AUTOMATIC DETECTION OF CIRCLING FLIGHT FOR SAILPLANES

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Introduction

Electronic navigation computers are now an accepted part of competition soaring. When properly used, they can significantly increase cross-country speeds by optimizing the cruise and climb regimes, as well as improving the accuracy of cross-country navigation. The instruments compute the altitude required to reach a distant goal for a given sailplane polar, distance, wind and McCready setting. Measurement of airspeed allows the distance to the goal and the altitude required to be continually updated automatically.

The distance accumulation function is similar to that of an automotive trip odometer with two important differences: The distance counts down rather than up; and automobiles rarely make 5 or 10 rotations in every available traffic circle (roundabout, rotary). While circling to gain height in thermals, the accumulation of distance must be suspended. Only the position drift due to wind remains.

There are additional reasons why it is helpful for the soaring navigation computer to know whether the pilot is circling or flying straight ahead. For example, during cruising flight, audio tones are often used to indicate the correct speed to fly. In circling flight, the tones are used to indicate the lift strength. It may also be useful to display different information in each of the two flight regimes.

Most present day soaring navigation computers use a manual switch called either a "Hold Switch" or a "Cruise/Climb Switch" to control the state of the computer. Unfortunately, actuation of the switch is easily forgotten under the stress of competitive soaring. Frequently, this causes the distance accumulation to gather unacceptable errors, and distance information is lost. This requires the pilot to re-enter his distance to the goal at a time when his attention is required optimizing cross-country strategy and flying safely.

Flapped sailplanes often have the "Hold Switch" actuated automatically when the flaps are in the "Climb" position. This works well in standard thermal flying where cruise is done in relatively still or sinking air. It is, however, unsatisfactory for "Dolphin-style" flight where climb flaps are used during cruise in lift.

Some computers have attempted to use airspeed as the criterion for climb/cruise switching. Usually, the assumption is made that cruising flight is done above the best L/D speed, while circling occurs at low airspeed. This system also fails in "Dolphin-style" flight.

As the design of the Cambridge S-NAV began in 1985, we asked competition pilots where improvements and contributions to the soaring technology could be made. Reliable, automatic cruise/climb switching was at the top of the list.

Sensors for detection of circling flight

Likely, sensors for detection of circling flight were reviewed. The three basic schemes were:

1. Magnetic sensing of the earth's field
2. Inertial techniques using a horizontal gyroscope
3. Detection of increased G-loading.

Some test flights with a single axis magnetometer were carried out in 1986. The sensitive axis was parallel to the flight direction. This technique would work well near the Equator, but most soaring is done at latitudes of 45 degrees and greater. In these locations, the dip angle of the earth's magnetic field is more than 60 degrees. This makes the device very sensitive to pitch, rendering it useless during dolphin-style flying. A gimballed magnetometer was considered but rejected on cost and size considerations.

Gyroscopes were also rejected for cost, size and power consumption reasons. We later discovered that American soaring pilot, Joe Emmons devised a gyro based on a low cost hobby motor with a flywheel and two micro switches. While cost-effective, this technique has serious reliability problems since small high-speed motors are usually not designed for continuous duty.

We also looked at a novel Fluidic Gyroscope which has found application in model aircraft. Rotation causes a jet of air to deflect slightly from being centered between two heated thermistor beads, thus unbalancing a thermistor bridge. We rejected this approach because of projected long development time and the requirement for a well regulated air supply.

It is well known that circling flight produces higher wing loading than straight flight. This is because we must generate additional lift to balance gravitational and centrifugal forces. At small bank angles, however, the increase in wing loading is very small. The relevant equation is:

$$G = \frac{1}{\cos\phi}$$

where ϕ is the bank angle measured from the horizontal. Table 1 shows just how small the increase is for low angles of bank.

ϕ	G
0°	1.0
15°	1.035
20°	1.064
25°	1.103
30°	1.155
40°	1.305
50°	1.556
60°	2.0

Table 1. Dependence of G-load for angles of bank.

We decided to design an accelerometer which would resolve 0.01 G and have long-term stability within 0.02 G.

