EAA Founder's Innovation Submission:

Enhanced AOA Aural Logic

The FlyONSPEED.org Team

30 April 2021

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Enhanced Aural AOA Tone Logic

Introduction

The FlyONSPEED group is a non-profit open-source organization dedicated to providing high quality Angle of Attack and education resources to the Experimental Amateur Built Aviation Community to reduce Loss-of-Control mishaps. **The FlyONSPEED mission is Loss-of-Control risk mitigation.**

Summary

The open-source hardware and software system developed by the FlyONSPEED group mitigates loss-of-control risk, increases precision during approach and landing operations, and reduces the probability of handling error during maneuvering flight by simplifying energy management. An effective hardware-based, non-automatic loss of control (LOC) solution must provide angle of attack (AOA), sideslip and energy cues. This proven, flight-tested, inexpensive, ergonomic system can be retrofitted to any airplane with an electrical system for less than $300 and meets all three requirements in a simple, intuitive manner. Based on logic that has been in successful used for 50 years in fighter aircraft, the FlyONSPEED system accurately computes AOA using differential pressure measurements from speeds V_{MAX} through post-stall (up to 50°) and sideslip angles up to 6°. Aural cues for AOA, energy management (EM), stall warning, sideslip, G and airspeed limits are provided to the pilot through the aircraft audio system. Within the normal flight envelope, AOA is calculated to an accuracy of 1/2° or less using a commercially available AOA probe or an inexpensive homebuilt probe. The system utilizes 3D stereo audio to provide sideslip cues by moving the AOA tone left and right in the sound field to mimic the behavior of the slip/skid ball. In addition to energy state, performance AOA cues are provided for L/D_{MAX} (optimum glide speed and best range), optimum approach and maneuvering AOA (ONSPEED), and stall. ONSPEED is a 0 P_S condition (neutral energy state). This allows the pilot to make a simple fast/slow determination regarding energy state. Best angle of climb occurs ONSPEED, and best rate of climb occurs at approximately L/D_{MAX}. The overload warning system (OWS) accommodates symmetric and asymmetric maneuvering (rolling G) and features pilot selectable limits for use during upset and aerobatic training. Airspeed warning sounds when maximum structural cruising speed is exceeded. All features may be turned on or off, and control is provided by a single knob. Because the system uses aural cues, there is no requirement for the pilot to look inside the cockpit. The FlyONSPEED system supports an optional, inexpensive visual display to compliment the aural cues. It is designed to be mounted in a head's up location. The display provides airspeed, performance AOA cues and G information visually. An on-board IMU provides derived AOA and calibration capability. The FlyONSPEED system can be accessed in-flight or on the ground via a WiFi interface on any computer, tablet, or smart phone. Recorded 50 Hz data may be

downloaded wirelessly post flight. If EFIS or other flight test equipment data are recorded, they are integrated at the appropriate sample rate (up to 50Hz) and synchronized utilizing GPS time. The system integrates with Garmin, Dynon, GRT and AFS EFIS (if equipped). The system is designed for inexpensive production or assembly by anyone with basic electronic skills. We are currently working on developing an auto calibration "wizard" appropriate for a private pilot skill set, reducing sideslip effect on pressure-derived AOA accuracy, and arranging for production of systems.

Self-Evaluation

1. **Expected effectiveness in reducing fatal LOC accident rate: 4.5**. Hardware-based solution addresses AOA, sideslip, and energy. Provides accurate, intuitive cues, full-envelope warning, and reduces risk of aircraft handling error during takeoff, landing and maneuvering flight. Reduced LOC in military use. Cuing optimized for manual flight control, requires pilot reaction. Downgrade to 4.5 due to manual nature of the solution. Note: Logic could be integrated with terrain avoidance and/or automatic recovery systems.
2. **Demonstrated affordability including ease of installation: 4**. The system costs $250 to build, optimized for ease of assembly. Optional visual display is $100. The wiring harness is $45. FlyONSPEED.org is non-profit, open source. Research, hardware designs, software, training materials and test results may be downloaded from our website at no cost. A differential pitot/AOA source (commercial [Dynon, Garmin, etc.] or homebuilt) is required. *Currently coordinating for a production version* and developing automatic calibration. Downgrade to 4 due to necessity of installing box and harness, and requirement for differential pressure source. However, *our logic and code could be readily adapted by manufacturers of existing systems and is offered to them open-source, offering a potential no-cost solution for existing users.*
3. **Effective explanation of why the solution is optimum: 5**. Accurate, intuitive AOA and energy cuing. Simplifies energy management during maneuvering flight. Accurate throughout flight envelope, excellent transient response. Also provides sideslip, G and airspeed cues. Thoroughly flight tested. Simple to learn and use. Simple to control (single knob). No requirement to look inside the cockpit. 50 years of successful military use: translates directly to GA-EA-B. Passes the KISS test.
4. **Effective use of time since original entry to develop the solution for the EA-B and GA market: 4.5.** Incorporated non-profit organization. Developed, tested three iterations of hardware and multiple versions of software. Completed low-rate initial production of 30 units for operational test and evaluation. Validated "homebuilt" version with volunteers in the field. Developed detailed builder's manual. Developed web-based resources including builder support for experimenters, training materials for users, and

technical resources. Currently coordinating for production units and automating the calibration process. Experimenting with sensor design to mitigate side slip effects on performance. All volunteer organization without specific timeline objectives--team members contribute as they have time available. Engineering, flight test, analysis, resource development, web and program management conducted by unremunerated volunteers. Downgrade to 4.5 due to non-timeline driven, volunteer nature of FlyONSPEED.org.

Program Update. FlyONSPEED.org was established after receiving the 2018 First Place Founder's Innovation Award. The FlyONSPEED team is an all-volunteer group dedicated to reducing LOC mishaps and providing high quality training resources to the EA-B community. We are a non-profit 501(c)3, open-source organization. Our work is available on our websites at FlyOnspeed.org and GitHub.com/flyonspeed. We are happy to collaborate with any individual or organization. Our capability may be useful to university students or organizations dedicated to improving flight safety. Interested collaborators may download an Excel workbook that describes our data recording capability, flight test methodology and calibration results. A PowerPoint presentation is available for download as well. Anyone may use our software and hardware designs or download training resources at no cost. 100% of our operating budget goes to hardware acquisition and direct operating expenses (internet, LLC, banking, etc). All developmental and operational flight test is accomplished out-of-pocket by volunteers. Our mission is to reduce LOC mishaps, have fun, learn and educate. Our motto is "No rush, get the physics right" and our solution passes KISS muster.

Performance of a coefficient of pressure (C_P) AOA system is hardware, algorithm and calibration dependent. We learned during testing of our first-generation system (which used an AOA % lift signal from a commercial, off-the-shelf [COTS] EFIS), that not all AOA systems are created equally--some are just progressive stall warning systems. Accuracy is only as good as the initial calibration. We observed pilots had difficulty calibrating and understanding cues provided by AOA systems and were generally lacking in knowledge of energy management. The FAA tested ten COTS AOA systems and described their system performance and shortcomings.[1] These insights lead to development of our 2nd generation, stand-alone system. Design objectives were accuracy throughout the flight envelope and ease of use. We also developed web-based training resources to support effective use of our logic and hardware; and increase general knowledge regarding energy management and AOA principles.

[1] Deters, Jordan, et al. "Cumulative System Evaluation Report of 10 Commercial Off-the-Shelf Angle-of-Attack Sensors and Display Systems." FAA Technical Center, Federal Aviation Administration, Oct. 2018, www.tc.faa.gov/its/worldpac/techrpt/tc18-19.pdf.

We have completed low-rate initial production (LRIP) of 30 systems, and 10 additional systems have been assembled in the field by volunteers to develop builder's documentation and assess ease of assembly by amateurs. Our websites are designed for pilots, hardware, and software users to learn and work in a collaborative environment. We are currently coordinating with a manufacturer for hardware production and preparing for operational test and evaluation (OT&E) by volunteers. LRIP hardware and wiring harnesses are provided to OT&E volunteer pilots at no cost. We have installed systems at the Sling Pilot Academy in Torrance, California for objective and subjective evaluation in a flight training environment. We will be conducting two Oshkosh forums discussing the system: how it works, how to use it and energy management academics associated with flying performance-based AOA cues. We are currently conducting developmental test of automatic calibration and trying to mitigate sideslip effects on the angle of attack solution by designing a better sensor. We have developed an optional visual energy display and are evaluating the feasibility of adding a recovery display to assist with post-stall and spin recovery. We are also coordinating to have production units available for purchase.

Background. All FlyONSPEED concepts have been proven in extensive military use. The aural AOA warning logic was developed by the USAF and McDonnell Aircraft for use in the F-4 to provide approach and landing cues and was adapted to help mitigate loss-of-control mishaps during maneuvering flight. All US fighter aircraft have used AOA as the primary reference for approach and landing since the 1960's. The OWS logic was developed for the F-15. The F-15 also had an intuitive spin recovery visual display that we would like to emulate. We have adapted and modified the AOA logic for the aerodynamics of a light wing loaded, straight-wing, propeller-driven aircraft and conduct ongoing flight test in representative EA-B types. The physics and aerodynamics that form the underpinnings of our software logic are based on the work of Dr. David F. Rogers, et al[2]. Dr. Rogers has graciously functioned as the senior academic advisor for our team. The basic principles of our C_P AOA solution are summarized in short paper[3] by Dr. Rogers. Our team includes test pilots, flight test engineers, electrical and software engineers. Our team members are all pilots and experimenters. Some have formal military or NASA experience. Our primary developmental test and evaluation (DT&E) aircraft are an instrumented RV-4, RV-10 and Zlin Z-50. The RV-4 is a fully aerobatic, low power loaded; low drag aircraft equipped with plain flaps capable of generating moderate yaw angles. The RV-10 is a utility category airplane equipped with slotted flaps utilizing an offset hinge line. Flap configuration has a significant impact on angle of attack calculation. The two common EA-B designs allow us fully to test the system under representative operational conditions. The Zlin Z-50 is a purpose-built competition aerobatic monoplane. The Zlin is capable of generating high beta angles ($\pm 25^{\circ}$) and

[2] Rogers, David F., et al. "Low-Cost Accurate Angle of Attack System." FAA Techncal Center, Federal Aviation Administration, Jan. 2018, www.tc.faa.gov/its/worldpac/techrpt/tc18-7.pdf.

[3] Rogers, David F. "Some Comments on Angle of Attack Systems Calibration." 2018.

is used primarily for experimenting with beta effect on various AOA probe configurations in an operational environment.

Concept. **The logic simplifies EM when maneuvering and provides takeoff and landing cues *independent of airspeed*.** Airspeed is affected by gross weight, G load and density altitude; performance AOA cues are not. The tone tells the pilot how to "pull on the pole" and how to "step on the rudder" (if optional 3D audio is used). It accommodates high G-onset rates and turbulence. It also warns the pilot when approaching the structural and airspeed limits. When approaching a G limit, the IMU knows if the aircraft is rolling and applies appropriate limits. G limits may be programmed to facilitate upset or aerobatic training in any airplane. When AOA is stabilized (e.g., approach and landing), it can be used as a "control" indication to optimize performance and fine tune pitch inputs. The AOA tone provides performance trend feedback and compensates for changes in bank angle, G loading, density altitude or aircraft weight. Interpreting aural cues is not dependent on the pilot's head or eye position, minimizing instrument cross-check requirements, improving the pilot's ability to monitor outside maneuvering references and conduct traffic scan. The cues also benefit instructional flight, making it easier for the instructor to provide precise commentary or instructions as well as providing real-time pitch control feedback to the student. Essentially, the tone is like ALWAYS flying with an instructor who will tell you if you are pulling too hard or not enough during maneuvering flight or misapplying rudder if 3D audio is used.

ONSPEED equals V_{REF} at 1G. The ONSPEED cue is an AOA, not an airspeed. ONSPEED AOA is not affected by gross weight, bank angle (G) or density altitude—it is always the same. No "gust additive" is applied to ONSPEED. The ONSPEED reference provides precise feedback to assist with stabilizing airspeed and attitude during approach and landing. It simplifies glide path corrections and helps avoid excessive or insufficient energy in the transition to landing. The logic allows the pilot to easily distinguish between a "slightly fast," "slightly slow" or ONSPEED condition; and provides intuitive trend information. It helps the pilot achieve consistent landing parameters. An ONSPEED cue also provides an easily interpreted 0 P_S cue, and "slow" and "fast" cues also allow the pilot to easily determine if specific power is negative or positive for a given power setting. It assists with energy management in all phases of flight. During maneuvering flight, optimum turn performance (0 P_S) occurs ONSPEED. The slow tone immediately tells the pilot that energy is negative. During takeoff, best angle of climb occurs ONSPEED, and best rate of climb occurs at approximately L/D_{MAX}. Best range glide occurs at L/D_{MAX} and maximum endurance glide occurs ONSPEED. ONSPEED is an optimum maneuvering parameter if engine failure occurs at low altitude. Sideslip is controlled by "stepping on the tone" when 3D audio feature is used. The OWS provides a verbal "G Limit" warning. High airspeed warning is provided by a programmable chime.

