Data Mining for Atmospheric Gravity Waves (Lee Waves)

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Abstract

Gravity waves can emerge as a result of the perturbation of atmospheric circulatory systems. They encompass periodic, yet geographically stationary, changes in temperature, pressure and vertical wind components. Occurrence of such waves is frequent if strong winds hit high mountains. Secondary effect of such waves may also be encountered as clear air turbulence (CAT) in commercial flights. Atmospheric gravity waves strongly influence weather phenomena and on a larger time scale climatic processes. They are responsible for the vertical transport and mixing of aire from the stratosphere up to the mesosphere. First results from research flights in the Pyrenees during the spring 2015 measuring campaign are reported. Several flights with a sensor equipped unpowered glider in altitudes between 2000 and 7000m were undertaken. Data Mining and Knowledge Discovery methods were applied. The results point to interesting patterns (states) in the structure and formation of lee waves and lead to the understanding of such flights as Wave Track Flight scenarios.

1 Introduction

By far the longest and fastest flights are nowadays reached in gliders flying in Lee Waves. For example, Klaus Ohlmann's 2010 world record flight over a distance of 1608 km and an average speed of 123 km/h were achieved in the lee waves of the Andes [1]. While much is known in principle about lee waves (see [2]) there are several open issues.

One of the most important points for the usability of lee waves for efficient long distance gliding is the leeward distance of the first upward list from the wave generating obstacle. This certainly depends on the strength of the wind and other atmospheric parameters. For these parameters, such as temperature, dew point, density, wind, equipotential temperature, and moisture, too few time series in the upward section vs the rotor vs the air below are available. As with the fine structure of thermals [3] there is a substantial lack of measuring time.

In this work we address the measuring of atmospheric parameters using low cost measuring equipment on low cost (zero cost) flights, i.e. the Open Glide Computer in non-profit, non-commercial (NC^2) glider flights. For such measurements swarm data mining methods [3] are necessary to reduce errors from low-cost sensors and pilot as well as aircraft biases.

The data presented in this work will show that 1) it is possible to distinguish between the main phases of flight, for example, wave distance gain, wave altitude gain, and rotor flight, by post data analysis, and 2) that the effective atmospheric vertical air speed in lee waves can be extracted from such data.

2 Classical Measurements

In early times when our modern ground based measurement devices were not available and aircraft less powerful than today, sailplane based data acquisition was largely used in field experiments for the exploration of lee wave phenomena. This is particularly true for the very first experiments performed in the 1930s in the Riesengebirge mountains then in South East Germany [4,5] and for the first Sierra Wave mission in the 1950s in the Owens Valley in East California [6].

The Sierra Wave experiment has been reviewed some 10 years ago by Grubišić who reports, that "in the 1951–52 field project the main observational platform was a sailplane. The research “fleet” consisted of 2 two-seater Pratt–Read sailplanes, equipped with a clock, an altimeter, indicators for the rate of climb, airspeed, and direction (compass), an accelerometer, an outside (fuselage) thermometer, and a barograph. In order to produce a continuous record of the flight data, the instrument panel was photographed at 1- or 2-s intervals on 16-mm film by two cameras in the rear of the cockpit. …this system afforded the Sierra Wave Project researchers a continuous record of sailplane flights for the postanalysis. The total flight time of sailplanes was limited to 4.5 h by the oxygen supply, and the tracking operation was limited by the film length to 1.5 h."[6].

Later, the significance of sailplanes as measuring equipment carriers has decreased owing to the availability of more sophisticated equipment like Lidars, scintillometers, Doppler sodars, radar wind profilers, microbarographs, and radiosondes. The last systematic active participation of sailplane ion such a measurement campaign took place during the French-Spanish PYREX mission in the early 1990s[7,8,9].

Major setbacks in the employment of sailplanes are that their flight path cannot be chosen at will, but is highly dependent on (or rather dictated by) the meteorological conditions as well as on the skill of the pilot and that the availability of space and energy severely limit the type and number of measuring devices that can be supported. Several other major studies of lee wave phenomena like the ALPEX and MAP missions in Europe and the T-REX follow-up mission of the Sierra Wave project have therefore relied exclusively on the combination of ground based and powered aircraft data acquisition[10,11].

