DYNAMIC NETTO VARIOMETER

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Introduction

Today's soaring variometers are not much better than the ones made a decade ago. The measuring and displaying of the vertical air movement (and/or change in glider's total energy) hasn't seen a major improvement since the introduction of the audio signal. The same can be said about the speed command function. The most a pilot can expect is a choice between total energy, static netto, and classic theory speed-to-fly reading. Even the variometer user interface has remained the same – an analog gauge complemented by an audio signal.Of course, the accuracy and reliability of variometers has improved substantially over the last decade. Good temperature and altitude compensations are now standard, and the problem of zero drift seems to have vanished.

What can we expect from the future developments in the variometer and speed command functions? Is an "Acceleration Corrected Total Energy Variometer" going to be "the ultimate variometer," as proposed by Koerner [1]? Also, is the variometer user interface going to improve, and how? This paper tries to answer these questions, and suggests a possible direction of further variometer evolution. It explains the shortcomings of modern variometers, and proposes a Dynamic Netto Variometer (DNV) as a solution.

Types of Variometers

Before we elaborate on the proposed new variometer, we will review the features of the existing types. The following classification is based on the meaning of variometer reading:

1. Vertical Speed Indicator (VSI) is also known as uncompensated variometer. Ideally, it shows the absolute vertical speed of a glider.
2. Total Energy Variometer (TEV) shows the vertical speed equivalent to the rate of change of a glider's total energy. In other words, it compensates for the change in potential energy (altitude) caused by the change in kinetic energy (airspeed), thus eliminating so called "stick thermals."
3. Total Energy Static Netto Variometer (TESNV) is based on TEV with an additional compensation for glider's static sink rate, which is obtained from the airspeed and the static polar of the particular glider. Assuming a stationary level flight with $n \approx 1$ (n stands for the normal load factor), this variometer shows the vertical velocity of the air mass regardless of the airspeed.
4. Acceleration Corrected Total Energy Netto Variometer (ACTENV) is a total energy variometer compensated for glider's sink rate at any value of normal acceleration. The appropriate sink rate is calculated by taking into account the airspeed, the normal load factor n, and the glider's polar. This variometer shows the vertical velocity of the air mass in a maneuvering flight as well as in a steady glide. At the time of this writing, this type of variometer is not available on the market, although its design is only a little more complex than that of a computerized TEV or TESNV.

Some recent electronic instruments can show more than one type of reading, for example, TEV and TESNV.

We can also classify the variometers according to *how* they produce their reading, based on: Type of construction (Mechanic, Electric, Analog electronic and Digital electronic); Principle of operation (Volume, Mass and Pressure derivative measuring) and; Type of total energy compensation (TE probe, Membrane and Electronic compensation).

Variometer Errors

All variometers are generally affected by two types of errors – internal and external. The internal errors result from two basic factors:

1. Principle of operation – volume, mass and pressure derivative measuring variometers react differently to changes in temperature and altitude. It is possible to compensate for these errors electronically.

2. Quality design and the precision and reliability of components. There is no real remedy for bad design and cheap parts.

The external errors distort the pressure signals before they reach the variometer.

The following classification is based on the causes of the external errors:

a) Pressure sampling errors

1. Static pressure error.
This changes with the airspeed, the angle of attack and the yaw angle, aggravating the situation, because a variometer derives its reading from the rate of pressure change, rather than the pressure itself.

2. Error in the TE probe pressure coefficient will cause a TE based variometer to be over or under compensated.

3. Total (pitot) pressure error is usually negligible when compared to the previous two, except for extreme yaw angles.

The errors can be reduced by selecting a good TE probe and optimum locations for static ports and TE probe. When the errors are known, suitable compensation could be implemented through the use of Digital Data Processing (DDP).

b) Pneumatic damping errors

Pneumatic damping errors introduce time constants that both delay and distort pressure signals. These errors occur in the tubing connecting the variometer to the pitot tube, static ports and TE probe. Different lengths of tubes only add to this problem causing an error in both accelerated flight and when the velocity of the outside air changes (e.g. in turbulence). The errors can be eliminated by installing adequate gust filters or, numerically, through DDP.

c) Acceleration induced pressure tubing errors

These errors are caused by changes in the normal acceleration and by rotations and angular accelerations around all three axes, interpreted by the variometer as either lift or sink. They can be offset in part by suitable DDP algorithms.

d) Interference errors

Errors can also be caused by mutual interference between the variometer and the other instruments that are connected to the same pressure system.

