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Quantitative Measurement Techniques for Vibration and Buffet

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Quantitative Measurement Techniques for Vibration and Buffet

by

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We the undersigned committee hereby approve the attached thesis, "Quantitative Measurement Techniques for Vibration and Buffet" by Edward Thomas Meyer

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Abstract

Title: Quantitative Measurement Techniques for Vibration and Buffet

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This paper outlines a proposed parameter for measurement of vibration and buffet in vehicles. It is intended to be used where applicable in lieu of raw accelerometer data or qualitative comments to measure ride quality, quantify vibration levels, and aid in certification matters.

In flight vehicle applications which employ fly-by wire flight control systems with closed loop and variable gain control laws, the phenomenon of buffet in its various forms is becoming somewhat specious as an aircrew cue in relation to the stability and control of flight vehicles. In these applications, stability and control throughout the operating envelope is designed into the flight control laws, and aircraft state is communicated to the flight crew by advanced avionics. This allows tactile cues such as airframe noise and vibration to become secondary when these systems operate normally.

A smoothed transformation of vibrational G-levels is proposed as a method to quantify vibration levels which would be perceived by aircrew or passengers. Such a value would be of use in developing improved certification criteria, and allow for greater scientific study and rectification of vibration and buffet phenomena. It could also lead to aircraft ride quality improvements, and quantified standard classification of atmospheric turbulence.

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Acknowledgement

The author thanks the Flight Test Engineering department of Gulfstream Aerospace Corporation for providing the experience necessary to see the need for the methods presented by this research, and for supporting the MSci in Flight Test Engineering program at the Florida Institute of Technology. The author also thanks the owners of BGS Transport for providing a flexible environment which allowed for the completion of this work, as well as those associated with the MSci in Flight Test Engineering program at the Florida Institute of Technology for creating new, enhanced opportunities for civilian flight test research and development.

The value of the opportunity to work outside the usual defined roles of ‘pilot’ and ‘engineer’ to gain a deeper understanding of aerospace problems and focus on their solution cannot be overstated.

Finally, the author thanks the many FBO’s across the United States and Caribbean for their free coffee and frequently empty conference rooms, where the majority of this work was composed.

Chapter 1
State of the Art in Vibration and Buffet Testing

Aerodynamic Mechanisms Causing Vibration and Buffet

In aerospace applications, vibration and buffet characteristics have been used to aid in definition of low-speed, high-speed, and high-load-factor flight envelope limits, generally as a proxy indication of local flow separation and an associated degradation in flying qualities (Reference 1). Local flow separation due to low flow energy and associated adverse pressure gradients is the mechanism driving local flow separation at low speed. Local shocks caused by exceeding the local critical Mach is the mechanism driving local flow separation at high speed. A mixture of these two phenomena (Dependent on the cruise speed of the airplane) drives local flow separation at high load factor for high-speed airplanes ($M_D > 0.6$). Note that buffet is a separate phenomenon from other dangerous aeroelastic phenomenon such as flutter, divergence, deformation instability, and control reversal as described in Reference 1.

Operating regimes where buffet occurs are determined during flight test, and form the low-speed, high-speed, or high-load-factor boundaries of the flight envelope. The high-load factor boundaries are reduced in the pilots operating handbook to give a range of allowable altitudes, weights, and turning bank angles.

In test conduct, this is accomplished by either increasing or decreasing the speed of the airplane until any prohibited vibration is felt by the pilot, or increasing load factor until buffet is felt by the pilot (Reference 2). That information is then compared to regulatory allowances by the flight test and engineering teams, and flight envelope limitations for the design are set accordingly in order to comply with the regulations.

Problems of Qualitative Basis

Within vehicle certification regulations, words such as ‘perceptible’, ‘deterrent’, ‘heavy’, or ‘excessive’, are used throughout as a way to attempt to articulate the specific level of vibration for the situation to serve as the trigger for protecting against the aircraft characteristic that is to be disallowed by that regulation. Further categorization is then provided in supplementary guidance material to attempt to explain further the types of characteristics to be disallowed (Reference 3). This approach relies heavily on qualitative pilot comments and associated conditions. As flight test comments related to buffet are primarily qualitative in nature, the task of analyzing and reducing the data to a defined point or line is difficult.

Additionally, the supporting datasets are quite cumbersome. Reducing a data point typically requires pilot comments to be interpreted, and audio to be synced to numerical and video data, making cross-discipline sharing, storage, and interpretation an issue. As the data cannot be seen graphically or experienced by anyone other than those who were aboard the aircraft, it is challenging to communicate the specifics of any resultant issue. The current approach is simple from a regulatory and test conduct standpoint, but leaves little room for scientific improvement or study on the part of the vehicle manufacturer.

As Figure **1** shows, vibration and buffet characteristics are one major component defining the final certified flight envelope for an aircraft. Because these characteristics are not defined quantitatively and are therefore very hard to study, vibration and buffet represent a large program-level technical risk that is not fully mitigated by scientific methods. A quantitative measure of these undesirable phenomena will aid in developing universal standards and facilitate study which could lead to future aircraft performance and ride quality improvements.

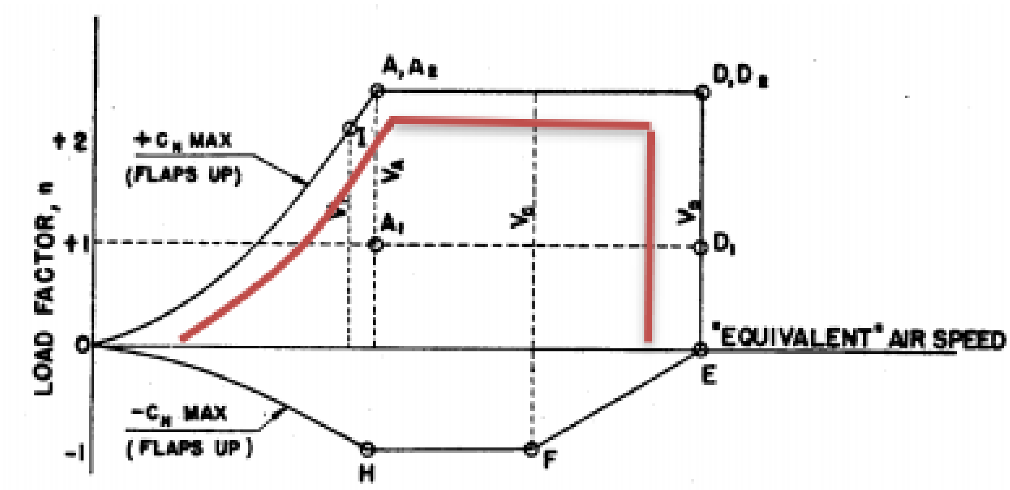

Figure 1 — Notional V-N Diagram. Red lines indicate potential envelope restrictions due to buffet

Design Limitations Created as a Result of Qualitative Basis

In flight vehicles which employ fly-by-wire control systems and advanced displays to effectively display the current aircraft state to the flight envelope limitations, tactile cues such as vibration and buffet feedback are less relevant when those systems operate normally.

As a result of these technological developments, one could imagine a situation where such a flight vehicle was artificially limited in its operational envelope by vibration and buffet, even though no hazard involving controllability or stability existed while all of the associated protection systems operated normally.

In situations where vibration and buffet do not directly result in a safety or controllability issue, vibration and buffet should be considered separate from those concerns.

State of the Art in Vibration and Buffet Measurement

While accelerometers are often installed in flight test vehicles to measure flight deck and cabin vibration levels, these measurements are not used for any direct certification purpose, as certification criteria still rely on qualitative observations made by the pilot. In typical flight test installations, an accelerometer capable of sensing high frequency data is mounted to the aircraft structure near the pilot/aircrew seat station (commonly a seat rail, fuselage frame, or other hard structural element). Recordings of high-frequency G levels in all 3 body axes are made at that station, and combined with flight condition data (airspeed, Mach, bank angle, steady state G, etc) from other sources and analyzed to further understand the specific mechanisms and causes of the sensed vibration.

While no quantitative standards exist in the regulations themselves, guidance material suggests that thresholds on vibrational G data from have been proposed without success. Notably, an exceedance of +/- 0.05G has been unsuccessfully proposed as a substitute for a pilot buffet call in Section 8, Paragraph 31 subsection 4 (page 145) of FAA Advisory Circular AC 25-7C (Reference 3).

For Transport Category Airplanes, buffet boundaries and associated design and structural considerations for buffet are covered by the following regulations:

Table 1 — Current Transport Category Airplane Regulations Concerning Vibration and Buffet

FAA Regulation	Title
14 CFR 25.201(d)	Stall demonstration
25.251	Vibration and Buffeting
25.253(a)	High-Speed Characteristics
25.255(e)-(f)	Out-Of-Trim Characteristics
25.305(e)	Strength and Deformation
25.427(d)	Unsymmetrical Loads
25.1517(c)	Rough Air Speed, V_{RA}
25.1585(d)	Operating Procedures

For Normal Category Airplanes, buffet boundaries and associated design and structural considerations are covered by the following regulations:

Table 2 — Current Normal Category Airplane Regulations Concerning Vibration and Buffet

FAA Regulation	Title
14 CFR 23.2160	Vibration, buffeting, and high-speed characteristics.

The accepted means of compliance for determining vibration and buffet levels for these regulations is entirely qualitative.

Chapter 2
Historical Background in Vibration and Buffet Classification

Genesis of buffet terminology

Buffet has long been considered an effective warning for aircrew against entering undesirable flight regimes. References 4 through 17 represent pertinent regulation changes relating to vibration, buffet, and controllability, starting with the original Civil Aeronautics Board (CAB) aircraft certification standards beginning in 1937 up through current FAA aircraft certification regulations. Figure 2 shows the history of vibration and buffet's use in US certification regulations for transport and normal category airplanes.

Year		Transport Category Event		Normal Category Event
2018				
2017				Amdmt 23-64: Part 23 Rewrite, buffet regulations condensed to 23.2160
2016				
2015				
2014				
2013				
2012				
2011				Amdmt 23-62: Change to closely match part 25
2010				
2009				
2008				
2007				
2006				
2005				
2004				
2003				
2002				
2001				
2000				
1999				
1998				
1997				
1996				
1995				
1994				
1993				Amdmt 23-45: Update to include VD/MD terminology
1992	Part 25	Amdmt 25-77: Refines verbiage for parts (a) and (b) of 25.251		
1991				
1990		Amdmt 25-72: Refines buffet boundary requirement	Part 23	
1989				
1988				
1987				
1986				
1985				
1984				
1983				
1982				
1981				
1980				
1979				
1978				
1977				
1976				
1975				
1974				
1973				
1972				
1971				
1970		Amdmt 25-23 adds requirements for buffet boundary		
1969				
1968				
1967				
1966				
1965		Part 25 Standards released, 4b.191 becomes 14 CFR 25.251		Part 23 Standards released, FAR 3.159 becomes 14 CFR 23.251
1964				
1963				
1962		Amdmt 4b-12 adds 4b.191, high speed characteristics, 'effective inherent warning'		
1961				
1960				
1959				
1958				
1957	CAR4b		CAR 4	
1956		Amdmt 4b-3 to 4b.162 notes mention buffeting in pilots controls as stall warning		
1955				
1954				
1953		CAR 4b amendment to 4b.162 adds notes mentioning vibration in pilot's controls		
1952				
1951				
1950		4b.162 and 4b.190 First mention buffet relating to stalls and high speed characteristics		
1949				FAR 3.159 No excessive buffeting, Stall warning buffet desirable
1948				
1947				
1946				
1945				
1944				
1943	CAR 4			
1942				
1941				
1940				
1939				
1938				
1937		No mention of vibration/buffet for stability or controllability		

Figure 2 — Summary of US Airplane Certification Standards relating to Vibration and Buffet: 1937- present day

Regulations concerning the definition of buffet and areas where it is allowable in any form have not significantly changed since 1962, in amendment 4b-12 of CAR 4b (the predecessor to the current 14 CFR part 25). That amendment added perceptible buffeting in level flight as a prohibited condition. Buffeting severe enough to cause structural damage was already prohibited. It also described perceptible buffeting as 'effective inherent warning', equal in significance to artificial speed warning (such as dedicated alerts designed to alert aircrew to an overspeed condition like an overspeed warning horn, clacker, etc.).

Since 1962, large advances have taken place in flight control systems, cockpit displays, crew alerting, and measurement devices, creating opportunities to move beyond qualitative concepts like perceptible buffeting with designed flight envelope limits and systems, provided that the total vibration environment experienced by aircrew and passengers is kept to acceptable levels by appropriate vibration and buffet standards.

To protect against system failures which would trigger degraded aircraft flight control modes, retreat envelopes should be defined as are commonly done for flight vehicles employing fly-by-wire flight control systems with progressive fail-down modes. In situations where degraded modes meant that designed aircraft systems were unable to provide effective aircrew warning, perceptible buffet would again be considered limiting within the retreat envelope.

Figure 3 presents a notional shift in the way that vibration and buffet is considered for flight vehicles which employ irreversible flight controls, closed-loop or variable-gain control laws, envelope protection, and advanced flight displays to effectively communicate the relationship between current aircraft state and flight envelope limitations.

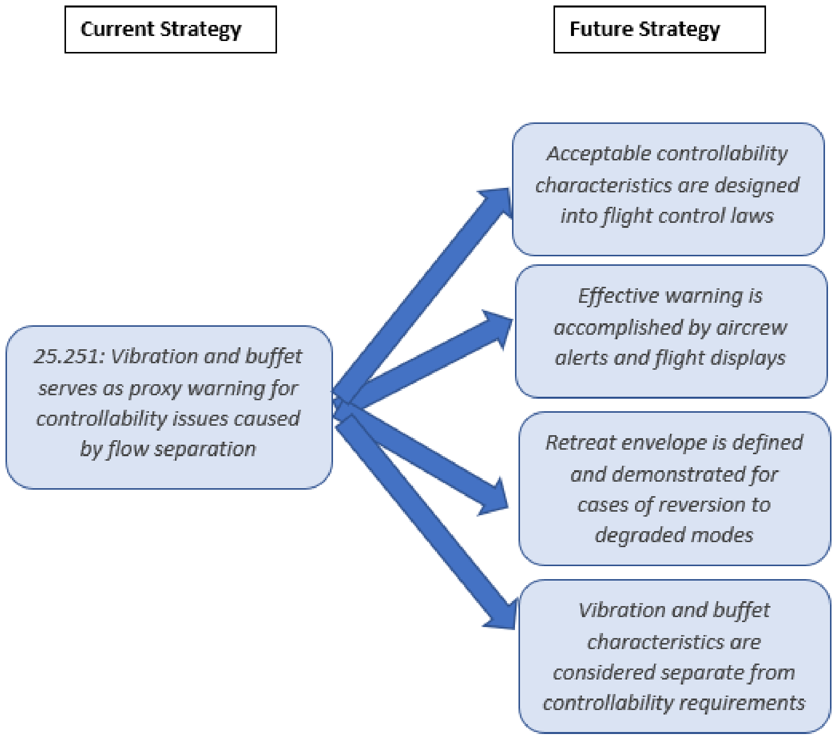

Figure 3 — Proposed Future Strategy For Vibration and Buffet Considerations

Chapter 3
Test Setup and Planning

Test Article

Tests were performed using a 1959 Beechcraft K35 Bonanza, S/N D-5832, shown in Figure 4. The Bonanza is a widely produced light airplane powered by a single 260hp reciprocating engine.

While it employs none of the advanced systems discussed in previous chapters, the test article did serve as an effective testbed to study measured vibration levels against perceivable qualitative changes in cabin vibration levels due to defined in-flight events. Changes in ambient cabin vibration levels due to runup, cowl flap extension, landing gear extension, flap extension, and stall were recorded.

The test article was operated under part 91 in the normal category. Cameras and sensors used to record measurements were installed inside the cabin via temporary adhesive mountings and did not materially alter the aircraft or its systems.

Figure 4 — The Test Article: 1959 Beechcraft Bonanza K35 S/N D-5832

Instrumentation

The instrumentation package consisted of a high definition camera and a small, self-contained shock & vibration data logger.

The shock and vibration data logger used was the MIDÉ Slam Stick C, a self-contained ruggedized device used in commercial applications, and is shown in Figure 5. It contains a solid state Micro Electromechanical System (MEMS) accelerometer and measures triaxial G at up to 500hz. It also measures attitude in quaternions at 50hz and measures ambient pressure and temperature at 1hz.