Figure 1: Gen 2 Hardware: Box, Control Switch and Optional Energy Display

Hardware. Our 2nd generation system is a stand-alone 10-ounce 4.2 x 3.2 x 1.2-inch box that contains differential and static pressure sensors, an IMU, Wifi/Bluetooth, processing and data storage components. It is equipped with a 15 pin DSUB and 3 1/4" OD quick release pressure fittings. Hardware, wiring schematics and a parts list is available on our GitHub site. The pilot interface is a simple push/twist knob equipped with an LED. Volume is fully adjustable, and radio cut-out logic depends on intercom settings selected by the user. System configuration is controlled via WiFi interface that runs on any phone, tablet or laptop. The energy display may be displayed on a phone or tablet in lieu of using the optional display hardware.

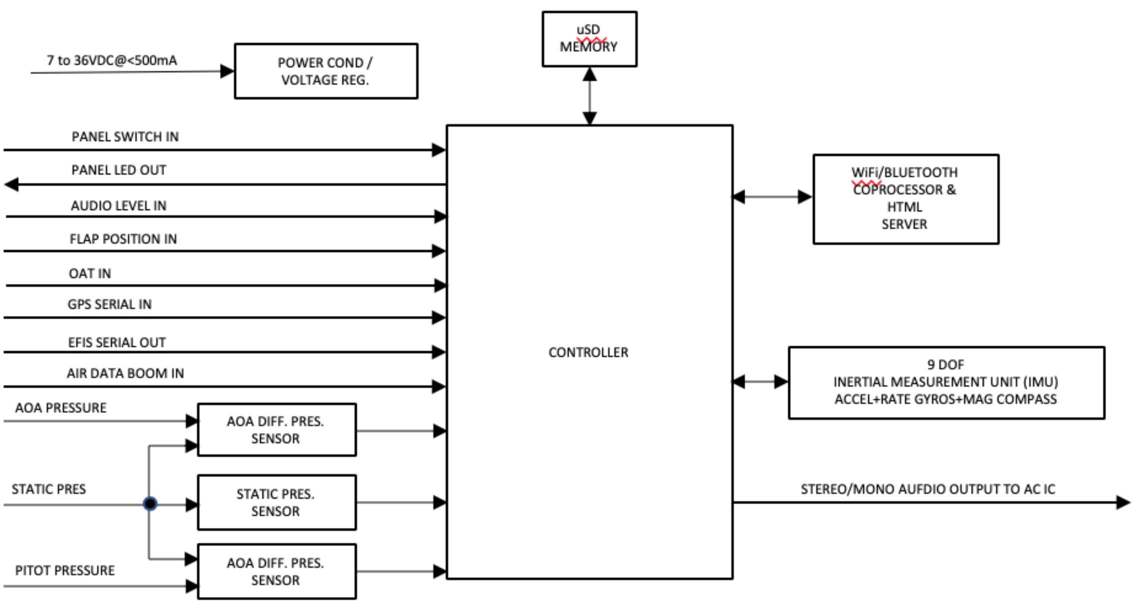


Figure 2: System Block Diagram

Software. The Gen 2 V3 system utilizes two software components: a WiFi module used for pilot interface and system software. The primary system processor is a Teensy 3.6 microcontroller equipped with a micro-SD card for data recording. The Teensy uses code written and compiled in Arduino format. There are some user selectable settings in the system software. Primary interface with the V3 is via the simple rotary switch. All calibration functions as well as data download are conducted via WiFi, but once the system is set-up, it is simply matter of adjusting volume. Current versions of our software may be downloaded from our GitHub site: WiFi Module and System Software.

System Production. **We are currently coordinating to have systems produced commercially for pilots that do not want to build one.** As a non-profit, our objective is to get hardware to the EA-B market at minimum cost; however, a precise system cost is not known at the time of this writing.

Video. Click on the links to view video demonstrations:

Narrated In-flight Demo (Gen 1 Audio) 1:31

Overshooting Final Turn (Gen 1 Audio) 0:31

250' AGL Simulated Engine Failure on Takeoff, return to runway for landing (Gen 1 Audio) 1:43

Windshear Encounter (Gen 2 Audio) 0:41

Green Eggs and Ham Syndrome. We thought the simplest approach to demonstrating the utility of these concepts would be to build a prototype and produce a video of using the system in action. What we learned is the first thing most folks focus on when they watch a video demonstration is the tone itself, which many perceive as distracting or annoying. "I am not enjoying the thought of a bunch of folks flying into Oshkosh with a constant tone in their ear, distracting them from hearing the tower telling them to go around…" is representative of some of the feedback we get. Another comment we have received is that unlike military flying, civilian aviation is simply too varied and unpredictable for this type of logic to be useful and is far more likely to be distracting. It is important to note that volume is fully selectable and easily controlled via a conventional knob; and radio cut-out features, half-volume during transmission/receiving, etc. may also be pilot selectable options, depending on type of ICS fitted. In actual use, the tone is quickly learned, readily internalized, and use becomes second nature. However, we understand that until folks have an opportunity to try it out, it's difficult to convey the utility it offers. We adapted this logic because it is simple, effective, inexpensive, and combat-proven. Our objective is to demonstrate the utility of the logic, provide easily manufactured (or homebuilt) hardware, software, educational resources, and accurate test results to the EA-B community.

AOA Tone Logic Description.

Figure 3 shows the aural tone logic in graphic form. The aural AOA logic improves upon conventional techniques by using distinct low and high frequencies, variable pulse rates and a steady tone that allows the pilot to easily ascertain energy state and hear key performance AOA cues. If 3D stereo audio is used, it allows the pilot to listen to sideslip by moving the tone left and right in the sound field to mimic the slip/skid ball. The simple, ergonomic logic allows the pilot to monitor AOA cues without reference to cockpit instrumentation. The aural logic is an extremely effective aid during takeoff, pattern, approach and landing, and maneuvering flight. It assists the pilot with avoiding or recovering from out-of-control conditions by providing an aural cue when approaching aerodynamic limits independent of airspeed, buffet or other handling cues (stick force lightening, wing rock, etc). Extensive baseline aircraft performance information can be derived from a properly calibrated system, which has the potential to greatly aid pilots flying EA-B types that may have limited flight test-derived performance information available for their airplane.

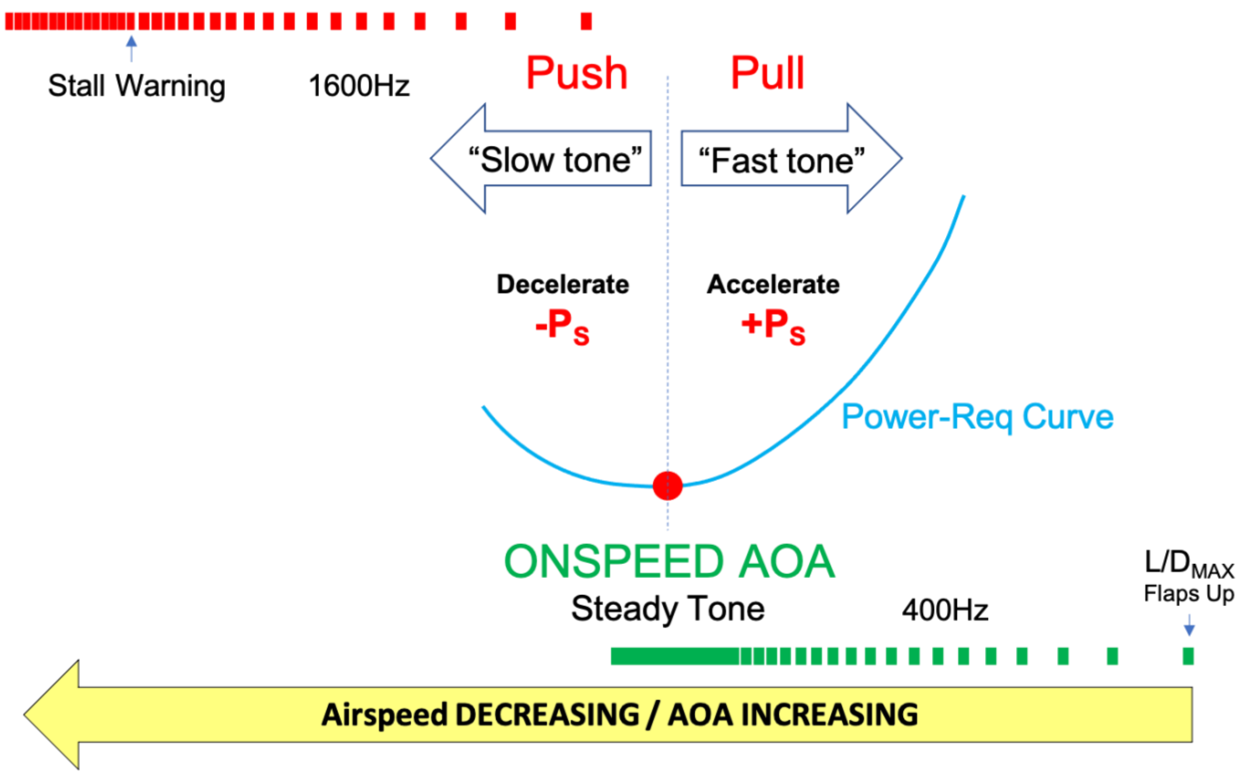


Figure 3. AOA Tone Depiction

Performance AOA cues are not affected by airplane gross weight, bank angle, load factor (G), airspeed, or density altitude. When maintaining optimum AOA, airspeed will vary if the aircraft maneuvers. ONSPEED is optimum AOA for approach to landing and provides optimum (maximum sustained) turn rate during maneuvering flight. ONSPEED AOA makes it easy to discern when the aircraft is in a 0 P_S condition, simplifying energy management. A "slow tone" equates to a negative energy state and a "fast tone" equates to a positive energy state, for a given throttle position. Ability to easily ascertain energy state is critical for maintaining aircraft control. When maneuvering at low altitude (e.g., landing), aircraft control requires more than avoiding a stall—it also requires maintaining an adequate energy state. This is readily accomplished by maintaining an ONSPEED condition. In cases where a negative energy state may be desired (e.g., short-field operations), the slow tone logic and progressive stall warning provide excellent cues allowing the pilot to maneuver on the "backside of the power curve" while maintaining full awareness of stall margin.

What the tone sounds like. As the airplane slows to L/D_{MAX}, a low (400Hz) beep begins at a slow pulse rate (1.5 pulses per second). As AOA is increased, the pulse rate of the tone increases to 6.5 pulses per second, until an ONSPEED (optimum AOA) condition is achieved, at which time the tone becomes steady. If the pilot continues to increase AOA above optimum, the frequency of the tone changes to a high pitch (1600Hz) and begins to beep again at 1.5 pulses per second. The pulse rate of the high frequency "slow" tone increases to 6.5 pulses per second until 5 MPH/KTS above stall, at which time stall warning is heard: high frequency beeps at 20 pulses per second. The stall warning tone is designed to be difficult to ignore. The software logic increases the volume of the high frequency "slow" tone as AOA increases. Volume adjustment is by means of a simple rotary knob. A single push of the knob enables or disables the system, as desired. An internal LED in the switch provides feedback to the pilot that the system is functioning properly.

How the tone logic works. When AOA is stabilized, it can be used as a "control" indication. The logic allows the pilot to fine-tune pitch inputs to optimize performance. It also provides performance trend information and progressive stall warning. The pilot is easily able to discern when the airplane achieves an L/D_{MAX} condition, optimum AOA (ONSPEED), and "fast" or "slow" relative to optimum AOA. The variable beep rate allows the pilot to fine tune "slightly fast" and "slightly slow" immediately adjacent to ONSPEED, as desired. The logic also allows the pilot to discern when approaching a stall, regardless of other aerodynamic cues (or lack, thereof). When 3D audio is used, the tone moves left or right in the stereo sound field with the slip and skid ball. The pilot "steps on the tone" to center it up. For most pilots, the primary utility of the aural warning logic will be found during approach and landing operations. Figure 4 incorporates the simple "push/pull" training model we've developed for explaining how to fly the tone in the pattern. This "pitch to control AOA, power to control glide slope" method is based on well proven USN approach and landing technique.