Early design efforts

In late 1986, final decisions about the S-NAV construction and functions had to be made. During one long, rainy weekend at Sugarbush Airport, we designed and built the servo-accelerometer. It was constructed from parts found in stock at Cambridge Aero Instruments. In particular, the meter assembly was borrowed from the Cambridge Mark IV Speed Director. See figure 1.

Solder wrapped around the meter needle unbalanced the meter movement, making it sensitive to acceleration. A photo-transistor and light-emitting diode (LED) were located on either side of an aperture formed by a hole drilled in the scale plate. The photo-transistor current was amplified and fed back to the meter coil. Thus, the needle is controlled to regulate the light passing through the aperture to a set value. At equilibrium, the force of gravity is exactly balanced by the magnetic force induced by current in the coil. The current in the coil is exactly proportional to the G-force. This method of measurement is well known and is called the Force-Balance Technique.

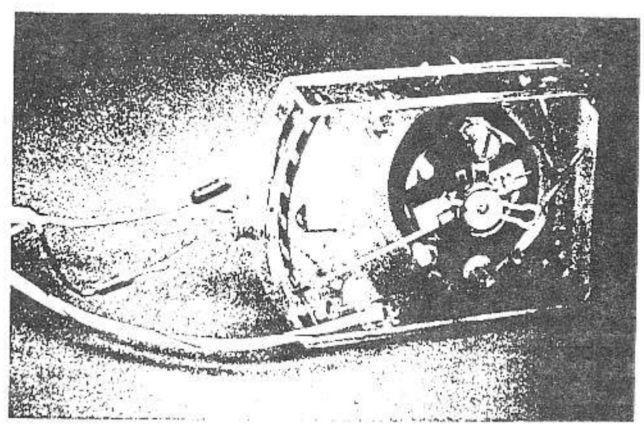


Figure 1. Picture of the "lst Version"

The performance of this device and its preliminary electronics was surprisingly good. It was then that we decided to include an accelerometer in the design of the S-NAV.

Another prototype was built for elementary flight testing. This version, shown in figure 2, used a plastic optical interrupter machined by us, and a meter movement of the same type as before. These components were mounted upon an aluminum L-bracket in a CAV variometer case, along with the feedback electronics. The front face of the instrument was calibrated to indicate G-units instead of knots.

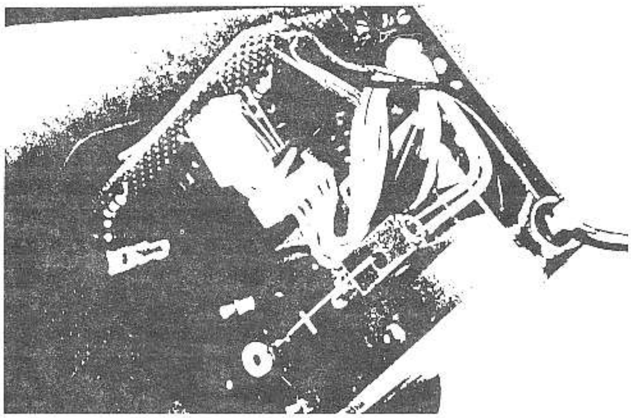


Figure 2. Picture of the "2nd Version" for flight testing.

The electronic G-meter was flight tested in an Aeronca Decathalon aerobatic airplane. Low-G testing was easy on the bench, but the Decathalon allowed us to explore the high-G behavior. Two nine-volt batteries powered the instrument. It was installed in the panel in a standard, 3.125 inch instrument hole. The accelerometer designer flew in the front seat and compared the readings of a conventional G-meter to that of the electronic prototype, while rear seat pilot Jim Parker executed loops, hammerheads, inverted flight and snap rolls. The new device worked flawlessly. Its output was indistinguishable from that of the mechanical counterpart. On an early December morning, with a blue sky and a green engineer, an electronic G-meter was born.

The production accelerometer

The next year was spent developing the production accelerometer. A custom meter movement with taut band suspension was designed. The taut band suspension technique has two advantages. First, it is inherently very rugged. Second, it has no friction, thus the resulting accelerometer has no hysteresis.

