Vario and instantaneous wind measurement using sensor fusion and digital signal processing

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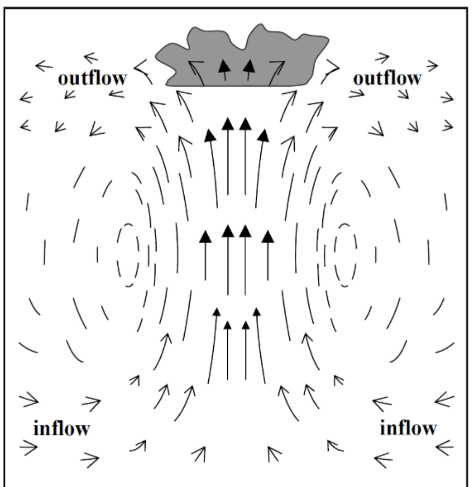
Knowing where the wind is blowing from

For the glider pilot, it is essential to know how the air mass is moving in its surroundings. Today's TEK Varios work very well for measuring vertical airmass movement as long as the airplane's speed is approximately constant, e.g., when circling. To prevent energy conversions due to “stick thermals” from being incorrectly displayed as rise or fall values, the Vario must be well compensated. However, horizontal changes in airmass movement, i.e., horizontal gusts, are interpreted by the TEK Vario as false climb or sink values. We will discuss this limitation in principle for physical reasons in more detail later.

As important as the vertical movement of the airmass is the horizontal component, which we commonly refer to as wind. Especially in mountain flying, slope flying and wave flying, pilots appreciate the wind information that is precise to the second. But the wind information is also very important for lowland pilots to find and center the thermals. Dinges showed this very clearly in an OSTIV article (Figure 1).



Figur 1 Inflow und outflow in der Umgebung eines thermischen Aufwindes

Figure 1 Flow conditions in a thermal bubble (Source: Dinges)

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The wind calculation

How do we get wind information in the aircraft and why haven't we had an accurate real-time display of the wind for a long time? The reason is that the wind estimation algorithms known today require a very long averaging time. They can only estimate the average of a constant wind and are therefore of very limited use.

The electronics available today (see box) allow wind estimation based on the wind triangle that every student pilot knows in his training (Figure 2).

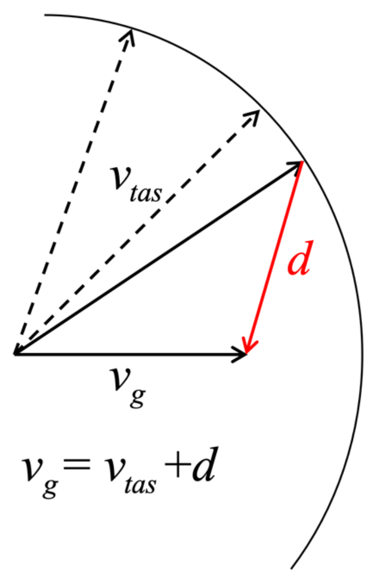


Figure 2 Wind triangle

The groundspeed vector v_g can be determined with the help of the GPS. With a magnetic sensor the direction of the true airspeed vector v_{tas} can be determined, the length of the v_{tas} vector we get from the dynamic pressure. The wind vector d is obtained by subtracting v_g - v_{tas}. The weak point of this type of wind determination is the magnetic sensor: this is very prone to electronic interference fields that cannot be compensated. Moreover, the geomagnetic field model is of limited accuracy. The errors of the magnetic sensor therefore quickly lead to large errors in the wind estimate.

The task is therefore: can the wind be determined without a magnetic sensor? Mathematically this means that only the length of the vector v_{tas} is known. One immediately sees that the determination of the wind vector d from the wind triangle is impossible. All vectors v_{tas} of the same length lie on a circle. Consequently, there exist any number of possibilities to satisfy the triangle equation.

However, if we consider two wind triangles shifted in time, things look completely different. If we assume for simplicity that the wind d is constant, there is only one solution for both wind triangles. For those interested in mathematics, the graphical solution is shown in Figure 3.

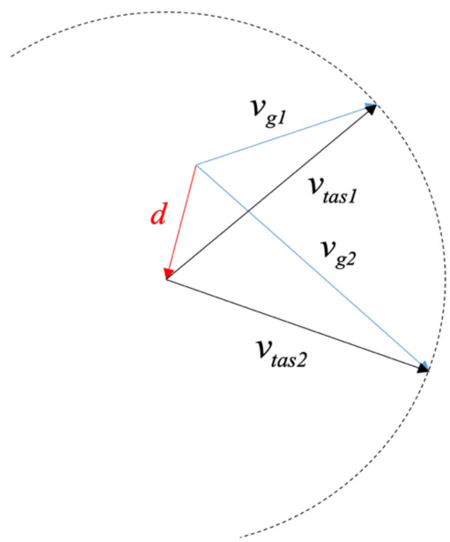


Figure 3 Determination of wind d by means of two wind triangles

In Figure 3, we assume that the magnitude of the vectors v_{tas} is the same in both triangles. Therefore, the endpoints of the two vectors v_{tas} must lie on the circle. The sum $d + v_{tas}$ is equal to the groundspeed v_g in the respective triangles.

To determine the wind, one could now proceed in principle as follows, see Figure 4. One calculates a value of the wind from each of two successive wind triangles. The estimated values of the last L (in Figure 4, L=4) are averaged.

