JOURNAL OF AIRCRAFT
Vol. 39, No. 1, January–February 2002

An Engineering Flight-Test Course Emphasizing Flight Mechanics Concepts

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To provide real-world experience for aeronautical engineering students at the U.S. Naval Academy, a flight-test engineering course was developed and implemented. The course used flights both in an actual aircraft and in a motion-based simulator. Cost, scheduling, manpower, and safety were the principal considerations in obtaining approval. Cost was contained by using a rented aircraft and limiting the course enrollment to 12 students. The availability of an experienced pilot in the chosen aircraft also contributed to cost containment. Data acquisition was accomplished using handheld and standard onboard instrumentation. Selecting benign flight-test profiles contributed to safety. Experimental results were excellent, and the course was well received by students.

Introduction

IN the late 1970s and early 1980s the aerospace engineering department at the U.S. Naval Academy offered a flight-test engineering course utilizing a leased Beech Bonanza F33A aircraft. At that time the aircraft was also used for demonstration flights in the introductory aerospace engineering course and in the stability and control course. At the end of the lease, the course was terminated because of cost and manpower considerations.

Efforts to reestablish the course in the early 1990s, using a leased or purchased aircraft, were unsuccessful for a number of reasons. However, in 1997 a number of factors combined to allow offering the course in the spring semester of 1998 on a trial basis. Specifically, these were 1) the availability of a faculty member who is an experienced Bonanza pilot, with over 1000 hours in Bonanza aircraft; 2) the availability of a rental A-36 Beech Bonanza at a local airport; 3) the decision to offer the course during a single semester rather than both semesters in order to minimize any impact on manpower; and 4) the decision to limit the number of students in the course to 12 to contain costs.

Based on a successful trial offering in the spring of 1998, the course was made a permanent part of the curriculum beginning with the spring of 1999.

General Course Description

The course is designed as both a lecture and laboratory course. There are two formal one-hour lectures each week, along with a two-hour laboratory session. The course is designed to provide practical application of the theoretical principles learned in aerodynamics, propulsion, flight performance, and stability and control. Topics include the background of flight testing, flight-test theory, flight-test data acquisition techniques, the purpose of flight-test, engineering test planning, flight-test instrumentation, data analysis, and report writing. Four flights are conducted in the aircraft. An optional fifth flight is flown, weather and time permitting. A motion-based variable stability flight simulator is used for several experiments. Several speakers from various U.S. Naval test flight activities provide real-world examples of flight testing.

Presented as Paper 2000-0530 at the AIAA 38th Aerospace Sciences, Reno, NV, 10 January 2000; received 19 January 2001; revision received 15 September 2001; accepted for publication 22 September 2001.

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Student Selection

Because of the limited class size, students compete for the course. Selection criteria include, in the aerospace engineering department's aeronautics curricula (The department also offers an astronautics curricula.), physically qualified as a naval aviator, grades, the opinion of the instructors, and a submitted application.

Laboratory Schedule

The U.S. Naval Academy's very tight scheduling, a limited laboratory period of two hours, and an airfield that is 20 miles from the Academy requires creative course scheduling. The 12 students in the course are split into two laboratory sections of six each. The six students in each laboratory section are split into two groups of three students. Each group of three students plus the aircraft pilot filled the four usable seats in the aircraft. One laboratory section meets during the two class hours just prior to lunch time, and the other meets during the two class hours just after lunch time. Each laboratory day, weather permitting, one group of three students from the morning section and one group from the afternoon section travel to the airport to participate in an actual aircraft flight. With 1 h and 40 min allotted to the lunch period, each section has a total of 3 h and 40 min to travel to the airport, participate in the flight, obtain lunch on their own, and return to the Academy. With each flight requiring approximately 1 h and 20 min, combined with 20-min pre- and postflight briefings and an approximate 35-min travel time, this period of time is quite adequate. While one laboratory group is flying, the other is conducting simulator experiments or working on writing flight-test reports.