This is only a brief list of factors that can reduce the accuracy of a variometer reading. For more detailed information, see references [2], and [3].

Type Dependent Operational Problems

a) Vertical Speed Indicator

Since it doesn't compensate for the airspeed changes, this variometer type is practically unusable during airspeed changing maneuvers; glider sink rate is shown together with the vertical air velocity.

b) Total Energy Variometer

Reading is affected by turbulence, wind shear and spatial lift gradient; sink rate is mixed with the vertical air velocity.

c) Total Energy Static Netto Variometer

Reading is affected by turbulence, wind shear and spatial lift gradient; doesn't correctly compensate for the sink rate in maneuvering flight ($n \approx 1$).

d) Acceleration Corrected Total Energy Netto Variometer

Reading is affected by turbulence, wind shear and spatial lift gradient.

It should be noted that the inclusion of glider sink rate into the variometer reading presents a problem only in cruising flight because a pilot's concern, once in climb, is to achieve the highest possible climb rate. A pure TEV is better suited for that purpose than any netto, because it directly shows the effective rate of climb.

The turbulence, however, is a problem in both cruise and climb. It can be alleviated by installing gust filters, but they increase the variometer time constant. Higher order filters and certain DDP algorithms can be used to reduce the turbulence "noise" to an acceptable level, without a significant increase in the response time [4].

Dynamic Effect of Spatial Lift Gradient

Everything mentioned so far is well documented in

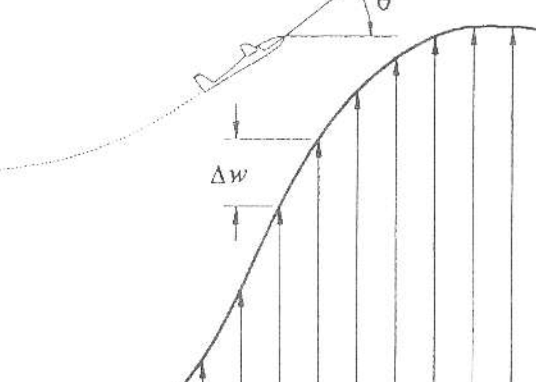

Figure 1. A typical thermal entry

w' [1/s]	v [km/h]	θ [°]	w_d [m/s]
0.02	100	10	-0.27
0.02	120	15	-0.57
0.04	120	15	-1.13
0.04	140	20	-1.98
0.06	140	20	-2.97
0.06	160	25	-4.63
0.06	180	30	-6.62
0.06	200	45	-9.44

Table 1. Magnitude of dynamic effect from spatial lift gradient

the existing variometry literature, except for one phenomenon – the influence of the spatial lift gradient (lift shear) on the total energy based variometer reading. Although the influence of the wind shear of the horizontal wind is acknowledged, the same effect is neglected in case of the vertical wind gradient.

A thermal, or any other type of updraft, can be viewed as a local wind in vertical direction. It usually possesses a distinct vertical wind gradient around its edge. The path incidence when entering and leaving a thermal can reach more than 30° above or below horizontal. In that case, a component of the vertical wind gradient will cause a change in the glider's airspeed, and that change will be reflected on any total energy based variometer. Further, as shown in Figure 1, the airspeed will be decreased by the vertical wind gradient. This will be shown on a TEV as a loss in total energy.

The difference in variometer reading caused by this dynamic effect (wd) can be calculated from the following formula [5]:

$$w_d = \frac{-v^2 w' \sin(2\theta)}{2g}$$

where v is the glider's true airspeed (TAS), $w'=dw/dx$ is the vertical wind gradient, θ is the path inclination angle and g is the gravity acceleration (9.81 m/s). Table 1 shows a few examples of how significant this effect can be on the reading of a TE variometer.

For instance, lift gradients of 0.06 s^{-1} (equivalent to 6 m/s per 100 meters), can be found around thermals in moderate to strong meteo conditions. Now, imagine pulling up into such a thermal at 160 km/h indicated airspeed (which is likely to be over 170 km/h TAS), and climbing at a 25° angle. The indication of a TE vario, with or without netto, will initially be reduced by 5.2 m/s due to the dynamic effect of lift shear. As the speed decreases, this effect will drop to 2.6 m/s at 120 km/h TAS. What makes this effect particularly adverse, is the fact that it occurs at the exact time when the decision is being made on whether to start circling or continue ahead.