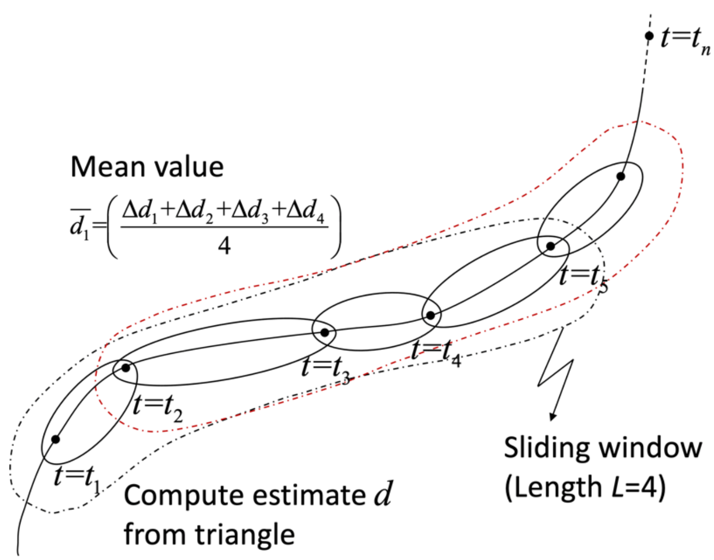


Figure 4 Heuristic algorithm for determining wind vector d

The problem of this solution is obvious. How many pairs of triangles should one process in the sliding window? How to determine the accuracy of the estimated values? The larger the sliding window, the greater the accuracy (since the errors of the individual estimated values cancel each other out on average). The precondition is that the true value of the wind in this window changes only slightly. On the other hand, one wants to keep the length of the window as small as possible to be able to follow changes of the wind. A compromise will therefore have to be found between the two contradictory objective functions of "accuracy" and "rapid rate of change".

However, the task is far more complicated. We have not considered vertical airmass movement.

The 3-dimensional wind triangle

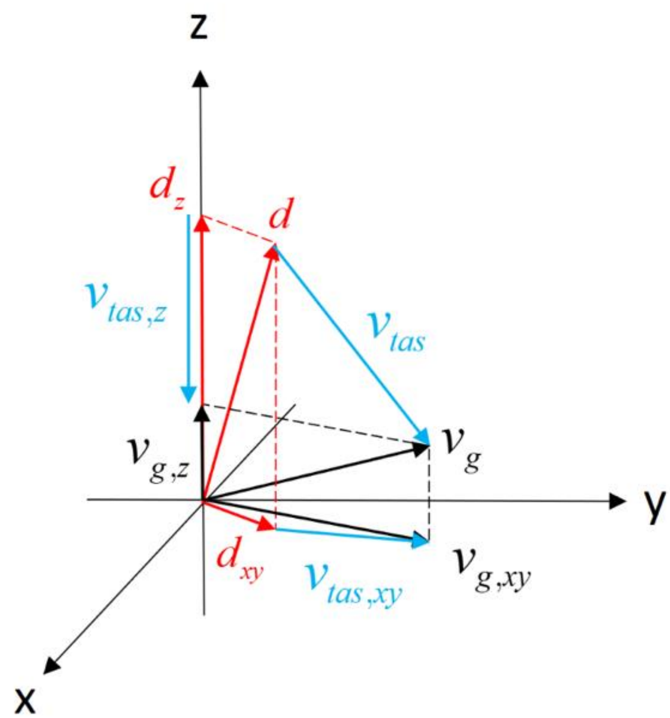


Figure 5 The 3-dimensional wind triangle

The airmass dynamics are three-dimensional. We must therefore extend our consideration to include the vertical dimension. For this purpose, we introduce the three-dimensional wind triangle, see Figure 5. All vectors now have three components. The projection of the wind vector onto the (x, y) plane is what we commonly refer to as "wind" in aviation. Using the same term for a three- or two-dimensional vector bothers the mathematician. Which vector is meant, however, should be clear from the context. The vertical wind component d_z corresponds to the "net climb" of the Vario. The two vectors v_g and v_{tas} have a z-component. The vertical component $v_{tas,z}$ is equal to the sink rate, $v_{g,z}$ is equal to the "real" climb rate of the airplane.

Problem, defined how to proceed?

The task is defined. How should we proceed in solving the problem? Here Immanuel Kant should be quoted: "There is nothing more practical than a good theory. "

Communications engineers have long since embraced this. Today's mobile communications technology operates very close to the information-theoretical limit. Very succinctly, this is captured in the sentence,

„We trade physical quantities (power-, bandwidth efficiency) versus signal processing complexity. “

Applied to three-dimensional wind measurement, this means that we design an algorithm that provides the most accurate wind indication possible (for all three dimensions), which can also follow rapidly changing wind vector changes ("second-by-second wind measurement"). The algorithm should estimate all three components together and not separate the vertical and the horizontal components. Mathematical system theory also answers the question under which conditions wind estimation is possible. In the limiting case of an exactly straight-line flight motion and perfectly calm air, this is not possible. All triangles are identical. However, we could show (Huang und Meyr) that the random changes in the *airmass movement* are sufficient to make the system "observable". In mathematical system theory, observability means that the state of the system can be determined from past measurements.

The algorithm we use is the Extended Kalman Filter (EKF), named after R.E. Kalman, who published the algorithm in 1960 (Kalman). The Kalman Filter is one of the most fundamental algorithms in digital signal processing; without the EKF, no *spacecraft* would have landed on the moon.

How does the EKF work?