Yet in quite another context, the sailplane has just recently experienced a renaissance as a means of data acquisition. The PERLAN project aims at reaching stratospheric altitudes in motor-less flight.[1] [13] Here, in-flight data have necessarily to be acquired (and ideally processed) by the sailplane equipment with the limited instrumentation available. Some recent work has been devoted to addressing the question how three-dimensional wind data can be extracted from the standard instruments available in the sailplane itself [15].

3 Glider Based Measurements

In this paper we would like to advocate the use of sailplanes for a continuous monitoring of wave phenomena. While dedicated missions like the Sierra Wave or the T-REX missions have provided a wealth of information about mountain wave systems that cannot be compared to what would be possible by an isolated

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experimental approach, the major drawback of such large scale experimental missions are their huge organizational and financial efforts and that a continuous monitoring is not possible.

Sailplanes on the other hand are low-cost devices that are nearly ubiquitously distributed all over the world and fly the wave whenever it occurs. They may be equipped with state of the art miniaturized measurement equipment in accordance with the space and energy available such that the technological gap that has evolved in the last decades between powered aircraft based measurements and sailplane based measurements has become much smaller.

In addition, it should be remembered that sailplanes also do have genuine advantages over the much heavier powered aircraft. First, quoting Grubišić again, "sailplanes were perfectly suited for measurement of vertical velocities because, due to a much smaller wing loading, they were capable of responding to wind gusts within seconds or within horizontal distances on the order of 50 m. For powered aircraft, depending on the wing loading, that distance was closer to 500 m."[6]. Therefore, sailplanes are able to provide much finer spatial and temporal resolution of in flight information than powered aircraft. While light motor-gliders or unmanned aerial vehicles might provide a similarly fine resolution, they suffer from other drawbacks as e.g. limited range or duration of operation.

Grubišić also states that "rotors, with their high degree of intermittence and small spatial scale, are very dangerous and difficult to sample using in situ aircraft measurements."[6] Indeed, rotors pose a severe danger to aviation and consequently any pilot not involved in a meteorological measurement campaign aims at avoiding any rotor contact. For sailplane pilots flying in the wave, however, using rotors as wave entry points is a standard procedure, so they can easily provide fine scale data of those parts of lee wave phenomena which are hardest to study.

4 Algorithmic Identification of Waves vs. Thermals

To the best of our knowledge, an algrorithmic discrimination has been only published so far by Ohrndorf and Ultsch [18-19]. The approach was to train a so called Artificial Neuronal Network (ANN) on several flights which contain thermals as well as flights in lee waves The ANN was a supervised neuronal network of the multilayer perceptron type and was trained using the back-propagation algorithm. The flights were classified by an expert pilot into 5 classes, three of which were “ridge”, “thermal” and “wave”. A Bayes Classifier, comparable with a Kalman filter had a classification performance around 80% [18]. In [20] finally a trained ANN had a classification accuracy of more than 98 %. This work proves the principal feasibility of an automatic classification approach, given enough and accurate data on lee waves are available.

5 Low Cost Measuring Equipment: the Open Glide Computer

With the advent of small yet very powerful all-in-one computers such as the Raspberry Pi or the Arduino nowadays the prices for such computers are << 100 EUR. A tremendous amount of low cost, yet powerful and reasonably accurate, sensors could be observed on the market. Driven by unmanned autonomous airborne observation bases, i.e. “do it yourself drones (DIY Drones)”, the prices of such equipment dropped tremendously over the last years. The Open Glide Computer is an Open Source project to build a data logger for gathering meteorological and flight data for mountain wave research [14]. The hardware is built around the Raspberry Pi, a credit card sized computer running Linux. Included are pressure sensors for static and dynamic air pressures, a high resolution GPS, a real time clock, an outside air temperature probe, 3-axis gyroscope (L3G4200D), 3-axis accelerometer

(ADXL345), 3-axis digital magnetic compass as well as air temperature and humidity sensors. The source code, including the board layouts, is available online for public use [14]. User Interfaces are a rotary encoder with push button for input and as output an 320x240 pixel 2.2" TFT. The IO part is designed such that it fits into a 57mm instrument hole for a typical glider instrument panel. The actual on-line measurements are combined into a pseudo IFR-flight-display, including an artificial horizon (see Figure 1 top picture right side). Pure hardware costs are presently below 500 EUR and still dropping. Parallel to the Open Glide Computer nowadays gliders are equipped with a GPS recording system (logger) which produces so called IGC files containing the on-board GPS system's fixes in a special format encrypted to ensure data integrity [15]. However, standard recording intervals are only of the order of one to several seconds, and with the exception of a static pressure sensor most of such devices are not equipped with any of the above listed sensors.