The force-balance accelerometer is a classical feedback system. Its time-domain response is a function of the electronic amplifier dynamics, as well as the dynamics of the taut-band suspension assembly. Considerable effort went into optimizing the system, both mechanically and electrically, to obtain a well damped response to acceleration inputs.

Preliminary test flights

In July of 1987, the first production version of the accelerometer was flown. An instrumentation package consisting of an HP-71B calculator, HP 3421A Data Acquisition/Control Unit, Cambridge Aero variometer and airspeed sensors, and the accelerometer. This equipment was mounted on the special rear seat instrumentation platform of the company's Janus CT sailplane. See figure 3.

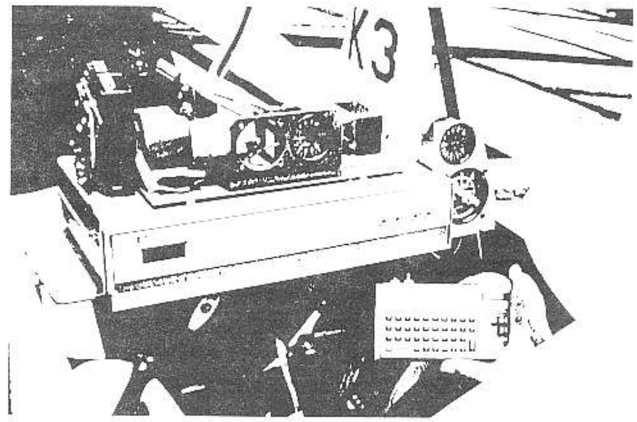


Figure 3. Janus CT with instrumentation platform.

The sailplane was flown at the U.S. Sports Class National Competition with Bruce Dyson as pilot. Technical personnel had rotating assignments in the backseat with the data acquisition equipment. Over the 7 competition days, we obtained about 1 hour of flight data using three HP-71B calculators as portable recording devices. The data was transferred to 3¼" disks using an HP 9114B disk drive. Later analysis and plotting was done on a VAX 8800 computer. A sample of plotted data is shown in figure 4.

The recording covers about 5 minutes of flight. On the left, the pilot slowed down as the vario seemed to indicate lift. When the lift failed to arrive, the pilot sped back up. On the right, an actual thermal was entered. The pilot slowed at 43 kt airspeed and began to climb. The G-force corresponds to a bank angle of about 30 degrees.

We learned several interesting points from this research.