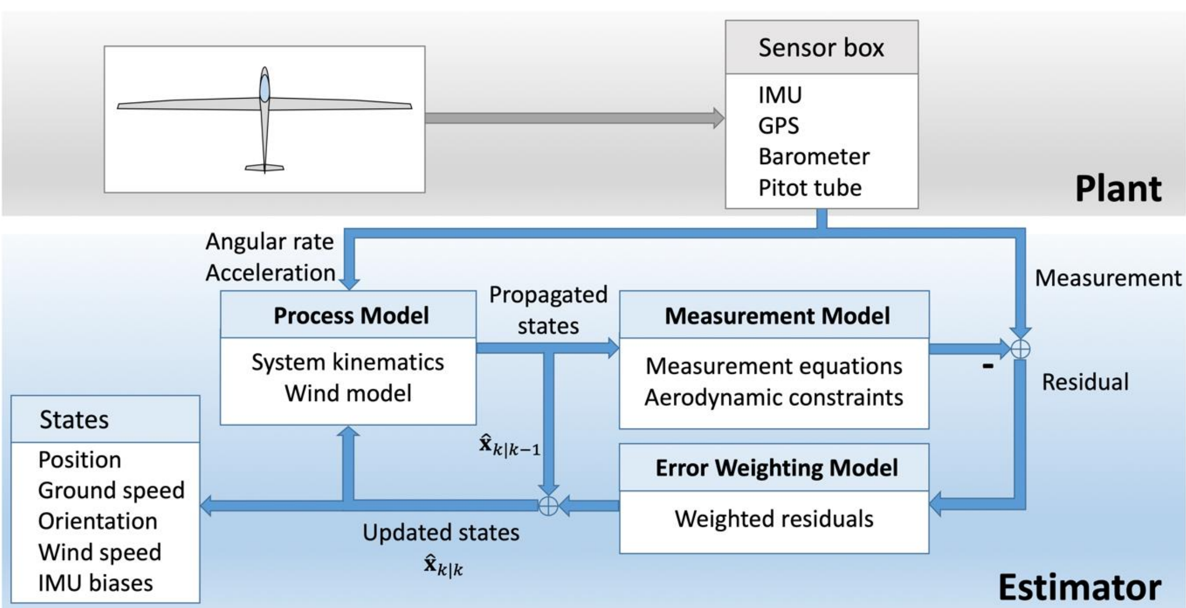


Figure 6 Sensor Fusion: Principle of the Extended Kalman Filter

The **HAWK** unit consists of an ARM processor and a sensor unit. The computer runs a *mathematical model* of the aircraft kinematics, airmass movement and sensor imperfections in real time. The model contains the state variables, such as the position *p*, the groundspeed v_g, the wind speed *d*. The model calculates these state variables in real time. The sensor box contains the following sensors: GPS, pressure sensors for static and dynamic pressure and an IMU (inertial measurement unit) with a three-axis accelerometer and a three-axis gyro sensor (angle changes). Depending on the sensor, signals are processed at a clock rate between 10 and 100 Hz.

The explanations in the following section are intended for the "techies". The other readers can skip them to the text block " It is clear that...".

The recursive calculation process consists of two steps. At the output of the *measurement model* are the expected measurement values. These are compared with the real measured values from the sensor box (IMU, GPS, static pressure, dynamic pressure). The errors (residual) are weighted in the *error weighting* block and added to the value $x_{k/k-1}$. The result $x_{k/k}$ is the estimated value which has processed all information of the sensor signals up to the time k. This step is called *measurement update*. From the corrected estimated value, a new value $x_{k+1/k}$, called prediction value, is predicted in the *process model*. The process model contains the a-priori information how the system is most likely to behave. This step is called *time update*. If the aircraft, e.g., a commercial airplane, flies only very flat turn the *values* will be well predicted with high probability. The Kalman filter calculates not only the prediction value but also its statistical accuracy (the variance).

It is clear that the Kalman filter is balancing between the a priori information of the process model (how trustworthy is the prediction?) and the accuracy of the sensors. If the sensors are very accurate, it trusts the measurement and overrules the prediction values. If the sensors are inaccurate, it relies on the prediction.

Due to the mathematical dependency of the variables, it is possible to estimate quantities that are not directly measured. There is no sensor for the three-dimensional ground speed v_g or the likewise three-dimensional wind speed *d*. A mathematical link exists, for example, between the speed and the position. The position change is equal to the product of speed and time interval. Consequently, an estimate of the speed is obtained indirectly from the measurable position.

There is only one dynamic pressure sensor, which is linked to the amount of v_{tas} (true airspeed) via a quadratic function, but gives no information about the direction of the velocity vector. But how can we still determine the direction of the velocity vectors? Answer: With the help of the three-dimensional wind triangles, as explained in the section on wind calculation. The prerequisite is that one chooses the variables in the EKF in such a way that this is possible. This choice is a very challenging mathematical task.

Figure 6 shows that there is a difference between the physical value and the estimated value. This error (residual) is processed in the EKF so that the corrected estimated value is as close as possible to the (unknown) physical value. Important: each individual error always corrects all state variables; this can be explained on the basis of the mathematical links. Practically, this means that no unreliable magnetic sensor is used. This would distort all estimated values, as experience with an earlier device has taught. The result is the same as when cooking a sophisticated dish: if the dish is salty, no matter how perfectly seasoned, it is still inedible.

The weighting of each sensor error signal is not discretionary, but is calculated based on the model parameters, the mathematical linkages of the state variables, the sensor accuracy, and the likely changes in flight trajectory, so that the root mean square error becomes minimal. For the correct application of the **HAWK**, it is important to understand what is meant by this statement.

This will be illustrated by the example of the vario signal. The pointer of a variometer oscillates randomly around a mean value. It should be noted: at each point in time the displayed value is the "best" value due to the optimal processing of all measured values of the past. Further averaging of the pointer deflection or the use of a smart filter only distorts this value, even if one subjectively believes that certain peaks belong to be "filtered away". We will go into this (perhaps disturbing) point in more detail when discussing the experimental data.

The fundamental property of the EKF - namely, that the error signal (residual) from a single sensor simultaneously corrects all state variables - makes testing very costly and challenging. Flight-only testing is far too lengthy and expensive. For this reason, we have built a MATLAB-based design environment. This allows us to record the sensor signals during the flight and later in the lab to analyze the algorithm in different configurations and possibly find sensor failures and reasoning errors. It is fascinating to "re-fly" the flights and analyze them.

The Wind Model

The EKF requires a mathematical model of the three-dimensional wind vector. The wind vector *d*(x, y, z; t) depends on the three spatial coordinates (x, y, z) and the time t. The wind field is described by very complex mathematical equations. For our purposes it is sufficient to use a greatly simplified model.

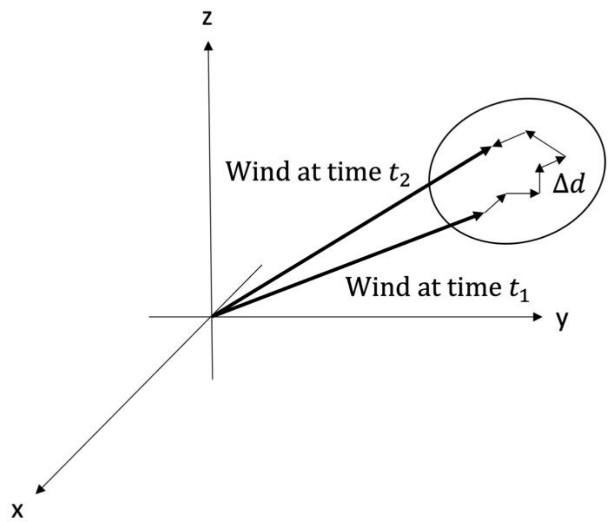


Figure 7 Time evolution of the wind vector

We assume that the wind vector consists of two elements: a slowly varying component and a rapidly varying random perturbation (Figure 7). From this we infer that the more turbulent the airmass movement, the larger the random increment. The three wind components are assumed to be mathematically independent. All three obey the same mathematical law.