Rental Aircraft

The aircraft used for the flight experiments is a 1977 A-36 Beech Bonanza, with the original 285-hp Continental IO-520 engine replaced with a 300-hp Continental IO-550 engine. The aircraft is also equipped with two 15-gallon tip tanks for additional fuel. All flights are conducted with the tip tanks empty. Although the aircraft is equipped with six seats in a convertible "club" or standard forward-facing arrangement, gross weight considerations limit practical use to four seats.

Cost

The aircraft rental fee, including fuel, is $142 per flight hour. Approximately $4600 was budgeted for flight time. The actual course, including a required pilot checkout in this particular aircraft with a flight instructor, practice flights for each experiment, and the actual flight experiments with students, required 27.6 h of flight time at a cost of $3956.70.

One significant cost consideration was that both the owner and the insurance company waived the normal checkout requirements in the aircraft because of the extensive experience of the pilot in a similar aircraft. This is estimated to have saved nearly $3000.

Pilot Qualifications

Minimum pilot qualifications were set at 1000 h pilot in command (PIC), 10 h PIC in the actual aircraft before carrying students, current Federal Aviation Administration (FAA) second-class medical, a commercial FAA pilot certificate (license) in single-engine land complex retractable gear aircraft, and an instrument rating.

Manpower Requirements

Because of the unique scheduling of the flight laboratory, the course is team taught. The first time the course was presented the faculty member who was the pilot conducted the detailed flight briefings during the lecture periods and did the flying for all of the flight laboratories. A second faculty member, who was a graduate of the U.S. Naval Test Pilot School, prepared and presented all background technical lectures and graded all of the flight laboratory reports. A third faculty member conducted the simulator laboratories.

The second time the course was presented two faculty members, who were pilots, equally shared the flight laboratories, the simulator laboratories, the technical lectures, and the grading of the reports.

Safety

Safety is of paramount importance. Unfortunately, any general aviation activity is considered hazardous by the large majority of the population. Naval officers and academic administrators are no exception. Using the Nall Report (Data are also available on-line at http://www.aspa.org/asf/publications/nall.html.)[1] as a basis, the instructors argued that the flight laboratories would be conducted under good visual meteorological conditions, within sight of the home airport, that each flight would be initiated with full fuel tanks, that adequate emergency fields would be available throughout each flight, and that all flights would be conducted in daylight. Thus, three of the statistically largest hazards were immediately eliminated, i.e., continued flight into instrument meteorological conditions, fuel exhaustion, and night operations. In addition, prior to the initiation of each flight laboratory and upon completion of each flight laboratory the pilot called the Academy. A detailed emergency plan was set up in the event of a mishap. This approach, combined with the significant experience of the proposed pilot, convinced the administration to initially approve the course on a trial basis and subsequently to permanently approve the course.

Integration with Other Courses

A flight-test engineering course, like a design course, represents a capstone course in the study of aeronautical engineering. Over 90% of the graduates from the aerospace engineering department at the U.S. Naval Academy enter naval aviation to become either pilots or naval flight officers. The Beech T-34, which is derived from the Beech Bonanza, is used by the U.S. Navy for initial flight training. Because of the heritage of the T-34, many elements of the T-34 are similar or identical to those of the Beech Bonanza. For example, the wings of the T-34 and Bonanza are aerodynamically identical. Consequently, a number of fundamental support topics were integrated into earlier courses in the curriculum. As examples, the lift distribution on the T-34/Bonanza wing is calculated in an aerodynamics course, the structural strength of the T-34/Bonanza wing is calculated in a structures course, and the drag of the entire aircraft is estimated during a subsonic wind-tunnel course. The fundamental performance of a model F33A Bonanza is calculated in a term problem in the performance course, and the static and dynamic longitudinal and lateral stability characteristics of the model F33A Bonanza are determined in a term problem in the stability and control course.

Instrumentation

Because the rental aircraft is FAA certificated and is used by other parties during the period that the course is conducted, modifications of the aircraft are not possible. Thus, data-acquisition instrumentation is limited to the standard aircraft instruments, e.g., airspeed indicator, altimeter, rate of climb (vertical speed indicator), manifold pressure gauge, tachometer, etc. The aircraft is equipped with a Hoskins fuel flow computer, which is used to accurately determine fuel remaining and thus weight for any given data point.

