	-1.2
	March	31	9,341	9,007	-3.6
	April	30	10,734	10,119	-5.7
	May	19	5,852	5,230	-10.6[1]
	June	30	10,939	10,127	-7.4
	July	31	10,138	10,145	0.1
	August	19	5,511	5,225	-5.2
	September	30	14,319	15,509	8.3
	October	31	12,719	13,252	4.2
	November	30	8,159	8,046	-1.3
	December	25	3,153	2,982	-5.4
2019	January	4[2]	434	N/A[3]	N/A[3]
	February	N/A[3]	N/A[3]	N/A[3]	N/A[3]
	March	13[2]	4,106	4,856	18.3[1]
	April	18[2]	6,745	7,489	11.0[1]
	May	12[2]	3,226	4,216	30.7[1]
Total		398	120,345	121,963	1.3

[1]Higher error likely due to antenna positioning issue and limited sample size.
[2]Limited data collected due to office maintenance activity at airport that resulted in multiple repositioning of the antenna and data collection unit.
[3]Unavailable estimation and comparison due to small data set.

Table 6. Overview of Monthly Processed Operations Counts From Version II and ATADS at KHUF Location 5

Date		KHUF Location 5			
		Days of Data	ATADS	Barometric Calibration Counts	Percent Difference
2018	April	3	981	N/A[1]	N/A[1]
	May	15	2,221	2,478	11.6[2]
	June	27	4,645	4,661	0.3
	July	28	4,578	4,424	-3.4
	August	28	4,561	5,147	12.8[3]
	September	30	5,821	5,315	-8.7
	October	21	4,000	3,562	-11.0[2]
	November	N/A[4]	N/A[4]	N/A[4]	N/A[4]
	December	N/A[4]	N/A[4]	N/A[4]	N/A[4]
2019	January	20	1,312	1,289	-1.7
	February	2[4]	320	N/A[1]	N/A[1]
	March	20	3,352	3,122	-6.9
	April	27	4,916	5,201	5.8
	May	31	6,487	6,568	1.2
Total		252	43,194	41,767	-3.3

[1]Unavailable estimation and comparison due to incomplete collection.
[2]Outlier due to the limited sample size caused a higher percentage error (Mott, 2018b).
[3]Airshow at KHUF during this month.
[4]Test break due to updating of the collection units.

Table 7 shows the original monthly operations counts at KTYQ. While KTYQ is a non-towered facility, initial operations counts processed by the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS) Project 29 team appear to be excessive, based on anecdotal evidence. For example, the FAA 5010 record for the calendar year ended December 31, 2017 for KTYQ lists a total of 33,940 operations. While it is not clear how those counts were determined, that figure is substantially less than extrapolation of previously collected data from the Blueavion unit would suggest.

Table 7. Overview of Monthly Processed Operations Counts From Version II at KTYQ Location 6 (Original)

Date		KTYQ Location 6[1]			
		Days of Data	Estimated Counts	ATADS	Percent Difference
2018	June	5	N/A[2]	N/A[1]	N/A[1]
	July	28	8,019	N/A[1]	N/A[1]
	August	28	9,245	N/A[1]	N/A[1]
	September	30	8,149	N/A[1]	N/A[1]
	October	29	8,504	N/A[1]	N/A[1]
	November	N/A[3]	N/A[3]	N/A[1]	N/A[1]
	December	N/A[3]	N/A[3]	N/A[1]	N/A[1]
2019	January	20	4,177	N/A[1]	N/A[1]
	February	25	6,480	N/A[1]	N/A[1]
	March	28	7,598	N/A[1]	N/A[1]
	April	27	8,049	N/A[1]	N/A[1]
	May	28	10,460	N/A[1]	N/A[1]
Future		In progress		N/A[1]	N/A[1]

[1]ATADS data was unavailable at KTYQ due to lack of an ATC facility.
[2]Unavailable estimation and comparison due to incomplete collection.
[3]Test break due to updating of the collection units.

