Available online at http://docs.lib.purdue.edu/jate

JATE

Journal of Aviation Technology and Engineering 9:2 (2020) 35–44

Atmospheric Pressure Calibration to Improve Accuracy of Transponder-Based Aircraft Operations Counting Technology

John H. Mott, Chuyang Yang, and Darcy M. Bullock

Purdue University

Abstract

In the United States, over 2,400 of the 2,941 non-primary National Plan of Integrated Airport System airports have limited means of establishing operations counts due to lack of available personnel. Precise counts of airport operations are helpful for allocating airport improvement funds, as well as for local and system planning. An emerging technology utilizing ADS-B position data to calibrate signal strength received from Mode C transponders, thereby capturing location information from over 90% of the aircraft operating in the National Airspace System, has successfully estimated operations counts at these non-towered airports with reasonable levels of accuracy. This paper evaluates the impact of further calibration of the model using an atmospheric pressure-based calibration method to improve the accuracy of operations counts. Over 10 million aircraft transponder records collected during 58 days at Purdue University Airport and Terre Haute Regional Airport were analyzed. Uncorrected operations counts and corrected counts using atmospheric pressures averaged both monthly and daily were compared with those obtained from tower-reported figures from the Air Traffic Activity Data System (ATADS) database. The overall accuracy of operations counts from uncorrected heuristics ranged from 5.5% to 13.6% as compared to ATADS over different time periods ranging from 55 to 58 days. Incorporating monthly and daily average pressures improved the count accuracy from 3.2% to 8.7% and from 2.6% to 9.3%, respectively. The test results suggest that the barometric correction method using monthly average pressures results in a modest improvement in overall percentage error and mean average error over the uncorrected method.

Keywords: transponder signals, aircraft operations, counting, ADS-B, Mode C, atmospheric pressure

Introduction

In the United States, the Federal Aviation Administration (FAA) invests over $2.5 billion each year in Airport Improvement Program (AIP) funding at 2,941 small commercial and general aviation airports (FAA, 2018). Accurate operations counts can play an important role in facilitating the equitable allocation of AIP funds to airports in the National Plan of Integrated Airport Systems, as well as establishing a comprehensive picture of the interrelationships between the components of the National Airspace System. Air traffic control personnel record aircraft operations manually at airports with air traffic facilities; however, over 90% of non-primary airports either are uncontrolled or have air traffic facilities with limited hours (Muia & Johnson, 2015). Reasonably accurate operations counts are not easily compiled at such airports.

http://dx.doi.org/10.7771/2159-6670.1222

Muia and Johnson (2015) summarized the accuracy and costs of deployment and maintenance of several existing counting methods and technologies; these include the multiplication of the number of based aircraft by an estimate of operations per aircraft, utilization of a ratio of instrument flight plans to total operations, and utilization of technology such as acoustic counting devices, trail cameras, and video image detectors. However, these existing counting methods have been employed with a limited degree of success (Yang et al., 2019) and are not easily scaled for large-scale deployment at non-towered airports.

Mott et al. (2017) devised a means of using aircraft transponder signals (Mode C, Mode S short squitter, and Mode S extended squitter) to establish aircraft operations counts. Mott et al. (2016) developed algorithms for Mode C transponder signals that produce estimates of improved accuracy with larger sample sizes at lower costs. Operations counts from this technology resulted in error rates over 30 to 179 days of data collection ranging from −4.9% to −1.4% as compared with recorded operations totals from the FAA Air Traffic Activity Data System (ATADS) database (Yang et al., 2019). That work was based upon an assumption of static pressure-based altitude reporting. However, normal changes in local weather conditions introduce variations in atmospheric pressure at airports.

Objective

This research was conducted in order to develop and validate an atmospheric pressure-based calibration method to improve the accuracy of aircraft operations counts at non-towered airports over monthly and longer data collection periods.

Count Registration Process

Altitude information is available from the majority of received transponder data records (Table 1) (Yang et al., 2019). Because transponder records from aircraft broadcasting either Mode C or Mode S short squitter messages contain no position or heading information, the distances of those aircraft from a ground-based receiver must be estimated from the received transponder signal strength (Mott, 2018b). The information containing barometric pressure is used to convert altitude data from Mode S short squitter records, reported relative to a standard datum of 29.92 inches, to above ground level (AGL) altitudes in order to compare them with traffic pattern altitudes (TPAs) (Mott & Bullock, 2018). The altitude information from the Mode C aircraft can be decoded from squawk octal codes from signal records (Table 2) (International Civil Aviation Organization [ICAO], 2014).

Transponder messages that are consecutive and broadcast from aircraft with altitudes below that of the airport traffic pattern and decreasing distances imply that a landing operation is being conducted, while those showing increasing altitudes and distances suggest that a takeoff operation is in progress (Yang et al., 2019).