Hand-held instrumentation includes stop watches, a Garmin GPS-92, a hand-held force gauge, a hand-held propeller tachometer (PropTach by Cardinal Electronics), and an accurate digital inclinometer. The aircraft static pressure system is Instrument Flight Rules certified. Hence, a bench calibration of the static system is available.

Flight Experiments

There are four (or five) flights and five (or six) flight experiments. Each flight is between 1.1 and 1.3 h duration.

Flight 1

To control costs, this first flight combines two experiments. The first experiment is to calibrate the airspeed indicator and altimeter. The second one is to determine the aircraft drag polar and the power required for steady level flight, i.e., to determine the airplane efficiency factor e, and the equivalent flat plate area f.

There are two unique aspects to this flight. The first determines the true airspeed. Originally, the time to fly a distance of two nautical miles along a constant global positioning system (GPS) track and its reciprocal to a distant waypoint were used. Subsequently, the classical technique of flying a constant heading between two ground references a known distance apart and recording the time was adopted. In both cases the tests were conducted at 1000-ft pressure altitude. The results indicated that the average of the GPS ground speed in the two directions along the constant GPS ground track yielded the true airspeed with an equivalent accuracy to the classical constant heading technique. Recently, an alternate method, called the horseshoe-heading technique, which uses GPS, was developed (see Appendix).[2–7] The horseshoe-heading technique increases safety because the flight can be conducted at a more reasonable altitude than that required to achieve accuracy using the classical technique.

The second aspect is that the level flight performance data are acquired simultaneously with the airspeed and altimeter calibration data. This is accomplished by flying constant power, i.e., constant manifold pressure, rpm and fuel flow, rather than constant level-flight-indicated airspeeds. Careful selection of power settings yields approximately 10-kn increments in level-flight-indicated airspeed. Originally the flights were conducted at a pressure altitude of 1000 ft ±20 ft. Using the horseshoe-heading technique allows conducting the tests at higher pressure altitudes. Three configurations are tested: clean, i.e., gear and flaps retracted; gear extended, flaps retracted; and flaps extended and gear retracted. Two of the four groups fly the test in the clean configuration, and the others fly either the gear extended or flaps extended configuration. Figure 1 shows the results for the level flight power required flight test.

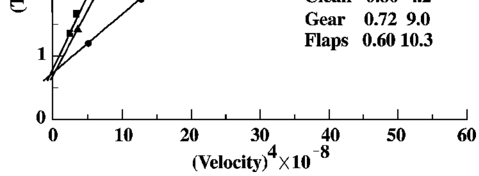

Fig. 1 Level flight power required result.

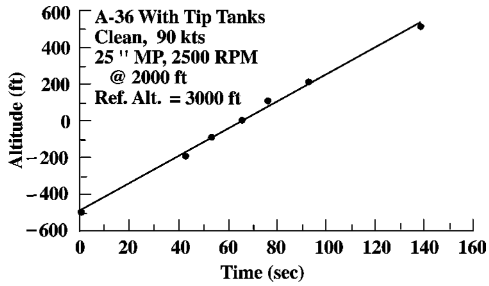

Fig. 2 Data from a single rate of climb run.

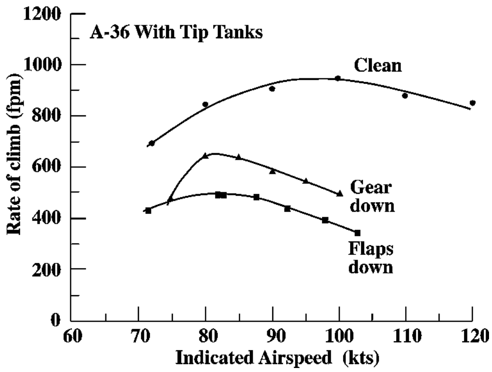

Fig. 3 Rate of climb for three configurations.