How the tone logic helps the pilot. The tone logic simplifies energy management tasks. Proper energy management is the key to maintaining aircraft control and optimizing performance. An airplane can stall at any airspeed and any attitude, but it only stalls at one, critical, angle of attack. If angle of attack can be precisely determined and controlled without having to look inside of the cockpit, loss of control risk is mitigated, and performance optimized simultaneously. The aural logic compensates for changes in bank angle/G loading, gross weight and density altitude. Aural cues for L/D_{MAX} and ONSPEED conditions are especially helpful. ONSPEED is applied during approach operations as optimum V_{REF}, and during maneuvering flight offers optimum turn performance. Any slow tone indicates a negative energy state and tells the pilot that corrective action is required. In conditions where maximum aerodynamic performance is desired (e.g., emergency dive recovery at low altitude where terrain is a factor), the aural logic allows the pilot to discern when approaching the aerodynamic (stall) limit. This can be especially beneficial in aircraft with limited aerodynamic stall warning and when operating any airplane with reduced static margin.

Ergonomics. The brain processes audio inputs faster than visual inputs (13ms vs 50ms), and sound is more effective than vision when the brain computes timing inputs. Aural AOA cues tighten the pitch control feedback loop. In a multi-modal sensory environment, auditory input reduces human reaction time. The tone logic conforms to human factors science, is not startling and conveys the appropriate level of urgency through acoustic features. Flying is based primarily on visual stimuli; the auditory sense is underutilized and readily available. Perhaps the greatest benefit of the aural AOA logic (other than simplifying energy management tasks) is that it is not necessary for the pilot to look inside the cockpit. The military has successfully integrated auditory caution and warning systems for numerous maneuvering and tactical applications, including flight envelope protection and performance cues. This approach has been highly effective in a demanding tactical environment increasing pilot situational awareness (SA) and assisting with energy management. The tone logic is simple to interpret and is readily "internalized" with minimal experience.

Stall Warning. A properly calibrated AOA system of any type provides outstanding stall warning. The aural AOA logic for stall warning is straight forward. As airspeed decreases below ONSPEED a frequency change occurs (400 Hz to 1600 Hz), pulse rate changes and volume increases. Stall warning is provided in the form of a high-frequency, high pulse-rate tone designed to mimic the sound of a stick or pedal shaker. Stall warning is a calibration parameter, and at 1G, it is recommended to set the warning 5 M/KIAS above stall. This $\approx 1.1V_S$ AOA will scale appropriately under G (accelerated stall conditions).

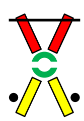
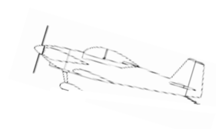
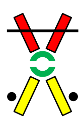
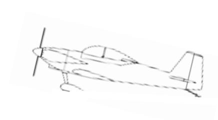
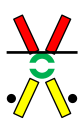
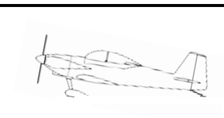
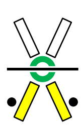
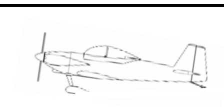
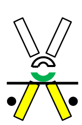
System Lag, Noise Damping and Sideslip Effects. Flight test has demonstrated that system lag is negligible at G-onset rates $\leq$ 2G's/second and excellent up to 4 G's/second. This minimal lag at normal G onset rates allows the system to function as a primary reference during approach and landing operations after the pilot has validated basic system performance ("heartbeat" LED indications and proper airspeed cross-check at 1G). This equates to good transient response during maneuvering flight or turbulent/gusty conditions. Instrumented flight test has shown that beta (sideslip) angle effects the accuracy of the AOA solution. Based on wind tunnel test, we expect sufficient "blanking" to occur at approximately 6^{o} beta for the typical COTS differential sensor. This has been verified by flight test. We are currently experimenting with different sensor configurations and derived AOA to mitigate side slip limitations. IMU derived AOA has proven to be accurate under normal (non-aerobatic) flight conditions. AOA is an inherently noisy signal. Damping is achieved by means of software filtering and the natural filtering provided by digital to analog conversion of the signal. Smoothing is pilot-adjustable and excellent subjective balance has been achieved between noise and transient response, making for a very pilot friendly, usable cue.

Normal Tone Operation and Adjustment. The pilot controls the system via the ON/OFF/volume rotary switch. A single, short push of the switch turns the system on and off. A voice "ONSPEED ENABLED" call-out and LED indicates the system is on. A single short push with "ONSPEED DISABLED" call-out and LED off indicates the system is disabled. During normal system operation, a long push and hold results in a "DATA MARK" call-out and inserts a data mark counter into the data to assist with post flight analysis if data recording capability is utilized. A "breathing" LED indicates normal operation. A solid LED indicates a system malfunction. A soft system reboot may be accomplished via WiFi interface. A hard system reboot is accomplished by cycling system power. The system may be turned on, off or reset at any time (i.e., on the ground or in flight, as desired). If angle of attack is high enough during flight and the system is turned on, tone will be heard. 3D stereo sideslip cuing is automatic if the airplane is equipped with a stereo ICS and 3D audio is enabled. The rotary switch also functions as a volume control.

Flying an ONSPEED Approach and Landing

Figure 4 shows how the AOA logic works in the landing environment. ONSPEED provides V_{REF} for pattern and landing operations. Percent stall values in the table are representative and may vary slightly from aircraft to aircraft. The optional visual display includes a trend indicator (horizontal line that moves up or down over the chevron), and the segments light up as depicted in Figure 5. This is an adaptation of a standard military display. When the trend indicator is aligned with the dots on the display (referred to as the "barbell"), the airplane is at a flaps up, L/D_{MAX} condition. When the trend indicator is in the center of the green doughnut and both doughnut segments are lit, the airplane is ONSPEED. To fly an ONSPEED visual approach from a typical pattern, the pilot slows to ONSPEED. Power is reduced, pitch and trim are adjusted to maintain ONSPEED. The pilot initially verifies proper AOA indication by cross-checking 1G indicated airspeed (V_{REF}).

Power is used to control glide path, and bank angle is adjusted to maintain desired ground track. The change in tone between ONSPEED, “slow” or “fast” is easy to discern. Power changes are easily compensated without phugoid excitation. A change in tone frequency to 1600 Hz and slow beeps indicate a “slightly slow” condition, in which case the pilot eases pitch slightly to re-establish a steady tone. Conversely, if the steady tone changes to a high pulse rate but doesn’t change frequency, a “slightly fast” condition exists, and the pilot increases pitch slightly to re-establish a steady tone. If bank angle changes, the tone pattern will compensate for additional G and provide immediate feedback to the pilot. If utilized, 3D audio assists the pilot with proper rudder coordination by moving the tone left or right in the stereo sound field, mimicking the slip/skid ball (the pilot “steps on the tone” when offset to properly coordinate rudder inputs). For a normal landing, the steady tone is maintained until the round-out prior to landing, where the pilot transitions to the slow tone.

Energy Display AOA Cue	AOA Expressed as % V_S	Aural Cue (Airspeed)	Attitude
	<1.10 V_S	Stall Warning	
	1.11-1.25 V_S	Slow	
	1.25-1.29 V_S	Slightly Slow	
	1.3-1.35 V_S	ONSPEED	
	1.36-1.4 V_S	Slightly Fast	

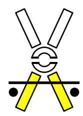
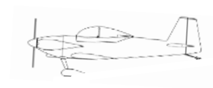
	>1.4 V_S	Fast	

Figure 4. AOA Logic in the Landing Environment

The basic pitch/power/tone relationships apply regardless of pattern technique and work identically on the final segment of an instrument approach. Under some conditions (gusty crosswinds, wake turbulence potential, etc.), it may be appropriate to maintain a "slightly fast" condition until approaching the runway threshold, when transition to ONSPEED is appropriate. If landing distance is critical and conditions allow, a stable, "slightly slow" transition to landing with power may be appropriate. The aural AOA logic simplifies visual and instrument pattern and landing operations while improving consistency: it greatly assists with achieving stable final approach parameters and arriving over the touchdown zone with proper energy for landing.

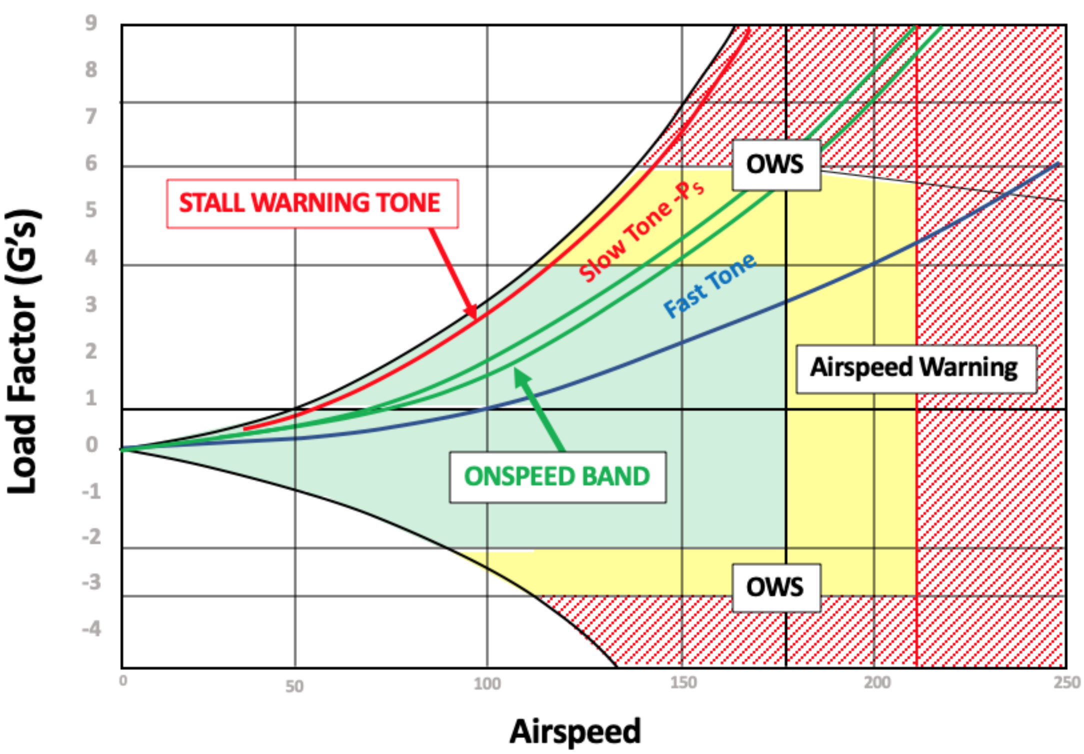


Figure 5. Aural Cues Overlaid on VN Diagram

AOA-Based Performance Cues

One important benefit of the aural AOA logic is its ability to convey key performance information to the pilot when properly calibrated. This is helpful for EA-B types where complete flight testing may not have been conducted and/or limited performance information exists. AOA-derived maximum angle or rate of climb, maximum range, or maximum endurance glide can be readily established and referenced by flying different tones. Also consider that limited or no pitot/static calibration testing may have been conducted in an EA-B aircraft, and accurate *calibrated* airspeed information or static source pressure error data may not be available. **Because the tone logic utilizes AOA, it operates independently of airspeed.**

Maneuvering Flight Application

The aural AOA logic also assists the pilot during maneuvering flight as ONSPEED AOA logic is independent of other factors and provides warning when aerodynamic limits are being approached. Figure 5 illustrates the positive G ONSPEED band overlaid on a representative VN diagram for a typical aerobatic EA-B type. **The slow tone indicates a negative energy condition.** In addition to AOA cues, overload warning is also provided for symmetric and asymmetric maneuvering. The green portion of the envelope is within asymmetric structural limits. When the appropriate G limit is reached (rolling/not rolling), a “G Limit” verbal warning is provided. High airspeed warning is provided in the form of a pilot programmable chime. Airspeed warning is based on IAS and it is recommended that it be set to maximum structural cruising speed.