Figure 5 — Closeup of MIDE Slam Stick C Mounted to Wing Carrythrough Structure

The high definition camera was a Garmin VIRB intended for use in action sports, shown in Figure 6. The camera contains an integrated Global Positioning System (GPS) reciever and Attitude and Heading Reference System (AHRS) unit which provides useful metadata correlated with video. It can also be remotely controlled via a smart device (mobile phone, tablet, etc), helpful in test applications where it may be mounted out of easy reach. The camera was mounted facing forward in the aft cabin with the instrument panel, pilot, and area above the data logger in view, as shown in Figure 7.

Figure 6 — Garmin VIRB Camera Installed on Cabin Ceiling

Figure 7 — Camera Field of View

The data logger was mounted to the top of the wing carrythrough structure between the two forward seats as shown in Figure 8 using the adhesive strips provided by the manufacturer and affixed per the manufacturer's instructions.

Figure 8 — Wide angle view of MIDE Slam-Stick C Mounted to Wing Carrythrough structure

During conduct of a test run, video was used to correlate pilot actions and aircraft state to data logger run times using the time stamp on the video to align datalogger information to video information. Video was used to manually transcribe flight parameters from the analog instrument panel at a 1hz rate. As no pilot voice audio was recorded, a "hack" hand signal from the pilot signified an important event such as buffet onset or configuration change, and specifics of the event were recorded in the flight notes. For the relatively small dataset recorded for these tests, an integrated data acquisition system was not necessary. For larger datasets, an integrated data acquisition system would greatly accelerate postflight analysis.

Test Procedures

Card 1: RPM Sweep on ground

On ground, with mixture leaned for best power and propeller set to high RPM, adjust throttle and record data for 10 seconds at the following RPM settings:

Idle, 900, 1000, 1100, 1200, 1500, 2000, 2200, 2300, 2400, 2500, 2600, Full throttle.

Card 2: Configuration Changes

At an altitude between 4,000 and 6,000 feet, trim for level flight at 103kt (Top of white arc). Set RPM at 2300 and lean for best power. Using throttle for level flight, record the following conditions:

- Clean (10 seconds)
- Cowl flaps in transit
- Cowl flaps extended (10 seconds)
- Gear in transit
- Cowl flaps + Gear extended (10 seconds)
- Flaps in transit
- Cowl flaps + Gear + Flaps extended (10 seconds)

Card 3: Power Off Stalls: Landing Configuration

At an altitude of between 4,000 and 6,000 feet with the airplane configured for landing, trim for level flight at 80kt. Set RPM at 2300 with mixture rich. Maintaining altitude and reducing power to decelerate, initiate a 1kt/sec deceleration to stall break. Use coordinated rudder to maintain wings-level after the break for 1-2 seconds. Recover to previous trim condition. Repeat for a total of 3 runs.

Card 4: Power Off Stalls: Cruise Configuration

At an altitude of between 4,000 and 6,000 feet with the airplane configured for cruise, trim for level flight at 80kt. Set RPM at 2300 with mixture rich. Maintaining altitude and reducing power to decelerate, initiate a 1kt/sec deceleration to stall break. Use coordinated rudder to maintain wings-level after the break for 1-2 seconds. Recover to previous trim condition. Repeat for a total of 3 runs.

Risk Assessment

Test planning took into consideration lessons learned over the author's 4 years of flight testing experience, salient points from *Commercial Aviation Safety (6th Edition)* (Reference 18) and guidance contained in FAA Order 4040.26B (Reference 19)

All maneuvers presented in this paper were conducted during day VMC in accordance with normal procedures in the airplane flight manual. Flight test instrumentation did not alter the external shape of the airplane or its systems.

Resulting risk level was low.

Chapter 4
Test Conduct

Test conduct consisted of 2 flights.

Flight 1

Flight 1 was performed on 4/17/2018. Cards 1 – 4 were conducted. During data review, it was decided that the original iteration of card 2 with configuration changes at their maximum allowable speed (cowl flaps in cruise, gear extension at V_{LE}, and flap extension at V_{FE}) was not as scientifically useful as performing all configuration changes at the same speed. Card 2 was revised to perform all configuration changes at the highest available speed for all configurations, V_{FE}, 103kias.

During data review it was discovered that data for the 3rd power-off clean stall for card 4 was lost due to an error in sequencing recording devices.

A refly of cards 2 and 4 was planned for flight 2 to correct these issues.

Total flight time was 1.2hrs. 1 takeoff, 1 landing. 16gal fuel consumed.

Flight 2

Flight 2 was performed on 5/23/2018. Revised card 2 and card 4 pickups were flown. The deck also contained an optional card 5 to record data in turbulence created by cumulus clouds.

Card 5 was conducted under a pop up IFR clearance. 3 transects of a small developing cumulus cloud at 120 degree heading intervals were performed at V_A to measure vibration levels due to turbulence. The top of the cloud was verified by inspection at 9,000ft MSL, the base of the cloud was verified at 3,000ft MSL, and transects were flown at 6,000ft

MSL. Data were recorded, and atmospheric soundings from that date were saved with the dataset, but results were considered to be outside the scope of this paper. Data is available through a google drive link on request.

Total flight time was 1.3hrs. 1 takeoff, 1 landing. 19gal fuel consumed.

Chapter 5
Data Reduction

The following figures outline the method for reducing the raw accelerometer data to a useful parameter which characterizes vibration and buffet. Figure 9 shows raw N_Z accelerometer data from a cruise configuration power-off stall. Note the wide scatter of the data, as well as the drift caused by changes in steady-state N_Z. Applying a threshold directly to these values (as proposed in reference 3) is not useful for characterizing intensity of vibration and buffet, as the raw accelerometer trace is subject to steady state N_Z drift and single-peak exceedances that would not necessarily be perceived as a net change in vibration level recognizable as buffet.

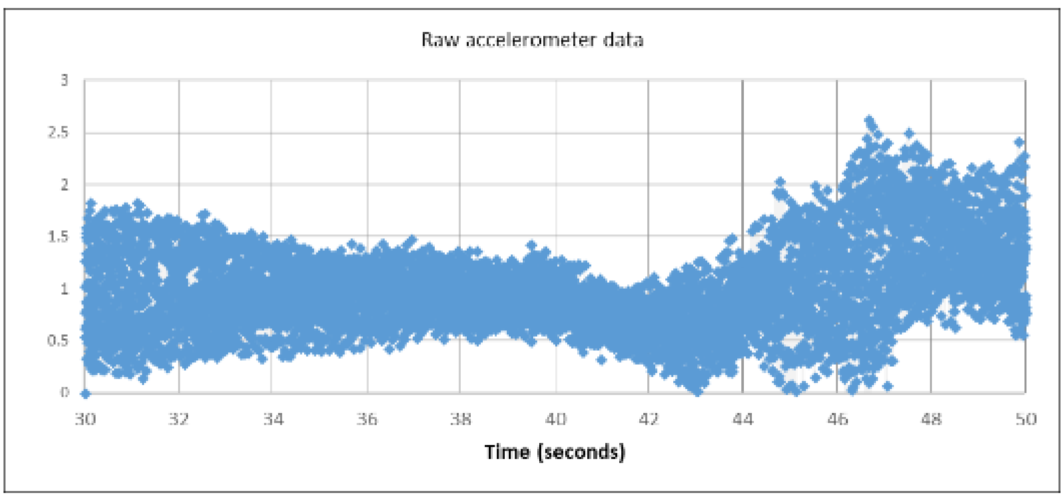

Figure 9 — Raw N_Z Accelerometer Data

Figure 10 shows a 0.5s moving average overlaid with the raw N_Z data. This is the steady state G of the airplane throughout the maneuver (load factor). Its influence needs to be removed from the dataset in order to understand the amount of total vibration occurring throughout the maneuver.

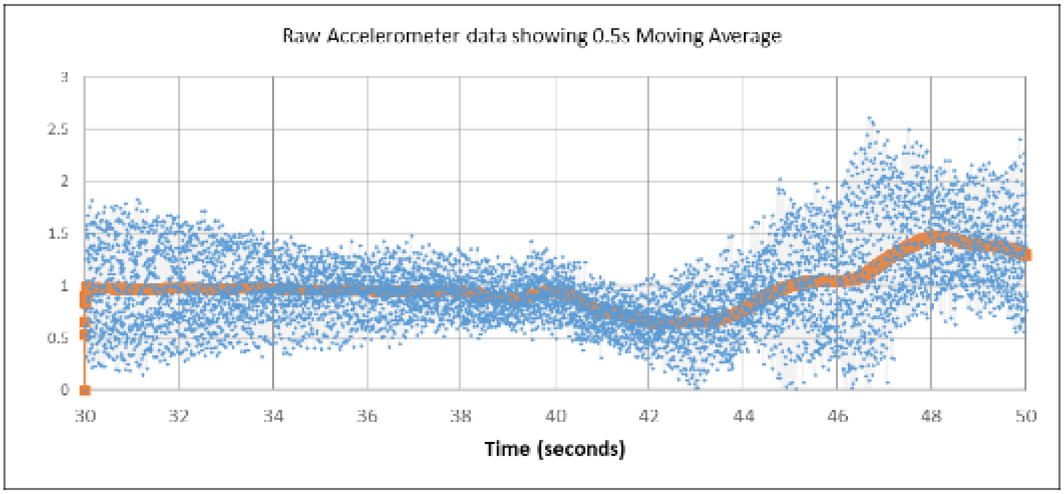

Figure 10 — Raw N_Z Data Overlaid on 0.5s Moving Average of Raw N_Z Data.

Figure 11 shows the result of subtracting the 0.5s moving average from the raw dataset. This allows us to see the total vibration measured by the accelerometer in terms of a ΔG from the steady state value.

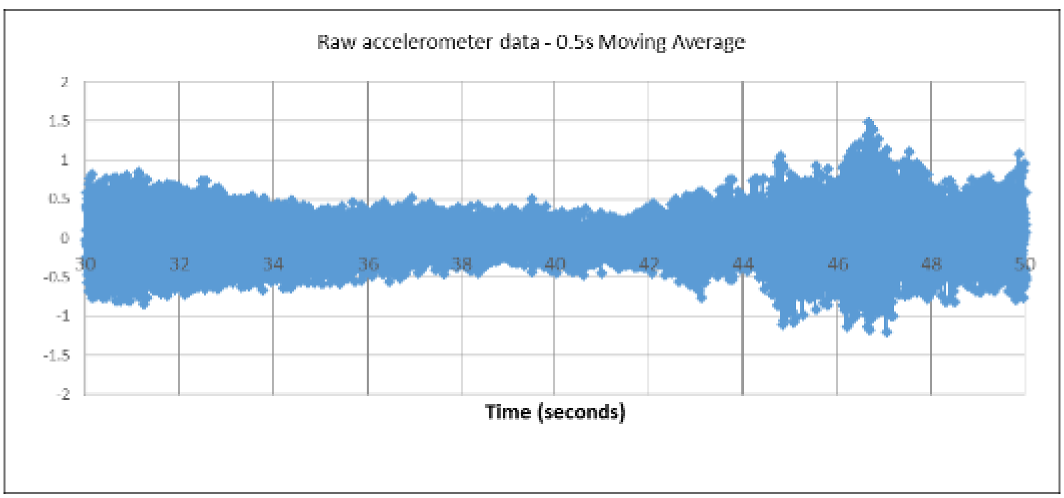

Figure 11 — Raw N_Z Accelerometer Data – 0.5 Second Moving Average of Raw N_Z Accelerometer Data

Figure 12 shows the result of taking the root-mean-square (RMS) of the data in figure 11, allowing the dataset to be considered as an intensity of vibration from the steady state g, analogous to 'buffet power'.

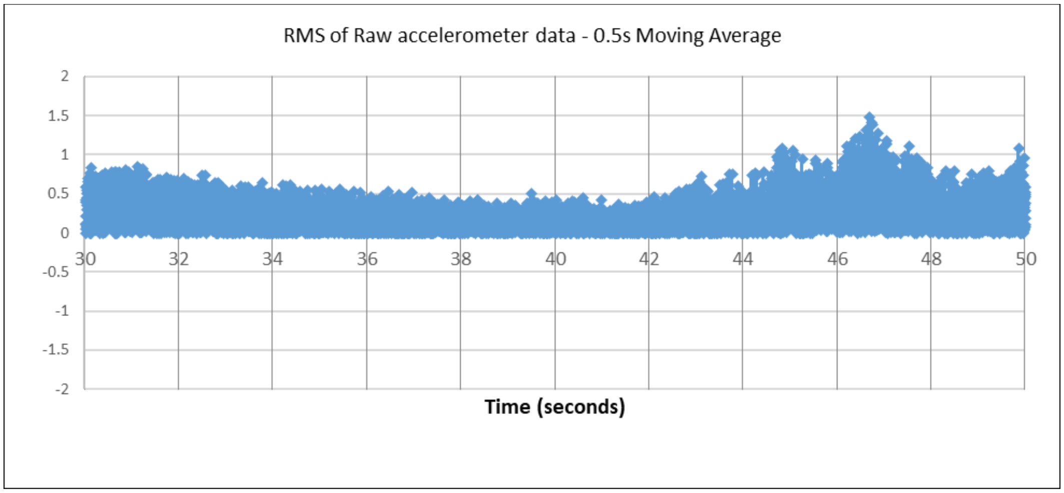

Figure 12 — RMS of data in Figure 11

Figure 13 shows the result of applying a 0.5s moving average to the data in Figure 12. The result is a smooth, monotonic parameter in units of G_{RMS} that can be used to compare the overall vibration level between two different flight conditions, or monitor vibration levels through a maneuver.

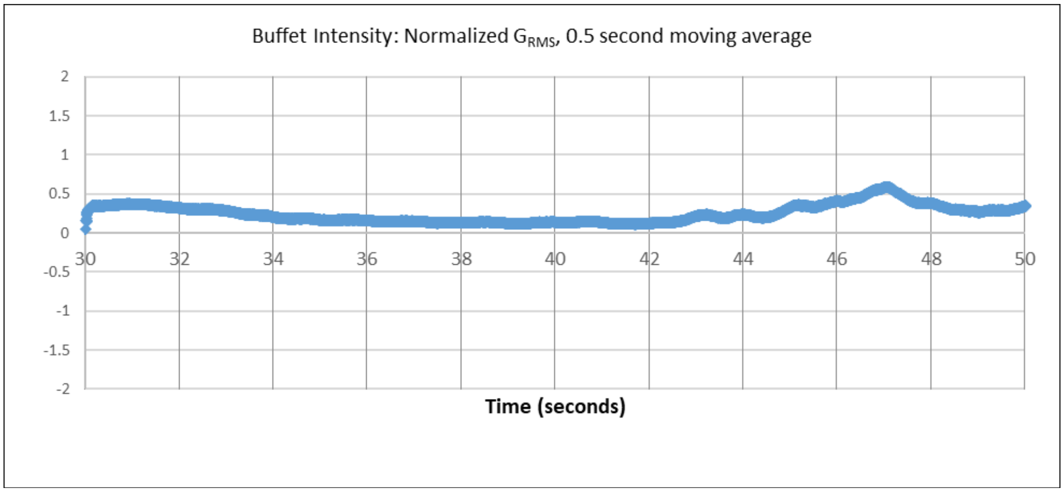

Figure 13 — 0.5s Moving Average of Data in Figure 12

No frequency filtering was performed on these data. Sample rate was approximately 500hz. Ambient noise, reciprocating engine dynamics, and propeller dynamics were likely large contributors to the overall vibration environment. It is expected that vibration and buffet which can be physically felt as a vibration, in contrast to noise or sound, which is primarily experienced as an aural cue, is a lower frequency phenomenon (~2-30hz).

The parameter may benefit from a low-pass filter. Given that various air vehicle types will have widely different vibration characteristics, however, the author declined to limit the dataset to a specific frequency range at this time. As more air vehicle types are analyzed, the parameter could be further refined to focus a specific frequency range of inspection which is characteristically recognized as airframe buffet.

Chapter 6
Results and Discussion

Buffet Intensity Values

Data from RPM dwells during ground runup were averaged over approximately 10 seconds per run to produce an average buffet value for that condition. These data were then plotted against RPM to produce Figure 14. As a reciprocating engine powered propeller driven airplane, it is expected that there will be large local peaks in vibration intensity across the RPM range due to plant dynamics and harmonics, as the buffet intensity line shows. The intent of these data is not to fully characterize the plant dynamics of the airplane, but they do show that there is a generally positive correlation between increased power setting and increased vibration intensity, as would be expected.