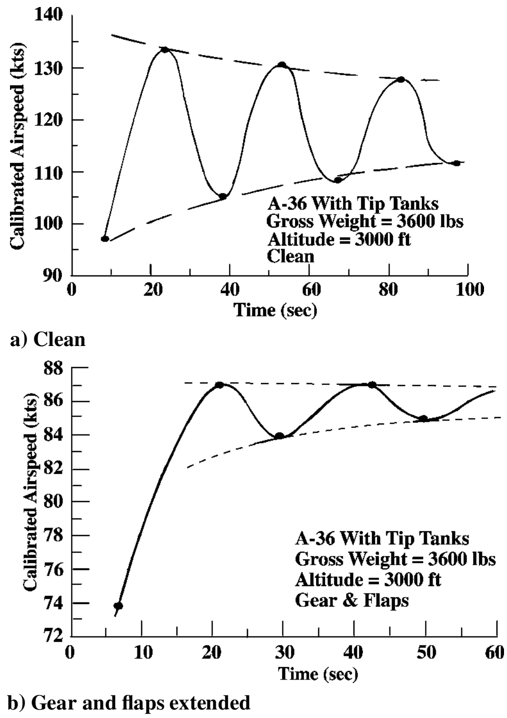

Fig. 4 Phugoid oscillation.

Flight 2

The rate of climb and velocity for maximum rate of climb are determined using the classical sawtooth climb technique. A pressure altitude of 3000 ft is used as the reference altitude. The climb is initiated approximately 800 ft below the reference altitude. Two stop watches are started at 500 ft below the reference altitude. One watch is used to record the time at odd hundreds below and above the reference altitude and the other to record the time at even altitudes. Again three configurations are tested: clean, gear extended, and flaps extended.

To illustrate the quality of the data, Fig. 2 shows the altitude as a function of time obtained for a single climb in the clean configuration. The slope of the line is the rate of climb for that specific velocity. Figure 3 shows results for the rate of climb in three different configurations referred to standard day conditions and an aircraft gross weight of 3600 lb. As anticipated, both the rate of climb and the velocity for maximum rate of climb decrease with increasing parasite drag (Fig. 1). These results compare favorably with expectations based on theoretical considerations.

Flight 3

This flight is designed to determine the stick fixed/stick free neutral point. In this flight the aft four seats in the aircraft are reconfigured from all forward facing to club seating. The center of gravity is varied by moving people from the aft-facing middle row of seats to the forward-facing most aft row of seats. Using this configuration allows up to four center of gravity locations without an intermediate landing. This saves considerable flight time.

A calibrated scale in degrees of elevator deflection is marked on the control column. With the elevator tab angle set to zero, the elevator deflection is determined for several airspeeds for a minimum of three positions of the center of gravity. The slope of the elevator deflection vs the square of the velocity curve is then plotted for each center of gravity position. Extrapolation to zero yields an estimate of the stick-fixed neutral point.

Similarly, the stick force is measured at each data point, and the slope of the stick force vs velocity squared plotted against the center of gravity yields an estimate of the stick free neutral point.

Flight 4

The flying qualities (e.g., rudder power, aileron power, phugoid mode, dutch roll and spiral mode characteristics and periods) are examined both qualitatively and quantatively on this flight. The flying qualities examined include the following:

1) Propeller "torque" effect on the track of the aircraft upon brake release after application of full power at the beginning of the takeoff roll is demonstrated.

2) The longitudinal stability of the aircraft trimmed for climb out is demonstrated by releasing the controls and observing that the airspeed remains steady.

3) The phugoid period and the amplitude of the oscillation are measured by initiating the oscillation and then timing when both maximum and minimum airspeeds occur and when the rate of climb is zero. These tests are performed in both the clean and landing gear and/or flaps extended configurations. Typical results are shown in Fig. 4 for both clean and gear and flaps-extended configurations. The clean configuration results are similar to those determined for an F33A Bonanza in the stability and control term problem. Noting that the A-36 has tip tanks, whereas the F33A study does not, precludes a direct comparison. However, from Fig. 4 the phugoid period at a reference airspeed of 120 kn is approximately 30 s, whereas the F33A study yields a period of 25.4 s.