Based on known geographic coordinate information from extended Mode S, Mott and Bullock (2018) created bounding cuboids for runways for which operations are to be registered (Figure 1). The coordinates of aircraft transmitting extended Mode S signals are examined regularly to determine whether those aircraft are operating within the three-dimensional runway cuboid. If the reported altitude of the aircraft is less than that of the airport's TPA, the aircraft's latitude and longitude position is within the horizontal plane of the bounding box, and the aircraft's heading is within 35° of the heading of the runway in question, the assumption is made that an operation is occurring. When an initial operation associated with a unique aircraft identifier is registered, no additional transponder records from that aircraft are used to register operations until the aircraft has departed the bounding cuboid and climbed above the threshold altitude for a prescribed period (Mott & Bullock, 2018).

Atmospheric Pressure-Based Calibration Method

Atmosphere pressure is a fundamental property related to aerodynamics, and measurements thereof utilizing various instruments provide important information to pilots. The pressure altimeter is considered a primary flight instrument. Atmospheric pressure varies with altitude and temperature. The International Organization for Standardization (1975) created a model denoted as the International Standard Atmosphere (ISA), which was extended by the ICAO

Table 1
Secondary surveillance equipment characteristics.

Data set field	Mode C	Mode S SS (basic Mode S)	Mode S ES (extended Mode S)
Timestamp	Yes	Yes	Yes
ICAO Hex ID	No	Yes	Yes
Altitude	Yes	Yes	Yes
Heading	No	No	Yes
Air/ground	No	No	Yes
Latitude	No	No	DF 17 only
Longitude	No	No	DF 17 only
Signal strength (8 values)	Yes	Yes	Yes

(1993). The ISA is a reference that is used as a baseline for atmospheric pressure measurements. The standard atmosphere at sea level has a temperature of 59 degrees Fahrenheit (°F) or 15 degrees Celsius (°C) and a surface pressure of 29.92 inches of mercury (″Hg) (FAA, 2016).

Density altitude is a useful term for aerodynamic performance computations in a nonstandard atmosphere; this is simply the altitude in the standard atmosphere corresponding to a particular air density. Air density is affected by changes in temperature, pressure, and humidity. Since air is a gas, it can be compressed or expanded. When air is compressed, a given amount of air occupies a lesser volume. Conversely, when pressure on a given amount of air is decreased, the air expands and occupies a greater volume. Table 3 provides the altitude correction to field elevation for various altimeter settings, and also indicates the variation from the standard temperature for those corrected altitudes (FAA, 2008, p. 11-3).

The ISA assumes a linear variation of temperature with geopotential altitude, and thus with absolute altitude over the small differences in altitude under consideration (ICAO, 1993, p. E-xi). The linearized equation for the altimeter correction c for temperature variation to be applied to the pressure altitude is

$$c = \frac{15-(t+0.00198h_{\mathrm{a}})}{273+t+0.00198h_{\mathrm{a}}-0.00099(h+h_{\mathrm{a}})}, \tag{1}$$

where t is the reported temperature in degrees Celsius, h is the aircraft absolute altitude, and h_a is the airport elevation above sea level (ICAO, 2006, p. III-1-4-3). For a TPA of 1,000 ft AGL, this simplifies to

$$c = \frac{15-t-0.00198h_{\mathrm{a}}}{272.01+t+0.00099h_{\mathrm{a}}} \tag{2}$$

Taking the partial derivative with respect to temperature, which is

$$\frac{\partial c}{\partial t} = \frac{-287.01+0.00099h_{\mathrm{a}}}{73989.4+544.02t+t^2+0.26929h_{\mathrm{a}}+0.00099th_{\mathrm{a}}}, \tag{3}$$

it is straightforward to see that the sensitivity of the correction factor c to temperature variations is reasonably small for the altitudes under consideration. Because of this, the authors have chosen to neglect the effects of temperature variation in the work presented here. Therefore, we shall henceforth refer to pressure altitudes exclusively.

Table 2
Example of Gillham-encoded altitude encoder output (ICAO, 2014).