Normal runup per the airplane flight manual is performed at 1700 RPM. The magnitude of the buffet intensity experienced at power settings above 1700 RPM was quite high. Due to gound reactions, the vibration intensity at these power settings was also much higher than would be experienced in free flight. Runs above 2100 RPM were abbreviated because of the intensity of the vibration. Buffet intensities above 1 G_{RMS} can be considered severe.

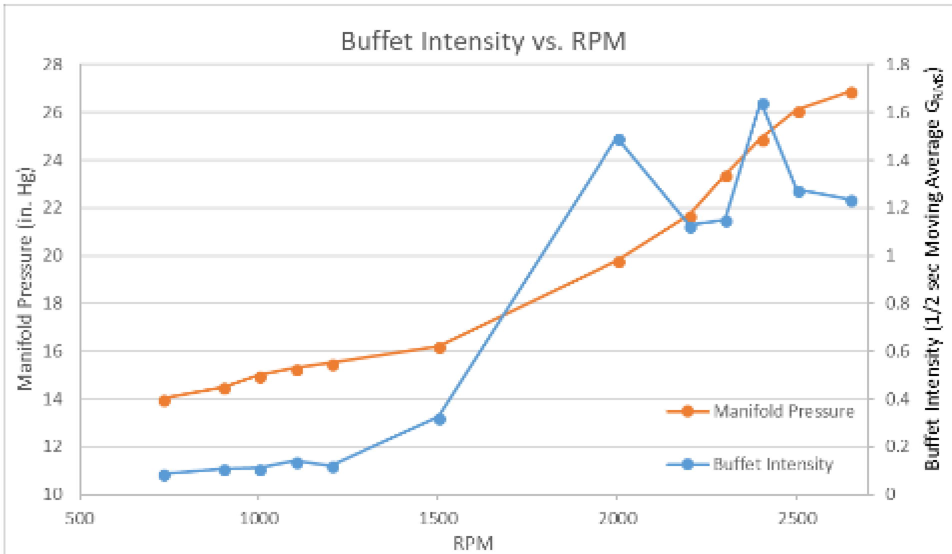

Figure 14 — Crossplot of Buffet Intensity and Manifold Pressure during Ground Runup

Perceptibility Thresholds

All changes in configuration produced buffeting which was perceptible.

Qualitatively, extension of cowl flaps produced a slight but noticeable rumble accompanied by a slight nose-down pitch trim requirement. Extension of landing gear produced a large increase in ambient vibration and noise accompanied by a large nose-up pitch trim requirement. Extension of flaps produced a slight increase in overall vibration and noise, a change in the overall tone of the vibration and noise which felt less rough than gear down only, and a large nose-up pitch trim requirement.

Quantitatively, 10 second averages of buffet intensity values at each configuration are presented in figure 15. Based on the results in the clean configuration vs. the cowl flaps extended configuration, changes in buffet intensity as small as 2.3% above baseline vibration levels can be considered perceptible.

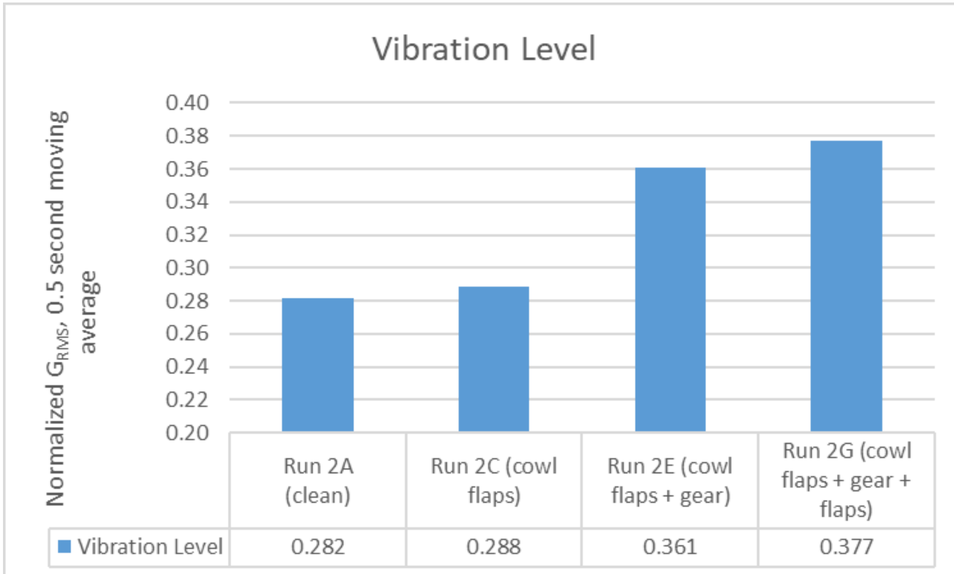

Figure 15 — Buffet Intensity Values at Various Airplane Configurations

Masking Effects

Buffet characteristics from various sources should not be considered additive. For example, extending cowl flaps when gear and flaps are already extended produces virtually no change in the perceived vibration level, as the baseline vibration level is already high.

During stall tests, stall buffet was much more severe in the clean configuration. While it is true that the absolute buffet intensity in the clean configuration was significantly higher, peaking at ~0.61 G_{RMS} clean vs. ~0.55G_{RMS} dirty, the majority of this perceived difference is due to the lower buffet intensity baseline in the clean configuration, making increases in the buffet intensity more noticeable.

Similarly, atmospheric turbulence of any kind can easily mask airframe buffet characteristics.

Applications

Vibration and buffet characteristics vary widely between air vehicle category, class and type. For the purposes of certification and guidance, any ranges, thresholds or limits established using this parameter should be expressed in terms of a multiple of the baseline vibration level experienced in a normal cruise condition to account for the differences between specific vehicle types.

A value expressed in multiple of cruise configuration baseline could be helpful in creating better certification criteria. A standardized measurement of cabin vibration levels could also be of use in independent ride quality studies , comparisons, and verifying the effect of enhancements.

References 20 through 23 cover recent work that is occurring to monitor turbulence and feed that data back into weather forecasting. The approach discussed in those efforts makes heavy use of transport airplane air data in its latest form, using angle of attack and airspeed to derive vertical and horizontal gust profiles. Early attempts used accelerometer data to derive vertical and horizontal gust intensities. Given that most General Aviation airplanes are or can be equipped with advanced cockpits that would contain solid state accelerometers, those earlier data reduction methods could turn General Aviation airplanes into an additional source for atmospheric data. Given that most General Aviation airplanes operate between 3,000 and 18,000ft MSL where most weather occurs, this dataset could be a valuable supplement to the data being recorded on airliners which primarily operate at higher altitudes.

Chapter 7
Conclusion and Recommendations

Buffet intensity can be measured using the techniques discussed in this paper, and used to quantify buffet characteristics. Data from additional flight vehicle types, categories and classes would aid in refining the parameter and developing useful thresholds and ranges to be used.

Gathering data on other vehicles and input from other pilots and engineers involved in airplane certification is an opportunity for further study.

It is hoped that the methods presented here can be applied to problems of certification, allowing for a wider range of allowable flight vehicles and operating conditions.

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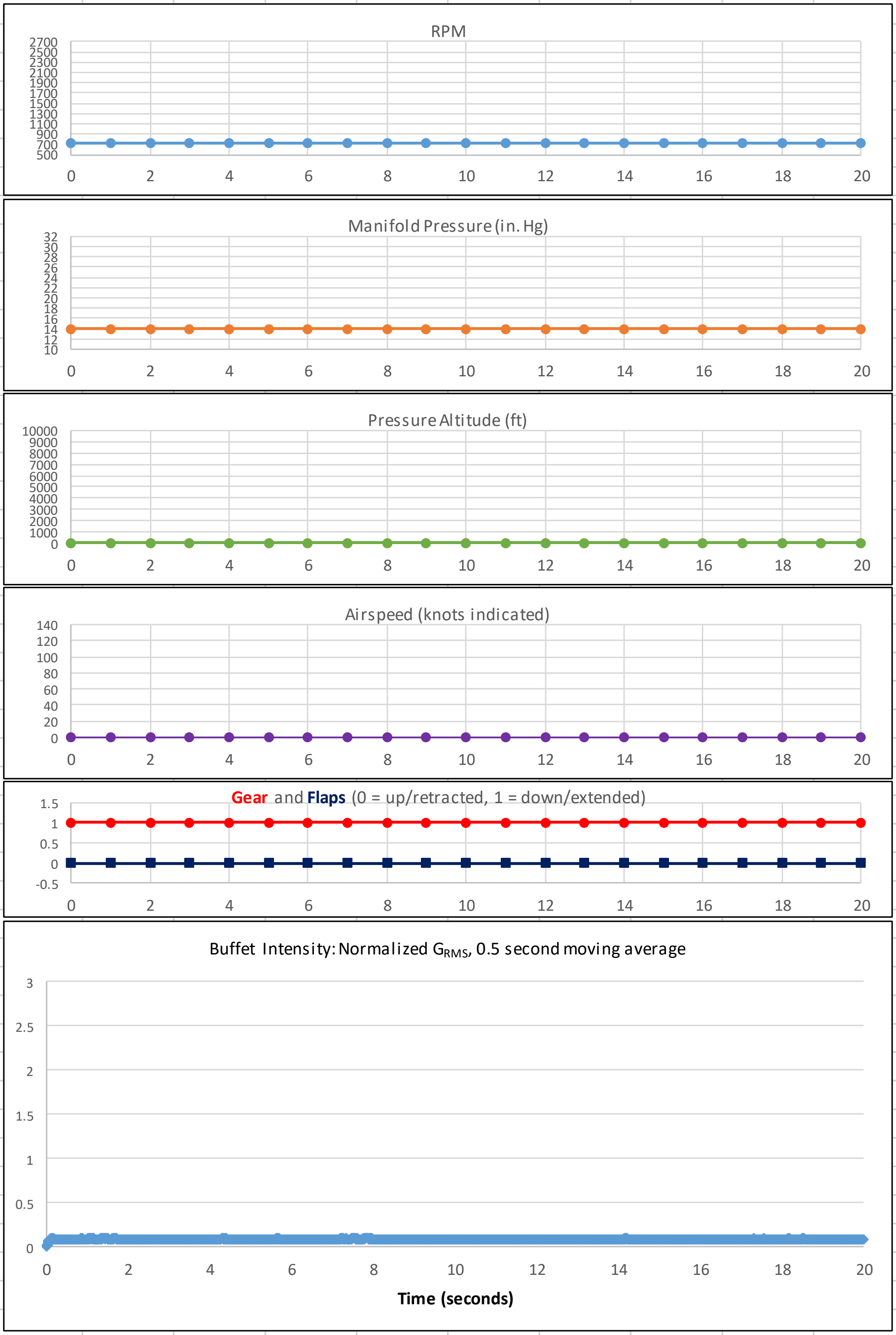
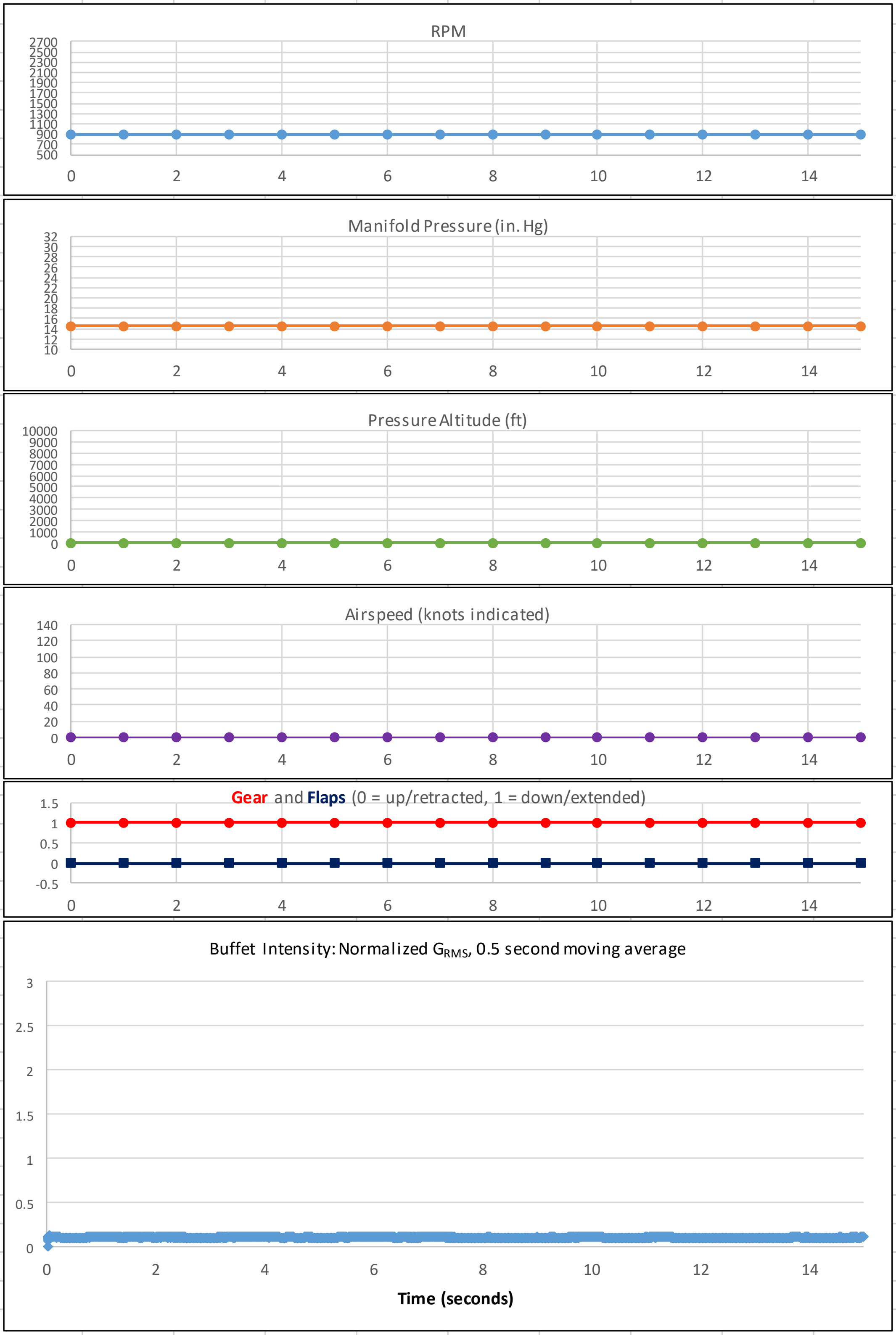
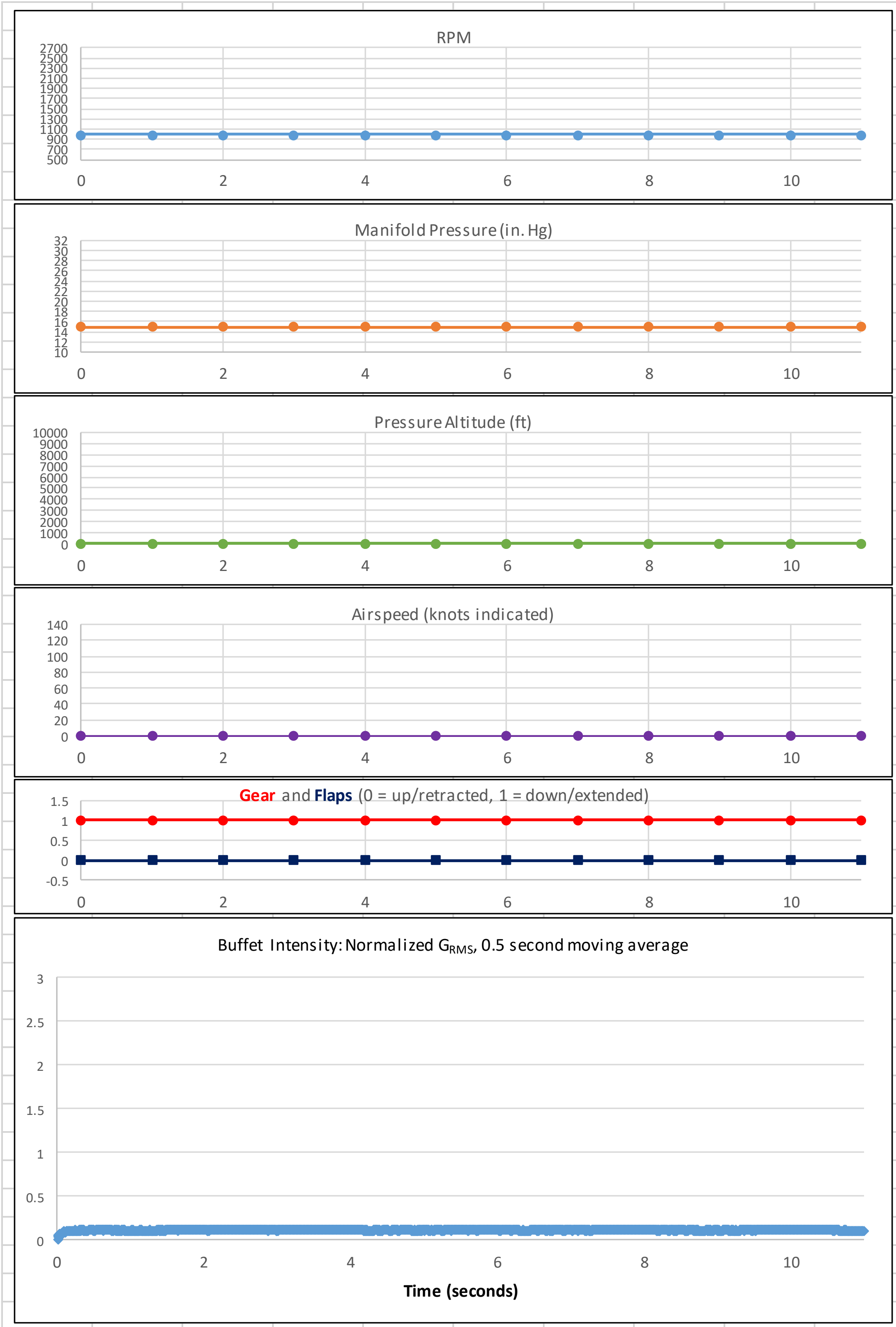
Appendix A
RPM Sweep on ground