The dynamic effect of spatial lift gradient cannot be treated the same way as the effects caused by turbulence (e.g. by filtering). The reason is that the updrafts are of much larger scale than the turbulence, so the duration of the lift shear dynamic effect can be a few seconds at the time. To cope with this problem, we would need a new type of variometer, capable of properly detecting and measuring the dynamic energy exchange. Its full descriptive name could be something like "Dynamic Effect and Acceleration Corrected Total Energy Netto Variometer." For the sake of simplicity we will refer to it as the Dynamic Netto Variometer (DNV).

DNV Design Objectives

A Dynamic Netto Variometer should be capable of performing the following tasks:

1. Showing the total energy exchange rate, with or without the dynamic effects resulting from turbulence, wind shear, and spatial lift gradient.
2. Separately showing the dynamic energy exchange (dynamic effect) arising from either spatial lift gradient, wind shear, or short period turbulence.
3. Showing netto lift clear of static and acceleration induced sink, and also clear of all dynamic effects.
4. Compensating for some of the external errors, primarily the acceleration induced pressure tubing errors and pressure sampling errors.
5. Implementing an improved speed command function.

DNV Block Diagram

A DNV has to be much more complex than any of the existing variometer types. The main reason is that the dynamic effect is not obtainable by direct measurements, but it has to be calculated by an intricate DDP algorithm. As shown in Figure 2, the input data for such calculation should, in addition to the usual variometer input, include normal load factor n (derived from normal acceleration), and flight path inclination θ.

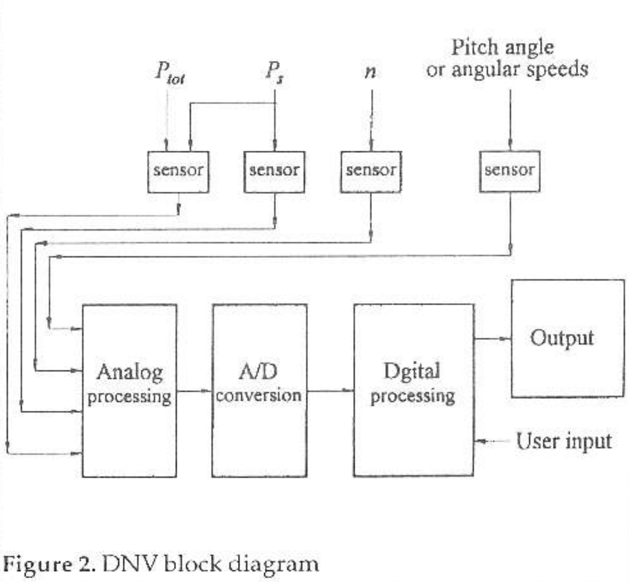

Figure 2. DNV block diagram

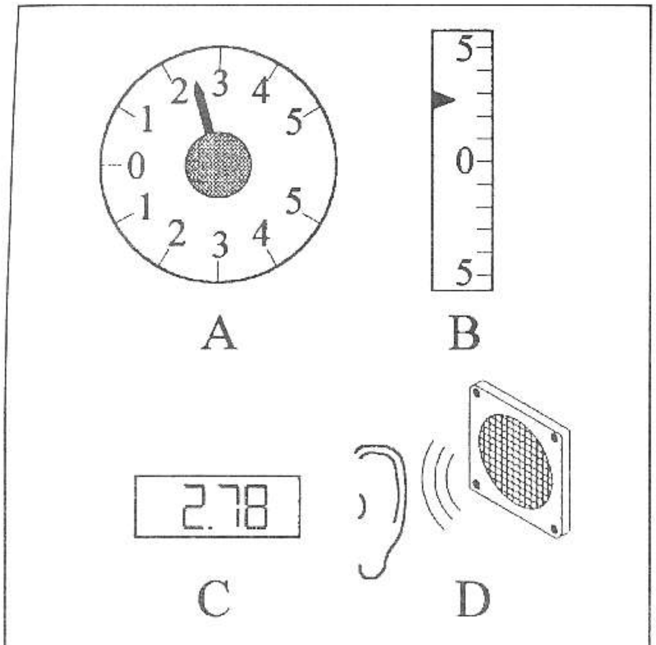

Figure 3. Existing types of variometer user interface

Normal acceleration can be directly measured by a relatively simple and inexpensive sensor. However, to obtain the path inclination, one has to use indirect methods, either measure pitch and bank angles by a gyro similar to the one found in attitude indicator, or measure angular velocities with rate gyros (as in turn and bank indicator).