The perspective representation of a three-dimensional vector on the display is not useful for glider pilots. Glider pilots are used to reading the vertical component of the vector on the Vario and interpreting the x-y components as "wind".

For an intuitive understanding of the model, we limit ourselves to the vertical component. We are used to interpreting the climb rate of the variometer by the movements of the pointer. For this reason, we consider the increment over a time interval of 1 second (Figure 8).

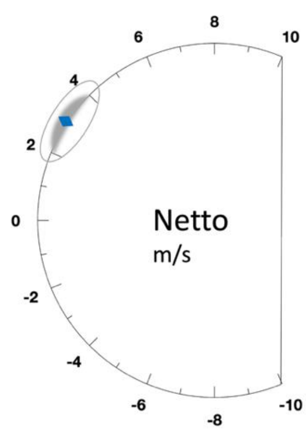


Figure 8 Display of the vario pointer, gray: the pointer fluctuations

In Figure 8, the variometer shows a value of 3m/s. This value corresponds to the slowly varying part of the model. The rapidly varying, random part corresponds to the fluctuations of the pointer around the mean value. The pointer fluctuations are Gaussian distributed, see Figure 9. The parameter standard deviation, σ_d determines how likely an increment around the mean of 3m/s is. For example, σ_d =1 m/s states that 68% of all changes are in an interval of 1 m/s. The value σ_d = 0.1 corresponds to a very calm air mass-most changes will lie in an interval of 0.1 m/s.

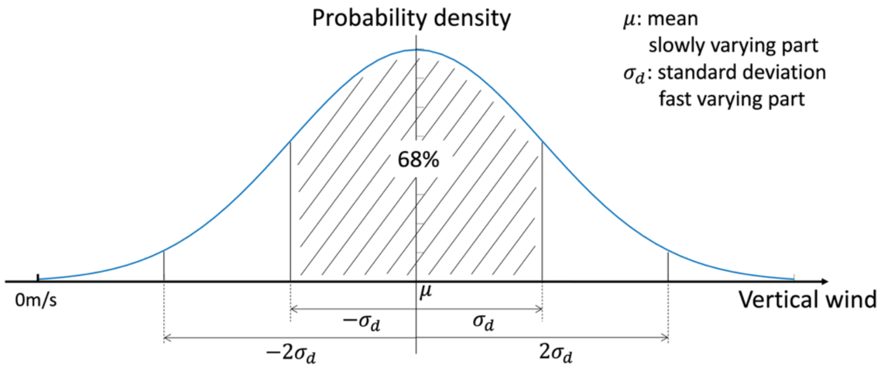


Figure 9 Gauss distribution of pointer fluctuations

Discrepancy between model and measurement

The true value σ_d is unknown to the instrument. The key question is therefore: how to choose the parameter value in the instrument to make the display usable? The only way is to use the same sensor signals for different values of the adjustable instrument parameter SIGWIND to analyze the behavior of the EKF. We can do this because the sensor signals are recorded at 100 Hz during the flight. The program code of the EKF in the laboratory is identical to the program code in the instrument.

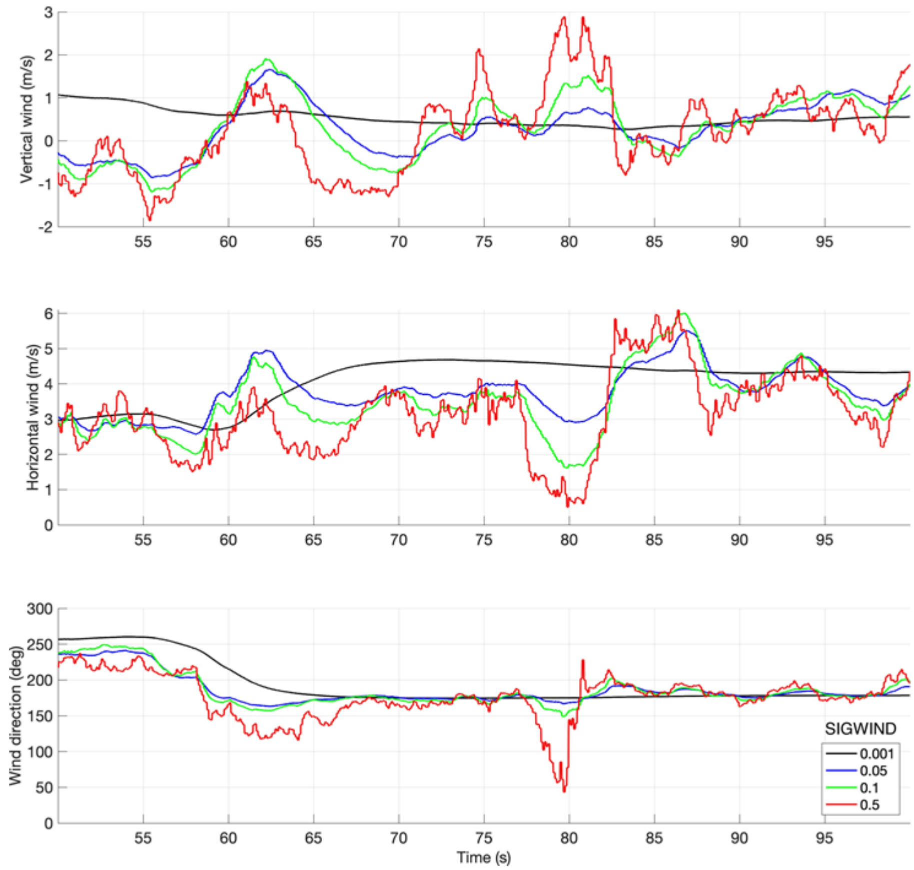


Figure 10 Behavior of air mass movements vertical and horizontal velocities and direction with different SIGWIND values (0.001, 0.05, 0.1, 0.5)

For example, let us assume a plausible value of SIGWIND = 0.1 for the (naturally unknown) model value. If we now select a very small value of SIGWIND = 0.001 (black curve), the algorithm averages the estimate since it considers large deviations as highly unlikely and therefore suppresses them. The behavior corresponds approximately to a Vario display with too large time constant. If we now assume a value that is much larger, namely SIGWIND=0.5 (red curve), the algorithm reacts very quickly to every change (corresponding to a very nervous vario display). The value 0.05 (blue curve) gives a subjectively usable display.