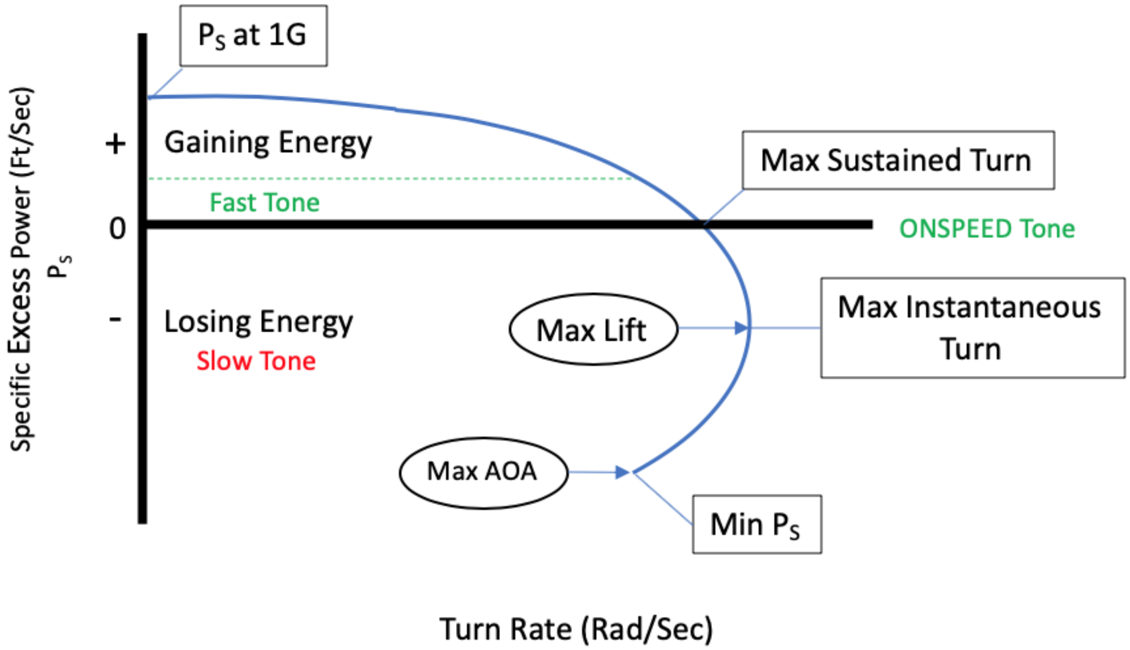


Figure 6. Specific Excess Power vs Turn Rate

Although maximum, instantaneous turn performance is obtained just prior to the aerodynamic limit, energy is negative and bleed rate is high. The ONSPEED range provides a suitable margin for handling error or sensor lag at high G onset rates, less energy bleed, best *sustained* (optimum) turn performance. This is shown in Figure 6. This greatly assists the pilot with energy management using one easily perceived cue. This cue can be particularly helpful for aircraft with reduced static margin or limited aerodynamic buffet cues by assisting the pilot with modulating and fine-tuning pitch inputs when approaching aerodynamic limits and trying to optimize performance. A good example of this benefit can be envisioned by imagining the back side of a loop or a Split-S begun at suitable airspeed. In this case, an optimum performance cue (ONSPEED tone) allows the pilot to apply sufficient back stick to help control airspeed by applying sufficient G (and hence aerodynamic drag) without overdoing it and inadvertently exceeding the aerodynamic limit by pulling too hard—in other words, **it gives the pilot a "just right" target for pitch control when operating near aerodynamic limits.** This can be particularly helpful for low-drag airplanes that accelerate rapidly when the velocity vector (flight path) is below the horizon.

The tone also assists the pilot during low positive G (zero to 1 G) maneuvering, providing warning at low indicated airspeeds or reduced cockpit G. This assists the pilot with proper "unload for control" handling techniques and works in any attitude. A secondary stall is another scenario where the aural logic can be beneficial in assisting the pilot with a maximum performance recovery from the initial stall by providing sufficient warning to assist with avoiding with over-control during recovery.

Overload (G) Warning

The pilot programs positive and negative G limits via WiFi interface. Asymmetric G limit is presumed to be 33% less than the symmetric limit. Asymmetric maneuvering is determined by roll rate. A maneuver is presumed to be asymmetric when roll rate as measured by the IMU is equal or greater than 20% of maximum roll rate. For example, the maximum roll rate of the RV-4 test bed (as defined by rapid, full aileron deflection at V_C and 1G sufficient to produce an aileron stall) results in a roll rate of 151°/second. 20% of 151 is 30°/sec. Roll rate to define an asymmetric condition is pilot selectable. An artificially low symmetric limit of +2.5 G's (+1.65 asymmetric) at 10-15°/sec is recommended for upset training in normal category airplanes, and a +4.5 G limit at 15°/sec is recommended for aerobatic training in the typical light aircraft approved for aerobatic flight. This allows familiarization with OWS operation and effect of "rolling G" on limits while operating well inside the envelope. OWS may be disabled if not desired.

Airspeed Warning

A simple chime is provided at a pilot selectable IAS. We recommend V_{NO} as an appropriate speed for most EA-B types powered by piston engines since this is a structural limit. The rate at which the chime repeats is a pilot selectable. In an aerobatic airplane, the cue provides energy information for maneuvering flight, and it is desirable to have the chime repeat at relatively short intervals (e.g, once every two or three seconds) so the pilot knows the airplane is at the top of the green arc without looking in the cockpit. However, for a non-aerobatic type, one a longer chime interval may be appropriate to remind the pilot that the aircraft is in the yellow arc. For EA-B types with a wide speed band that can exceed the dynamic speed limit (V_{NE}) at high altitude cruise and during descent operations, the V_{NO} warning is particularly useful. Airspeed warning may be disabled if not desired.

Instructional Use

The audio logic is very helpful in a flight training environment. It provides precise AOA cues (and sideslip feedback if 3D audio is used) for briefing, descriptive commentary and real-time directive cues as the student builds a sight and feel picture. For example, a maximum performance takeoff that was described as "accelerate to X knots, smoothly rotate to 12-15 degrees of pitch at a rate of 2 degrees per second, capture and maintain Y knots until obstacles are cleared, then reduce pitch to 8-10 degrees and accelerate to Z knots" with "X, Y and Z knots" adjusted appropriate to gross weight and altitude, is simplified to "smoothly rotate ONSPEED and maintain ONSPEED until obstacles are cleared and then reduce pitch to accelerate to L/D_{MAX}." As another example, when instructing a loop, in lieu of describing multiple airspeeds, G loads, and attitude/airspeed check points, as well as discussing the finer points of low-speed pitch control when inverted and proper application of G on the back side of the maneuver, etc., the brief is reduced to "establish XXX IAS, smoothly apply 3 G's, catch ONSPEED and adjust pressure on the stick to maintain it until completing the loop." Using reduced OWS limits during upset, aerobatic and aircraft handling training allows the instructor to achieve a simulated limit at a suitably low energy condition to allow the student to maneuver well within maximum structural and airspeed limits of any airplane. In general, the logic allows the instructor to spend more time describing sight and feel pictures and less time providing precise attitude/airspeed/G targets that tend to absorb considerable student "RAM." It also allows use of the USN technique for approach and landing: "pitch to control tone (AOA), power to control glidepath."

Calculating Angle of Attack Using Coefficient of Pressure

Measuring Angle of Attack. Angle of attack (α) is the angular difference between a reference line and the relative wind. Typically, when pilots refer to AOA, they refer to the difference between the relative wind and the chord line of the wing. This is referred to as geometric AOA or α_G. The AOA at which the airfoil produces zero lift (which is negative for a cambered airfoil) is referred to as the zero lift AOA (or zero-lift line), labeled α_{ZLL}. Absolute (or total) AOA, simply abbreviated α, is the angular difference between the relative wind and α_{ZLL}. These basic relationships are shown in Figure 7. We initially calibrated the system to compute absolute angle of attack, however this approach requires flight test techniques and data reduction deemed beyond the capability of the typical recreational pilot. To facilitate ease of calibration, we define angle of attack as the difference between the relative wind and the fuselage reference line (α_{FRL}). This technique provides excellent performance throughout the entire speed band of the aircraft and allows use of the on-board IMU to facilitate calibration.

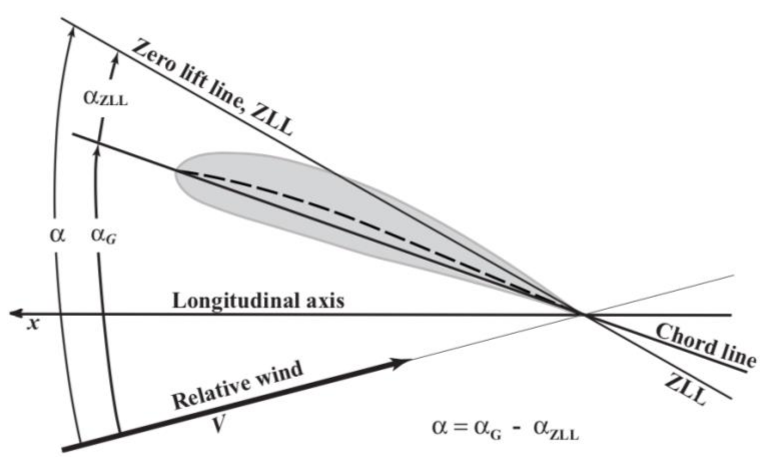


Figure 7. Angle of Attack.[4]

Fundamental Angle of Attack. The fundamental angle of attack is L/D_{MAX}.[5] It is *designed* into the aircraft. L/D_{MAX} provides best glide and best range AOA in propeller driven airplanes. The angle of attack for L/D_{MAX} can be calculated: $\alpha \frac{L}{D} max = \frac{1}{a}\frac{b}{S}\sqrt{\pi f e}$ where a is the aircraft linear lift curve slope, b is wing span, S is wing area, f is equivalent parasite drag and e is Oswald's efficiency factor. Each of these variables is an aircraft design factor. *None of these parameters are weight, load factor (G), or density altitude*, thus α L/D_{max} functions i*ndependently* of these factors. From L/D_{MAX}, two other key performance parameters can be derived: α_{PRmin} and α_{CC}. α_{PRmin} is the AOA for minimum power required (the bottom of the power-required curve) and corresponds to maximum endurance, minimum sink rate, maximum thrust and forms the basis for determining $\alpha_{ONSPEED}$. $\alpha PRmin = \sqrt{3}\alpha \frac{L}{D} \max = 1.73\ \alpha \frac{L}{D} max$. α_{CC} is the AOA for Carson cruise. $\alpha cc = \frac{1}{\sqrt{3}} \alpha \frac{L}{D} \max = 0.58 \alpha \frac{L}{D} max$.[6]

Calculating ONSPEED. For approach and landing, ONSPEED is a kinetic parameter and occurs at a velocity equal to approximately 130% of stalling speed in the landing configuration. For most aircraft, a $\pm$ 1° $\alpha_{ONSPEED}$ band will correlate with 1.25-1.35 V_{S1}. In terms of energy for a piston-powered, propeller driven aircraft, ONSPEED occurs at minimum power required (i.e., maximum thrust available). Minimum power required/maximum thrust available correlates with a 0 P_S condition where $Ps = V(\frac{T-D}{W})$ where V equals velocity, t equals thrust, d equals drag, and w is weight. This normalizes units of motive force to gross weight and includes aerodynamic and friction effects. When thrust and drag are in equilibrium for a given power setting, P_S is zero. ONSPEED cues (fast/slow transition) are validated by flight test in each flap configuration (when appropriate). **Flight test has shown that an ONSPEED band ± 1° α (± 4-5 M/KIAS) to be an optimal compromise between capturing minimum power required and optimizing kinetic energy for approach and landing.**

Aircraft Curve. The most fundamental aspect of accurately computing angle of attack from differential pressure is properly capturing the aircraft curve. Different techniques for doing this are depicted in Figure 8. The simplest is to measure differential pressure (P_1-P_2) at a nominal cruise speed and 1.1V_S and connect the two points. This is the ΔP 2-Point Calibration line. This results in an AOA computation that is accurate at the two calibration points but has error at other points (the grey area under the line). This logic results in accurate stall warning but induces significant error at other AOAs and does not capture the entire curve to V_{MAX}. A more accurate

[4] Rogers, David F., "Absolute Angle of Attack," 2013, p.2. Nar-associates.com.
[5] Rogers, David F., "Fundamental Angle of Attack," 2013. Nar-associates.com.
[6] Rogers, David F., "Some Comments on Angle of Attack Systems Calibration," p.1, 2018. Nar-associates.com.

technique is to capture ΔP at multiple points from V_{MAX} to V_{MIN}. If we fit a curve to those differential pressure points, we get the Multi-Point Calibration Line. This is the most accurate way to capture the aircraft curve with minimum error.