Rate gyros are less expensive.

Speed Command

Since we are proposing a totally new type of variometer, this is a good opportunity to review the speed command function.

The speed commands that are built into today's variometers (and flight computers) are based on the classic MacCready speed-to-fly theory. The following are two major deficiencies of that theory:

1. It assumes that the updrafts drift with the prevailing wind at 100% of the wind speed. While this is usually true for thermals in light wind conditions, it is completely wrong in case of ridge lift and lee waves.
2. Any static speed-to-fly rule produces negative results when applied in a zone with a significant lift shear. For example, pulling up while the lift is increasing not only reduces the TEV reading, but also results in a real loss of total energy [7].

The first problem can be solved by taking the updraft drift into account. This can be done either exactly, as suggested in [6], or approximately.

To prevent the speed command from prompting the pilot to incur dynamic losses, the variometer has to be capable of properly detecting and measuring the dynamic effect. Therefore, this feature can only be incorporated into a true DNV.

User Interface

The existing ways in which variometers present the information to a pilot are shown in Figure 3.

The majority of pilots prefer the type A display, probably because of the way the human brain gathers and processes information. Judging by the fact that "a picture is worth a thousand words," the type A display is the most suitable for the purpose of quickly conveying the information to a pilot. Its reading can be quickly interpreted by observing the inclination of the needle, and there is no need to continuously read the numbers or to count the marks on the dial.

The currently available technology can be used to improve greatly the existing variometer user interface by employing a higher level of data processing in order to improve the quality and usability of the output, and by using graphic presentation to show a large quantity of data concurrently, in a way that can be easily perceived and understood by the pilot.

The proposed solution is to show the recent history of variometer reading in a form of a moving diagram. It is also suggested that different types of diagram should be used for cruising flight and for circling (Figure 4).

In the cruising mode, the display shows a diagram with the horizontal distance traveled on the horizontal axis, and the variometer reading on the vertical axis. Since the diagram always shows the last portion of the path, the curve on it moves with the speed proportional to the horizontal component of the airspeed. The length of the path covered by the diagram is adjustable by the pilot. Such real-time diagram provides a much more complete picture than a simple variometer gauge. A pilot can observe the current reading, its tendency and