The test flights showed that the choice of the wind parameter is not very critical. Most pilots chose a value between 0.05 and 0.2. The value of 0.07 was the most common value.

Experimental results

The HAWK has been tested by several pilots over the past year. Here are some interesting analyses from those flights. First a flight by K. Ohlmann on the slope of the Chabre in weak conditions (Figure 11 and 12):

Comment von Klaus Ohlmann

‚Bei zunächst sehr müden Hangaufwinden konnte man sehr schön direkt ablesen wo es gerade noch ging, weil ein bisschen Wind, und wo nicht, da Wind zu schwach. Hangwind an der Chabre, gemischt mit Thermik mit sehr mäßigem Nordwind und dann unter Cumuli schwacher Ostwind an den Südosthängen bei Orpierre. Das sollte gut im ersten Log sichtbar sein.'

‚With initially very tired slope winds, one could read very nicely directly where it just worked, because of a weak wind, and where not, because the wind was too weak. Slope wind at the Chabre, mixed with thermals with very moderate north wind and then under cumuli weak eastly wind on the southeast slopes near Orpierre. This should be well visible in the first log.' (translated)

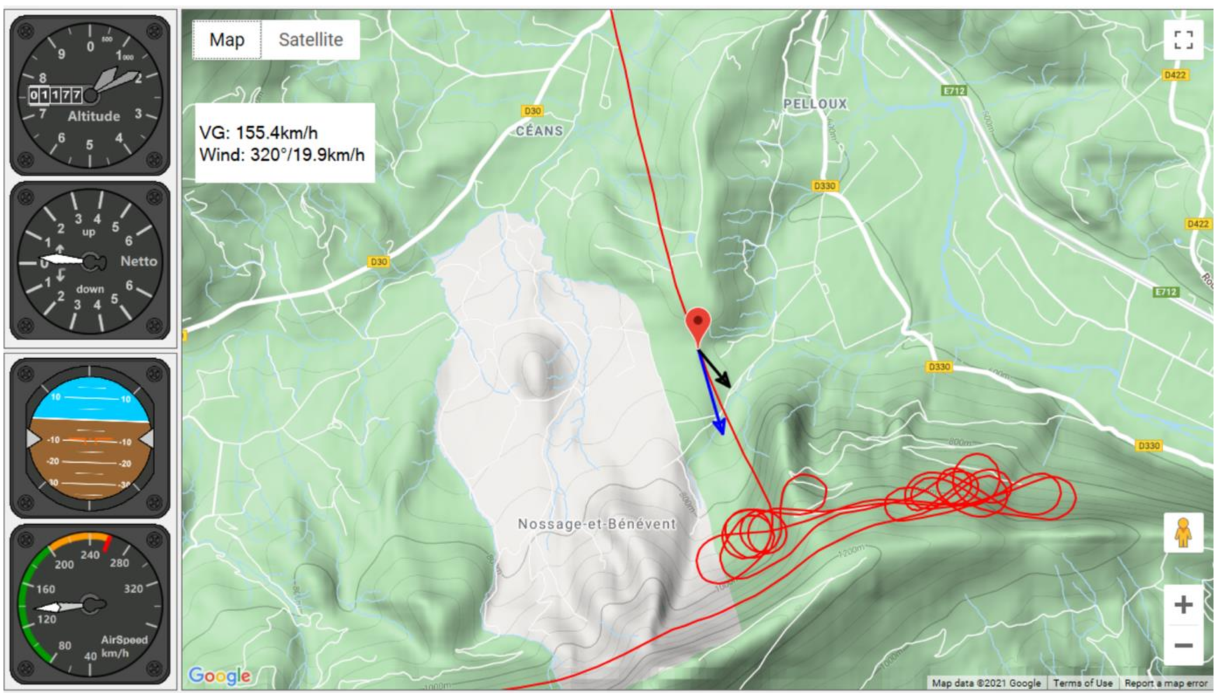


Figure 11 Flight of K. Ohlmann on 31.08.2020 from Serres

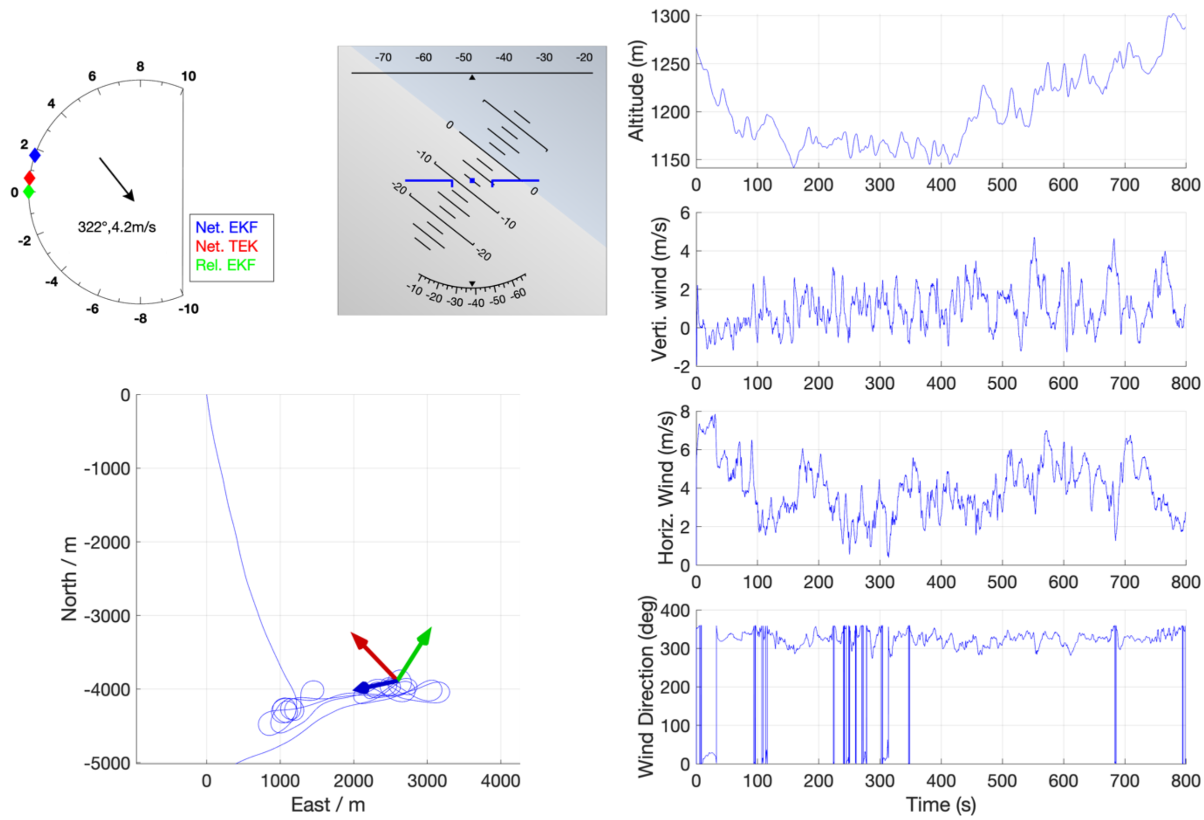


Figure 12 Altitude, vertical wind speed and horizontal wind reflects Klaus's statements on the weak winds

The same flight nicely showed the Venturi effect in the valley southeast of Serres (Figures 13 and 14).