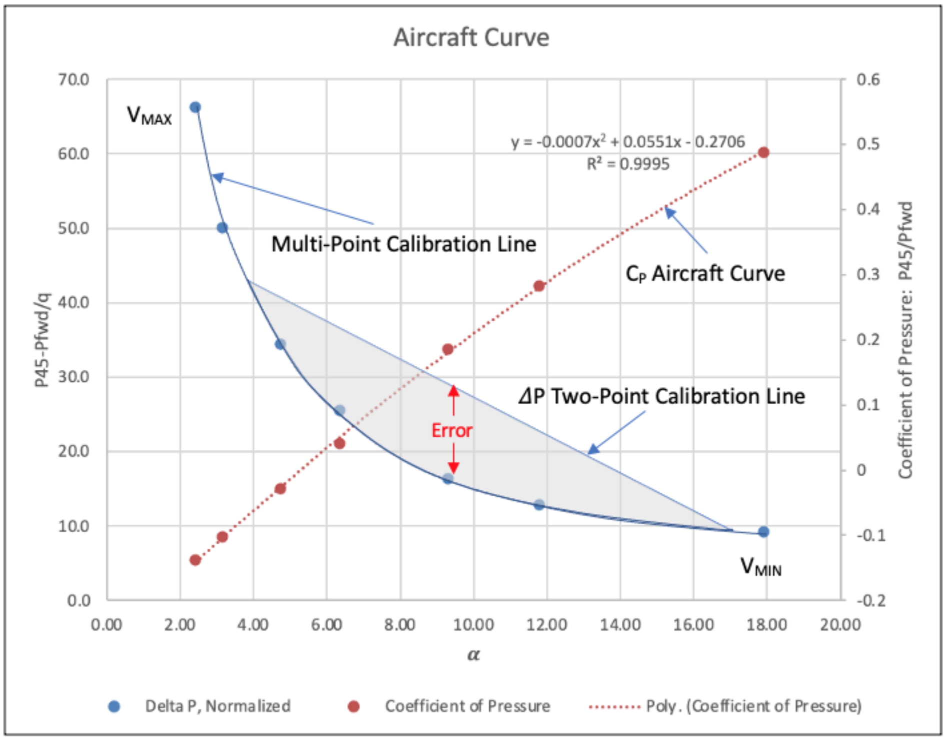


Figure 8. Aircraft Curve

A typical technique for deriving AOA from differential pressure is to utilize static pressure (ΔP/q) for normalization, however *current FAA guidance precludes access to the pitot static system in certified aircraft.* Although this guidance does not apply to EA-B types, we chose to pursue a solution that will work in any aircraft. The optimal physics-based solution is to use P_{FWD}/P_{45}, however in some cases, COTS sensors may produce a zero value for P_{45} as pressure transitions from negative to positive, resulting in a subsequent divide by zero error. To mitigate this, we use P_{45}/P_{FWD} since P_{FWD} does not go to zero during normal flight. Use of this technique allows a linear or polynomial regression to accurately capture the aircraft curve with either a series of set points or a simple deceleration maneuver. The C_P solution is calculated with 8-digit precision utilizing a floating decimal point to provide an accurate, high-speed solution. The CPU can handle up to 16-digit precision, but based on analysis, we haven't found it necessary to utilize that capability. The C_P aircraft curve is derived from flight test data using conventional trim shot techniques and programmed via WiFi interface. The WiFi interface accommodates 2nd, 3rd and 4th order polynomial, logarithmic or linear curves and as many flap settings as desired (for aircraft equipped with a flap position sensor). Using this technique results in accurately computing AOA to within a ¼ to ½° (or better) throughout the normal flight envelope and capturing post stall AOA up to approximately 50° with sufficient accuracy to drive a planned (future) recovery display.

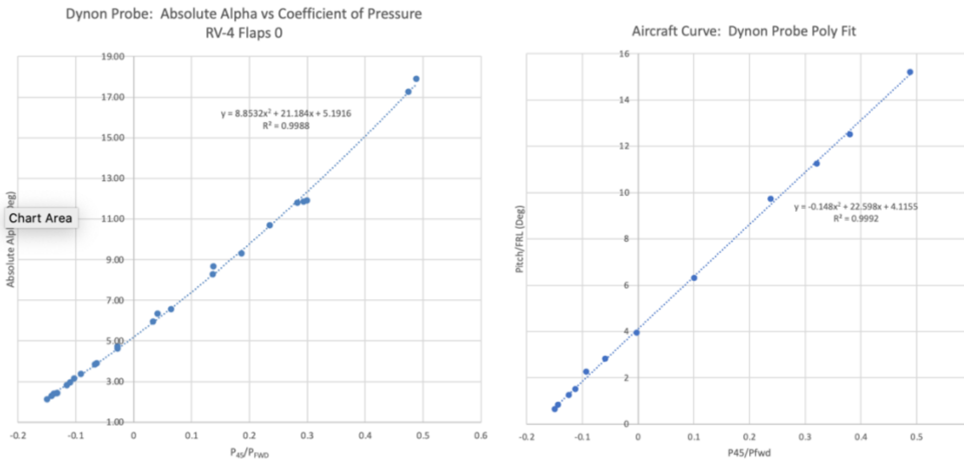


Figure 9. Physics Based and Pitch Based Curves

Physics-Based and Pitch-Based Calibration. Figure 9 depicts two techniques tested to measure AOA. Both utilize data from conventional trim shots at multiple parameters for each flap configuration. The first technique requires post-flight analysis to determine C_D and C_L from unaccelerated, stable parameters obtained during conventional trim shots and results in an accurate physics-based computation of α.[7] The second technique utilizes pitch ($\theta = \alpha$) during unaccelerated, stable flight during trim shots to derive α_{GEO}.[8] Either technique accurately captures α to within a ¼ to ½°.

IMU Derived Angle of Attack Calibration. Although the Rogers and Gracy calibration techniques shown in Figure 9 provide good performance, they demand a relatively high level of pilot skill and require post-flight data reduction. They also impart some minor error as it is impossible to achieve an exact zero VVI over the duration of a trim shot. **With the on-board IMU, it is practical to compute derived angle of attack and allow the software to compute the aircraft curve.** Two types of automated solutions are currently in developmental flight test: dynamic and static. During a dynamic calibration, the pilot simply puts the system in calibration mode and decelerates from V_{MAX} to stall while maintaining altitude plus or minus a few hundred feet. An alternate "static" calibration is achieved by the pilot flying desired performance points. Either technique is deemed reasonable for the average private pilot. Testing is ongoing to determine if one method is preferable over the other and operational test and evaluation by users will be

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[7] Rogers et. al., "Low-Cost Accurate Angle of Attack System" DOT/FAA/TC/18-7, 2018

[8] Gracey, W., "Summary of Methods of Measuring Angle of Attack on Aircraft," National Advisory Committee on Aeronautics (NACA), Langley Field VA 1958.

required to validate efficacy in the real world. Derived angle of attack is the difference between the pitch and flight path of the airplane as shown in figure 10. We are using IMU pitch adjusted to the fuselage reference line to derive AOA. In this case, $\alpha FRL = \theta - \arcsin\left(\frac{\left[\frac{dh}{dt}\right]}{V}\right)$ where αFRL = angle between relative wind and fuselage reference line, θ = pitch, dh/dt = vertical velocity and V = TAS.[9] This technique has been validated using a high-precision VectorNav VN-300 GNSS/INS system equipping our RV-4 testbed. Results of IMU-based calibrations are shown in Figure 11.

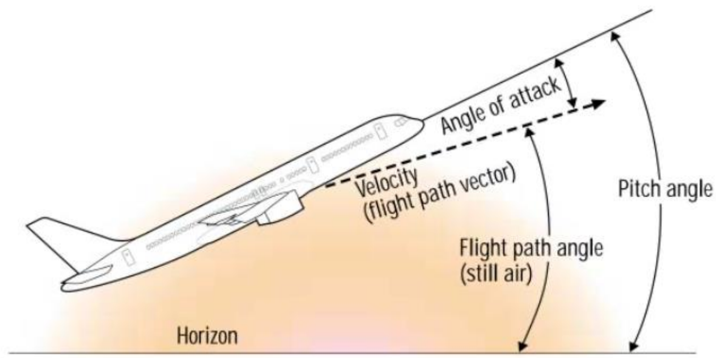
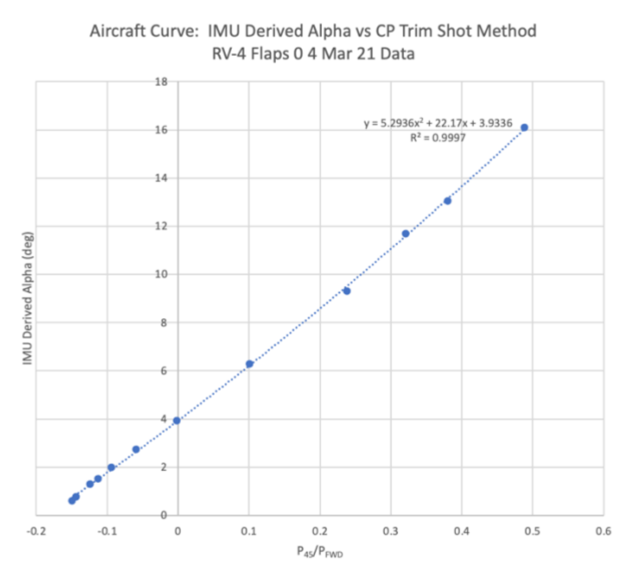
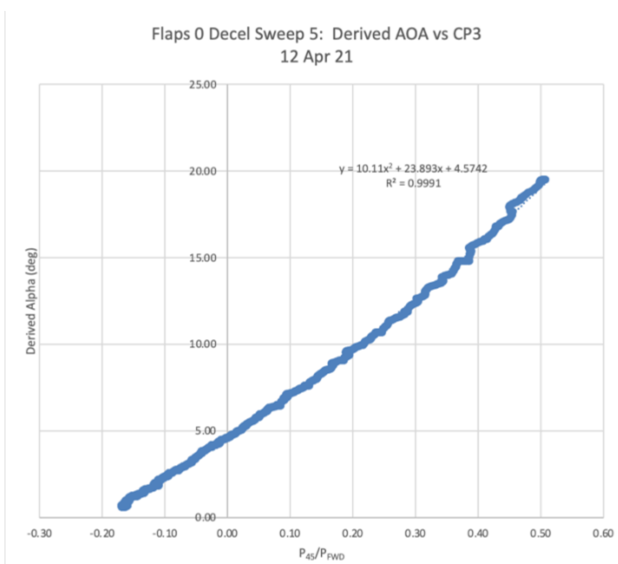


Figure 10. IMU Derived AOA





[9] Ly, Jack Kevin, "Angle of Attack Determination Using Inertial Navigation System Data From Flight Tests." Master's Thesis, University of Tennessee, 2017. https://trace.tennessee.edu/utk_gradthes/4757

Figure 11. IMU Derived Curves

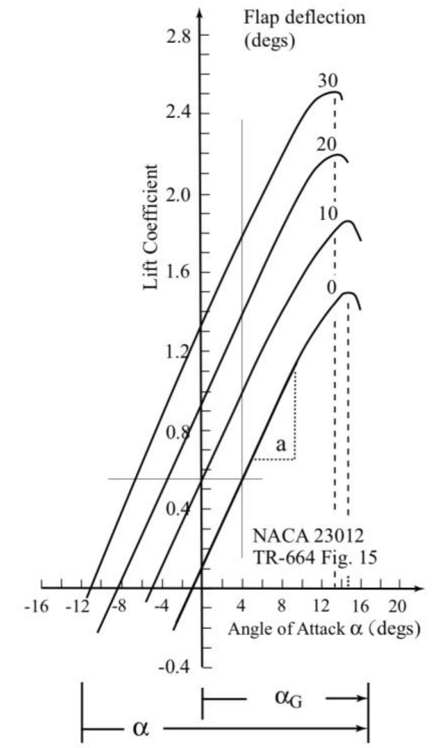


Figure 12. Effect of Flaps on AOA[10]

Effect of Flaps on AOA.

The effect of flaps on AOA is shown in Figure 12 for slotted flaps. The curves are derived from wind tunnel testing of a 23012 section and detailed in NACA TR-664.[11] The important thing to note in Figure 12 is the effect flaps have on α and α_G. We have learned through flight test and analysis that the *type* of flap fitted has a significant impact on aircraft calibration curves. Plain flaps have minimal impact, however slotted flaps have a significant impact. **It is practical to utilize a single curve calibration for aircraft equipped with plain flaps, but not an aircraft equipped with slotted flaps. A flap position sensor and multiple curves (one for each normal flap setting) are *required* for aircraft equipped with slotted flaps and *desired* for aircraft equipped with plain flaps to properly calculate AOA.** Another important effect of flaps is on the L/D_{MAX} and hence, ONSPEED alpha: as flaps are deployed, α L/D_{MAX} and α ONSPEED begin to marry up. Also, if C_D is plotted against flap position, there is a flap setting that provides lift benefit (generally 25-50% of available flaps) with minimal drag in the event

[10] Rogers, "Absolute Angle of Attack," 2013, p.2

[11] Wenzinger, Carl J, et al., "Wind-Tunnel Investigation of an NACA 23012 Airfoil with Various Arrangements of Slotted Flaps," NACA TR-664, 1939.

engine-out maneuvering is conducted close to the ground (e.g., engine failure after takeoff). This "ONSPEED, lift flap" combination provides optimum maneuvering capability engine-out when maneuvering close to the ground.