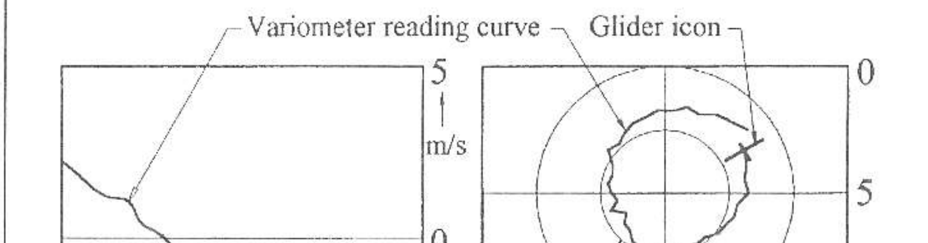

Figure 4. Graphic variometer display

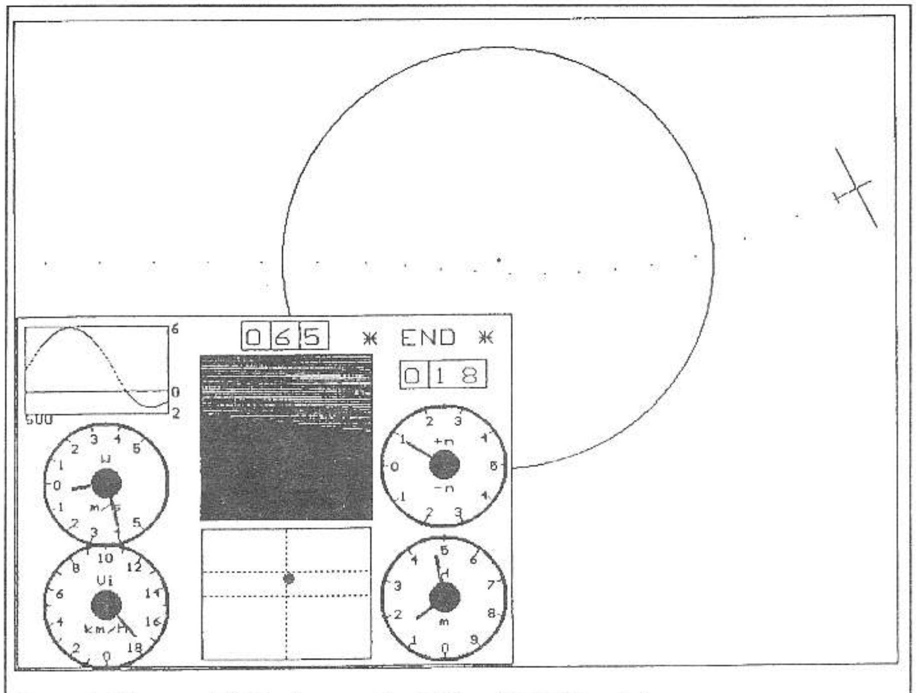

Figure 5. 18 second flight done on the Glider Flight Simulator

its recent history, all at a mere glance.

The circling mode display shows whether the thermal is properly centered, and if not, to indicate the location of the center (or centers), and is drawn in a polar coordinate system. The curve shows the recorded variometer readings during the last full circle. A small icon of a glider can be drawn at the current position. With this kind of display, the pilot can dedicate less time and attention to monitoring the instrument, and more to other important activities.

Design and Testing Requirements

In order to develop a DNV, one has to design and test both hardware and software components that will be implemented. A substantial part of that work can be done through computer simulations of the variometer operation.

These require large amounts of data representing the continuous input of the actual instrument. The data should reflect different flight modes in different meteorological conditions, and various measurement errors. In order to obtain the input data for the variometer simulations, one can rely on either in-flight measurements or computer flight simulation. The simulations offer several advantages, namely:

1. In-flight measurements are time consuming, costly and require expensive equipment. On the other hand, once a suitable software for flight simulations is developed, the cost of using it is minimal.
2. The atmospheric environment in which the in-flight measurements are done cannot be controlled. Therefore, some special cases like strong turbulence and radial component of thermal lift, may never be investigated.
3. In-flight measurement contain embedded errors that usually cannot be isolated. In computer simulations, the effects of external errors can be very precisely determined.

Variometer Simulation Software

Variometer Simulation Software (VSS) package has been created by CuSoft, to facilitate the development of a DNV. The VSS package includes Glider Flight Simulator (GFS) and Variometer Simulator (VS) PC based programs.

The main purpose of flight simulations made with GFS is to produce input data for the VS program. GFS can perform real-time interactive 3-D flight simulations with adjustable time increment and precision. The simulated atmospheric environment can include thermals of different strengths, widths and shapes, with optional radial air flow in or out of the thermal center. It can also simulate random 3-D turbulence with adjustable maximum strength and mean wave length.