4) The short-period oscillation demonstration is a nonevent. However, the aircraft oscillation is allowed to continue into a phugoid oscillation to demonstrate that the actual aircraft exhibits multiple oscillatory modes when responding to a disturbance.

5) The divergence of the spiral mode is measured by first trimming the aircraft in steady level flight, then establishing a steady level 20-deg bank, releasing the controls, and timing the bank angle increase or decrease. These tests are performed in both the clean and landing-gear-extended configurations and the results compared. Results are shown in Fig. 5. The aircraft starts in a 20-deg left bank but diverges to the right. This, of course, is counter to the expected result and leads to a lively discussion until the pilot points out that during the flight all fuel has been burned from the left tank. The results also illustrate the importance of the drag of the gear and flaps in controlling the rate of divergence.

6) The period of the dutch-roll mode is determined by initiating the mode and measuring the time for multiple oscillations. The shape of the mode is observed to determine the relative damping in roll and yaw. These tests are performed in both the clean and

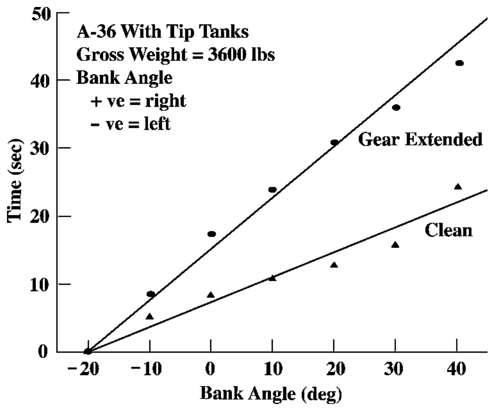

Fig. 5 Divergence of the spiral mode.

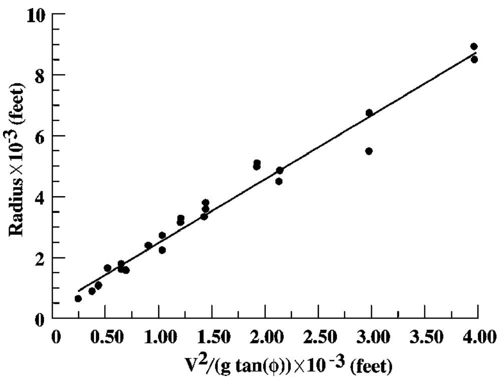

Fig. 6 Level turn performance.

landing-gear-extended configurations. In the clean configuration at 120 kn indicated airspeed, the flight-test results give a period of approximately 2.2–2.4 s. These results agree favorably with a period of 2.3 s at a true airspeed of 157 kn determined for the F33A in the stability and control term problem.

7) Roll control of the aircraft is established by first placing the aircraft in a steady 30-deg banked turn in one direction and, using full opposite aileron, determining the time it takes to roll the aircraft into a 30-deg bank in the opposite direction.

8) The lateral static stability of the aircraft is established using a steady heading sideslip. Here the aircraft is established in a sideslip using full rudder and flown along a straight path along a ground reference. The sideslip angle, bank angle, and aileron deflection are determined using the heading indicator, a digital inclinometer, and the known gearing ratio for the ailerons. The ratio of bank angle to sideslip angle indicates the stability of the aircraft.

9) Trim changes with configuration and power changes are demonstrated while the aircraft returns to the airport by setting power and trim for controls-free level flight at the approach speed, noting the elevator trim tab setting, releasing the yoke, and extending the landing gear. After steady flight is established, power is readjusted, and the aircraft retrimmed for level flight at the approach speed. The elevator trim tab setting is then compared with the earlier setting. A similar demonstration is done while extending flaps.

Flight 5

The level turning performance of the aircraft is determined in this optional flight. The objective is to verify that the turn radius varies linearly with the ratio of the velocity squared and the tangent of the bank angle, i.e.,

$$R = V^2/g \tan\phi$$

Using a reference pressure altitude of 3000 ft, the aircraft is flown at constant bank angles of 10, 20, 30, and 45 deg and constant indicated airspeed through 360 deg of heading. A handheld GPS (Garmin GPS 92) interfaced to a notebook computer is used to digitally acquire latitude and longitude coordinates at 2-s intervals. The wind effect is removed and the radius of the turn determined. The results for two different flights flown by two different pilots are shown in Fig. 6.