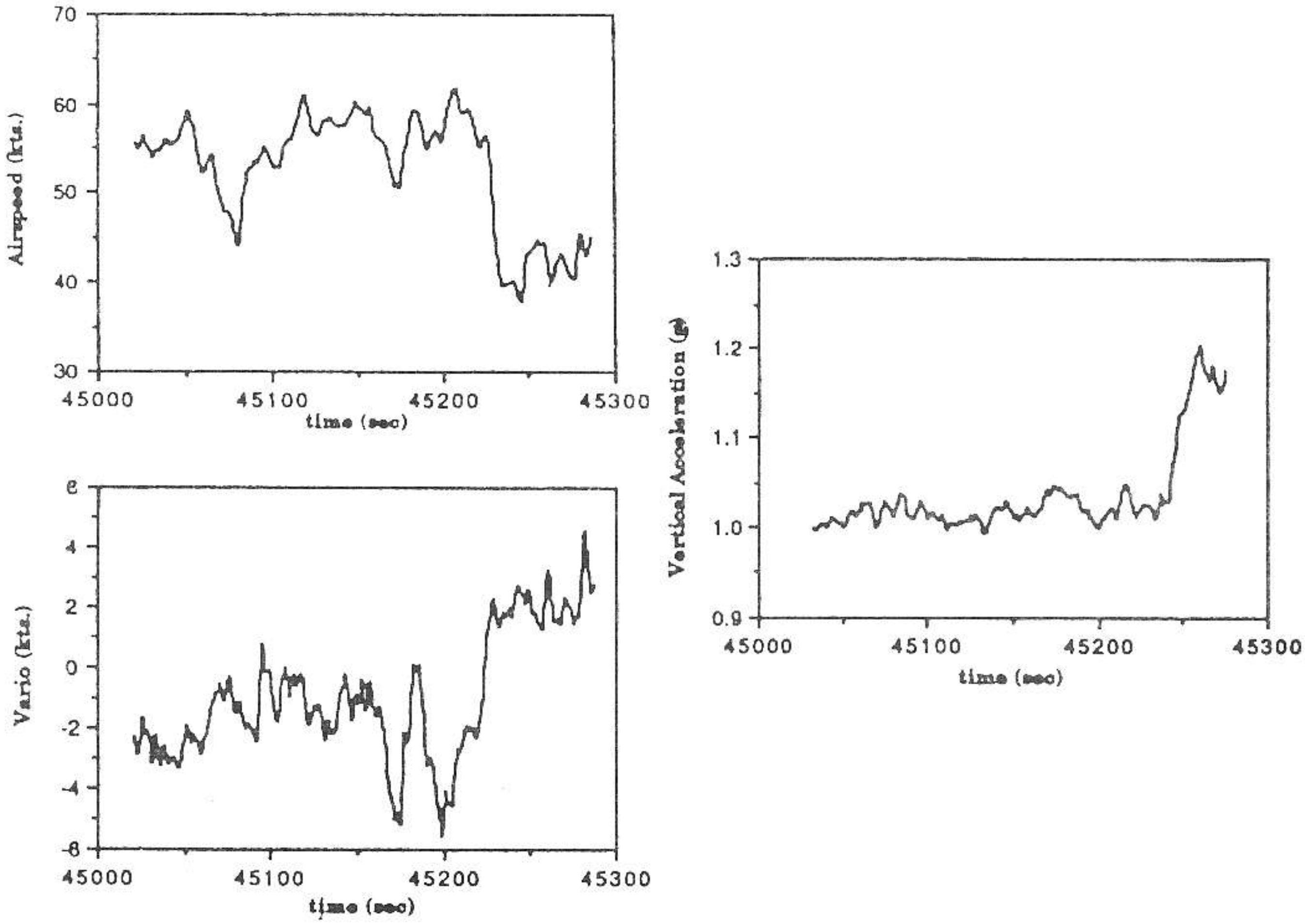
1. The accelerometer had short-term stability adequate for the task of distinguishing between cruising and circling flight.

2. The accelerometer appeared to indicate thermal airmass motion before the variometer in some situations. This is to be expected because vertical acceleration is the derivative of vertical velocity. More work remains to be done on the possible utility of this information.

3. The recording made it very easy to quantify the difference in climbing technique between novice and experienced pilots. In particular, an experienced pilot stabilized his airspeed in climb much more quickly than a low-time pilot.

4. Inclusion of airspeed data in the algorithm for detecting circling flight would probably improve its performance.

Figure 4. Plotted data as one result of the test flights.



S-NAV accelerometer and computer hardware

In production form, see figures 5 and 6, the accelerometer is an integral part of the Cambridge Aero Instruments S-NAV. It is attached vertically to the upper printed circuit board of the computer. It shares space on this board with Airspeed, Variometer, Altitude and internal temperature sensors.

The acceleration signal is fed to the computer with a resolution of 0.005 G/count. The full scale of measurement is +/− 8 G.

A condensed block diagram of the computer is shown in figure 7. An eight-channel 12 bit analog/digital converter brings data in from the sensors for processing in the 80C51 microcontroller. Eight channels of 8-bit digital/analog converters control all output functions such as meter indicators, sound and even display contrast. All signal processing is done with the microcontroller.