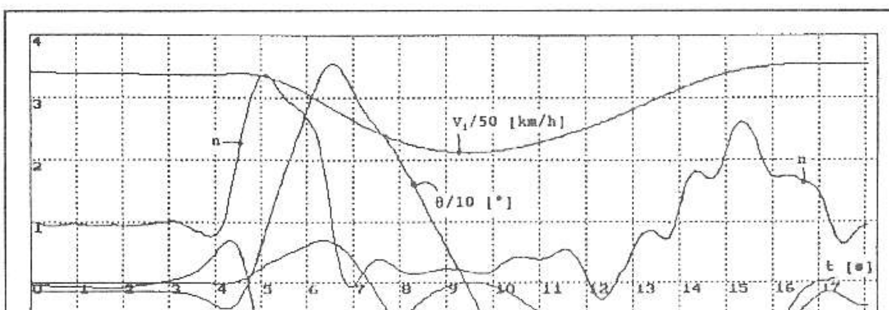

Figure 6. Selected flight variables during the simulated flight

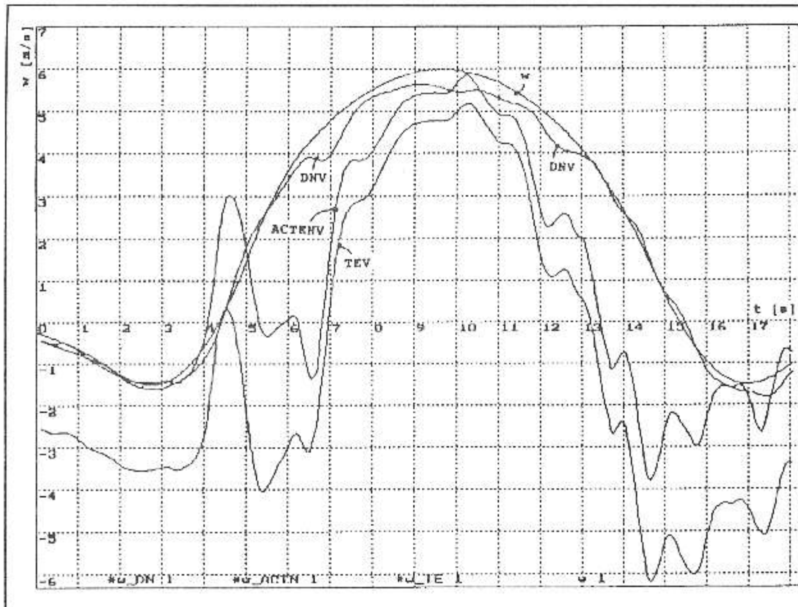

Figure 7. TEV, ACTENV and DNV readings; smooth thermal

The GFS user interface features a top view of the flight area and a scalable instrument panel, complete with a graphic variometer display and an audio signal. As a result, GFS can also be used to test and optimize the DNV user interface even before building the prototype.

GFS can output the values of some 80 different flight variables into a text file for subsequent display and processing by VS. Among these variables are total, static and TE probe pressure signals, which can optionally include acceleration induced pressure tubing errors.

The VS program is the actual test-bed for different DNV algorithms. Its input can be either a GFS output file, or flight measurement data converted into appropriate text file format. VS provides means of introducing additional errors and time constants into input signals, in order to determine variometer response in real-world conditions.

Sample Results

We will illustrate the qualitative jump provided by the DNV by a few sample results obtained from the Variometer Simulator program. The input data were taken from an 18 second flight made on the Glider Flight Simulator, with the sampling rate of 20 times per second (0.05 second time interval).

The simulated flight was made with a standard class glider (DG-300) with the pitot tube in the nose, the static ports on the sides of the cockpit and the TE probe mounted on the vertical fin. The wing loading was 33 kg/m^2 and the starting altitude was 1500 meters. The flight traversed a thermal with a parabolic cross-section, the diameter of the updraft zone of 400 meters and the maximum updraft velocity of 6 m/s in the thermal center.

Figure 5 shows the Glider Flight Simulator screen picture at the end of this flight. The flight path is indicated by a series of dots in the top view of the flight area. The dots are plotted at one second intervals. The big circle indicates the thermal edge. Note that the projection of the glider is blown up approximately 7 times relative to the scale in which the thermal and the flight path are shown. Also shown is the program's instrument panel with the graphic variometer display in the top left corner.

Figure 6 shows a time diagram of the flight parameters during the simulated flight. V_i is the indicated airspeed, n is the normal load factor, θ is the path incidence angle, Φ is the bank angle and w_d is the dynamic effect of the spatial lift gradient. The diagram applies to the case without turbulence or radial thermal component. Note that the airspeed generally follows the speed-to-fly suggested by the classic MacCready theory. As a result the dynamic effect is mostly negative, with the total dynamic loss equivalent to the loss in altitude of around 22 meters.

The diagrams in Figures 7 through 9 show the simulated readings of TEV, ACTENV and DNV during this flight, compared with the actual vertical speed of the air w. All measurements include the acceleration induced tubing errors. The total energy is derived from the static and the total pressure in all diagrams.

Some of the diagrams include the turbulence effects.