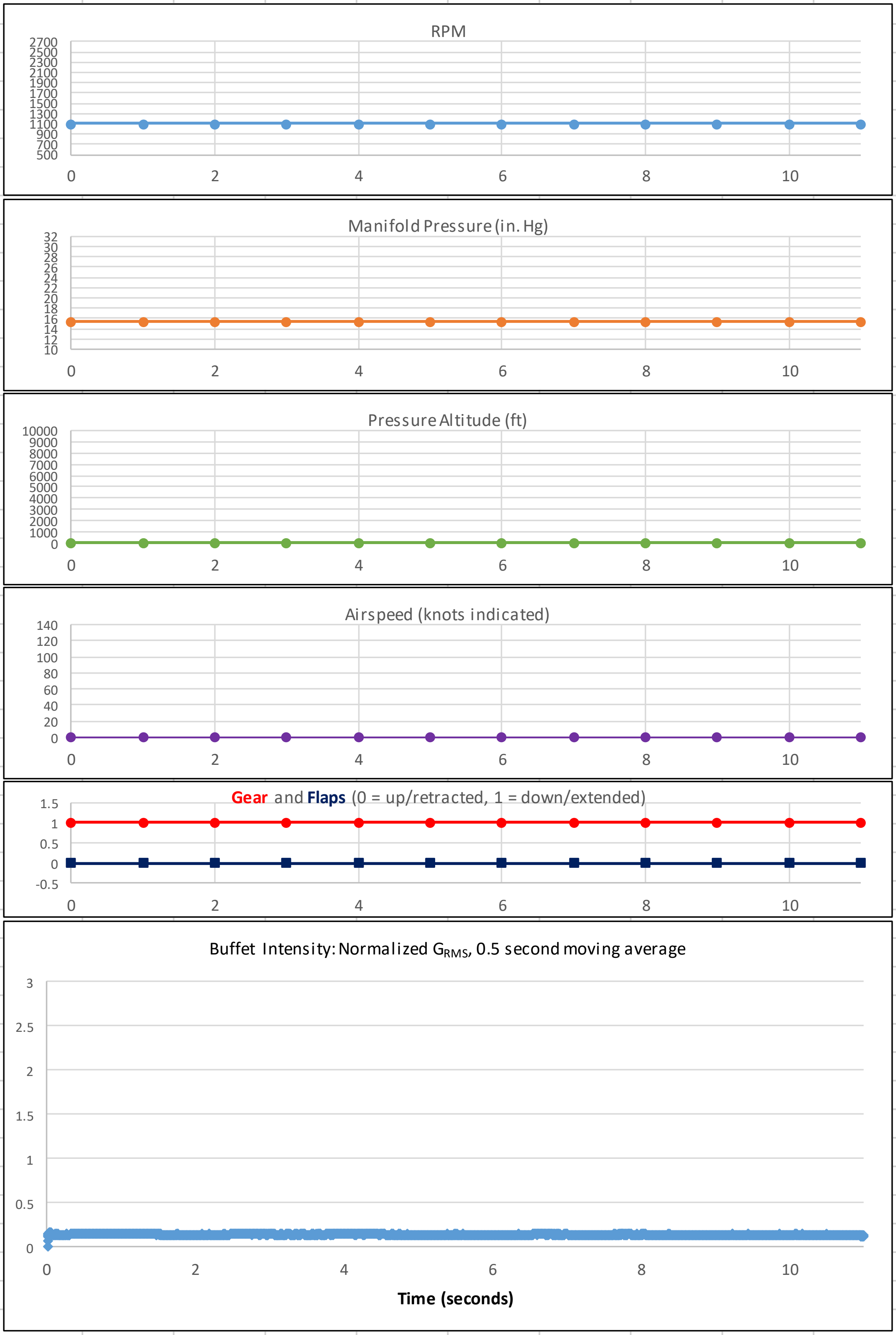
Run 1A	On Ground, Idle	Flight 1, 4/7/18



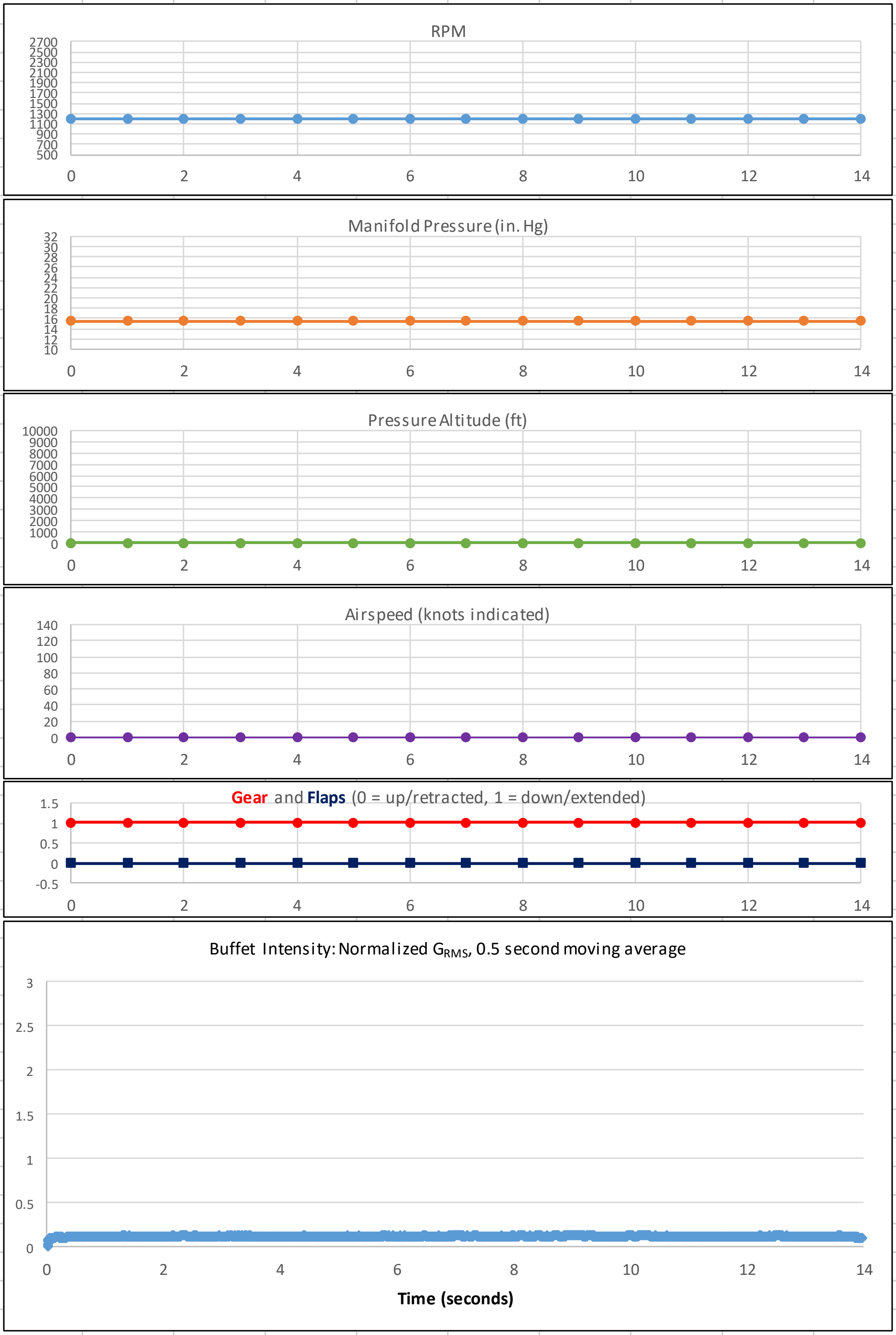
Run 1B	On Ground, 900RPM	Flight 1, 4/7/18



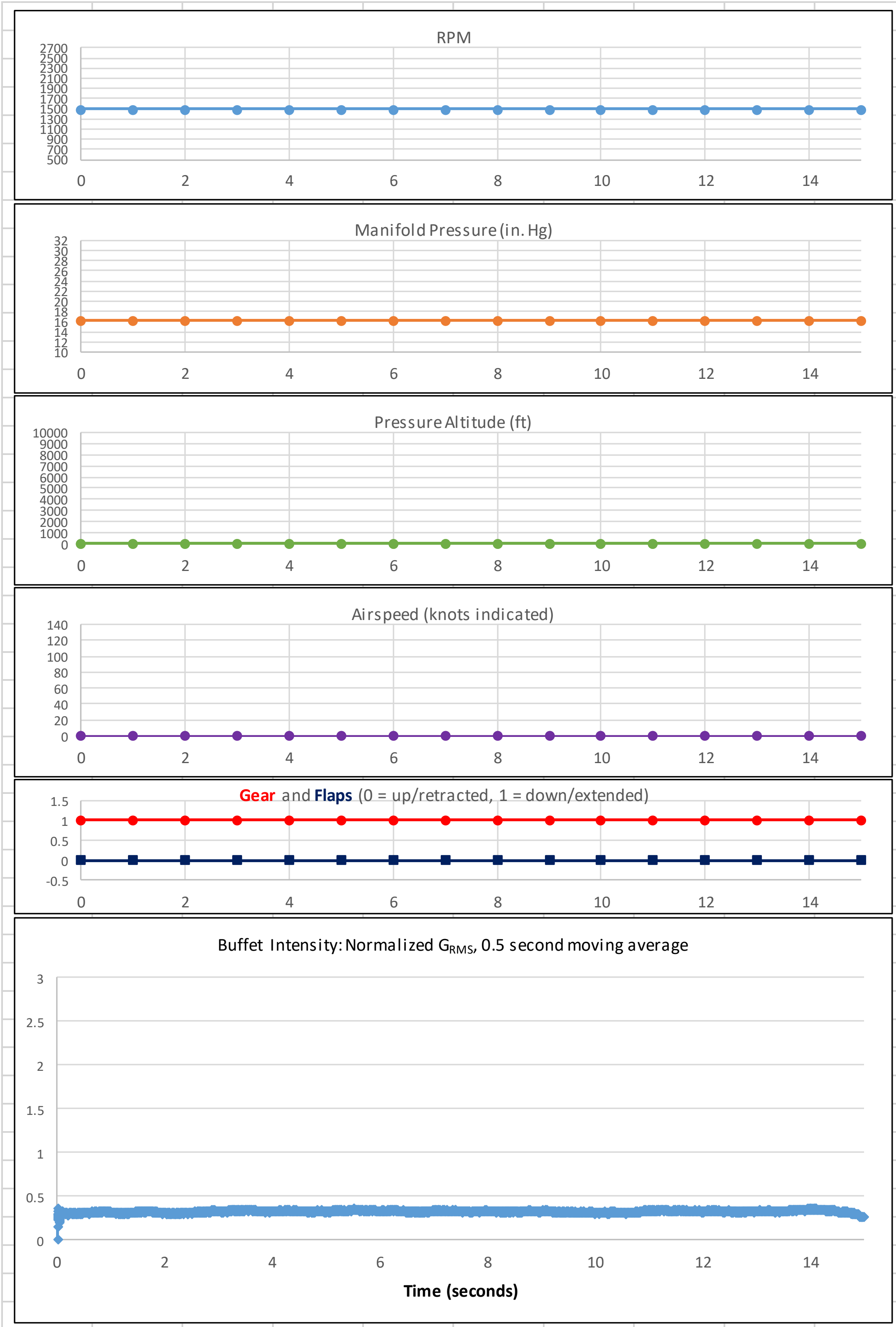
Run 1C	On Ground, 1000RPM	Flight 1, 4/7/18



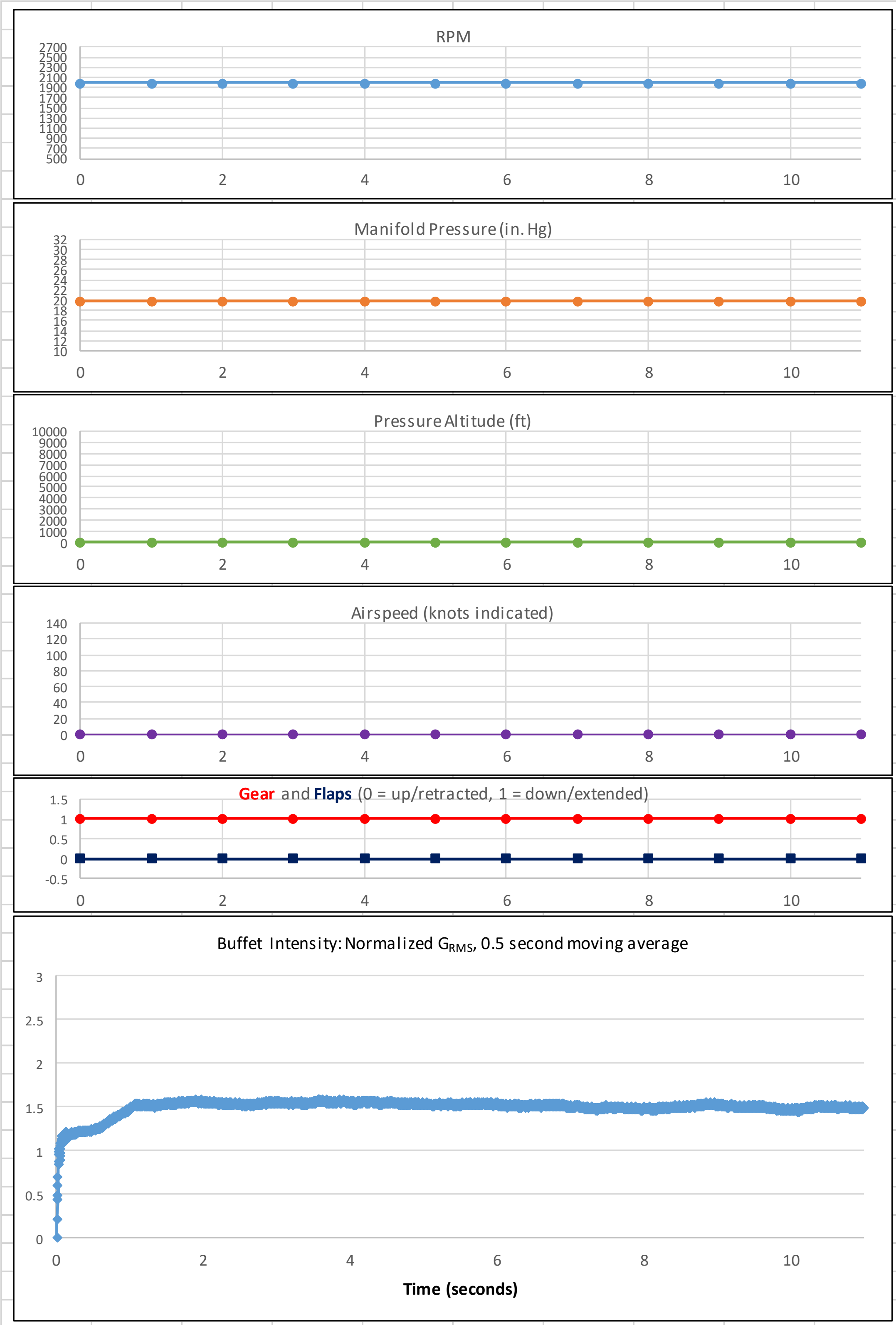
Run 1D	On Ground, 1100RPM	Flight 1, 4/7/18