Figure 1: Open Glide Computer

6 Data Mining Methods

All the data considered above was not collected with the aim to measure atmospheric parameters in Lee waves. If several gliders fly the same area with the same goal in mind- to go as efficiently as possible on a large cross country flight, this is a typical example of so called "Swarm Data". A swarm of pilots in high performance sailplanes were sent out to find the best thermal or rotor lift, center as efficiently as possible and try to find the best possible climb in Lee Waves. The aim of each member of this swarm is to fly the longest distance or the fastest average speed at that day. This can only be done by making the best (= most efficient) use of every meteorological situation. So we do not possess planned measures. However, we can assume that the pilots fly as best they can.

The data gathering is not done for measuring, however, the "need for speed" will urge each pilot to efficiently find thermal or rotor lift, then wave lift and then go along the wave track flight as efficiently as possible. In order to do so he or she must use the flight, respectively meteorological states (see next chapter) as efficiently as possible. Individual biases are, for example pilot performance, different search and usage strategies of the flight states, different gliders with different performances and, of course, different measurement calibrations. All this must be compensated by swarm data mining methods. See [3] for a successful example of the application of such methods for the fine structure of thermals using data from gliding competitions.

The data was analyzed using the R software (version 3.2.1 for Linux; http://CRAN.R-project.org/), in particular the CRAN packages ABC analysis, and Adapt Gauss, and Matlab$^{®}$ (MathWorks, Natick, MS, USA) software packages in particular the databionics tool box (dbt)[http://www.unimarburg.de/fb12/datenbionik/software].

7 Wave Track Flying States and Scenarios

A primary aim of the analysis is to see differences in the atmospheric parameters, for example, in the uplift part of a Lee wave vs the downswing part or the rotor vs. thermals. Here we define for the first time systematically different states of a wave track flight. This definition serves as the basis of a state based flight analysis (time series analysis) using Hidden Markov Models (HMM) [15], respectively Kalman Filters [16].

A typical wave track flight will follow this scenario (see the blue arrows in Figure 2).

From Preflight and Start the pilot will aim for the luv side of the mountain in order to gain height in hang flight. Along this way some sink may occur. If hang gliding has reached its top altitude the pilot will enter the Rotor eventually using some thermals for further height gain. On the rising side of the Rotor the pilot will (hopefully) gain altitude so he or she can fly upwind into the upward swing of the Lee Wave (Wave Height Gain (WHG). In the WHG state the flight will usually gain a first top altitude as a preparation/prerequisite for the next flight state: Distance Gain (DG). Ideally, once the glider has obtained the desired cruising altitude, further flight is done in straight flight such that the altitude is maintained. This can be achieved by adjusting the horizontal speed of the sailplane in such a way that wave lift will just compensate for the sink rate of the sailplane. The track of the sailplane is then aligned with the line of maximum wave lift, and the net vertical speed is zero while the horizontal speed is variable. The variation of wave lift in the laminar flow of the wave is smooth and occurs on timescales of tens of seconds.

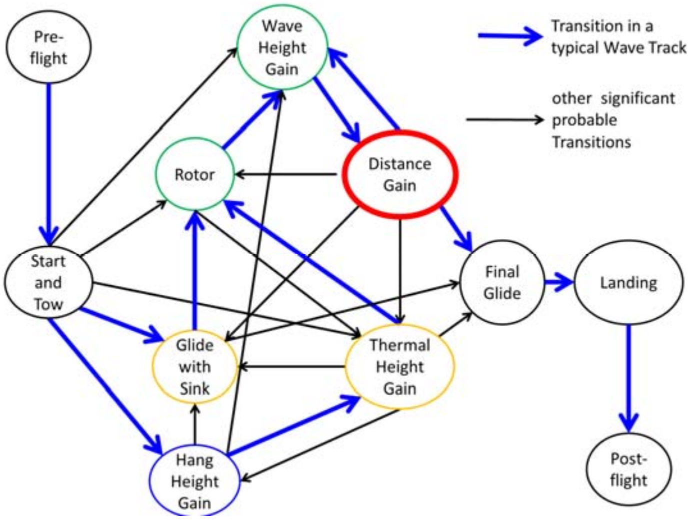

Figure 2: States in a Thermal Track Flight (HMM)

In strong wave conditions it can occur that the sink rate of the sailplane cannot be made large enough owing to having reached the maximum speed of the sailplane, so that instead of further increasing the speed the flown track needs to be detuned from the line of maximum wave lift. Now all speeds have fixed values: the horizontal speed of the glider is its maximum speed v_{NE}, wave lift has the same magnitude but opposite sign as the sink rate of the glider traveling at v_{NE}, and the net vertical speed is 0.