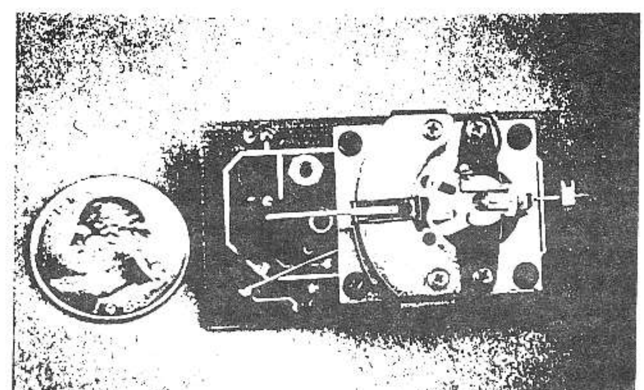


Figure 5. Photo of the production form of the G-meter.

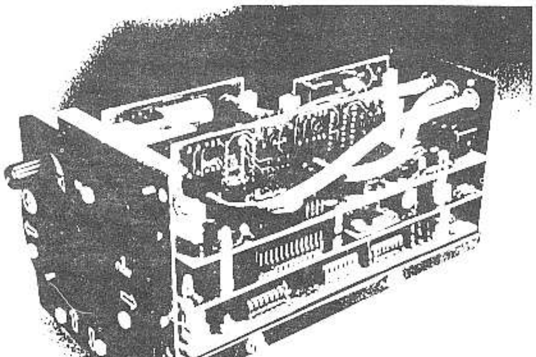


Figure 6. Photo of the S-NAV with top cover removed.

The algorithm for detection of circling flight

During the spring and summer of 1988, the accelerometer was extensively test flown in both single-place and two-place high-performance sailplanes. The second readout of the S-NAV was configured as a sensitive G-meter with a range of 0 to 2 G. In this way, we could quantify the G-forces we felt as we flew under a variety of conditions.

We began with the simple algorithm for determining circling flight. If the acceleration was greater than 1.1 G for 5 seconds, circling was assumed. The delay was to avoid problems from dolphin-flight. Conversely, if the acceleration was less than 1.1 G for 5 seconds, then straight flight was assumed.

Test flights showed poor behavior, particularly in turbulent thermals. The unit would switch from climb to cruise as the lift went from strong to weak within one circle. A quick calculation showed that a lift gradient of 1 m/s in 1 second is equivalent to an acceleration of 0.1 G. If circling was done at 25 degrees, and the lift went from 1 m/s to 0 m/s in 5 seconds, the algorithm would fail.

From extensive test flying, we identified three situaitons for which reliable switching between cruise and climb was required:

a. Strong conditions where the bank angle would exceed 40 degrees, and airspeeds would be above V_m, the speed of maximum glide angle.

b. Typical soaring conditions with bank angle above 25 degrees and airspeed below V_m.

c. Weak soaring conditions where the bank angle might be around 20 degrees, and airspeed would be less than V_m.

Conversely, any reasonable pull-up in "dolphin-style" straight flight must not activate the switch. Fortunately, this task is made easier because the accelerometer only responds to the component of gravity along the vertical axis of the sailplane. Increased acceleration is noted during the initial transition from level to climbing flight. However, during climb along a straight path, the observed acceleration is reduced by the cosine of the climb angle.