Upon detailed examination of the counts, one primary problem became evident. Mott, Yang, and Bullock (2019) developed a technique to correct Mode S counts for local variations in atmospheric pressure. Aircraft transponders report altitudes based on a standard pressure datum of 29.92 ″Hg. As local pressures vary from standard as is typical with weather patterns, transponder-reported altitudes can no longer be used to determine above ground level (AGL) altitudes accurately without correction for pressure variations. Specifically, if pressures are higher than standard, decision thresholds must be decreased. Because the count registration heuristics compare reported altitudes to a fixed airport traffic pattern altitude (TPA) to determine whether potential counts should be registered, the most straightforward means of applying the proper correction is to adjust the TPA for variations in pressure. While the TPA correction was applied to the Mode S data for KTYQ, it was not applied to the Mode C decision plane, typically set for 300′ AGL. This lack of correction resulted in a higher-than-normal proportion of Mode C operations at KTYQ, which led to the discovery of the problem.

Correction of the Mode C decision plane for pressure variations is important to different degrees. Not applying the correction is not especially critical for airports that are not in close proximity to other airports or that do not have high levels of Mode C traffic otherwise operating near the airport, provided distance estimates are reasonably accurate. However, it is likely that KTYQ's proximity to several other airports, as well as substantive level of Mode C traffic operating under visual flight rules in the vicinity of the airport, can cause Mode C aircraft operating at those airports or overflying KTYQ to register unwanted operations. This suggests a greater need to correct the Mode C decision plane at KTYQ for non-standard pressures.

Additionally, minor adjustments were made to Mode S parameters to reduce the compensation for suboptimal antenna placement that was originally included. After corrections to the Mode C plane and Mode S parameters were applied, the total operations counts at KTYQ were reduced from 72,344 to 33,457 over a 248-day period. The corrected monthly counts are provided in table 8, and a comparison of the differences between the corrected and uncorrected counts at KTYQ is made in table 9. The counts in May 2019 appear to be higher than normal, possibly because of increased GA activity in the spring. If the May 2019 data are included, extrapolated annual counts for KTYQ total 49,049. If the May 2019 counts are backed out of the new total and the remaining counts are extrapolated over a full year, the resulting annual total is 34,495, which is quite reasonable when compared with the most recent available data from KTYQ's 5010 record. Hence, it appears that the reprocessed counts at KTYQ are acceptable. Note again that no ATC facility exists to provide a basis for comparison; however, using the FAA rule of thumb of multiplying Instrument Flight Rules (IFR) operations by a factor of 4 yields a similar annual operations figure.

Table 8. Overview of Monthly Processed Operations Counts From Version II at KTYQ Location 6 (Corrected)

Date		KTYQ Location 6[1]			
		Days of Data	Estimated Counts	ATADS	Percent Difference
2018	June	5	N/A[2]	N/A[1]	N/A[1]
	July	28	2681	N/A[1]	N/A[1]
	August	28	3798	N/A[1]	N/A[1]
	September	30	3415	N/A[1]	N/A[1]
	October	29	3704	N/A[1]	N/A[1]
	November	N/A[3]	N/A[3]	N/A[1]	N/A[1]
	December	N/A[3]	N/A[3]	N/A[1]	N/A[1]
2019	January	20	1883	N/A[1]	N/A[1]
	February	25	3135	N/A[1]	N/A[1]
	March	28	3402	N/A[1]	N/A[1]
	April	27	4147	N/A[1]	N/A[1]
	May	28	6490	N/A[1]	N/A[1]
Future		In progress		N/A[1]	N/A[1]

[1]ATADS data was unavailable at KTYQ due to lack of an ATC facility.
[2]Unavailable estimation and comparison due to incomplete collection.
[3]Test break due to updating of the collection units.

Table 9. Overview of Differences Between Original and Corrected Counts at KTYQ

Date		KTYQ Location 6		
		Days of Data	Absolute Difference	Percent Difference
2018	June	5	N/A[1]	N/A[1]
	July	28	5338	-66.6
	August	28	5447	-58.9
	September	30	4734	-58.1
	October	29	4800	-56.4
	November	N/A[2]	N/A[2]	N/A[2]
	December	N/A[2]	N/A[2]	N/A[2]
2019	January	20	2294	-54.9
	February	25	3345	-51.6
	March	28	4196	-55.2
	April	27	3902	-48.5
	May	28	3970	-37.9

[1]Unavailable estimation and comparison due to incomplete collection.
[2]Test break due to updating of the collection units.