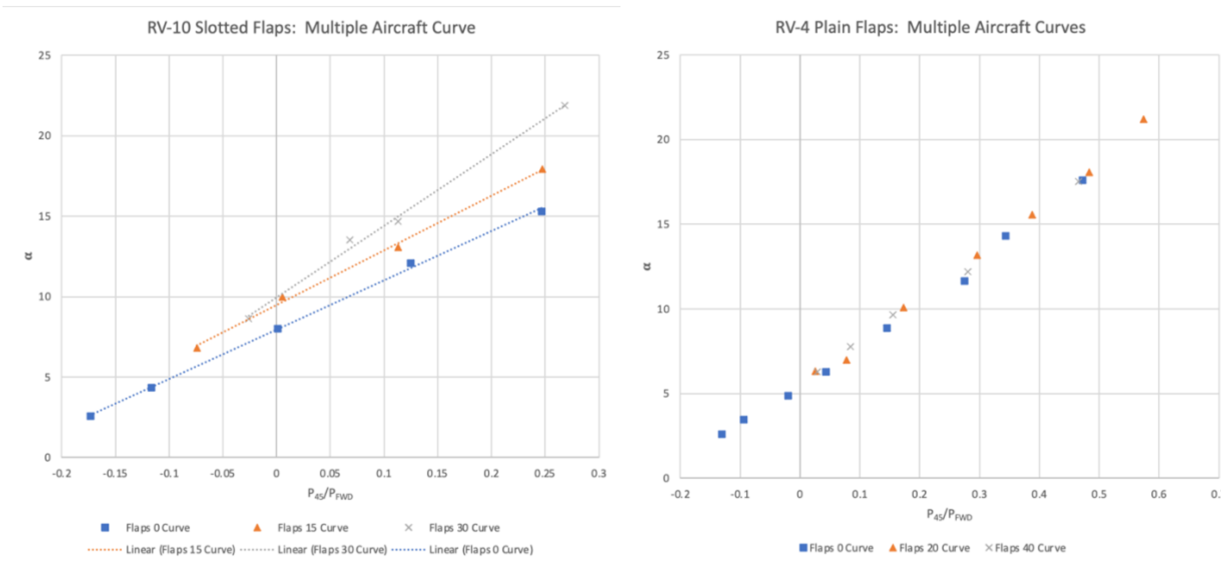


Figure 13. Type of Flap, Effect on Aircraft Curves

Effect of Flaps on Aircraft Curve. Figure 13 shows the results of plotting calculated α against C_P for two different aircraft: one with and one without slotted flaps. Note that the airplane with slotted flaps (RV-10) has three distinct curves, while the airplane with plain flaps (RV-4) has essentially one curve for all flap settings. If the airplane is equipped with plain or split flaps, it's practical to utilize a single calibration curve. Although the accuracy of the AOA calculation is decreased slightly using this technique, it negates the requirement for a flap position sensor, simplifying installation and calibration. If, however, the airplane is equipped with slotted flaps, it's not practical to use a single curve without significant degradation in performance, and a flap position sensor is warranted. If a flap position sensor not fitted, then it is recommended that the airplane be calibrated in a normal landing configuration and degradation at other flap settings be accepted.

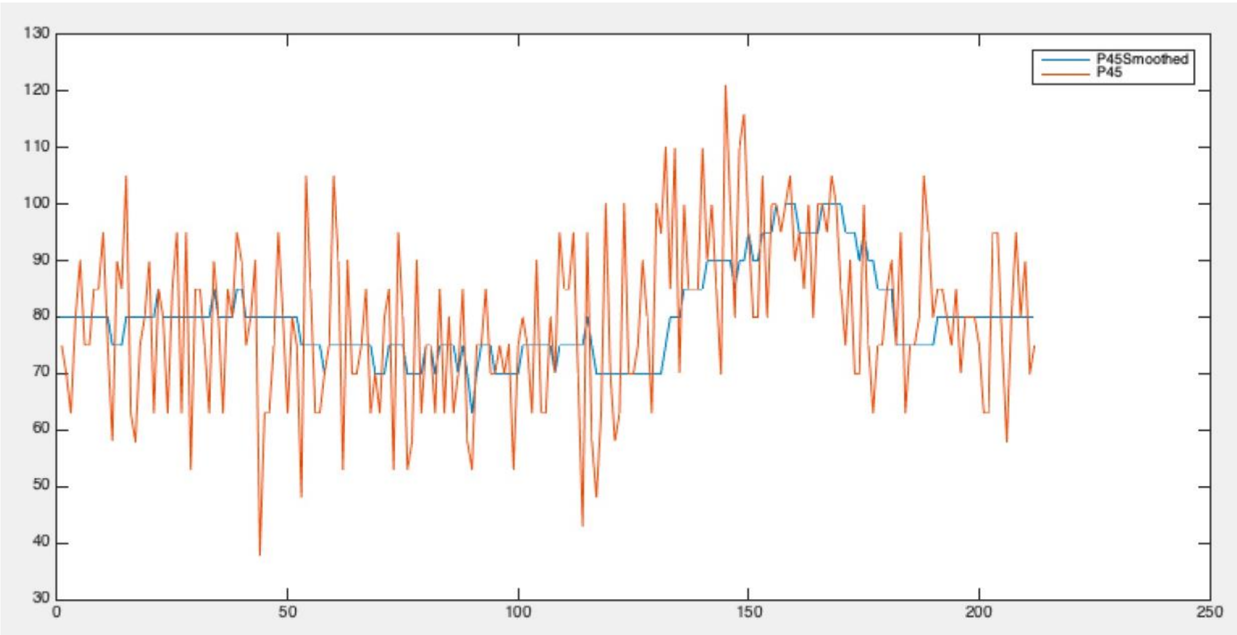


Figure 14. Signal Smoothing: P45 raw vs P45 smoothed

Signal Noise and Smoothing. To be usable, the AOA signal must be sufficiently smooth and timely (minimum lag). By nature, the raw AOA signal is noisy. This is shown in Figure 14. An unprocessed signal bounces around continuously. By sufficiently smoothing the signal in a timely manner, it can be used to fly precise performance α references. The logic uses a two-step process to achieve this. The first step is to smooth the raw pressure signal using "moving median" logic. Due to the large spikes in the raw pressure signal, a median solution is preferred over a moving average. Look-back for this calculation is pilot selectable via WiFi interface and is typically set to the previous 15 values. Exact setting depends on the length of tubing used to connect the sensor to the pressure transducers. This initial smoothing acts as an effective low-lag time spike filter. Current software then applies Gaussian smoothing logic to the computed AOA value. Look-back for this calculation is also pilot selectable. The value set will be a compromise between signal lag time and smoothing, i.e., a higher number will result in more lag, but a smoother signal. By minimizing lag (measured in G/second onset rate), we can accommodate pilot control inputs and turbulent conditions. 1G = 32 ft/sec. For typical airplanes, a maximum control input of 2G/second is desired to allow for inertial response and to avoid excessive energy bleed. Additionally, most light aircraft are designed to withstand a structural gust load of 50 FPS. Thus, minimum performance must accommodate at least 2G's per second. Median filtering is depicted by the blue line in Figure 14.

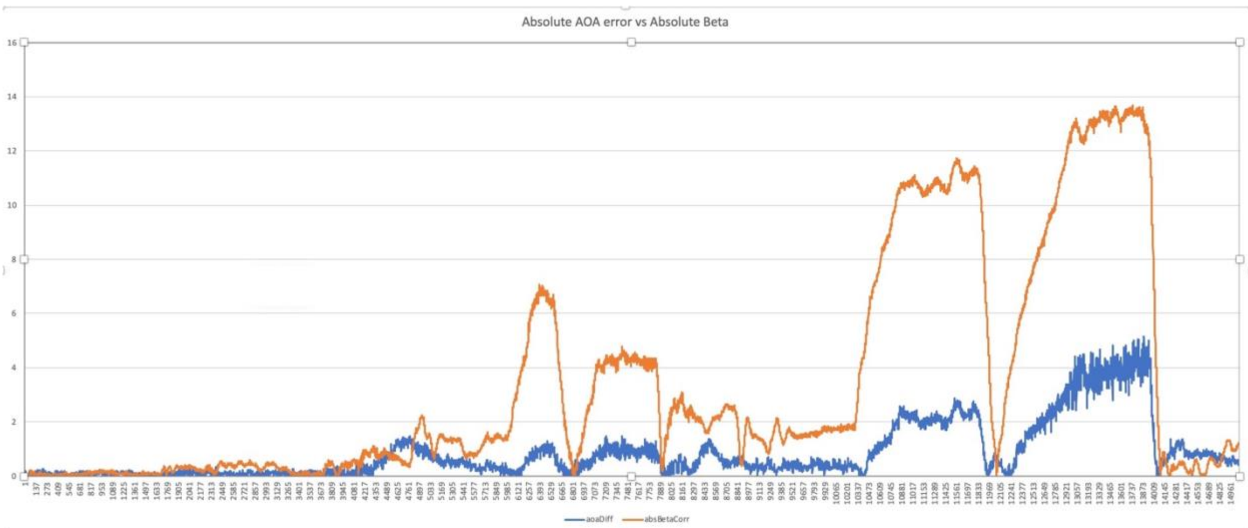


Figure 15. Beta Induced Alpha Error

Sideslip Limits and Beta Correction. An inherent limitations of C_P sensors that extend into the flow field is susceptibility to sideslip induced error and blanking at side slip angle in excess of approximately 6°.[12] Conventional two-port AOA sensors have no capability to measure β utilizing differential or C_P. It is for this reason we have integrated an IMU into the Gen 2 system. The challenge is to derive accurate β utilizing vector sum from the data provided by the gyros on the IMU chip. The typical EA-B type can generate sufficient sideslip to cause blanking and computed α error. This is shown in Figure 15. In this figure, the orange line is β and the blue line is α. β is depicted as an absolute value (normally left β is recorded as negative and right β is recorded as positive). Note that as β angle increases, α error increases. Sufficient rudder authority and engine power effects result in AOA tone blanking in a full, inside left slip as may be encountered during a base turn, however loss I momentary and recovers nearly instantly when sideslip angle is reduced. Due to power effects, it is not possible to achieve blanking in a right hand inside slip condition in the RV-4. The ZlinZ-50 test aircraft has the capability to generate up to 25° of yaw in either direction and will be the primary testbed for investigating alternate probe configurations and other possible β solutions.

Flight Test Results

Flight Test Aircraft. Our primary instrumented flight test airplane is a Van's RV-4 equipped with a 160 HP Lycoming O-320-D2J engine and a custom 2nd Generation Catto 68 x 72" composite fixed pitch propeller with a measured activity factor of 97. The airplane has a wingspan of 23' 0",

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[12] David F. Rogers, "Investigation of a General Avaiation Differential Pressure Angle of Attack Probe," Journal of Aircraft, Vol 50, No.5, Sep-Oct 2013, pp. 1668-1671.

a chord of 54 inches, a wing area of 110 sq ft and utilizes at constant chord, constant thickness NACA 23013.5 airfoil section. The wing loading at maximum allowable gross weight of 1500 lbs is 13.63 lbs per square foot. Power loading is 9.375 HP/lb at maximum allowable gross weight. The aircraft has a basic operating weight of 983 lbs and a typical test weight between 1238 and 1328 lbs. The airplane has plain, manual flaps with three positions: 0°, 20° and 40°. A linear potentiometer type flap position sensor is installed to provide flap position information to the AOA system. The primary AOA system fitted is a Gen 2 V2 (identical to the productionized V3, with minor board configuration and wiring differences) mounted in the cockpit on the longitudinal axis of the aircraft. A Dynon pitot/AOA probe that fits in a conventional AN-5812 mounting under the left wing consistent with the Van's drawings for pitot location. This probe provides P_{FWD} and P_{45} pressure. The forward end of the probe is at 26% MAC, 8" below the lower surface of the wing. The secondary AOA system is a Gen 2 V1 system is fitted remotely to the left aileron bell crank inspection plate and is attached to an adjustable (angle) Alpha Systems differential pressure angle of attack probe. The forward edge of this probe is at 30% MAC and protrudes 4" below the wing. The angle of the Alpha Systems probe is adjustable. The aircraft is fitted with dual Dynon DY-10A EFIS. EFIS data is provided to the secondary DAS (wing-mounted Gen 2 V1 box) at a serial output at a rate of 50Hz. The aircraft is fitted with a Spin Garage removable air data test boom above the left wing tip. It is equipped with alpha and beta vanes capable of measuring both with an accuracy of better than 0.1° through $\pm$ 40°. It is also fitted with a Keil Probe to measure pitot and static pressure. It transmits wirelessly to a receiver in the cockpit at a data rate of 20Hz. The airplane is equipped with a VectorNav VN-300 GPSS/INS reference system. The VN-300 is mounted directly to the Gen 2 V2 DAS on the aircraft longitudinal axis near the aircraft center of mass. The VN-300 measures dynamic pitch, roll and yaw to an accuracy of .03°. Gyro data are transmitted and recorded in a single integrated file at 50Hz. Multiple data sources are integrated utilizing GPS time. The VN-300 utilizes two GPS antennas separate from ship's systems. It is temperature and pressure compensated. Pitch is aligned with the fuselage reference line of the aircraft. Up to 32GB of data may be recorded. The V2 system records approximately 50MB/hour while the secondary V1 DAS records approximately 25MB/hour. Data are downloaded post-flight from the primary system via WiFi, and the secondary wing mounted system via USB cable. The RV-4 may be fitted with up to three camera systems (forward, left oblique and standby airspeed indicator) for test work. The baseline camera configuration is a single camera forward looking camera mounted over the pilot's right shoulder. All test sorties are flown with a minimum of one camera to assist with mission reconstruction during debrief. All test video is maintained online for collaborative access. The WiFi interface also allows recording of the live display screen utilizing a smart phone or tablet.