Gillham binary code	Squawk octal code	Height (m)	Height (ft)
000 000 011 011	0660	−30.48	−100
000 000 011 010	0620	0	0
000 000 011 010	0630	30.48	100
000 000 011 100	0610	60.96	200
000 000 010 010	0220	152.4	500
000 000 110 010	0320	304.8	1000

From a climatological perspective, atmospheric pressure exhibits seasonal variation. This variation affects the pressure-sensitive aircraft altimeter, and, consequently, the uncorrected operations counting heuristics proposed by Mott et al. (2017). When local atmospheric pressure is higher than 29.92″Hg, an aircraft altimeter will cause the aircraft's transponder altitude encoder to transmit an 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 the local

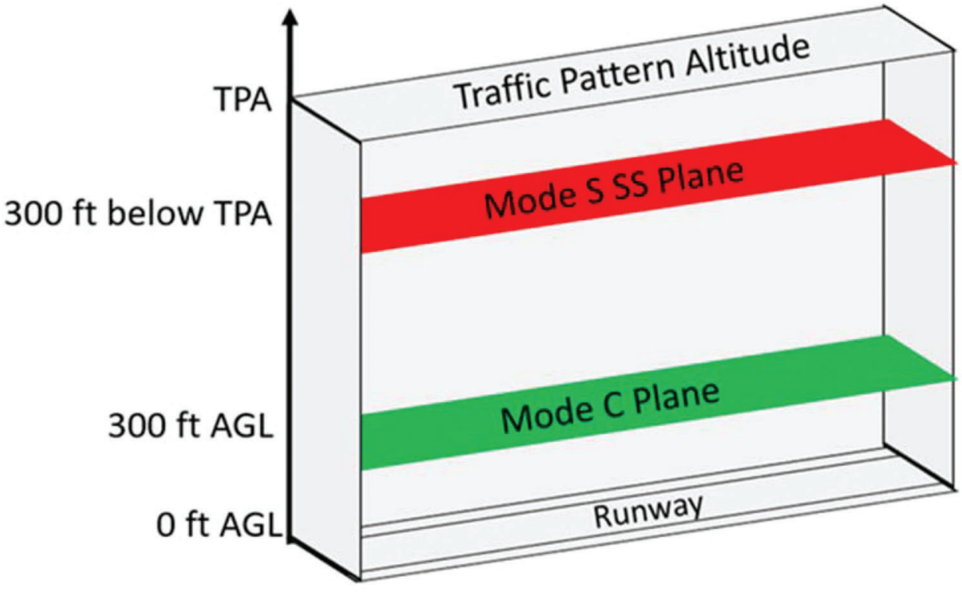

Figure 1. Threshold altitudes used in operations count registration (Mott et al., 2016).

atmospheric pressure is below 29.92″Hg. If the corresponding threshold altitude used in the decision heuristics is not adjusted for atmospheric pressure variations, the incorrectly registered aircraft altitudes may result in overcounting or undercounting of operations. Hence, two calibration models were developed to mitigate the effects of pressure variations upon the related operations counts (Figure 2). Two models were evaluated for correcting the traffic pattern altitude in the decision heuristics:

- the monthly average pressure at a particular airport and
- a daily average pressure.

A simple linear regression analysis between altimeter setting and altitude correction was developed for both models using the range of data in Table 3. The corresponding regression equation, with a 95% level of confidence, is

$$Y = -921.778x + 27580.9, \tag{4}$$

where Y is altitude correction (ft) and x is altimeter setting (″Hg). This equation provides an adjusted $R^2 \geqslant 0.999$ in both cases.

The pressure corrections computed by this means are thus applied to the thresholds used in determining whether the aircraft in question is engaged in an operation. From a practical standpoint, raising the threshold tends to increase the registered number of operations counts, due primarily to the increase in airspace volume over which boundary transitions are detected. Similarly, lowering the threshold tends to reduce the counts. Mott (2018a) provides a more complete discussion of the overall process of registering operations counts using this decision heuristic approach.

Experimental Data Collection and Analysis

To validate the proposed methodology, the authors examined data collected from a set of Blueavion f1 devices, manufactured by Bluemac Transportation Data Systems (Yang et al., 2019). This system utilizes a signal processing algorithm that is self-calibrating and provides substantial flexibility with regard to location relative to the airport (Mott et al., 2016). The devices collected data at the Purdue University Airport (KLAF) and the Terre Haute Regional Airport (KHUF) over 55 days and 58 days, respectively (see Figure 3). KLAF and KHUF are both FAA towered airports that have official logs of airport operations.

At KLAF, a Blueavion device with an indoor antenna was installed just inside an office window facing southwest on December 1, 2017. The same device was deployed in the terminal building at KHUF on April 28, 2018 (Yang et al., 2019).

According to Mott's operations registration heuristics (Mott, 2018b), the TPA should be located approximately 1,000 ft AGL. Because the mean sea level elevations of KLAF and KHUF are 605 and 589 ft, respectively, the TPAs for both KLAF and KHUF are 1,600 ft at a standard sea level atmospheric pressure of 29.92″Hg. Based on the properties of atmospheric pressure (Table 3) and the runway bounding cuboid (Figure 2) mentioned previously, the calibrated TPAs at KLAF and KHUF are shown in Table 4. These calibrated TPAs refer to the altitude in the standard atmosphere that corresponds to 1,000 ft AGL.