These two only slightly different flight modes occur most likely when airspace regulations forbid further height gain, a situation which is not uncommon under good wave conditions.

While Distance Gain (DG) is the most desirable state from the point of view of a pilot all the flights are limited by regulations which usually forbid glider flights at night time. So the final states of a typically wave track flight are Final Glide, which can be well over 100 km distance, Landing and the Post flight phase with the glider on the ground. A flight is only termed a wave track flight (WTF) if DC is achieved for a substantial proportion of the total flying time.

Wave height gain mode represents flying towards the next turn point, but in contrast to the distance gain mode discussed before, now the speed of the glider will be fixed to the speed of minimum sink, and the net vertical speed of the glider will be the meteorological wave lift diminished by the relatively small minimum sink rate of the glider. Of course the height gain mode is also needed when altitude needs to be gained before attempting to cross to another wave system or, most often, after having crossed to another wave system.

All speeds of the gilder and the air will undergo large changes on rather small time-scales of a few seconds only:

horizontal and net vertical speeds of the glider, vertical speed of the sir and sink rate of the glider.

8 Data

Data was gathered in the Cerdanya Research Camp (CRC) measuring campaign in 2015 [21]. The CRC is organized and supported by the academic flying group of Frankfurt Main, Germany (AKAflieg)[22]. While several ICG files from different flights and days were available only the measurement sets from the Open Glide Computer of one glider was available in 2015. A swarm data analysis, however, allowed to geo-referentially locate the positions of the wave lifts in the Spanish Pyrenees (yellow circles in Figure 32) and the presumed Locations wave triggering obstacles i.e. the highest windward watersheds of the mountain (red circles in Figure 3). These positions were extracted on n=6 ICG files of different glider flights Wind was estimated from prediction and calculated from the Open Glider Computer (OGC) log. OGC logged data were n= 31300 data points (cases, fixes) in d = 25 different time series (variables, dimensions).

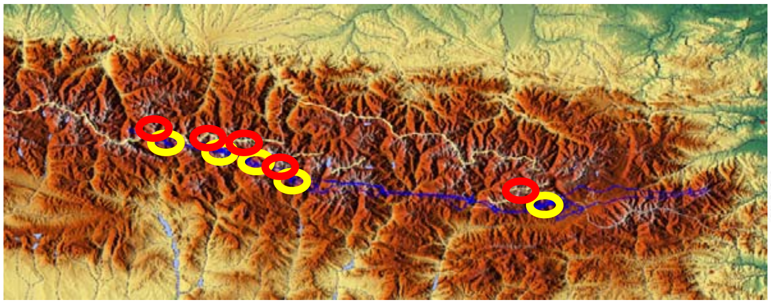

Figure 3 Locations of wave Lift and presumed wave triggering obstacles i.e. the highest upwind watersheds (luv).

The speed dependent vertical sink was calculated from the calibrated air speed. Using the glider's polare, in this case a DuoDiscus see Figure 4. Formulas for calculation and notation are given in the appendix.