Simulator Flights

The simulator is a Singer-Link GAT-IV modified for variable stability. The simulator is equipped with a motion system allowing roll, pitch, and yaw but has no visual system. A digital data-acquisition system is used to acquire the data. Here, the students actually fly the simulator while collecting data. Allowing the students to fly the simulator gives them a feeling for the precision required of the pilot during the actual flights.

Flight 1

Determine the drag polar using power-off glides (idle descent). From these data the airplane efficiency factor e and the equivalent flat plate area f are determined.

Flight 2

The rate of climb using the level flight acceleration technique (specific excess power) is determined. This experiment illustrates an alternate technique to the sawtooth climb used in the actual aircraft. The level flight acceleration technique is frequently used for high-performance aircraft.

Flight 3

Determine the effect of aft c.g. movement on the flying qualities of the simulator. Here the c.g. is actually moved aft of the aft c.g. limit to illustrate the difficulty of flying the aircraft. This experiment could not be conducted in the actual aircraft.

Reports

One of the fundamental purposes of the course is to strengthen both student writing and organizational ability. To this end, each student is required to submit a formal detailed report on each of the experiments conducted in the aircraft and a short memo style report on each of the experiments conducted in the simulator. The report style and format is based on that required at the U.S. Naval Test Pilot School. Very detailed critiques of each report are written by the instructors. The result is a very noticeable improvement in the quality of the reports during the course.

Conclusions

A senior-level flight-test course was developed and presented in an economical, safe environment using a rental aircraft combined with a motion-based simulator. With only handheld and standard aircraft instrumentation experimental results were excellent.

Student enrollment in the aeronautical engineering program has noticeably increased since the reinstitution of the flight-test engineering course. Students indicate that the flight-test engineering and the design course are the two most interesting and rewarding courses in the curriculum.

Appendix: True Airspeed Using GPS

Introduction

Using the global positioning system (GPS) to determine position error has many attractions. However, GPS determines ground speed and ground track resulting in significant errors if not used carefully.[2,3]

Perhaps the first to suggest an accurate technique for determining position correction errors using GPS was David Fox writing in *Kitplanes*.[4] Fox's method required flying three perpendicular GPS tracks at the same indicated airspeed.

The National Test Pilot School,[5] Rogers,[2] and Smith[3] suggest flying directly into and away from the wind and averaging the resulting GPS ground speed. The difficulty in this technique is in determining the wind direction. Variation in wind direction and velocity contribute to sometimes unacceptable errors.

The U.S. Air Force Test Pilot School[6] suggests flying perpendicular to the wind in both directions along a GPS track, thus canceling the effect of the wind. Although this method reduces the errors caused by variable wind direction and speed, the wind direction must still be determined.

Flight-test personnel at the Federal Aviation Administration (FAA) suggest that after entering a GPS waypoint several thousand miles away the aircraft be flown directly toward and away from the waypoint. The difference between two fixed distances along the track and along the reverse direction is then timed with a stopwatch. With a large distance to the waypoint, the aircraft follows nearly parallel tracks inbound and outbound between GPS distance rings, thus minimizing the error caused by the wind. A variation of this technique (with smaller distances) was originally used at the U.S. Naval Academy.

Craig Cox at Rea Computing extended Fox's technique to use constant headings instead of constant tracks. This method, which has been called the horseshoe-heading method, has significant advantages. For example, sequential constant headings at 90-deg intervals are easier to fly than constant tracks, headings can be in any direction as long as they are at 90-deg intervals, the method can be used at any reasonable altitude, and the direction and magnitude of the wind does not need to be predetermined. The method was first published in June 1997 as a Java Applet on the REA Web site (data also available on-line at http://www.reacomp.com/true_airspeed). Subsequently, at the request of users the derivation of the equations was included on the Web site in February 2001. Although the derivation resulted in a quadratic equation in the square of the true airspeed, the Java Applet uses an iterative method to solve the equation. The following derivation, although independently obtained, closely follows that presented on the Rea Computing Web site. It is presented here for completeness. It is the technique currently used in the flight-test course.