Results and Discussion

Records from the KLAF installation over a 55-day period and the KHUF installation over a 58-day period were analyzed by using the uncorrected decision heuristics, monthly average pressure correction, and daily average pressure correction. Recorded ATADS counts are considered baseline values and have been shown to have reasonable accuracy (Mott, 2018a). Use of these data enables one to quantify an overall percentage difference between algorithm-registered operations counts and baseline counts. Note, however, that the difference may consist of either registered operations when none occurred, or missed operations when actual operations did occur, and the data here do not permit discrimination between the two situations.

At KLAF, results from the uncorrected heuristics showed a percentage difference between the resulting counts and the FAA ATADS counts of 13.6% over the full 55-day period, with an 8.7% difference over the same time period using monthly average pressure corrections and a 9.3% difference using daily average pressure corrections. The monthly percentage differences from the uncorrected heuristics range from 10.6% to 21.4%, while the monthly and daily percentage differences using the calibration method vary from 8.5 to 9.2 and from 8.4% to 11.7%, respectively (Table 5).

At KHUF, the monthly and daily average pressure corrections resulted in 3.2% and 2.6% differences, respectively, compared with ATADS over the full 58-day period, while the uncorrected heuristics resulted in a 5.5% difference over the same time period. The accuracy of the monthly counts obtained from the uncorrected heuristics ranged from 5.3% to 5.8% compared to ATADS, while the monthly and daily average pressure corrections resulted in monthly percentage differences ranging from 1.2% to 5.8% and from 0.6% to 4.1%, respectively (Table 6).

In order to investigate the potential advantage of daily average pressure corrections over monthly average pressure corrections, a data set at KHUF for the month of April 2019 was processed using the uncorrected decision heuristics, the monthly average pressure correction method, and the daily average pressure correction method (Table 7). Note that this particular test data set was chosen because the average barometric pressure over that month was 29.92″Hg, implying a calibrated traffic pattern altitude of 1601 ft, virtually the same as the uncalibrated TPA of 1,600 ft. As a result, the counts from the monthly average pressure