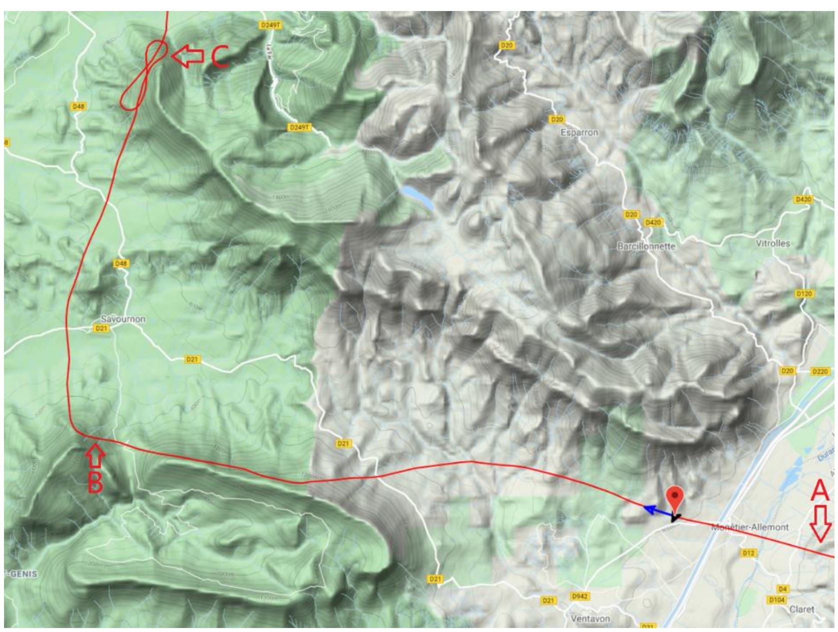


Figure 13 Approach from the Durance to Serres

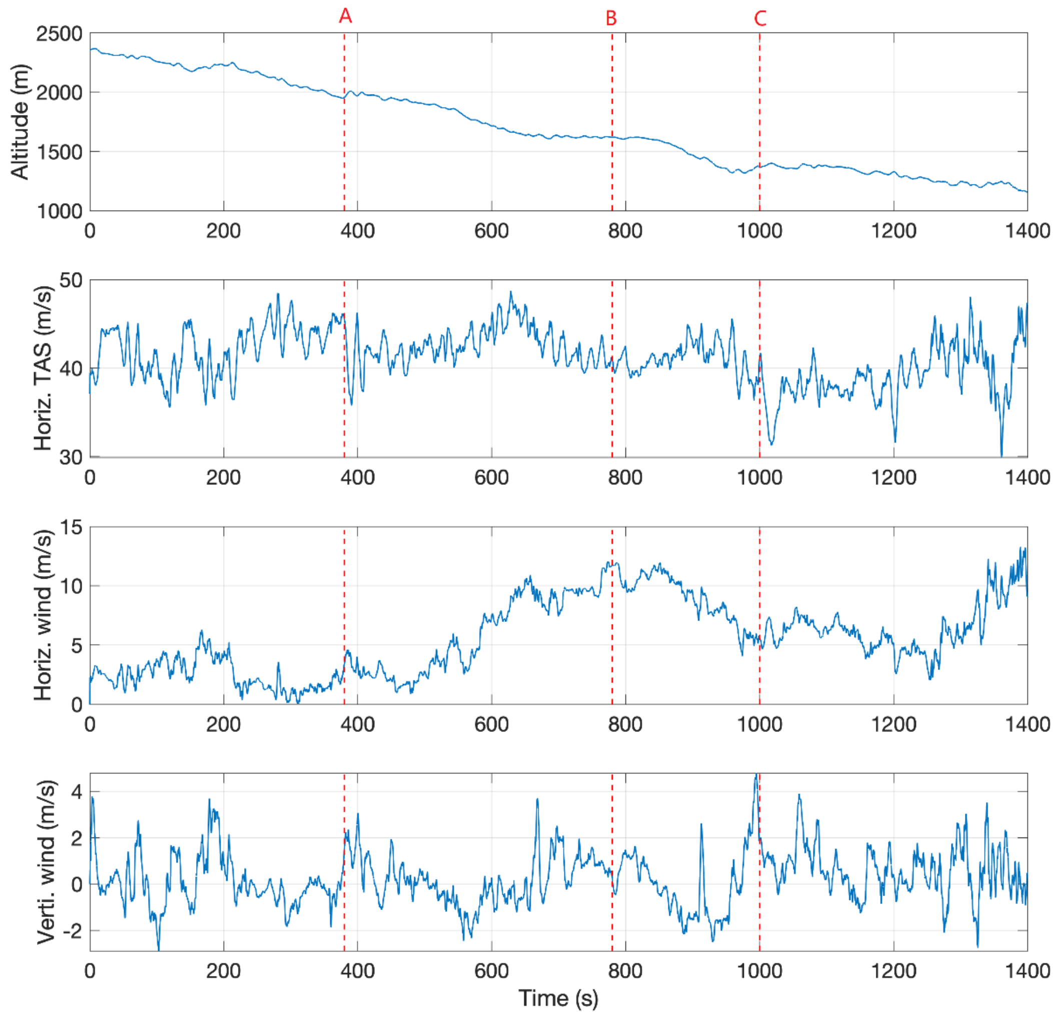


Figure 14 Approach from the Durance to Serres

Quote Klaus Ohlmann

‚Der zweite Log zeigt sehr schön den Anflug von der Durance nach Serres mit der bei Nordwind typischen ausgeprägten Windzunahme und Westdrehung im Venturi zwischen der Badewanne und der Crete de Selles. Wirklich phantastisch dieses Phänomen life im Instrument mitzuverfolgen. Neben der aktuell wertvollen Information zum Anfliegen des richtigen Hangs ergibt sich damit eine ausgezeichnete Möglichkeit die komplexen Strömungsverhältnisse im Gebirge zu analysieren und zu verstehen. ‘

‚The second log shows very nicely the approach from the Durance to Serres with the strong wind increase and west turn in the *Venturi* between the bathtub and the Crete de Selles, which is typical for north winds. Really fantastic to follow this phenomenon live in the instrument. In addition to the currently valuable information for approaching the correct slope, this provides an excellent opportunity to analyze and understand the complex flow conditions in the mountains. *‘ (translated)*

Comparison of TEK and EKF

The TEK Vario and the EKF measure the same physical quantity, but with completely different measurement methods. Therefore, for a meaningful comparison of the results, differences in the measurement methods must be addressed.

A conventional TEK measures the vertical airmass movement, based on the law of conservation of energy. In perfectly still air, a change in kinetic energy (velocity) is compensated by an exactly equal change in potential energy (altitude). If you pull the stick and therefore the airplane climbs, the pointer remains at zero. The TEK Vario is perfectly compensated. Note that we have neglected the small sink rate of the glider in this statement.