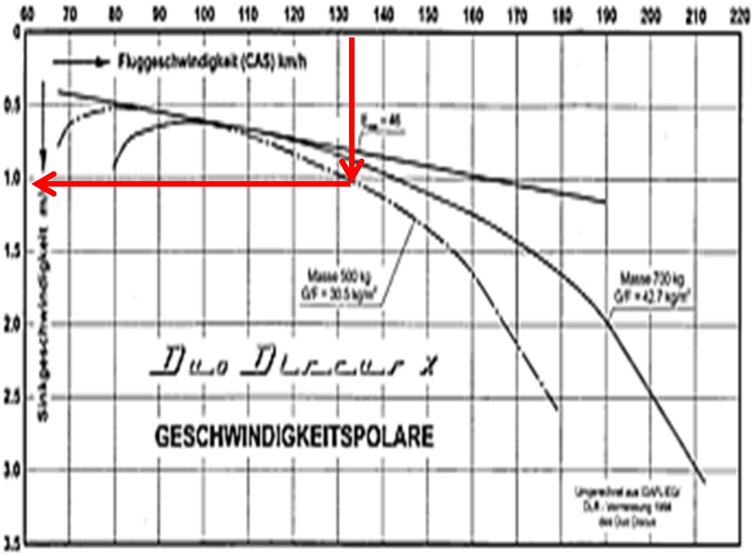

Figure 4: Calibrated air Speed vs Sink taken from the Glider's polare.

9 First Results

A barogram, i.e. GPS altitude vs flight time, is shown in Figure 5. The flight was conducted by Alfred Ultsch as PIC and co-pilot (PF) Robert Fromm at March 31th 2015 [25]. Start and landing airfield was the La Cerdanya airport in the Spanish Pyrenees (LECD).

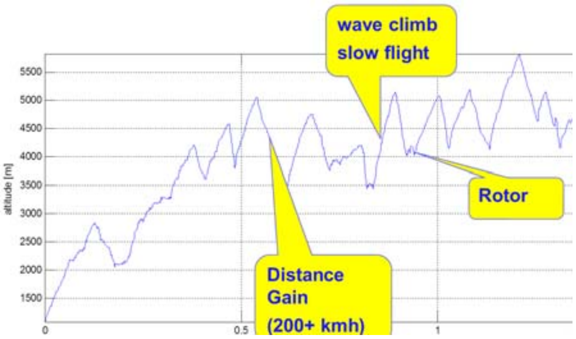

Figure 5 Barogram of Wave Track Flight.

Predicted wind field showed a North-Westerly direction. This is consistent with Figure 3. Wind speeds were predicted above 50 km/h and a positive, i.e. increasing, wind sheer was predicted and encountered (data not shown).

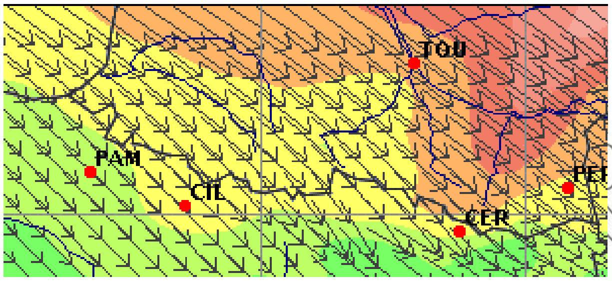

Figure 6 Predicted wind field at FL 80.

Using the formulas for (see appendix) we calculated from the sensor data:

u^{net} [m/sec]	net vertical air speed
u^{polar} [m/sec]	polar vertical sink = f(glider)
u^{stick} [m/sec]	pilot‘s reaction (= „stick lift“ = dynamic height gain due to deceleration of glider
v_i^{TAS} [km/h]	True air speed of glider

This allowed also to calculate the wave “strength” that day with a mean at 5 [m/sec], (sdev ± 1.8 [m/sec]), see green time series in Figure 6. Using the stated velocities as defined above, the Rotor, Thermal Wave Climb and Distance Gain (DG) states could be identified.

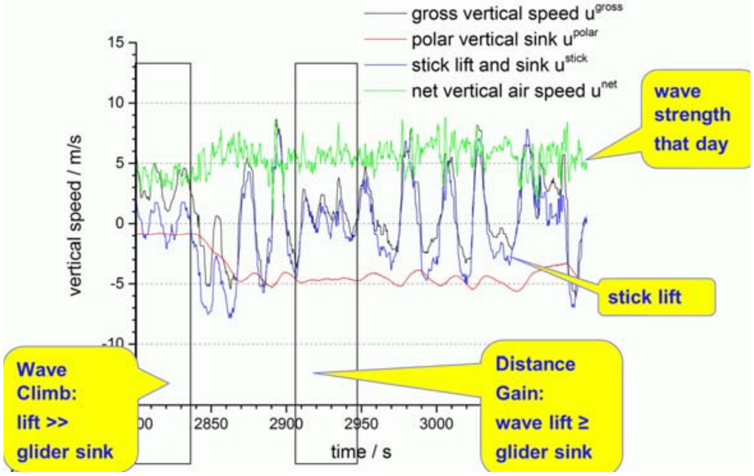

Figure 6 Identified WTF states, shown are Wave Climb and Distance Gain

The state Rotor is quite dramatic. As can be seen in Figure 7, which is on a seconds time scale, the up-down component of the Rotor show a variation from more than +15 m/sec to - 10 m/sec within seconds time. Such turbulent air is a heavy burden for pilots, planes and passengers.