Doug Gray[7] extended Fox's basic method and the horseshoe-heading method to arbitrary GPS tracks. For accuracy, the GPS tracks should be approximately 90 deg apart. Although the aircraft heading, altitude, and indicated airspeed are held constant, only the three GPS ground speeds and ground tracks are required to obtain a solution for the TAS.

Horseshoe-Heading Method

From Fig. A1 parts a), b), and c), respectively, the three equations in the three unknowns V_T, V_N, and V_W are

$$(V_T - V_N)^2 + V_W^2 = V_1^2 \tag{A1}$$

$$(V_T + V_W)^2 + V_N^2 = V_2^2 \tag{A2}$$

$$(V_T + V_N)^2 + V_W^2 = V_3^2 \tag{A3}$$

where V_T, V_N, and V_W are the true airspeed and northernly and westerly components of the wind, respectively. V_1, V_2, V_3 are the three measured GPS ground speeds for the three successive headings. Expanding and adding Eqs. (A1) and (A3) yields

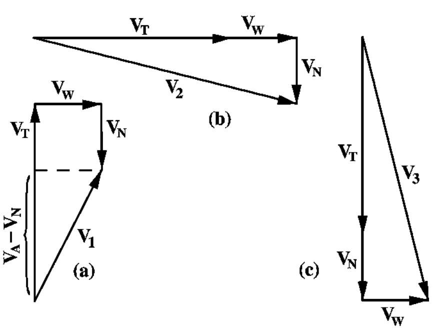

Fig. A1 Horseshoe-heading method.

$$2V_T^2 + 2V_N^2 + 2V_w^2 = V_1^2 + V_3^2 = P \tag{A4}$$

Similarly, expanding and subtracting Eq. (A3) from Eq. (A2) yields

$$-2V_T V_N + 2V_T V_W = V_2^2 - V_3^2 = Q \tag{A5}$$

Finally, subtracting Eq. (A3) from Eq. (A1) yields

$$-4V_T V_N = V_1^2 - V_3^2 = R \tag{A6}$$

V_1, V_2, and V_3 are the known GPS ground speeds. Hence, P, Q, and R are known; and Eqs. (A4), (A5), and (A6) represent three equations in the three unknowns V_W, V_N, and V_T. Solving Eq. (A6),

$$V_T V_N = -R/4 \tag{A7}$$

Substituting Eq. (A7) into Eq. (A5) yields

$$2V_T V_W = Q - R/2$$

or

$$V_W = (Q - R/2)/2V_T \tag{A8}$$

From Eq. (A7)

$$V_N = -R/4V_T \tag{A9}$$

Provided the true airspeed is available, the wind direction and magnitude are known from Eqs. (A8) and (A9). The true airspeed is obtained by substituting Eqs. (A8) and (A9) into Eq. (A4) and expanding to yield

$$V_T^4 - (P/2)V_T^2 + (2Q^2 - 2RQ + R^2)/8 = 0 \tag{A10}$$

Equation (A10) is a quadratic equation in V_T^2. An analytical solution is of course immediately available. Specifically

$$V_T = \sqrt{\left(-b \pm \sqrt{b^2 - 4c}\right)/2} \tag{A11}$$

where $b = -P/2$ and $c = (2Q^2 - 2RQ + R^2)/8$.

Because a hand-held aviation GPS typically displays the ground speed to only three significant figures, an analysis of the effect of GPS ground speed round-off error (GPS ground speed ± 1 kn) on the value calculated from Eq. (A11) was examined for the case where the wind velocity was one-half of the true airspeed and the wind direction was directly abeam the second leg. For general aviation aircraft true airspeeds—75–200 kns—the maximum error in the calculated true airspeed is approximately 1 kn. Additional credibility for the horseshoe-heading method is provided by inflight measurement by Lewis[5] at the National Test Pilot School using a Merlin III aircraft. Lewis, using a trailing cone for comparison, found excellent agreement with the horseshoe-heading GPS method in determining position error corrections.

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