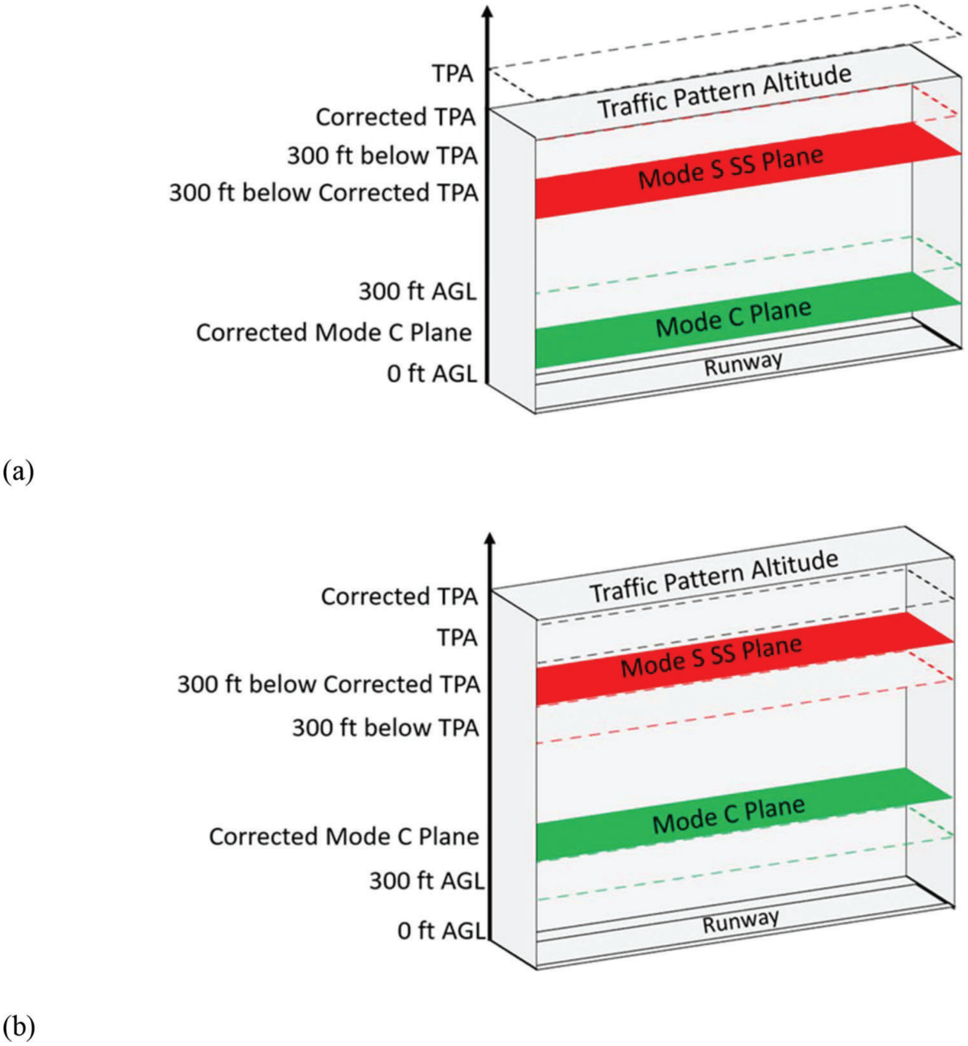

Figure 2. Calibrated runway bounding cuboid. (a) Calibration based on local atmospheric pressure lower than 29.92″Hg. (b) Calibration based on local atmospheric pressure higher than 29.92″Hg.

Table 3
Properties of standard atmosphere (FAA, 2008, 2016; ICAO, 1993).

Altimeter setting (″Hg)	**Altitude correction (ft)**	**Temperature**	
		(°C)	**(°F)**
29.7	+205	14.64	58.35
29.8	+112	14.84	58.71
29.9	+20	15.04	59.07
29.92	0	15.00	59.00
30.0	−73	15.23	59.41
30.1	−165	15.42	59.76
30.2	−257	15.62	60.12
30.3	−348	15.82	60.48

correction are identical to those from the uncorrected heuristics, since aircraft altitudes are reported only to the nearest hundred feet. Note also that the percentage errors in Table 7 are expressed relative to the total monthly ATADS count.

One can define the mean average estimation error as

$$\mathrm{MAE}=\frac{\sum_{i=1}^{N}|\widehat{d_i}-d_i|}{N}, \tag{5}$$

where $\hat{d}_i$ are the daily operations count estimates (from either uncorrected heuristics or corrected heuristics using monthly or daily average pressures), d_i are the daily ATADS counts, and N is the number of days in the collection period. Errors calculated from the KHUF data set suggest that the barometric correction method using daily average pressures results in both a slightly lower overall percentage error and mean average error (Table 8) than either the uncorrected method or the correction using monthly average pressures. While the daily average pressure correction appears to provide the best results at Terre Haute, the same is not true for Lafayette. Hence, any advantages of daily pressure correction over correction using monthly average pressure are inconclusive.