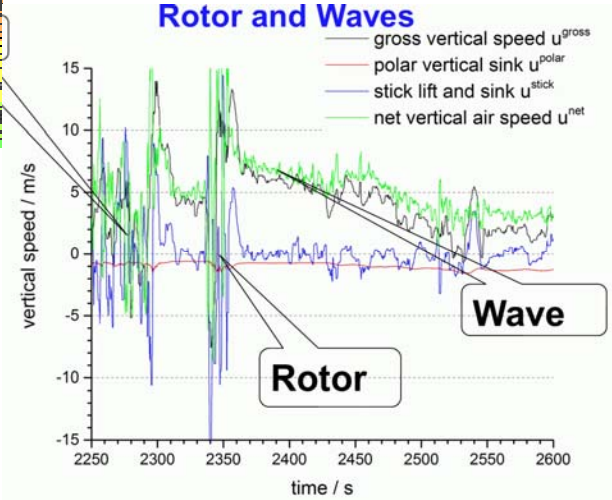

Figure 7 Rotor vs. Wave states

10 Discussion

There are extremely few published measurement data sets on the atmospherics conditions in Lee waves. In order to capture wave data from many flights in different weather conditions and landscapes would be necessary. However, nowadays the policy to obtain our own flight data back from the OLC database (www.onlinecontest.org*)* for scientific purposes is unfortunately too restrictive to allow such research. A submission of our flight data to an open source database such as, for example, www.skylines-project.org/about will help to overcome this problem.

A first measuring campaign on n = 34 flights, however with only n=1 Open Glider Computer, allowed the automatic identification of the flight states (see Chapter 6). A first report was given in [23].

In particular the wave triggering watersheds and the average wave lift could be calculated from the data.

11 Conclusion

We demonstrate here that with low-cost and easily available instrumentation it is possible to analyze the extreme conditions prevailing in turbulent and laminar regimes of lee wave systems. Above all, such data can be acquired almost casually without active participation of the pilot or any need to compromise on his or her flying related goals. Thus, a continuous monitoring of lee waves becomes feasible, particularly in the hard-to-access rotor regimes and in ascending laminar flow which is of significant importance in view of the temporal and spatial variations of lee wave systems reported in previously performed large scale field missions. With swarm data mining methods [3] there is, however, a necessity to reduce errors from low-cost sensors and pilots, as well as, aircraft biases. First results presented here demonstrate the feasibility and usefulness of this approach.

Acknowledgement

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Appendix

Fomulas

calculation of vertical air mass movements:

gross vertical speed =
polar vertical sink(glider) +
) +
net vertical air speed

$u^{gross} = u^{net} + u^{polar} + u^{stick}$

$\boldsymbol{u_i^{gross}(gps) = \frac{h_k-h_i}{t_k-t_i}}$

$\boldsymbol{u_i^{gross}(baro) = \frac{p_k^{stat}-p_i^{stat}}{p_i^{stat}\cdot(t_k-t_i)}\cdot\frac{RT}{mg}}$ using static and dynamic pressure with $p(h) = p_0 \cdot \mathrm{e}^{-mgh/RT}$

$v_i^{TAS} = \sqrt{\frac{2\mathrm{RT}_i}{m}\cdot\frac{(p_i^{pitot}-p_i^{stat})}{p_i^{stat}}}$ where p^{pitot} is the dynamic pressure

$u_i^{stick} = \frac{1}{2\mathrm{g}}\frac{(v_k^{TAS})^2-(v_i^{TAS})^2}{(t_k-t_i)}$ from total energy conservation

Notation

u^{gross}	[m/sec]	gross vertical speed = easy and precisely obtained from GPS data
u^{net}	[m/sec]	neo vertical air speed
u^{polar}	[m/sec]	polar vertical sink = f(glider)
u^{stick}	[m/sec]	pilot‘s reaction (= „stick lift“ = dynamic height gain due to deceleration of glider
v_i^{TAS}	[km/h]	True air speed of glider