However, even a perfectly compensated TEK shows us horizontal wind changes (gusts) as climbing (if the wind shear is positive) or sinking, although there is no vertical air motion (Figure 15). These false indications are due to the measurement method (one-dimensional energy conservation) and cannot be compensated.

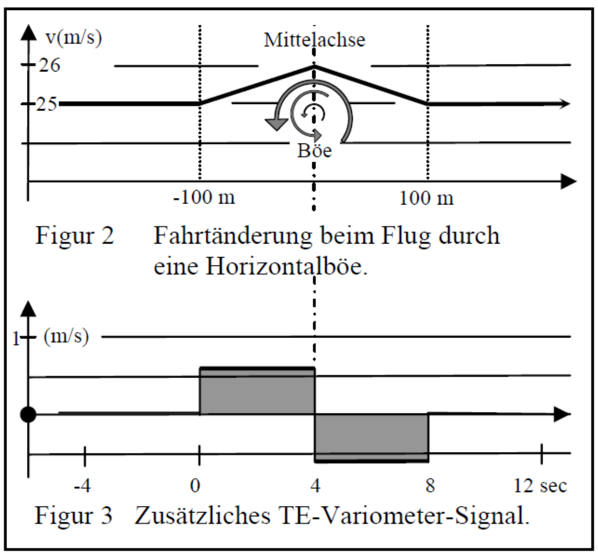


Figure 15 Deflection of the TEK-Varios while flying through a horizontal gust (Source: Dinges)

The EKF estimates all three dimensions of air mass movement simultaneously. It is designed to correctly process time-varying air masses. When flying, this is the decisive advantage of the "EKF Varios". If the EKF indicates a climb during fast forward flight, the indicated climb value is equal to the climb of the vertical airmass, independent of the speed of the aircraft and horizontal speed or flight path changes.

From what has been said, it follows:

- Because of the systematic error of the TEK, a comparison of the two Varios in the transition from fast straight flight to circling is not meaningful. Every good pilot has learned through much practice to "correct" the errors of the Vario in his head.
- The "EKF Vario" does not need compensation. This is an advantage in practice.

Figure 16 shows the HAWK (blue) and TEK (red) vario displays when circling in an ASH25 in a weak, rough updraft.

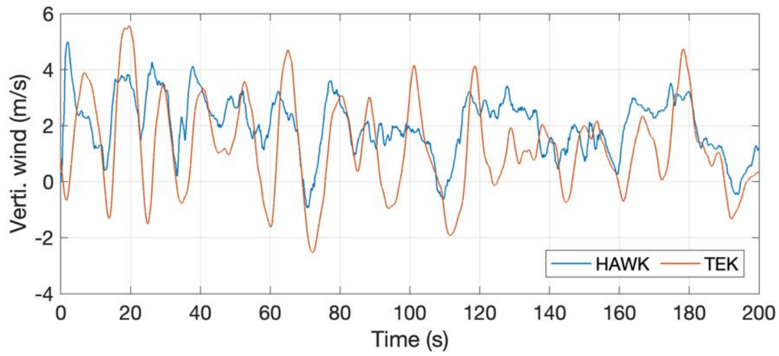
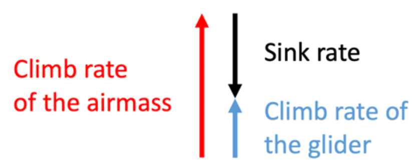