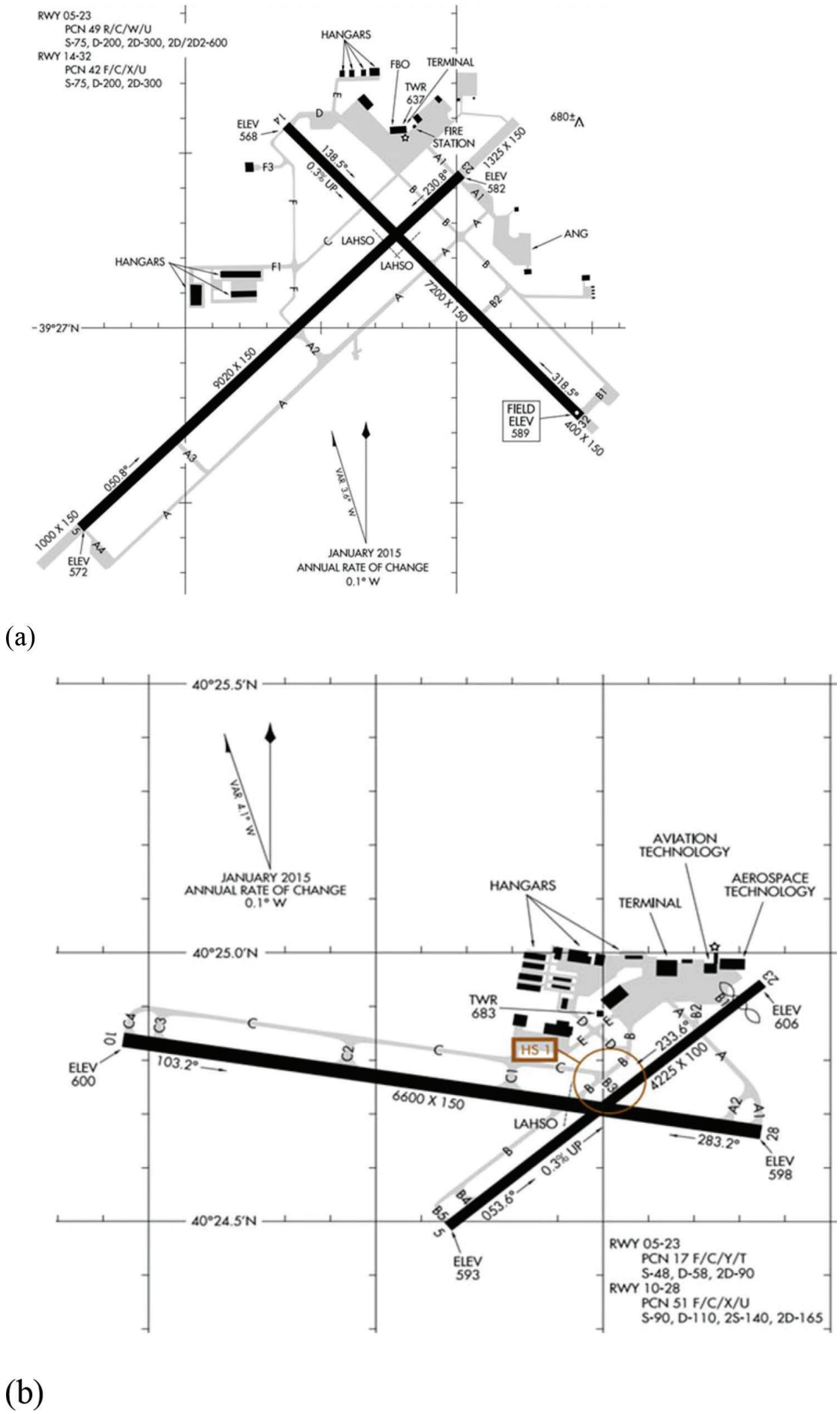

Figure 3. Field deployments of Blueavion device: (a) Purdue University Airport (KLAF) diagram and (b) Terre Haute Regional Airport (KHUF) diagram.

Table 4
Calibrated traffic pattern altitudes based on monthly average atmospheric pressure.

		Purdue University Airport (KLAF)		Terre Haute Regional Airport (KHUF)	
		Pressure (″Hg)	**TPA (ft)**	**Pressure (″Hg)**	**TPA (ft)**
2018	November	30.07	1463	30.07	1463
	December	30.06	1472	30.22	1324
2019	January	30.13	1407	30.14	1398
	February	30.07	1463	30.08	1453
	March	30.15	1389	30.16	1380
	April	30.16	1380	29.92	1601
	May	29.92	1601	29.93	1592

Table 5
Accuracy comparison of monthly operations counts between uncorrected heuristics and barometric calibration at Purdue University Airport (KLAF).

	Days	ATADS	Uncorrected	Δ%	Monthly correction	Δ%	Daily correction	Δ%
Nov.	30	8,159	9,024	10.6	8,860	8.5	8,850	8.4
Dec.	25	3,154	3,830	21.4	3,443	9.2	3,524	11.7
Total	55	11,313	12,854	13.6	12,303	8.7	12,374	9.3

Table 6
Accuracy comparison of monthly operations counts between uncorrected heuristics and barometric calibration at Terre Haute Regional Airport (KHUF).

	Days	ATADS	Uncorrected	Δ%	Monthly correction	Δ%	Daily correction	Δ%
April	27	4,916	5,201	5.8	5,201	5.8	4,950	0.6
May	31	6,487	6,835	5.3	6,568	1.2	6,759	4.1
Total	58	11,403	12,036	5.5	11,769	3.2	11,709	2.6

Figure 4 shows a scatter plot of the counts from each of the three methods versus the ATADS counts for April 2019 at KHUF. Note again that the counts from the uncorrected method and the method employing monthly average pressure correction are virtually identical for the reason given above, and that these data points overlap on the plot. Note also that significant operations undercounts occurred during the first two days of the month. Examination of the ATADS data for Terre Haute indicates that a large number of itinerant general aviation operations unregistered by the algorithm occurred on those dates, possibly resulting from low-altitude training aircraft inbound from another nearby airport (FAA: 3I3). These undercounts can be seen as deviations below the 45° line on the plot.

As one examines the long-term count comparisons (Table 9), it is evident that the percentage errors from employing the atmospheric pressure calibration procedure (regardless of whether the pressures used are the monthly or daily averages) are much lower than those obtained from the uncorrected heuristics. Note that there are some gaps in the data themselves that occurred due to hardware and software updates that were performed on the collection units. Regardless, the test results suggest that the atmospheric pressure-based calibration method can improve the accuracy of transponder-based operations counting technology at non-towered airports.

Future Research Opportunities

Further research opportunities may include examining additional means of refining the signal processing algorithm decision heuristics, and an examination of optimal transponder receiving antenna placement. An expansion of the correction method to include temperature variations is an additional research opportunity.