Air Data Boom Calibration. Two boom calibrations are required, baseline and upwash. Baseline curves for alpha, beta, pitot and static are provided by the manufacturer. Baseline curves are applied in the system software via user selectable settings. Data is transmitted wirelessly and recorded at 20Hz. EFIS GPS time is used to sequentially integrate 20Hz boom data with 50Hz pressure, IMU, GNSS/INS and EFIS data. Our software interfaces with Dynon DY-series and SkyView, AFS, MGL and Garmin G3X equipment. Upwash curve was derived from conventional trim shots for each flap setting (Flaps 0, 20 and 40). GNSS/INS Derived alpha was used to increase accuracy. Both GNSS/INS pitch and boom alpha vane are aligned to the fuselage reference line, so any installation misalignment is accommodated. Dynamic boom correction is required for maneuvering flight. The algorithm accounts for G and pitch rate. This dynamic correction works when motion is about the lateral axis. Because of the wing tip mounting location, the alpha vane is affected by aircraft roll as well. An analysis option also accommodates roll rate, if appropriate, however experience has shown that best performance is obtained when the lift vector is stabilized relative to the plane of motion of the maneuver, and test maneuvers are conducted accordingly. by examining data from 22 trim shots. 8 Trim shots were flown in at flaps 0 and 7 each at flaps 20 and 40. Pitch angle (θ) was derived from 50 Hz EFIS data. θ was set to zero degrees with the aircraft leveled (fuselage reference line [FRL] at zero degrees). Boom measured alpha (α_{MES}) and θ were taken at each trim shot. In level, unaccelerated flight $\theta = \alpha$. The RV-4 has a +0.5° angle of incidence relative to the FRL. The boom mounts are designed to align the boom with the FRL. There is an installation error of 0.1° nose up on the boom relative to FRL, thus the total delta between the boom and FRL is +0.4°. The boom has been flight envelope tested to 230 MPH (200 KTS) TAS and +6 G's. Because the RV-4 is equipped with plain flaps, it's practical to combine all data points into a single plot to derive a single upwash correction. Boom upwash correction (ε) is applied during data analysis.

Developmental Flight Test Methodology. Flight testing was conducted to validate the performance of the aural AOA, OWS and airspeed warning logic as developed for use in a representative light wing loaded, straight wing, propeller driven EA-B aircraft in all phases of flight. A build-up approach was utilized of representative maneuvers to baseline Gen 2 performance. The calibrated test boom and GNSS/INS reference gyro were fitted for all test sorties 61 channels of data are recorded. As of 12 April 2021, over 100 hours of dedicated Gen 2 flight test have been flown in the RV-4 testbed. The following elements were flown and evaluated during the test program. Three different coefficient of pressure techniques were evaluated using absolute alpha, pitch derived alpha and IMU derived alpha curves:

Element 1. Aircraft (FRL) leveled to 0° in pitch and roll. Gen 2 V2 IMU, VN-300 GNSS/INS sensors and air data boom vanes calibrated.
Element 2. Multiple trim shots in Flaps 0, 20 and 40 configurations to develop aircraft curves.
Element 3. Cue set point validation with each curve change.
Element 4. Flaps 0, 20 and 40, 1knot/sec or slower bleed rate, determine $V_{WARNING}$, V_{BUFFET}, and V_{STALL} and measure α_{FRL}. Assess tone performance in primary and secondary stall.

Element 5. Wind up turns to 4.5 G's.

Element 6. Transient response tests: 2-4G pulls to +30°, .5G unload to -30° at various smoothing settings.

Element 7. 6.0 G slice back. Assess OWS aerobatic mode at aircraft limits.

Element 8. 2G loaded barrel roll. Assess OWS asymmetric training mode (1.65G warning).

Element 9. 5G break turn to corner from V_{NO}, transition to corner. Assess tone performance during maximum rate sustained turn.

Element 10. 4-5G Accelerated stalls at variable G onset rate break turns to assess system lag: 1G/second; 2G/second; and 3G/second. Assess tone performance in primary and secondary stall warning.

Element 11. 3G ONSPEED Loop.

Element 12. Dive test airspeed warning chime at V_{NO} (IAS) and V_{NE} (TAS), not to exceed V_{NE} + 5 TAS.

Element 13. Maximum performance aileron roll. Measure maximum roll-rate for asymmetric G calculation. RV-4 provides reliable aerodynamic feed-back thru reversable flight control systems as maximum deflection roll produces a noticeable aileron stall.

Element 14. Assess AOA, OWS and airspeed warning during normal aerobatic maneuvers.

Element 15. Uncoordinated full stalls (1/2 left and right rudder; ball displaced 1 ball width at break).

Element 16. 1-turn incipient spins, left and right.

Element 17. 3-turn spins, left and right.

Element 18. Full rudder yaw excursions and V_C, L/D_{MAX} and ONSPEED (approximately 15° β left and 10° β right). Assess 3D audio cuing performance.

Element 19. Inside slips in descending base turn (full rudder displacement, ailerons sufficient to generate nose track), flaps 0, 20 and 40 configurations at IDLE power.

Element 20. At altitude, conduct simulated engine-failure in Flaps 0 takeoff configuration with recovery straight ahead.

Element 21. At altitude, conduct simulated engine-failure in maximum performance takeoff configuration (Flaps 20) with recovery straight ahead.

Element 22. Repeat element 22 and conduct 180-degree turn after simulated engine failure.

Element 23. Repeat element 23 and conduct 180-dgree turn after simulated engine failure.

Element 24. At altitude, conduct turning stalls in flaps 0, 20 and 40 configurations from simulated base turn.

Element 25. Slipping departure from controlled flight. Recover NLT 360° of uncommanded roll.

Element 26. Skidding departure from controlled flight. Recover NLT 360° of uncommanded roll.

Element 27. Conventional overhead patterns, flaps 0, 20 and 40. Assess ONSPEED performance and 3D audio sideslip warning in calm and turbulent conditions.

Element 28. 180-degree power off ONSPEED approach and landing.

Element 29. Conduct L/D_{MAX} and ONSPEED simulated flame-out patterns. Pattern A 1500' AGL, L/D_{MAX} descending spiral, transition ONSPEED and Pattern B 3000' AGL, ONSPEED steep spiral.
Element 30. 250' AGL V4 Cut, return for ONSPEED landing.

System Accuracy. The design goal was to produce a C_P derived AOA solution accurate to 0.25° to 0.5° throughout the normal flight envelope. Computed AOA is compared to corrected boom and (in some cases) IMU-derived AOA to establish overall system accuracy. Figure 16 shows upwash and an IMU-derived linear flaps 0 calibration curve for the RV-4. Similar techniques are used for flap 20 and 40 configurations and produce results shown in Table 1.

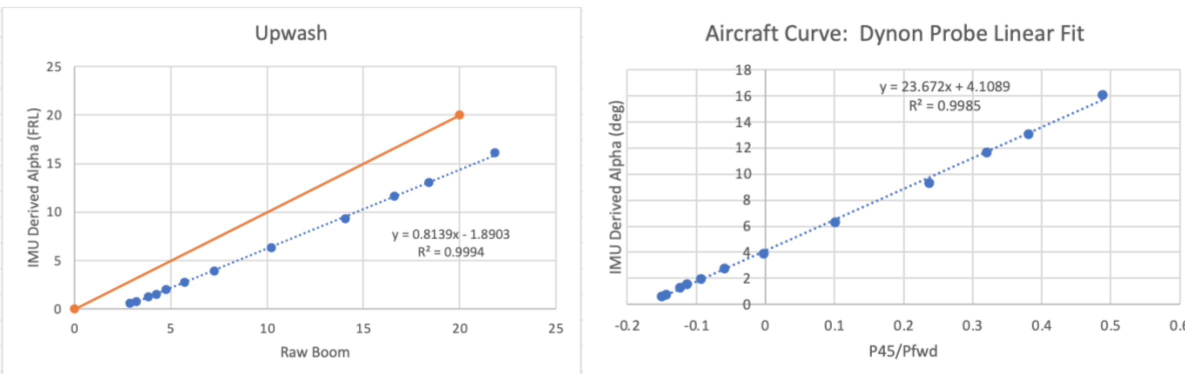

Figure 16. Representative IMU Derived Upwash and AOA Calibration Curves

Table 1: Computed AOA Error Across Aircraft Speed Band[1] (RV-4 Testbed)	
Flaps 0	Absolute Average Error V_{MIN} to V_{MAX}[2]
Dynon Probe	.084°
Alpha Systems Probe[3]	.307°
Flaps 20	
Dynon Probe	.089°
Alpha Systems Probe[3]	.264°
Flaps 40	
Dynon Probe	.125°

Alpha Systems Probe[3]	.266°

[1]Flaps 0 Speed band V_{MAX} to V_S. Flaps 20/40 speed band V_{FE} to V_S.
[2]Absolute error = air data boom corrected for upwash – computed AOA at a stable flight condition.
[3]Probe angle is adjustable. Probe mounted at 55° for these tests.

Transient Response. Multiple flight test maneuvers were conducted to assess transient response capability of the system. Several are depicted in Figures 17-20. One thing to note in all figures is the accuracy of non-dimensionalized system performance (0-1, with 0 equating to low alpha and 1 equating to stall). In Figure 18, the perturbation in the boom plot at the beginning of the maneuver is roll-induced error as the lift vector is rotated prior to being set for the pull to stall.