Table 10 provides the monthly count estimates for KASW. Note that because both KTYQ and KASW are non-towered airports, the ATADS counts were unavailable, so no comparison with baseline counts could be made.

Table 10. Overview of Monthly Processed Operations Counts From Version II at KASW Location 7

Date		KASW Location 7[1]			
		Days of Data	Estimated Counts	ATADS	Percent Difference
2019	January	6	N/A[2]	N/A[1]	N/A[1]
	February	28	2343	N/A[1]	N/A[1]
	March	28	2310	N/A[1]	N/A[1]
	April	30	2821	N/A[1]	N/A[1]
	May	28	1577	N/A[1]	N/A[1]
Future		In progress		N/A[1]	N/A[1]

[1]ATADS data was unavailable at KASW due to lack of an ATC facility.
[2]Unavailable estimation and comparison due to incomplete collection.

Note that there is some overlap and disjunction in various data collection periods due to the times when the different versions of the devices were available for testing. In addition, some gaps in the data itself occurred due to losses of electrical power to field-based units, repositioning of the antenna at KLAF, or updating of collection units. Tables 3-10 respectively describe difficulties that occurred at each airport and during what month. Regardless, the test results suggest that the preproduction prototype of the transponder signal-counting device is an accurate means of counting operations at non-towered airports.

4. FURTHER WORK

The data collection and validation described herein is continuing at KLAF, KHUF, KTYQ, and KASW, and new deployments are being implemented at additional small GA airports with fewer annual operations than those examined in this study. It is recommended that future research should include a refinement of algorithms to further improve the accuracy of the signal-processing algorithms and decision heuristics, and an extraction of ancillary information from collected data, including aircraft type. This information is expected to provide additional insight to airport managers about the fleet mix of aircraft operating at their respective airports.Also , the automatic adjustment of altitude decision thresholds in software is required function of the devices used commercially. Because barometric pressure values are archived for numerous airports, the data required to make the threshold corrections are readily available; the retrieval process is straightforward and can be easily programmed. This will ensure the greatest possible accuracy in the count registration process.

5. CONCLUSIONS

Current unmanned automatic operations counting technology at non-towered airports are somewhat inaccurate, labor-intensive, and sensitive to prevailing environmental conditions. The technology described in this report has the capability to provide information about aircraft operations that is either not available from other automated counting devices (e.g., acoustic counters) or not available without a great deal of effort (e.g., visual records from security/trail cameras).

This project validated a cost-effective data collection system for non-towered airport operations counting and found that is more accurate than traditional counting technologies. Version I and Version II devices were deployed to validate the accuracy of the aircraft operations estimation technology developed by Mott and Bullock. Over 150 million transponder records from Purdue University Airport (KLAF), Terre Haute Regional Airport (KHUF), Indianapolis Executive Airport (KTYQ), and Warsaw Municipal Airport (KASW) were collected and processed to produce regular operations counts. Over different time periods which ranged from 8 days to 180 days, the accuracy of operations counts from the Version I devices ranged from -10.2% to 7.6% as compared to Federal Aviation Administration Air Traffic Activity Data System (ATADS) counts. The Version I test results suggest that the new method of registering operations counts based on transponder signal data is more accurate than other approaches currently in use.

This report also presented and validated a barometric calibration method, which is used to improve the accuracy of operations counts. Over longer time periods that ranged from 31 days to

398 days, the differences between ATADS and estimated operations counts from Version II ranged from -3.1% to 3.0%.

This report summarized the monthly error rates. Looking at months where there were at least 27 days of data collected, the monthly percentage errors at KLAF ranged from -5.7% to +8.3. For KHUF, the monthly errors ranged from -8.7% to 12.8%. The highest percentage of over count (12.8%) occurred at KHUF in August 2018 during the month an air show occurred. If the month the air show occurred is excluded, the KHUF monthly percentage errors ranged from -8.7% to 5.8%.