Conclusion

Operations counting technology that is currently employed at non-towered airports typically requires significant personnel involvement, is sensitive with respect to the environment, and does not produce results of an acceptable degree of accuracy. This study developed and validated an atmospheric pressure-based calibration method that can improve the accuracy of transponder-based non-towered airport operations counts. Data obtained from Blueavion devices were examined to validate the method proposed by the authors. Over 10 million transponder records from KLAF and KHUF were processed to produce operations counts. Heuristics were developed using TPAs that were uncorrected for barometric pressure variation, corrected using monthly pressure averages, and corrected using daily pressure averages. The resulting count estimates were

Table 7
Comparison of uncorrected, monthly-corrected, and daily-corrected operations counts at KHUF, April 2019.

Date	ATADS[a] (operations/day)	Uncorrected count estimate	Error[b] (%)	Estimate corrected with monthly average pressure	Error[b] (%)	Estimate corrected with daily average pressure	Error[b] (%)
1	365	96	−5.4	96	−5.4	76	−5.9
2	408	292	−2.3	292	−2.3	237	−3.5
3	409	484	1.5	484	1.5	423	0.3
4	217	316	2.0	316	2.0	245	0.6
5	185	300	2.3	300	2.3	279	1.9
6	267	257	−0.2	257	−0.2	237	−0.6
7	16	55	0.7	55	0.7	55	0.8
8	404	391	−0.2	391	−0.2	404	0.0
9	325	285	−0.8	285	−0.8	300	−0.5
10	282	243	−0.7	243	−0.7	253	−0.6
11	44	95	1.1	98	1.1	117	1.5
12	103	132	0.5	132	0.5	142	0.8
13	207	227	0.4	227	0.4	204	−0.1
14	2	85	1.6	85	1.6	85	1.7
15	373	310	−1.2	310	−1.2	295	−1.6
16	227	200	−0.5	200	−0.5	185	−0.9
17	179	228	1.0	228	1.0	235	1.1
18	4	88	1.7	88	1.7	89	1.7
19	3	53	1.0	53	1.0	57	1.1
20[c]	5	77	1.4	77	1.4	79	1.5
24	190	198	0.1	198	0.1	188	0.0
25	7	52	0.9	52	0.9	52	0.9
26	103	117	0.2	117	0.2	126	0.5
27	78	89	0.2	89	0.2	99	0.4
28	159	198	0.7	198	0.7	190	0.6
29	221	178	−0.8	178	−0.8	153	−1.4
30	133	152	0.3	152	0.3	145	0.2
Total	4916	5198	5.7	5201	5.8	4950	0.7

[a]Operations counts were retrieved daily from ATADS. [b]Percentage error calculated as (Estimated daily count − ATADS daily count)/Total monthly ATADS count. [c]Testing break due to updating of collection unit.

Table 8
Summary of residuals for KHUF operations count data, April 2019.

Metric	Uncorrected	Monthly average pressure correction method	Daily average barometric correction method
Sums of absolute error differences[a]	1522	1525	1508
Mean	56.3	56.4	55.8
Minimum	−269	−269	−258
Maximum	115	115	94
MAE	56.37	56.48	55.85

[a]Calculated over 27 days of data at KHUF for April, 2019.

Table 9
Cumulative operations count summary for KLAF and KHUF.

	Days	ATADS	Uncorrected	Δ%	Monthly correction	Δ%	Daily correction	Δ%
KLAF	55	11,313	12,854	13.6	12,303	8.7	12,374	9.3
KHUF	58	11,403	12,036	5.5	11,769	3.2	11,709	2.6