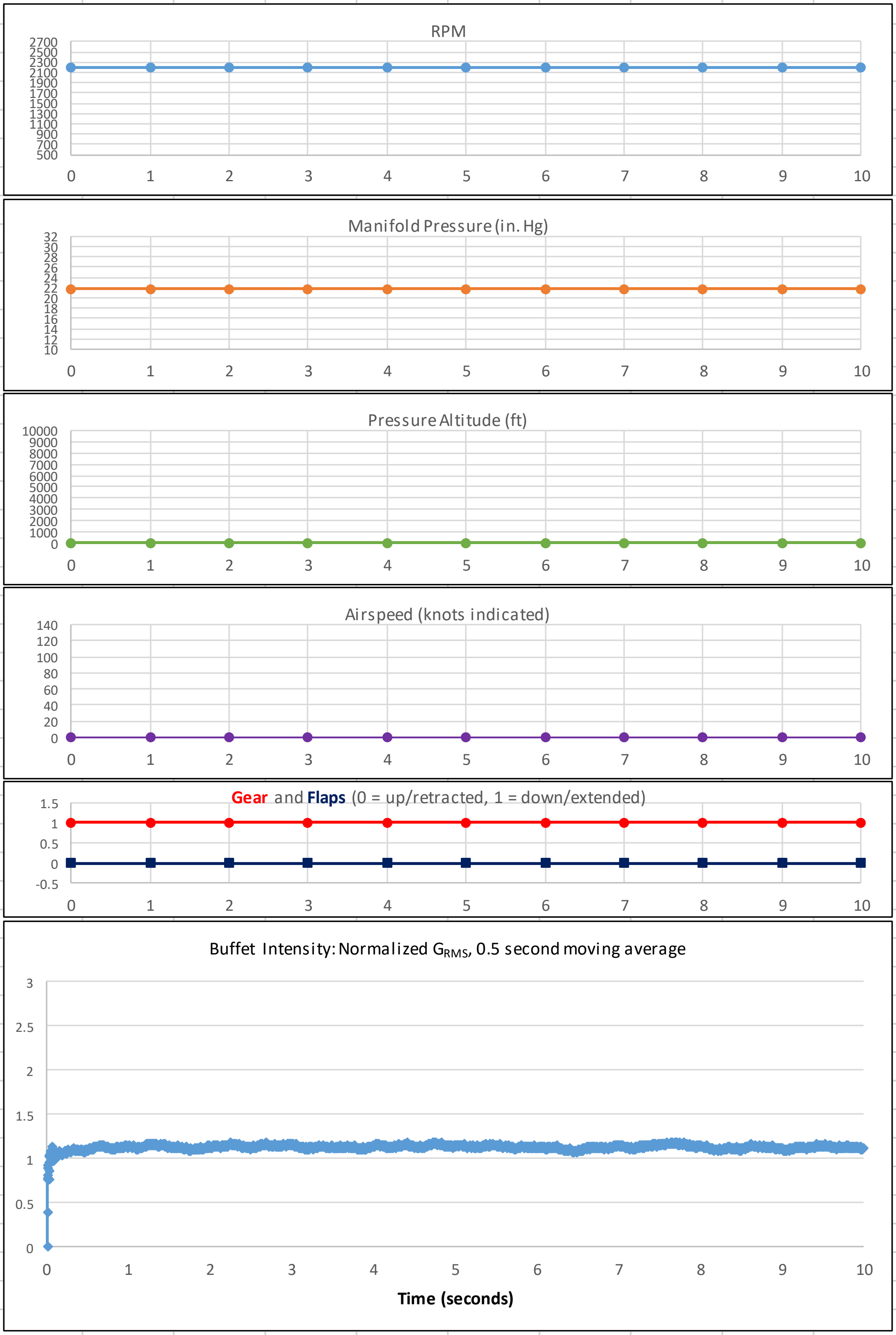
Run 1E	On Ground, 1200RPM	Flight 1, 4/7/18



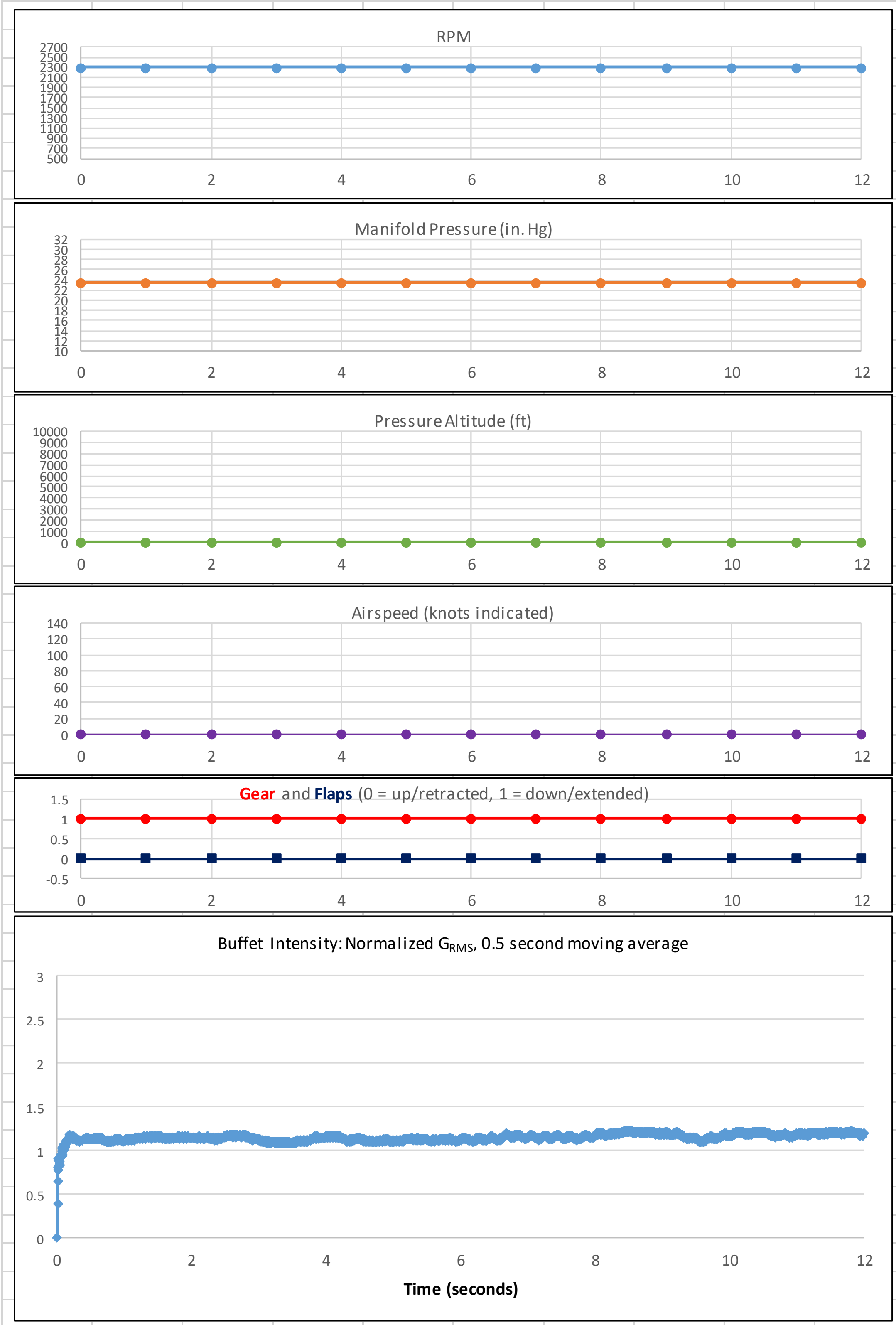
Run 1F	On Ground, 1500RPM	Flight 1, 4/7/18



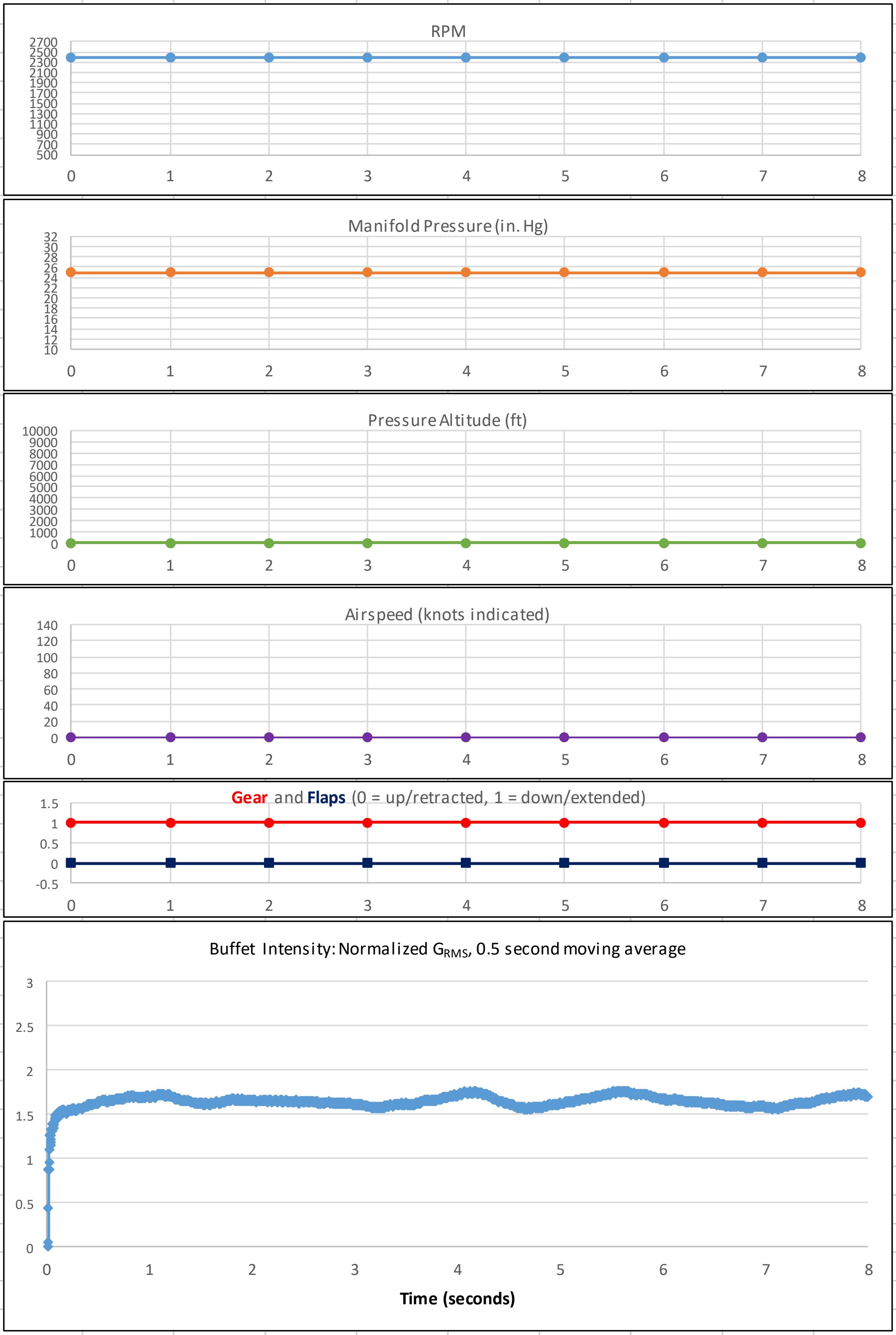
Run 1G	On Ground, 2000RPM	Flight 1, 4/7/18



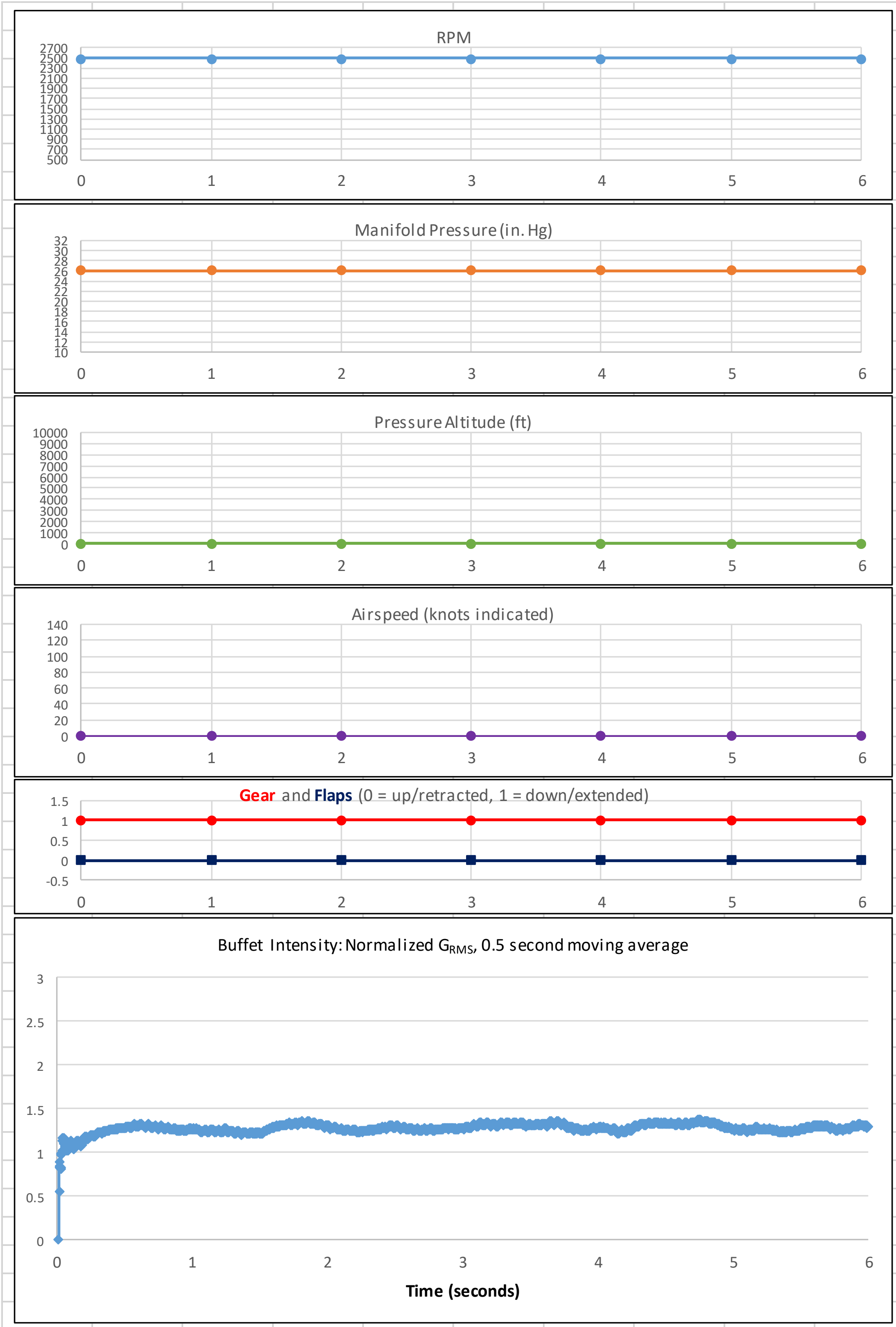
Run 1H	On Ground, 2200RPM	Flight 1, 4/7/18