Figure 16 Comparison between TEK and EKF: the estimated or measured values of the airmass movement

Average values in the shown period of 9.0s and 201.3s

Average climb rate of glider (v_g):	0.6 m/s
Average Netto d_z (EKF):	2.0 m/s
Average sink rate v_{tas} (EKF):	-1.3 m/s
Average Netto (TEK):	1.2 m/s
Average sink rate (circle polar):	-1.1 m/s
Average relative Vario:	0.9 m/s
Average (Netto EKF – Netto TEK):	0.8 m/s

Table 1 Averaged Values of climb and sink



Vertical wind triangle

Comment on Table 1: The climb value of the EKF Vario, referred to as " Netto d_z (EKF)", is shown in the second row. The corresponding value of the TEK Vario is shown in the fourth row. The difference of the short-time values of both climb values deviates considerably from each other. In the table the average values of the signals are calculated. The EKF shows 2.0 m/s climb. Subtracting the airplane's sink rate -1.3 m/s gives the true climb rate of 0.7 m/s. The inherent sink rate depends, among other things, on the steepness of the angle of bank and the sideslip angle. If one circles with a sideslip angle of 10-15 degrees, this creates an additional drag. The EKF calculates a stronger sink rate, which is compensated mathematically with a larger climb, so that the wind triangle is fulfilled. In the present flight, the value of v_{tas} is 0.2 m/s larger than the value of the average sink rate of 1.1 m/s calculated from the circle polar. The TEK Vario shows a Netto climb rate of 1.2 m/s. If the average sink rate of -1.1 m/s is subtracted from this, the TEK Vario shows a value that is too small.

Other applications

The available data allow a wealth of further evaluations. HAWK knows the attitude of the aircraft and can display an artificial horizon. Another important parameter is the angle of attack. Figure 17 shows how, with decreasing speed, the "angle of attack" (AoA) increases until the aircraft stalls.

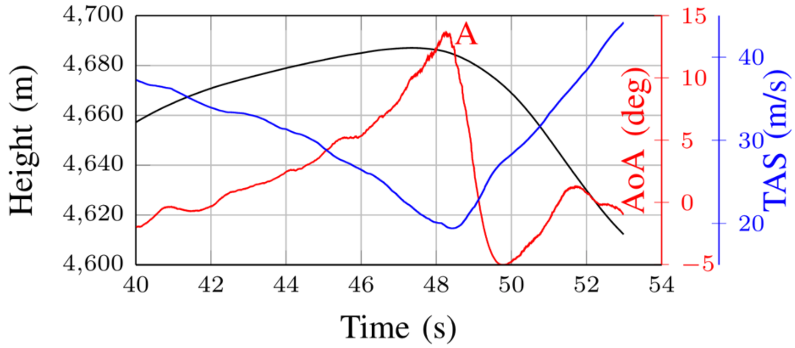


Figure 17 Stall

The AoA could be used in different ways. For example, as a classic stall warning. All relevant values are available in the HAWK and can be included. For example, when flying along a slope in gusty conditions, there are always situations in which the AoA becomes too large without this being announced - even with supposedly enough speed reserve. Stall on slope or during outlandings is a far too frequent cause of serious accidents. It is conceivable that AoA information is used differently depending on the phase of flight. When flying close to the ground (during takeoff, approach, and slope), a warning is given before exceeding a critical angle of attack. This could be indicated, for example, by vibration of the control stick. Would it be conceivable that the optimum angle of attack is displayed when circling in thermals? It would also be possible to configure it according to the pilot's needs. For example, a different warning level could be selected for student pilots than for a competition pilot.

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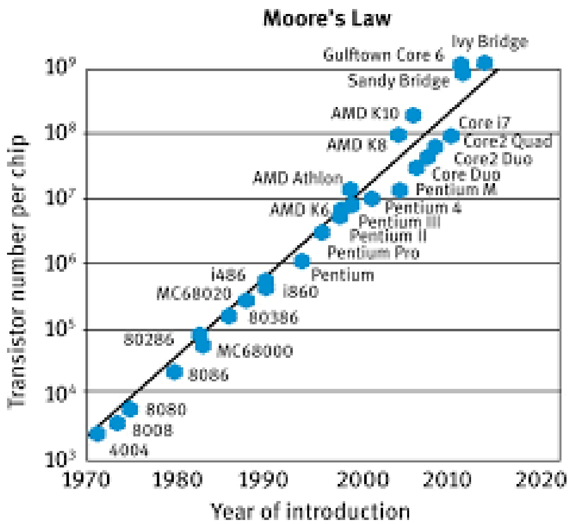
Moore’s Law

The skeptics will ask: Why have these devices only been developed now? Just marketing hype or ingenious idea? Neither the one nor the other. Thanks to advances in semiconductor technology, the computing power of microprocessors is now enormous. „Moore's Law“ states that the number of transistors on a chip increases tenfold approximately every 6 years, „10 x every 6 years“.



This allows us to use highly complex algorithms, which 10 years ago were only used in military technology or space travel for cost reasons, in numerous other applications today.

Semiconductor sensors, with amazing accuracy, have also become very small and very cheap. One can find semiconductor sensors such as triaxial accelerometers, triaxial gyros, pressure sensors, and GPS modules in large numbers in smartphones, automotive technology, and measurement and automation technology.

The use of semiconductor sensors whose signals are processed using complex digital signal processing is strikingly referred to as "sensor fusion." In sensor fusion, analog operations, e.g., a difference formation in the TEK nozzle, are not simply replaced by digital operations. Rather, digital technology allows solutions that cannot be implemented in analog technology.

Against this background, the interest in accurate and fast wind measurement has increased very much in the last years. Approximately in parallel and independently of each other, Beni Bachmeier and Meyr&Huang have been working on the task of wind measurement and have come to comparable results. Out of personal interest, we have subsequently exchanged ideas in order to compare the results.

The device **anemoi** by Beni Bachmeier is a stand-alone device for horizontal wind measurement accurate to the second. Our solution, **HAWK**, estimates three-dimensional air mass motion and thus provides a wind measurement (x- and y-component) and additionally the vertical z-component: a vario display.