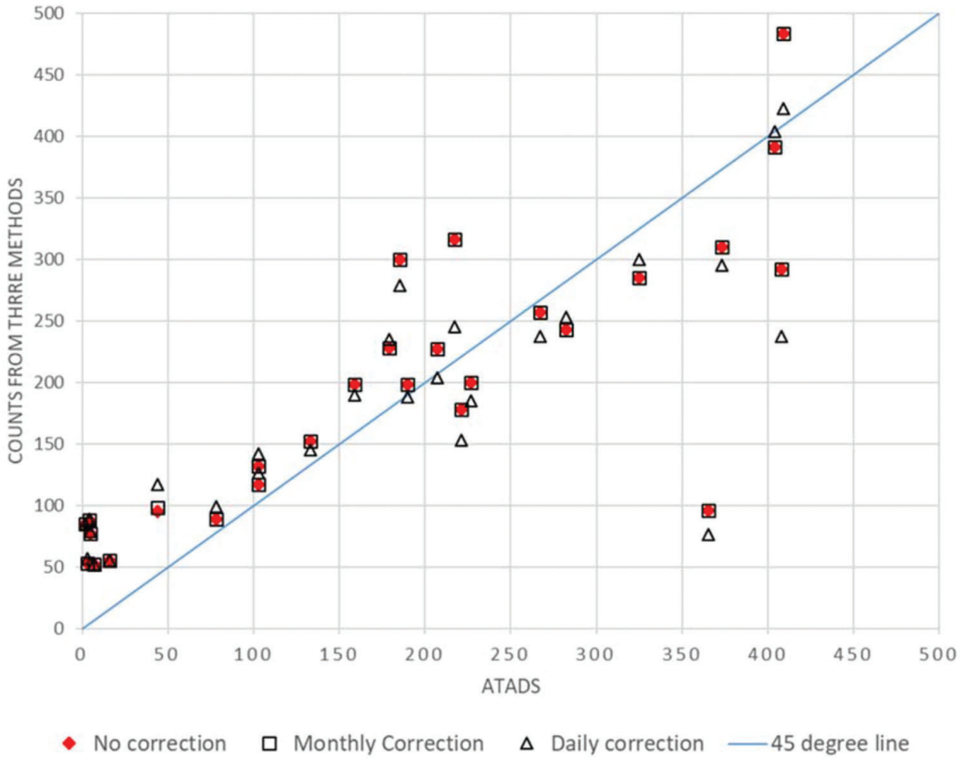

Figure 4. Scatter plot of operations count comparison between ATADS and three correction methods, KHUF, April 2019.

compared with FAA ATADS operations counts. The accuracy of monthly operations counts from the uncorrected heuristics ranged from 5.3% to 21.4% as compared to ATADS, while the accuracy of monthly operations counts obtained from monthly average pressure correction and daily average pressure correction ranged from 1.2% to 9.2% and from 0.6% to 11.7%, respectively. The overall accuracy of operations counts from uncorrected heuristics ranged from 5.5% to 13.6% as compared to ATADS over different time periods ranging from 55 days to 58 days. Over those same time periods, the differences between the operations count estimate and the ATADS data using monthly and daily average pressures ranged from 3.2% to 8.7% and from 2.6% to 9.3%, respectively. The results suggest that the barometric correction method using monthly average pressures results in a modest improvement in overall percentage error and mean average error over the uncorrected method. The results were mixed for using daily barometric correction, with improved accuracy observed at KHUF, but slightly degraded accuracy observed at KLAF.

Acknowledgements

This research was partially funded by the FAA's Project to Enhance General Aviation Safety and Sustainability (PEGASAS) Center of Excellence. The pre-production prototype was provided by Bluemac Transportation Data Systems. The authors have no financial interest in Bluemac Transportation Data Systems.

References

Federal Aviation Administration. (2008). *Pilot's handbook of aeronautical knowledge.* No. FAA-H-8083-25A. Washington, DC: U.S. Department of Transportation.

Federal Aviation Administration. (2016). *Airplane flying handbook.* No. FAA-H-8083-38. Washington, DC: U.S. Department of Transportation.

Federal Aviation Administration. (2018). *2019–2023 National Plan of Integrated Airport Systems (NPIAS) report*. Washington, DC: U.S. Department of Transportation.

International Civil Aviation Organization. (1993). *Manual of the ICAO Standard Atmosphere (extended to 80 kilometres [262,500 feet])* (3rd ed.). Doc 7488-CD. Montreal, Canada: ICAO.

International Civil Aviation Organization. (2006). *Procedures for air navigation services: Aircraft operations* (5th ed.). Doc 8168. Montreal, Canada: ICAO.

International Civil Aviation Organization. (2014). *Annex 10—Aeronautical telecommunications—Volume IV—Surveillance radar and collision avoidance systems* (5th ed.). Montreal, Canada: ICAO.

International Organization for Standardization. (1975). *Standard atmosphere*. ISO 2533:1975. Geneva, Switzerland: ISO.

Mott, J. H. (2018a). Measurement of airport operations using a low-cost transponder data receiver and collection unit. *AIAA Journal of Air Transportation*, *26*(3). doi: http://arc.aiaa.org/doi/abs/10.2514/1.D0117

Mott, J. H. (2018b). Estimation of aircraft distances using transponder signal strength information. *Cogent Engineering*, 5(1). https://doi.org/10.1080/23311916.2018.1466619

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. https://doi.org/10.1109/TITS.2017.2700764

Mott, J. H., McNamara, M. L., & Bullock, D. M. (2016). Estimation of aircraft operations at airports using nontraditional statistical approaches. In, *Proceedings of the 2016 IEEE Aerospace Conference*. Big Sky, MT: IEEE. 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. https://doi.org/10.3141/2626-02

Muia, M. J., & Johnson, M. E. (2015). *Evaluating methods for counting aircraft operations at non-towered airports*. Airport Cooperative Research Program Report No. 129. Washington, DC: Transportation Research Board. https://doi.org/10.17226/22182

Yang, C., Mott, J. H., Hardin, B., Zehr, S., & Bullock, D. M. (2019). Technology assessment to improve operations counts at non-towered airports. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*(3), 44−50. https://doi.org/10.1177/0361198119835804