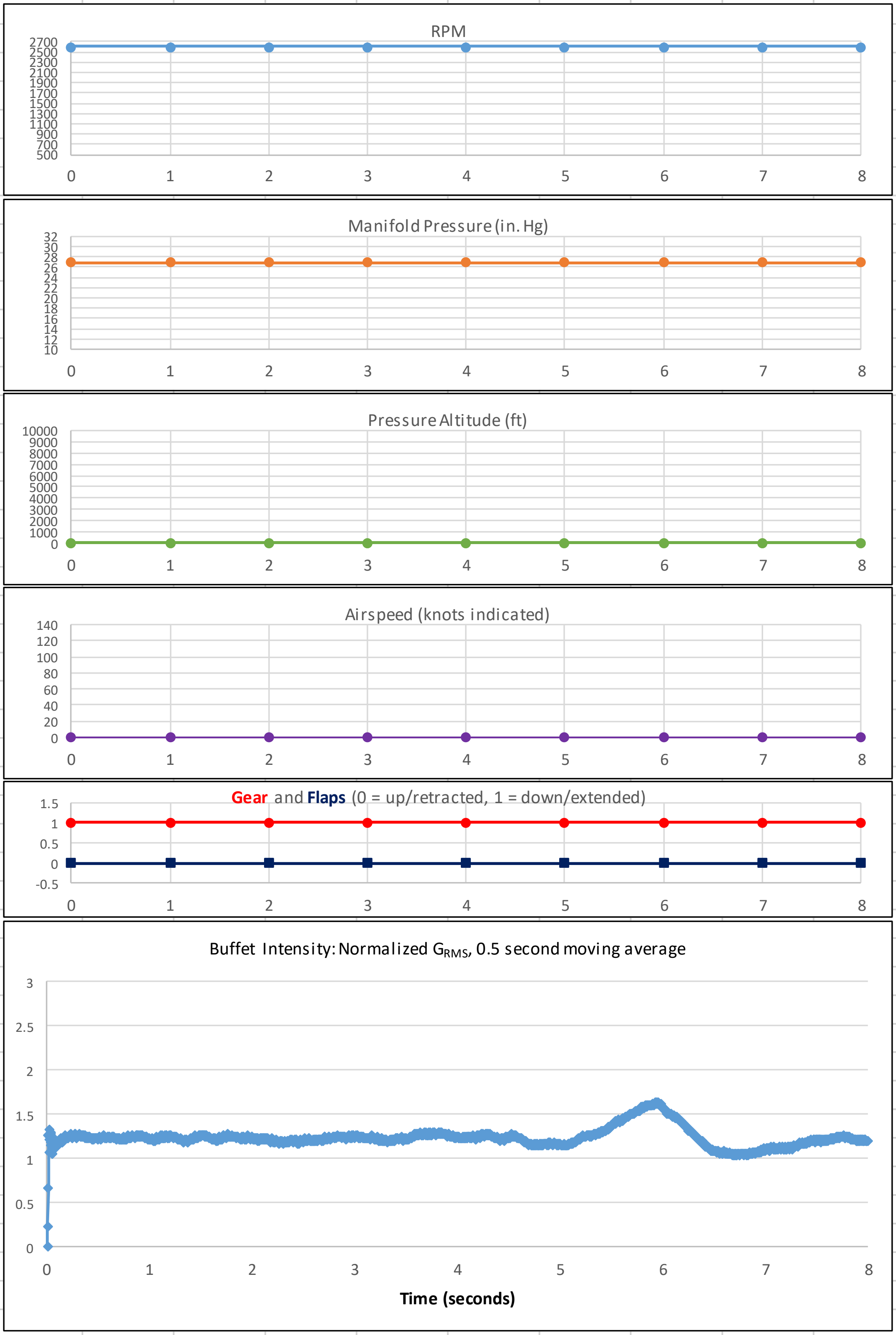
Run 1I	On Ground, 2300RPM	Flight 1, 4/7/18



Run 1J	On Ground, 2400RPM	Flight 1, 4/7/18

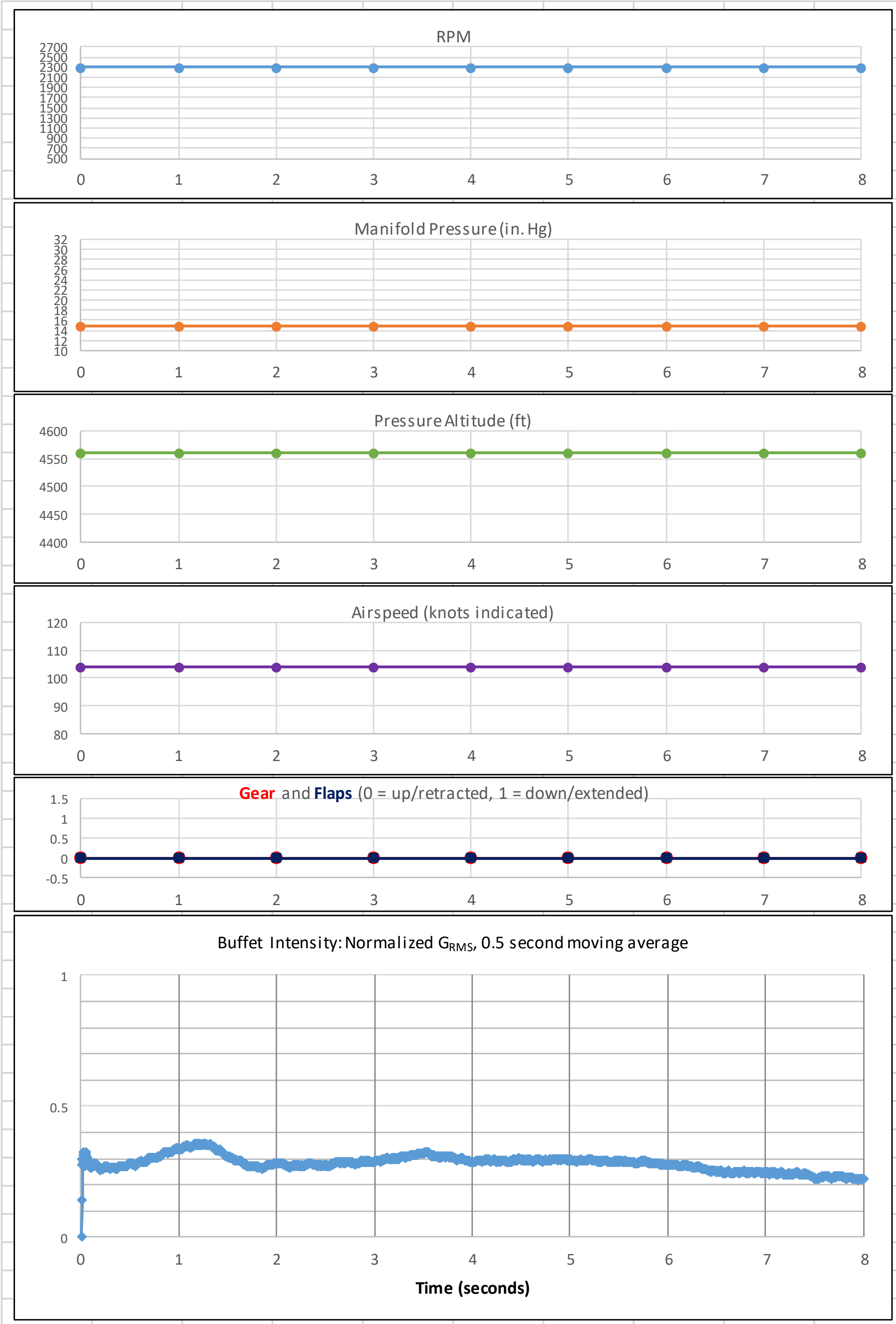


Run 1K	On Ground, 2500RPM	Flight 1, 4/7/18

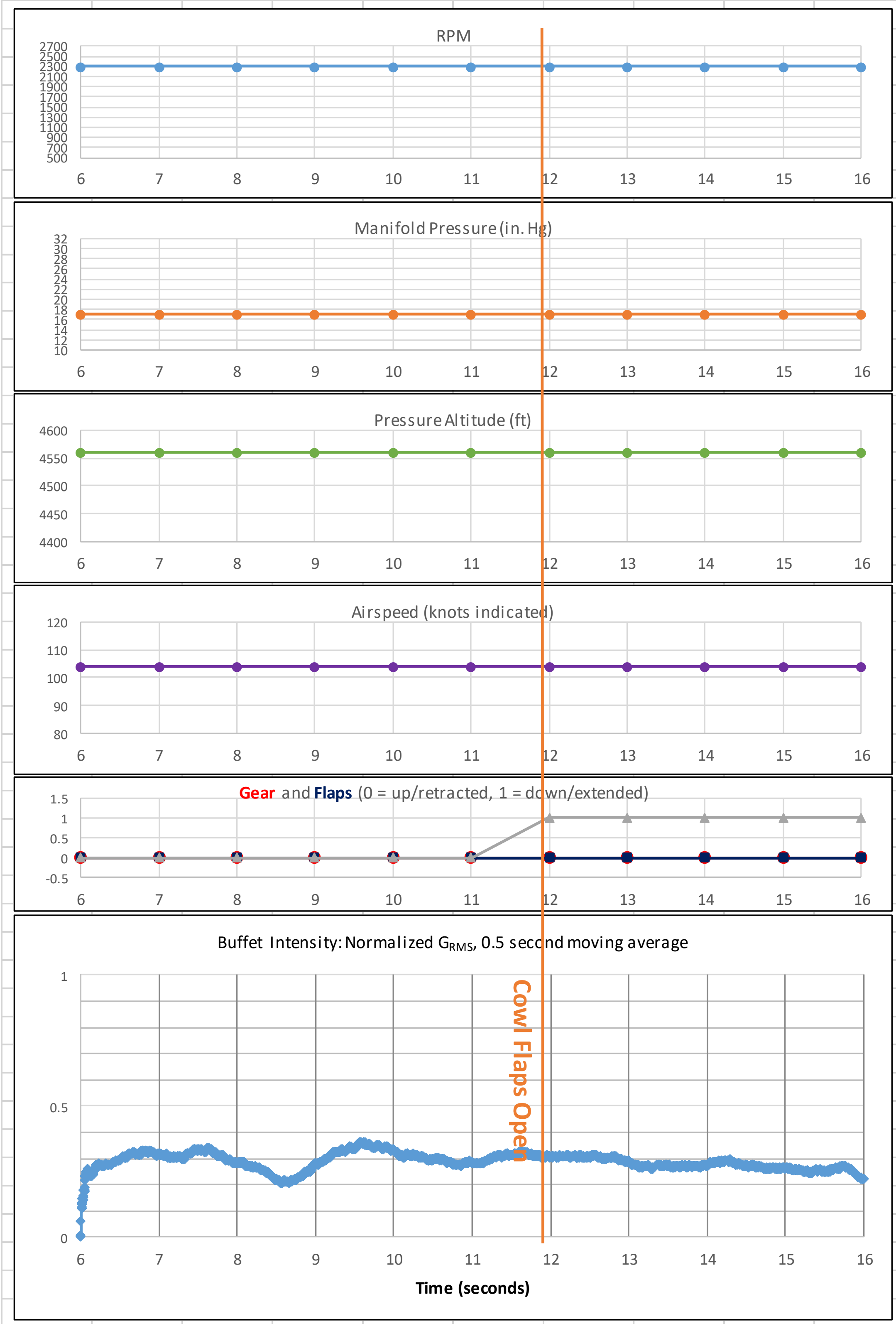


Run 1L	On Ground, 2600RPM	Flight 1, 4/7/18

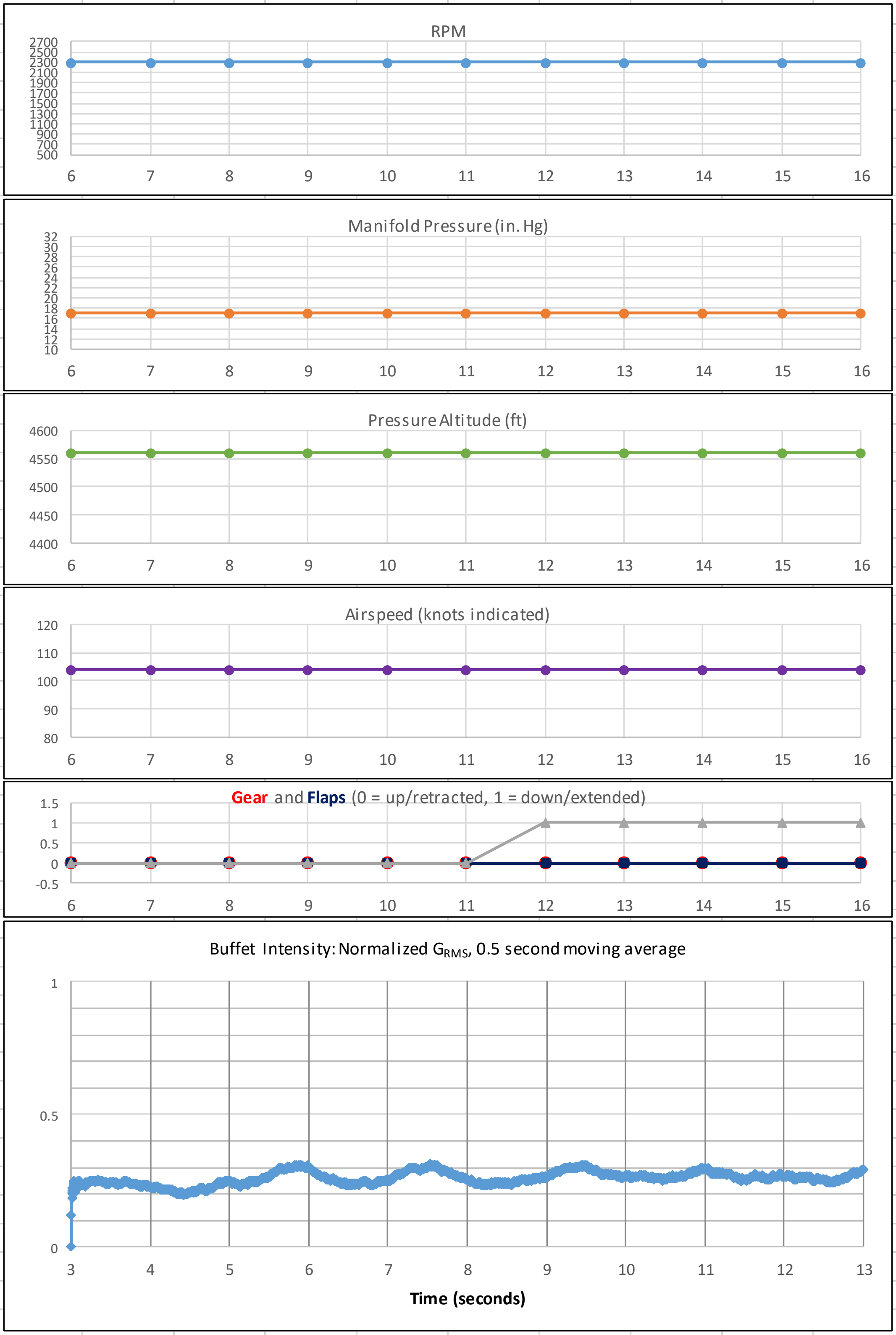
Appendix B
Configuration Changes



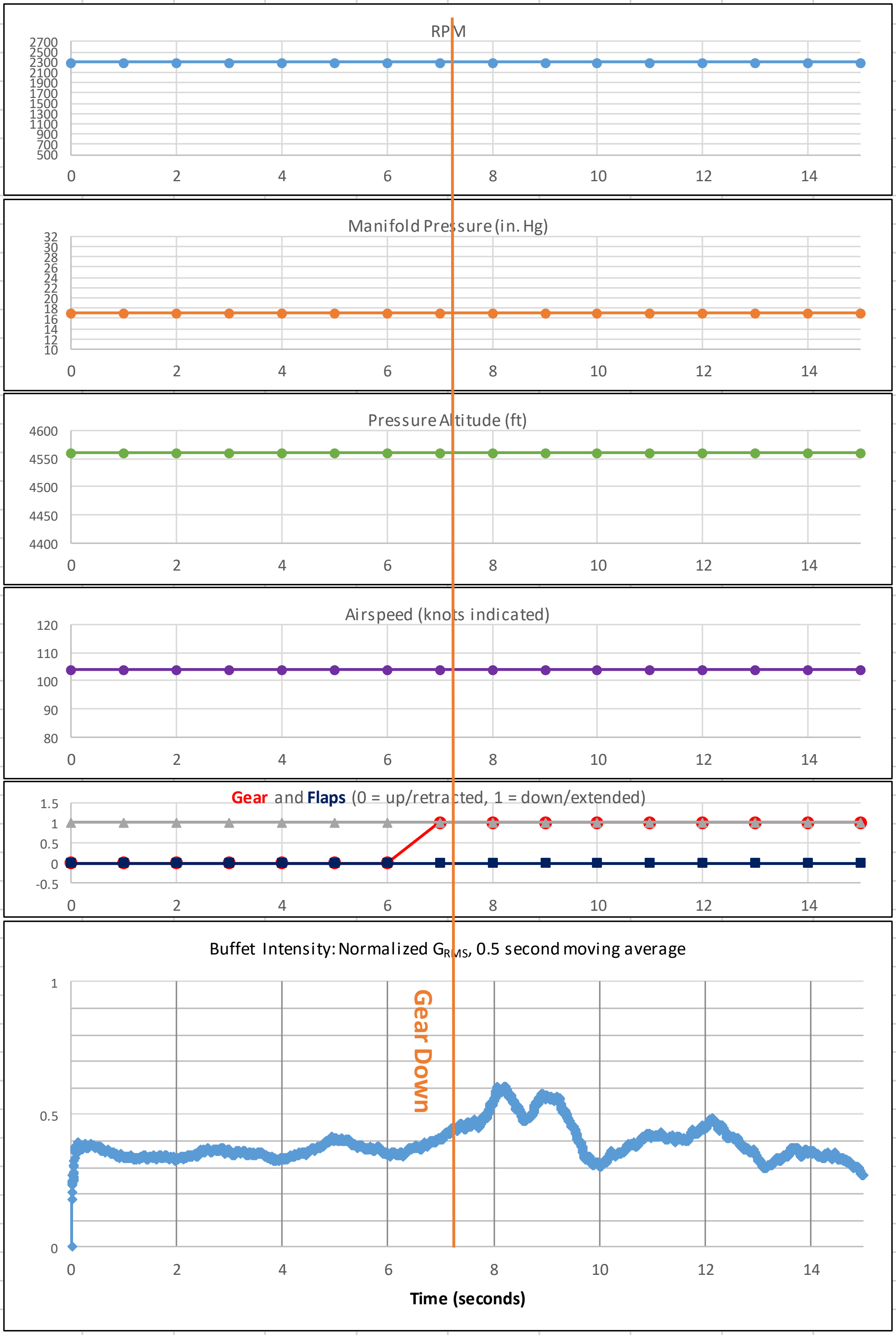
Run 2A	Baseline Vibration Level, Clean Configuration	Flight 2, 05/23/18