Note that there is some overlap and disjunction in various data collection periods due to the times when the different versions of the devices were available for testing. In addition, some gaps in the data itself occurred due to losses of electrical power to field-based units, repositioning of the antenna at KLAF, or updating of collection units. Regardless, the test results from the Version II device suggest that the preproduction prototype of the transponder signal-counting device is an accurate means to count operations at non-towered airports.

6. REFERENCES

Airport Cooperative Research Program (ACRP) (authored by Muia, M. J., & Johnson, M. E.). (2015). *Evaluating methods for counting aircraft operations at non-towered airports*, (ACRP Report 129, prepared for the Transportation Research Board). Retrieved from https://doi.org/10.17226/22182

Bahler, S. J., Kranig, J. M., & Minge, E. D. (1998). Field test of non-intrusive traffic detection technologies. *Transportation Research Record: Journal of the Transportation Research Board, 1643*(1), 161-170. Retrived from https://doi.org/10.3141/1643-20

Bureau of Transportation Statistics. (2019). *Active U.S. air carrier and general aviation fleet by type of aircraft*. Retrieved from https://www.bts.gov/content/active-us-air-carrier-and-general-aviation-fleet-type-aircraft

Comitz, P. & Kersch, A. (2016). Aviation analytics and the internet of things. *Proceedings of the 2016 Institute of Electrical and Electronics Engineers (IEEE) Conference on Integrated Communications Navigation and Surveillance, Herndon, Virginia,* 2A1-1-2A1-6. doi: 10.1109/ICNSURV.2016.7486327

Federal Aviation Administration (FAA). (2008). Chapter 11: aircraft performance. *Pilot's Handbook of Aeronautical Knowledge.* Retrieved from https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/13_phak_ch11.pdf

FAA. (2018). *National Plan of Integrated Airport System (NPIAS) 2019-2023*, Retrieved from https://www.faa.gov/airports/planning_capacity/npias/reports/media/NPIAS-Report-2019-2023-Narrative.pdf

FAA. (2019). Current equipage levels. Retrieved from https://www.faa.gov/nextgen/equipadsb/installation/equipment/

McNamara, M., Mott, J. H., & Bullock, D. M. (2016). Leveraging aircraft avionics for fleet and airport management. *Transportation Research Record: Journal of the Transportation Research Board, 2569:1*, 32-41. Retrieved from https://doi.org/10.3141/2569-04

Mott, J. H. (2018a). Estimation of aircraft distances using transponder signal strength information. *Cogent Engineering, 2018*(5),. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/23311916.2018.1466619?needAccess=true

Mott, J. H. (2018b). Measurement of airport operations using a low-cost transponder data receiver and collection unit. *American Institute of Aeronautics and Astronautics (AIAA) Journal of Air Transportation, 26:*(4), 147-156. Retrieved from https://arc.aiaa.org/doi/pdf/10.2514/1.D0117

Mott, J. H., & Bullock, D. M. (2018). Estimation of aircraft operations at airports using mode-C signal strength information. *IEEE Transactions on Intelligent Transportation Systems, 19*(3), 677-686. Retrieved from https://ieeexplore.ieee.org/document/7932966

Mott, J. H., McNamara, M. L., & Bullock, D. M. (2016). Estimation of aircraft operations at airports using nontraditional statistical approaches. *Proceedings of the 2016 IEEE Aerospace Conference, Big Sky, Montana,* 1-11. Retrieved from https://doi.org/10.1109/AERO.2016.7500536

Mott, J. H., McNamara, M. L., & Bullock, D. M. (2017). Accuracy assessment of aircraft transponder-based devices for measuring airport operations. *Transportation Research Record: Journal of the Transportation Research Board, 2626*(1), 9-17. Retrieved from https://doi.org/10.3141/2626-02

Mott, J. H., Yang, C., & Bullock, D. M. (2019). *Atmospheric pressure calibration to improve accuracy of transponder-based aircraft operations counting technology at non-towered airports.* Unpublished manuscript.

Sanfilippo, S., & Robb, M. (2018). Dump1090. Retrieved from http://github.com/MalcolmRobb/dump1090