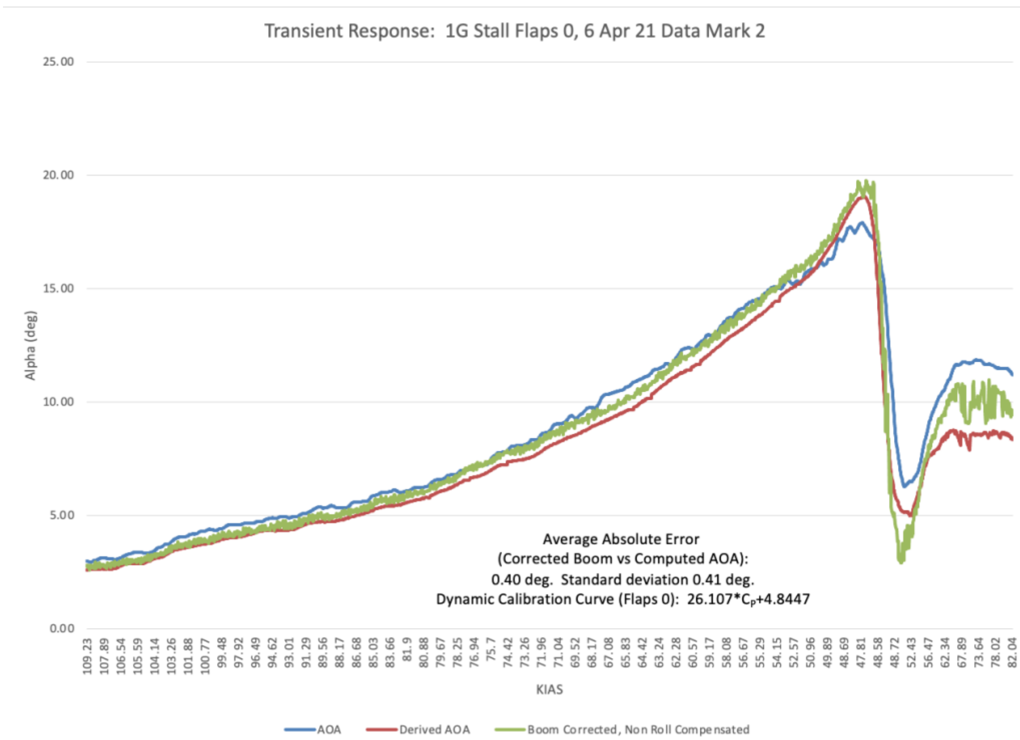

Figure 17. 1G Deceleration to Stall

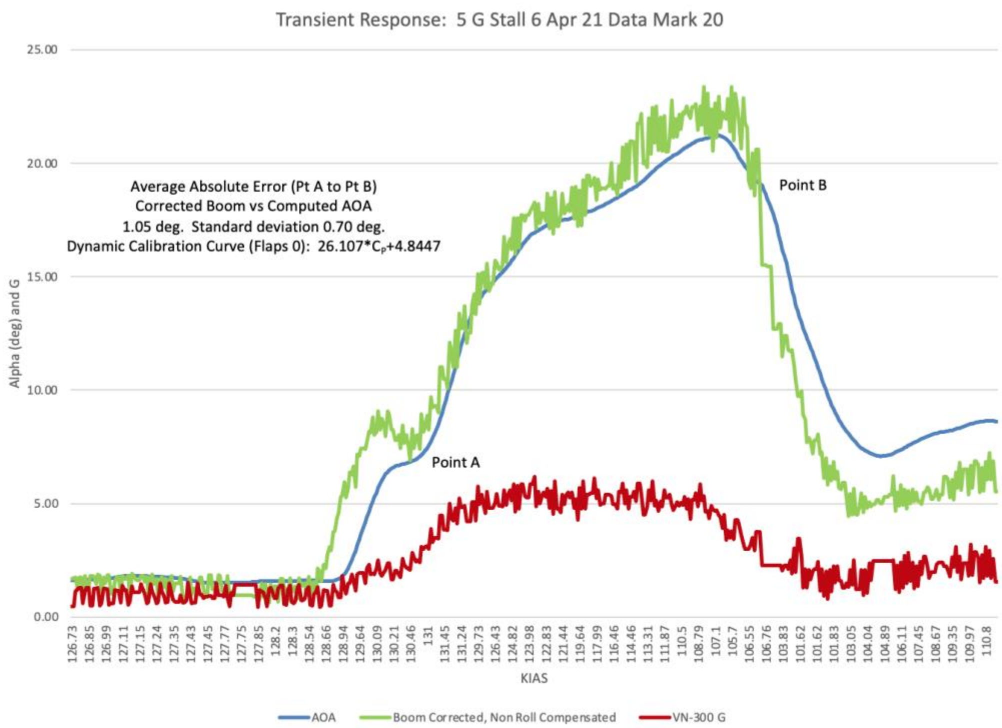

Figure 18. 5G Accelerated Stall

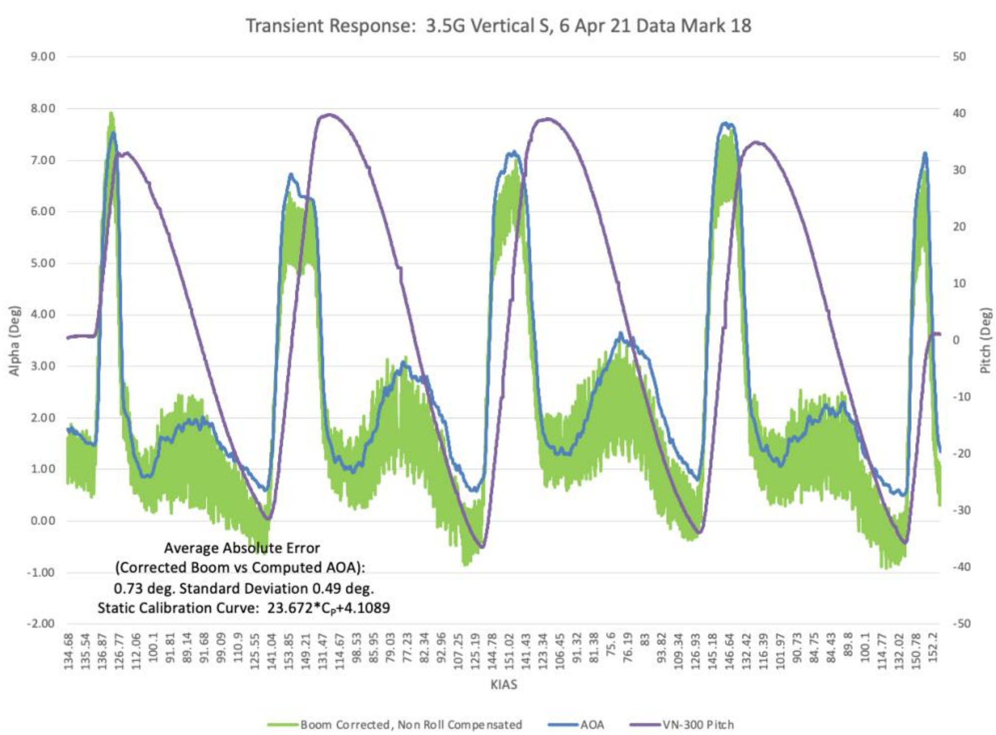

Figure 19. Vertical S maneuver

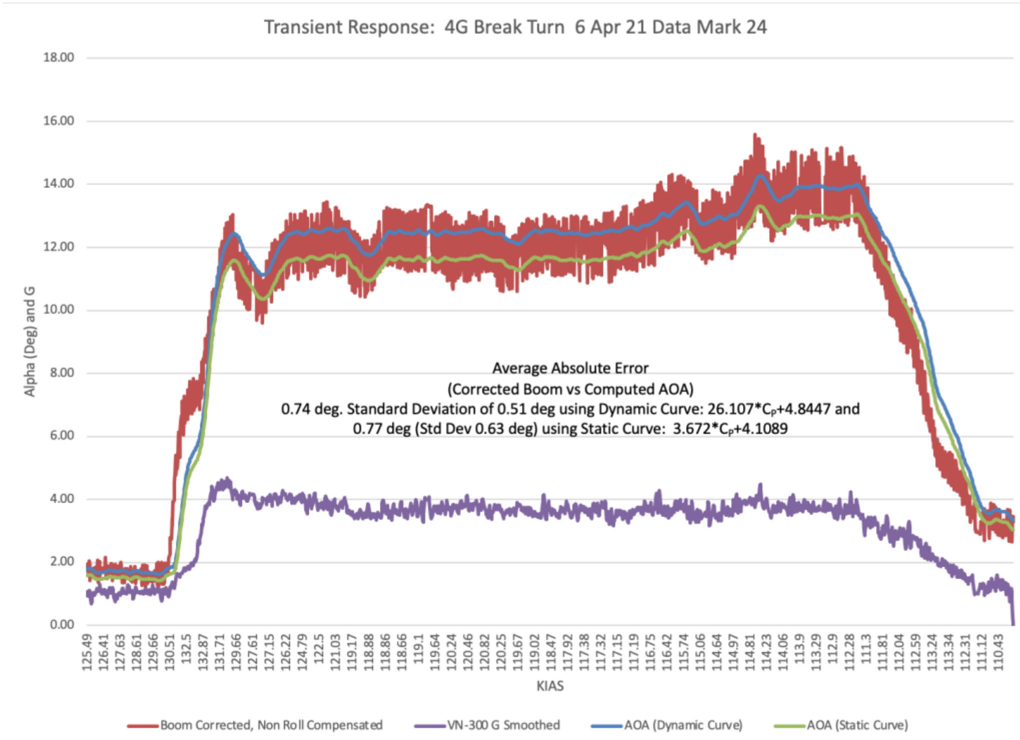

Figure 20. 4G Sustained Break Turn

System Performance Summary.

Overall, system performance of the Gen 2 V3 hardware and software has proven to be adequate throughout the flight envelope of the RV-4 test aircraft. Response rates are appropriate to assist with proper pitch/AOA control under all-attitude maneuvering conditions. Lag at normal G onset rates (3G's per second or less) has been shown to be minimal. AOA tone performance mimics the original USAF/McDonnell system quite well. At very high G onset rates (approaching 4G's per second) and depending on smoothing settings, there is some tone lag. However, the system recovers quickly enough to provide accurate warning information prior to any stall achieved during test. Overall, sideslip effects are negligible with coordinated rudder application, however with the Dynon AOA probe it is possible to generate β more than the 6° aerodynamic limit to the left. Any sideslip present induces an error in the C_P AOA solution. Under normal, non-acrobatic conditions, in both calm and turbulent conditions, the system installed in the test aircraft responded quickly and accurately, capably providing primary speed/AOA reference during pattern and landing operations. Testing conducted during wind shear conditions showed good performance. **The ability to easily discern an L/D_{MAX} or ONSPEED condition and, hence, aircraft energy state during maneuvering is especially helpful.** The logic provides a high degree of utility in the event of an engine-out/power loss condition. During maximum performance maneuvering flight, up to 6G aircraft limits, tone performance is adequate to establish optimum AOA in all aircraft attitudes. Excellent stall warning is provided at G onset rates up to 3G/sec. Stall warning is especially helpful when aerodynamic cues are minimized (e.g., during conditions of relaxed static stability [high pitch/high power or aft CG] and very low airspeed/G conditions). Post-stall performance using C_P normalization techniques is adequate up to approximately 50° α. System lag is minimal, and a maximum performance recovery may be flown utilizing aural cues, if desired. Adequate secondary stall warning is provided. Overall, performance in the normal flight envelope through stall is excellent. The OWS functions in a manner that mimics the USAF/McDonnell system quite well. Symmetric and asymmetric (rolling) G warning is adequate to the envelope limits of the test aircraft. Airspeed warning is adequate at selectable speeds up to V_{NE} + KTS TAS. 3D audio sideslip cueing is adequate throughout the flight envelope.

Low Rate Initial Production (LRIP). The Gen 2 V3 hardware meets electrical design standards appropriate for use in aircraft. The configuration utilizes thru-hole components that allow for production as well as assembly by folks with basic electronic assembly skills. A two-prong LRIP solution was pursued: 30 factory-built units and 10 field assembled units were produced. The field assembled units validated the "buildability" of the design and allowed for development of detailed assembly and programming instructions in a collaborative environment. Our current hardware designs, parts lists, schematics and software are available for download. Training, program update and forum resources for collaboration are incorporated in our website. LRIP equipment will be dedicated to OT&E and on-going developmental test.

Operational Test and Evaluation. Distributed OT&E will be conducted by volunteers. Hardware (Gen 2 V3 box and associated wiring harness) will be provided to testers by FlyONSPEED.org at no cost. Testers will be responsible for installation, software loading, system calibration and system configuration control. Documentation and design of experiment will be provided by the FlyONSPEED team. Analysis will be conducted collaboratively with volunteers. Systems have been provided to the Sling Pilot Academy in Torrance, California for installation in flight school aircraft for the purpose of gathering subjective and objective data in a flight training environment. We are also coordinating NASA Langley Research Center to supply a system for their Lancair Columbia 300 research aircraft currently testing automatic recovery logic.

OT&E Objectives

1. Develop and validate automatic calibration.
2. Develop software logic to measure sideslip angle using the on-board IMU and correct C_P derived AOA to compensate for error induced by sideslip angle.
3. Garner objective and subjective data in a primary and advanced training environment. Conduct a quantitative analysis.
4. Validate baseline system performance in an operational environment.

5. Validate energy display performance in an operational environment.
6. Experiment will all commercially available differential pressure sensors, AFS-style wing surface ports and simple, homebuilt two-tube differential sensor.

OT&E Flight Test

Element 1. Transient response tests

1: V_C 20" pull-up to 1.1 V_S, 20" push-over to V_C

2: V_C 10" pull-up to 1.1 V_S, 10" push-over to V_C

3: V_C 5" pull-up to 1.1 V_S, 5" push-over to V_C

Element 2. Normal Takeoff and Climb

Element 3. Maximum Performance Takeoff and Climb

Element 4. Cruise Climb (CHT)

Element 5. Normal Landing, Power On, Full Flaps

Element 6. Normal Landing, Power Off, Full Flaps

Element 7. Normal Overhead Pattern

Element 8. Normal Rectangular Pattern

Element 9. High-speed Final, Transition to Normal Landing

Element 10. Operation in Gusty Conditions

Element 11. Stalls

1: Power off, power off recovery

2: Power off, power on recovery

3: Power on, power off recovery

4: Power on, power on recovery

5: Cross-controlled

6: Turning

Element 12. Departure Power Failure (at altitude)

Element 13. SFO, 1500' and 3000 AGL, Pattern A and B

Element 14. V4 Cut, turn-back

Way Ahead. Our most significant challenge is developing an AOA probe or IMU-derived correction for sideslip induced C_P error. We are currently finishing up implementation of the initial automatic calibration and are pressing ahead with OT&E. We look forward to the opportunity to collaborate with any organization that is pursuing similar or complementary technology