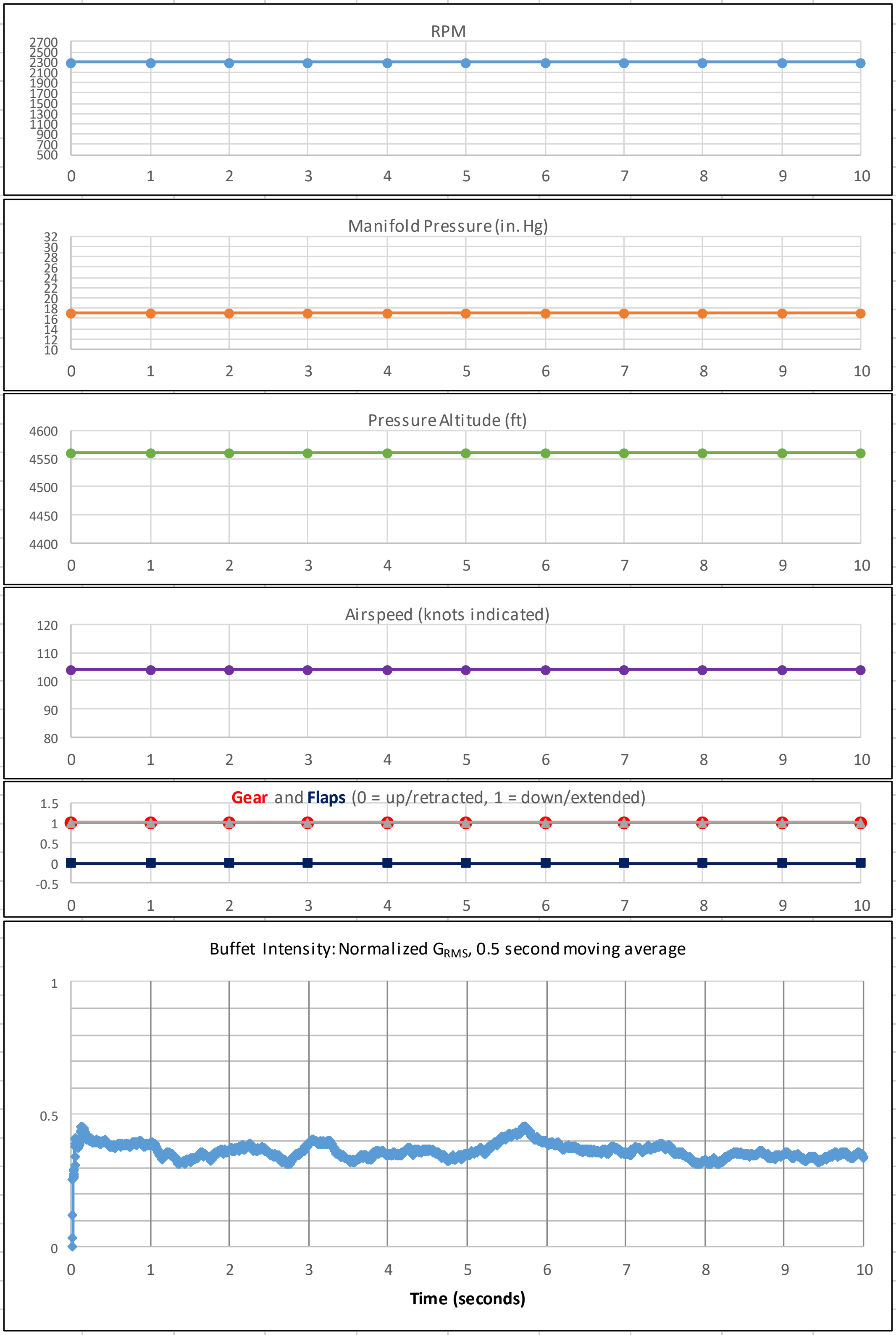
Run 2B	Cowl flaps in transit	Flight 2, 5/23/18



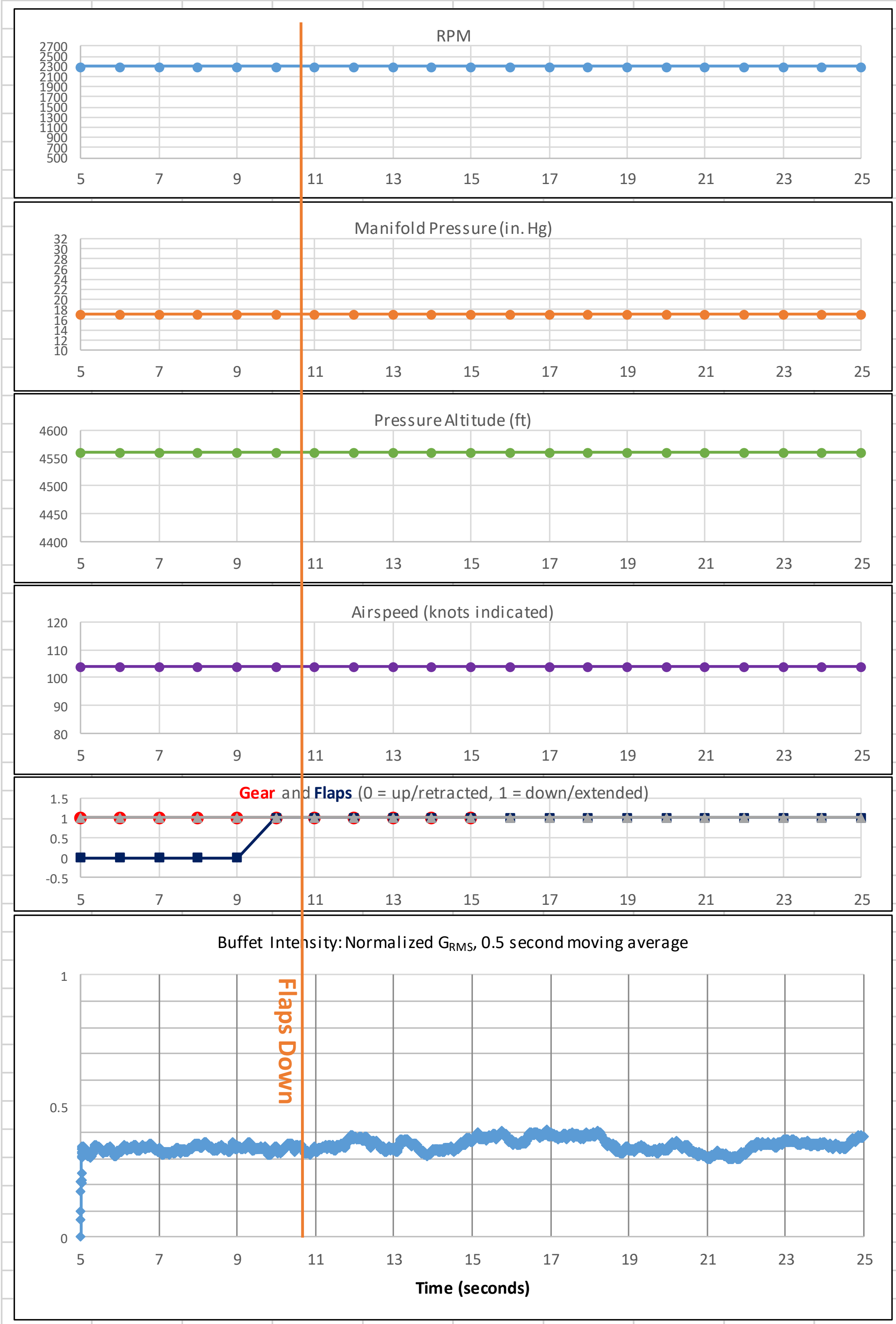
Run 2C	Cowl Flaps Open	Flight 2, 5/23/18



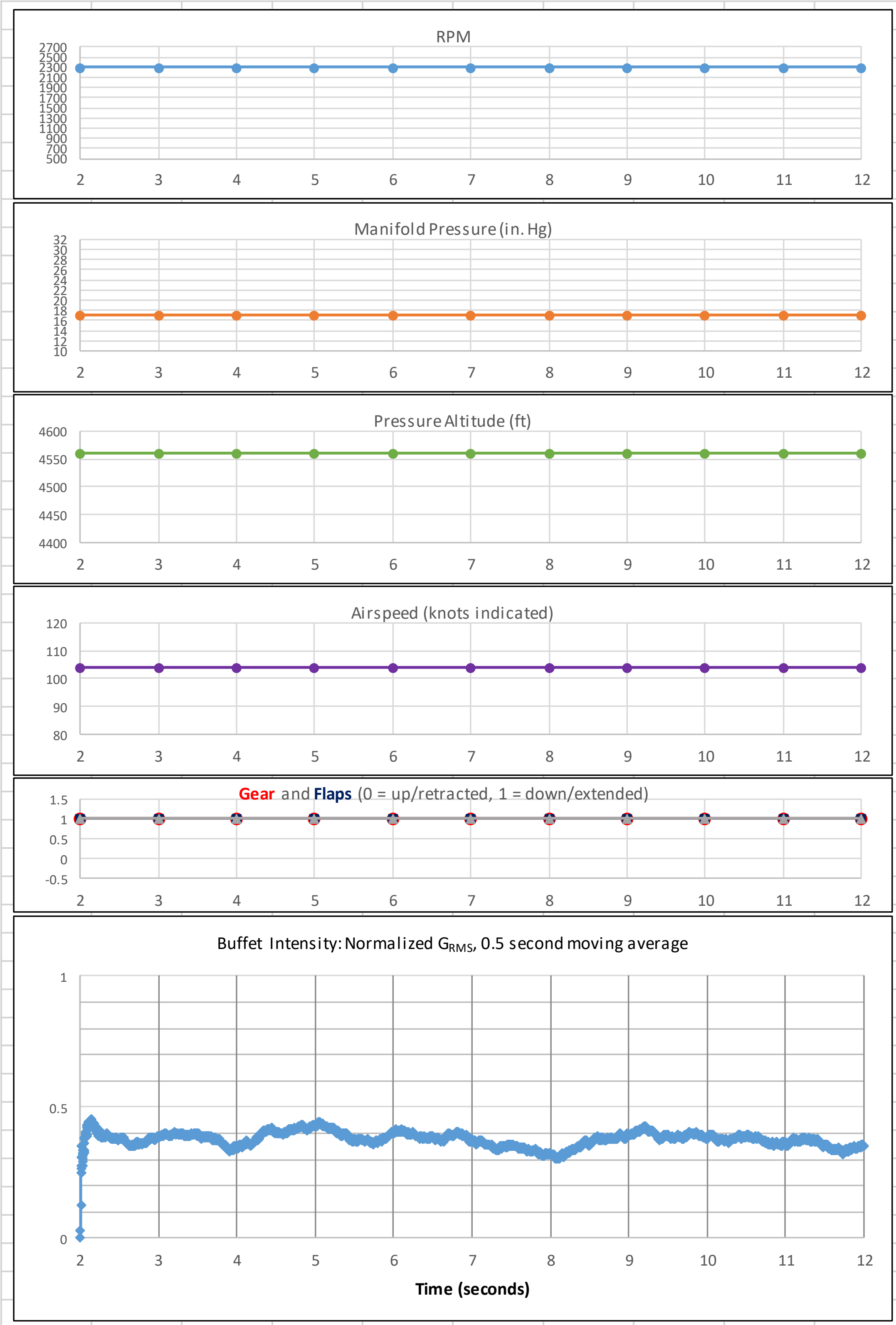
Run 2D	Gear In Transit	Flight 2, 5/23/18