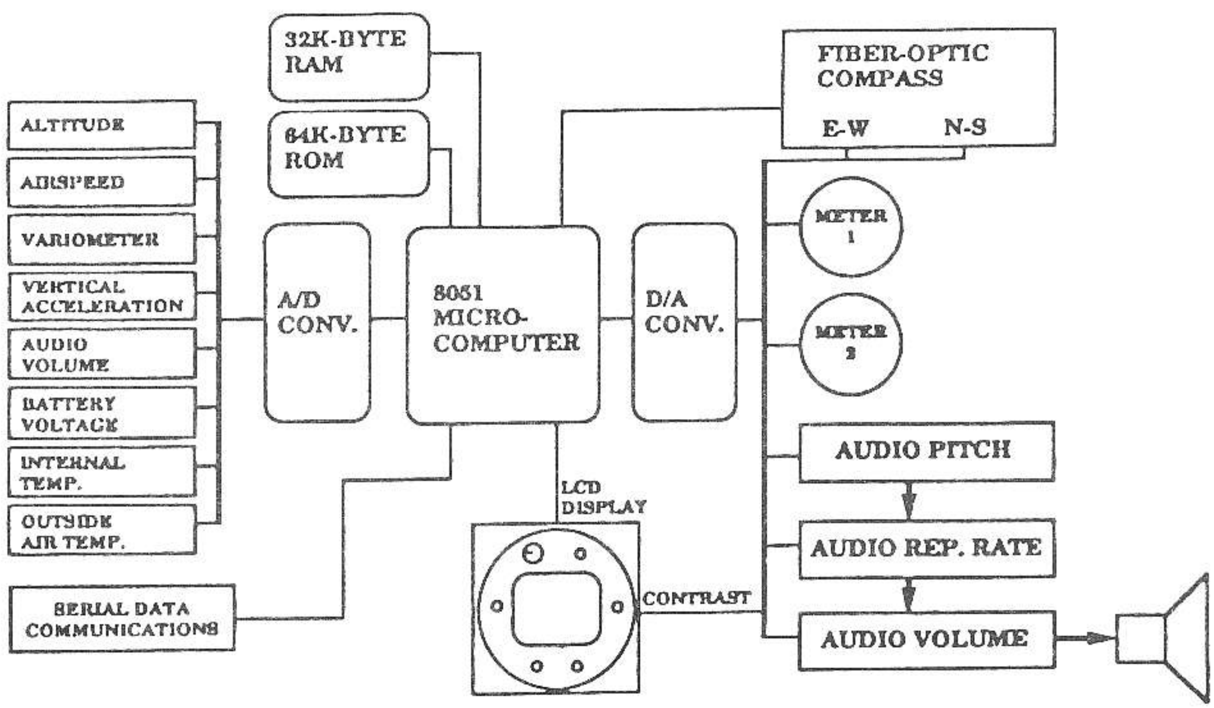


Figure 7. Block diagram of the S-NAV.

We further identified two conditions where reliable switching from circling to straight flight must be made:

a. Typical exit from a thermal into still air accompanied by an airspeed transition from below to above V_m.

b. Exit from a thermal into a cloud street or wave with lift. In this case, the pilot might well stay below V_m in cruising flight.

Exit switching must be avoided for all reasonable lift and maneuvering conditions during circling flight.

The final algorithm was formulated in terms of entrance and exit conditions for circling flight. The form of the equations is shown in table 2.

Entrance Conditions	Exit Conditions
$G > k_1$ for t_I	
$\cup$	
$G > k_2 \cap V < V_m$ for t_1	$G < k_2 \cap V > V_m$ for t_1
$\cup$	$\cup$
$G_{avg} > k_3$	$G_{avg} < k_3$

where $k_1 > k_2 > k_3$ and G_{avg} is G averaged over approximately one rotation of circling flight.

Table 2. S-NAV circling flight detection algorithm.

Flight performance

For ordinary thermal flight, the algorithm performs very well. The typical delay from initiation of the turn to switching is about 5 seconds. The delay on exit to cruise above V_m is also about 5 seconds. Equal delay on entrance and exit means that, to first order, the error in distance accumulation due to delay is cancelled.

In weak thermals with shallow bank angles, the delay in switching may be up to 10 seconds. Similarly, exit into lift below V_m may introduce extra delay.

Dolphin-style flight works equally well for reasonable maneuvers. Extreme maneuvers such as pull up to stall speed from V_{ne} may cause switch to the circling state. Even in this case, the circling state is exited within 10 seconds.

Wandering around the base of a loosely organized thermal also causes problems for any algorithm based on acceleration. If the sailplane is flown at bank angles less than 15 degrees for extended periods, the increase in G loading is too small to maintain the circling state.

The situations which may falsely trigger the automatic cruise/climb algorithm have an acceptably low probability of occuring during flights when speed optimizing has a higher priority than land-out prevention.

Summary

Over a 3 year period we have developed a sensitive accelerometer and a software algorithm to automatically detect circling flight in sailplanes. The results are available in a commercial Soaring Navigation Computer. The response from pilots who flew the system during the 1988 season has been very favorable.