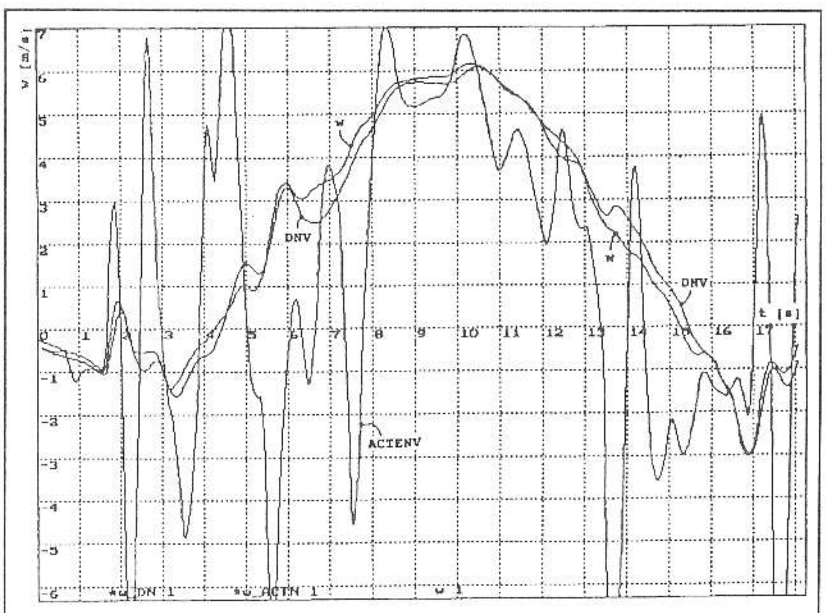

Figure 8. ACTENV and DNV readings; with turbulence

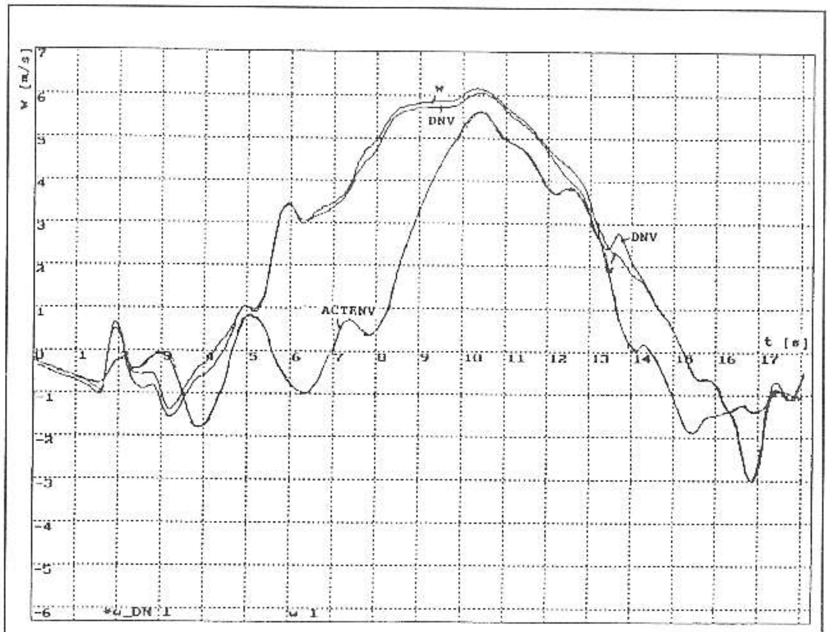

Figure 9. ACTENV readings; with turbulence; input Tc = 0; tubing error correction; second order gust filter; output Tc = 0.75 s; DNV readings; with turbulence; input Tc = 0; tubing error correction

In these, the maximum speed of both horizontal and vertical gusts is 2 m/s, and the mean wave length of the gusts is 50 meters.

In Figures 7 and 8 the input time constants (Tc) of all the measurements are set to 0.1 second, while the output Tc is zero. In Figure 9 the input Tc is zero, and for ACTENV readings an output Tc of 0.75 seconds.

The presented diagrams clearly demonstrate that adding the compensation for the normal acceleration (as in ACTENV) doesn't improve much upon the ordinary TEV or TESNV. The effects of the pressure measurement errors, turbulence and the spatial lift gradient can be dealt properly only by the DNV, while TEV and ACTENV have to resort to various filters in an attempt to neutralize them. For example, Figure 9 shows that in order to produce an acceptable (but far from ideal) indication, the ACTENV has to employ compensation for tubing acceleration errors, a smart numeric gust filter and a 0.75 second time constant, while in case of a DNV, the optimal output is obtained with only the acceleration induced tubing error compensation, without any need to introduce extra time constants into the system.

Current DNV Development Status

Dynamic Netto Variometer is being developed as a joint venture between CuSoft Research Inc. and Varcom Sailplane Computers. In the initial phase, the mathematical model and algorithms for the DNV were developed and refined with the help of the VSS package. Numerous simulations have been performed, resulting in refinements to the original DNV algorithms. So far, the tests have demonstrated a clear superiority of the DNV over all other variometer types. The proposed new graphical output has been interactively tested using the GFS program with encouraging results. A prototype of a DNV is currently being constructed, and is expected to be flight tested in 1994.

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