Run 2E	Gear Down	Flight 2, 5/23/18

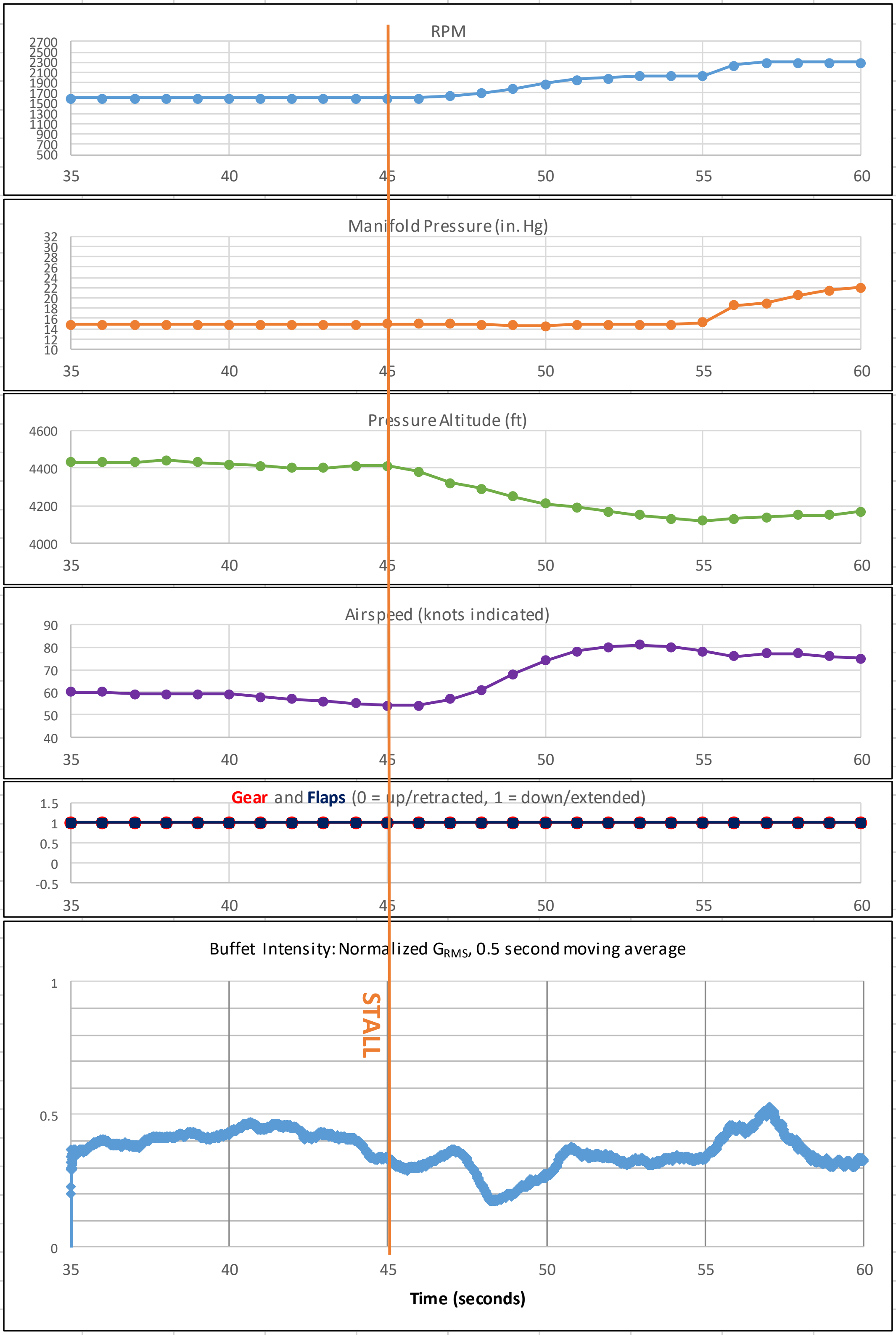


Run 2F	Flaps In Transit	Flight 2, 5/23/18

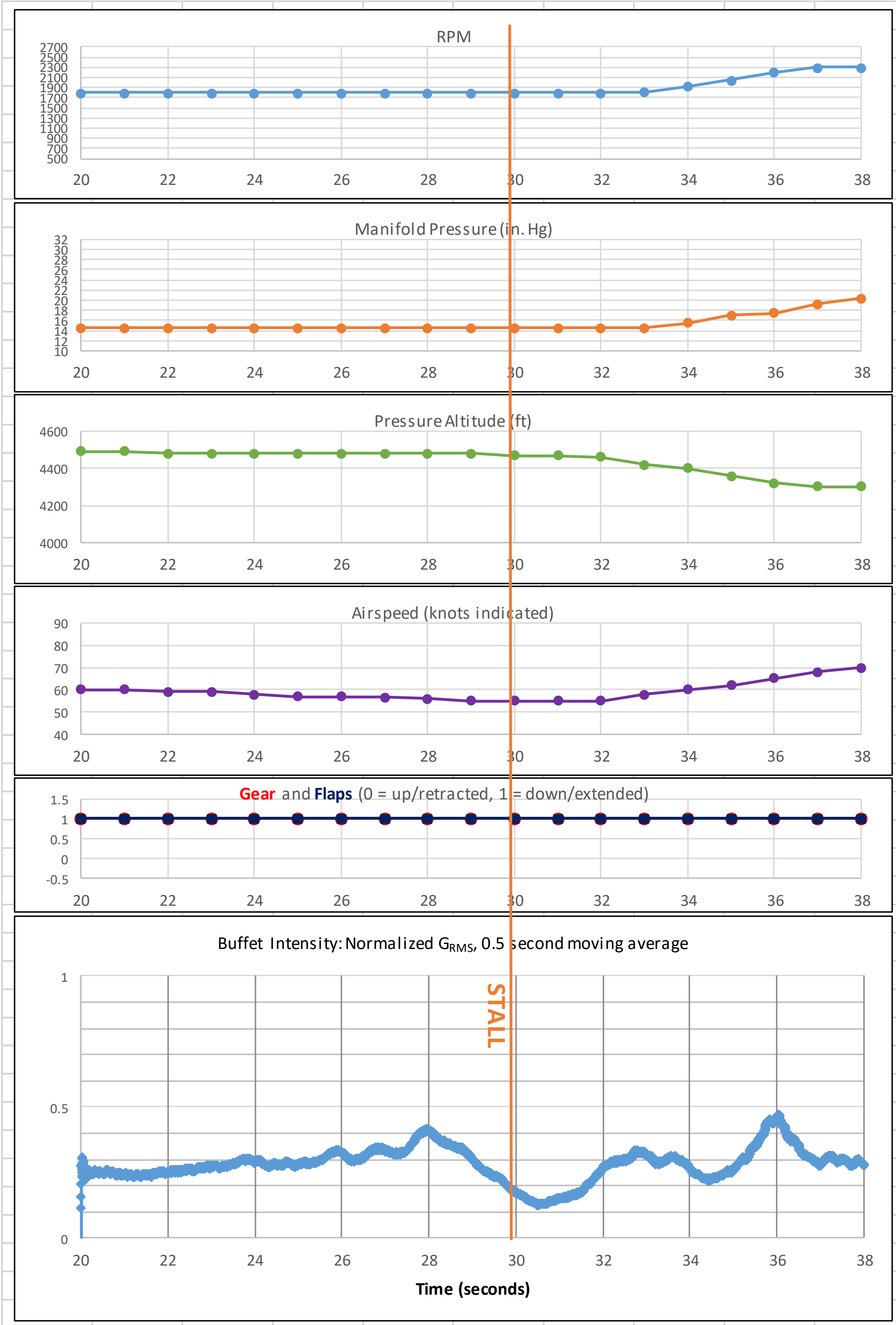


Run 2G	Flaps Down	Flight 2, 5/23/18

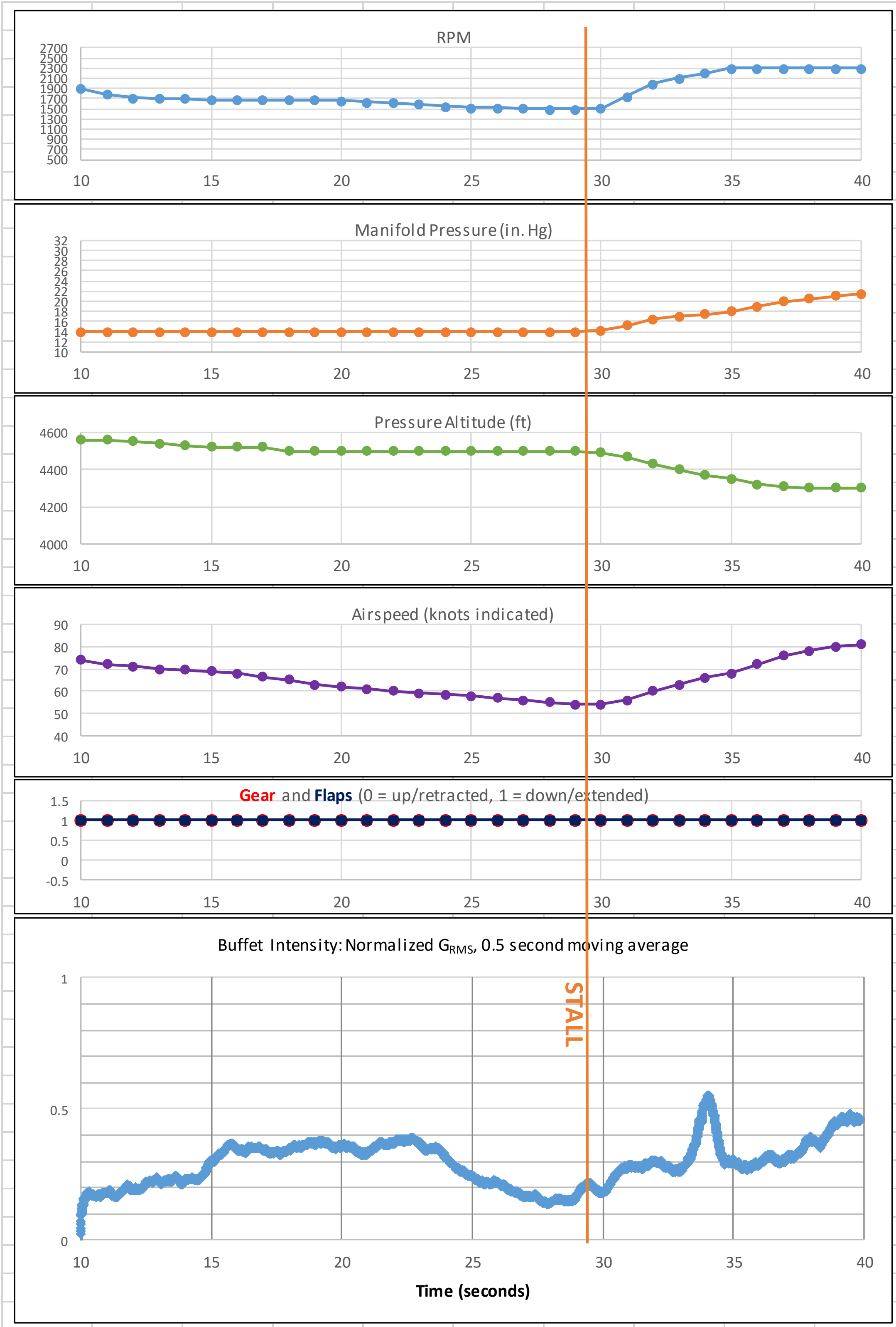
Appendix C
Power off stalls – Landing configuration



Run 3A	Power-Off Stall, Landing Configuration, Run 1	Flight 1, 4/7/18

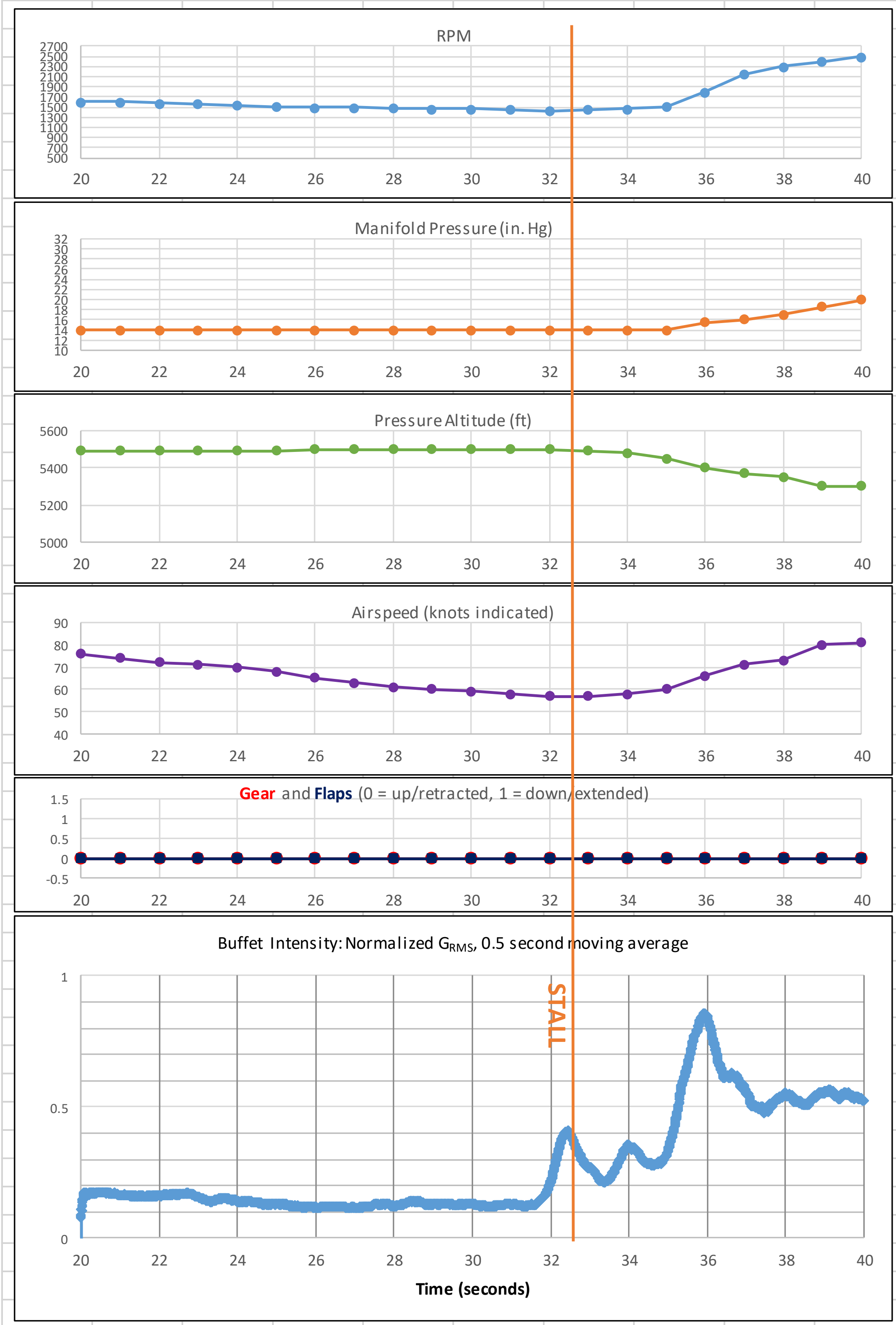


Run 3B	Power-Off Stall, Landing Configuration, Run 2	Flight 1, 4/7/18

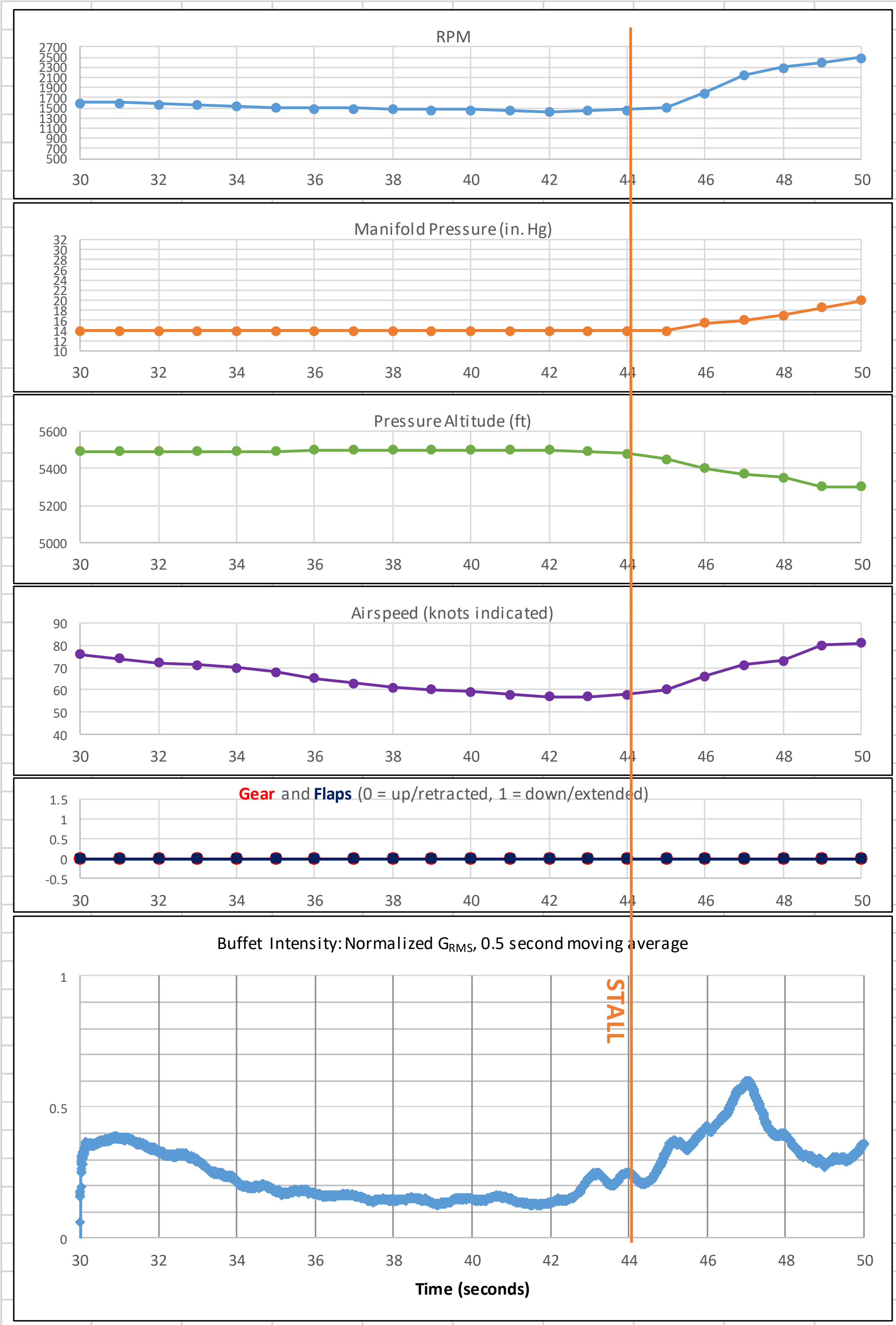


Run 3C	Power-Off Stall, Landing Configuration, Run 3	Flight 1, 4/7/18

Appendix D
Power off stalls – Clean Configuration



Run 4A	Power-Off Stall, Clean Configuration, Run 2	Flight 1, 4/7/18



Run 4A	Power-Off Stall, Clean Configuration, Run 3	Flight 1, 4/7/18