USE OF SATELLITE NAVIGATION FOR SAILPLANE PERFORMANCE MEASUREMENTS

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SUMMARY

Currently the most commonly used method for sailplane performance measurements is comparison to a sailplane with well known performance, as performed routinely at the Idaflieg summer meetings. Necessary for evaluation of the data is a very precise knowledge of the relative position of the sailplanes during the test flight. Carrier-phase positioning with satellite navigation systems is able to provide this precise reference, not only at the beginning and end of each measurement interval, but during the entire flight. Additional sensors are employed to reduce the influence of the pilot' s flying technique.

The basics of sailplane performance calibration are discussed, as is the principle of carrier-phase positioning and its implementation for the task at hand. A small and simple measurement system concept is described and flight tested.

Experiences using this technique in parallel to the classical measurements during the Idaflieg summer meetings of 1995 and 1996 are discussed and the potential and restrictions of the new technique is evaluated. Results available at the current time show the new technique to be comparable to current methods in accuracy, but with the potential to reduce necessary man power, time and cost in performing and evaluating sailplane performance measurements.

In addition pilot training for such tests can be improved by providing pre-flight and post-flight briefings with precise flight track displays and the currently stringent procedures for flight patterns can be somewhat relaxed, thus reducing the pilot error component in the measurements.

Abbreviations

Idaflieg	Interessengemeinschaft Deutscher Akademischer Fliegergruppen (Association of German Academic Soaring Clubs)
DLR	Deutsche Forschungsanstalt fur Luft-und Raumfahrt (German Aerospace Research Establishment)
GNSS	Global Navigation Satellite System; describing a generic satellite navigation system
GPS	NAVSTAR-Global Positioning System
AK-5b	Standard Class Glider designed and built by the Academic Soaring Group (Akaflieg) at the University of Karlsruhe
C/A on Ll	Coarse/Acquisition Code on the first L-band frequency (civilian usable code and frequency of the GPS-system).

Introduction

Many important technologies in aviation, such as laminar flow airfoils and composite materials construction have been developed and first introduced in the soaring community. The necessity to use the sun's energy efficiently continuously stimulates innovations in this area. Due to the current high performance standards of modern gliders, extremely accurate measurement techniques are necessary to compare the influence of modifications on the lift / drag ratio and thus the gliders efficiency.

The problem of accurate measurement is never more evident than in the task of calibrating another system. Generally the method used for reference has to be one order of magnitude better than the one under test. In the case of flight measurements this often is hard to fulfill with measurements using conventional means due to the system dynamics. Current reference systems such as laser tracker or optical reference systems allow accuracies of about 0.2m - but since their operating characteristics are well understood they provide sufficient measurement integrity for successful operation.

Satellite navigation, on the other hand has proven to be an accurate and very cost effective means of positioning in the geodetic domain, allowing accuracies in the sub-centimeter range. Although most of the applications demonstrating these accuracies are static, allowing post-processing and smoothing of the data, in principle dynamic positioning is possible and experiments demonstrating this have been performed, exhibiting accuracies in the order of a few centimeters. In less accurate applications such as documenting a glider's flight path for competitions, satellite navigation has found a permanent place in the last years, due to its ease of use and small implementation. The idea to join the accuracy of geodetic use with the small size of soaring flight recorders thus should lead to a cost-effective tool to improve both a pilot's proficiency by allowing post-mission analysis with the capability to optimize the sailplane's performance through the exact measurement of technical improvements on energy use. Therefore this paper will try to illustrate some of the challenges and identify critical areas, by explaining the operating principle of carrier-phase positioning with satellite navigation systems and demonstrating the difficulties encountered in arriving at the precise position solution, as well as detailing the methods used to overcome them.

Although the experiments shown have used the U.S. satellite navigation system GPS, the results are applicable to other existing and planned systems as well; therefore the generic term GNSS will be used throughout this paper.

Measurement Task and Requirements

Currently the most commonly used method for sailplane performance measurements is the comparison to a sailplane with well known performance (Glider Comparison Method), as performed routinely at the summer meetings of the DLR and the Idaflieg (/ Schmerwitz /). Based on the knowledge of the performance of a reference glider which is constantly recalibrated using a large number of flights with the Partial Glide Method one can assess perfor-

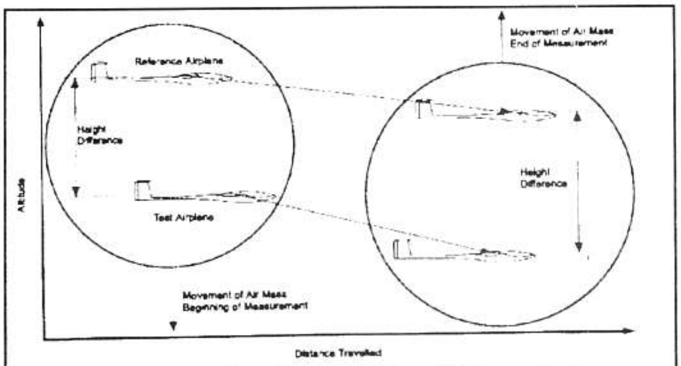

FIGURE 1. Principle of comparison flight technique.

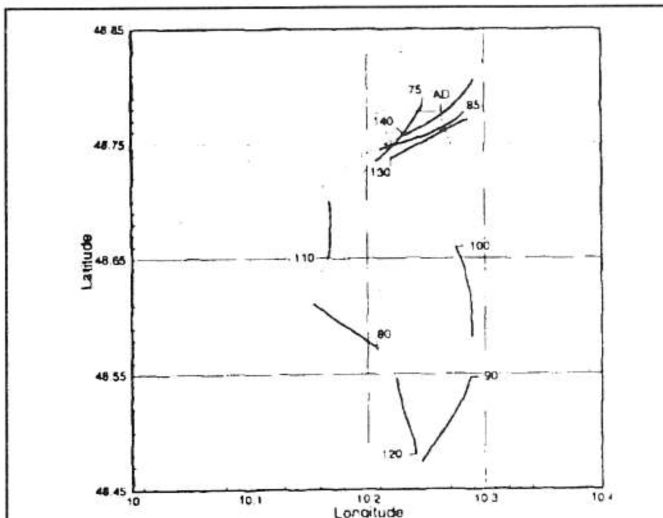

FIGURE 2. Typical flight path.

mance differences. Necessary for evaluation of the data is a very precise knowledge of the relative position of the sailplanes during the test flight. This has traditionally been performed using photogrammetric techniques, requiring a photo plane and limiting time resolution of the measurements as well as imposing limits on the flight path (Figure 1). The advantage of the comparison flight technique is the reduction of weather errors, since both aircraft move approximately in the same air mass.

The reference sailplane is owned and operated by the DLR and its long-time use for only this purpose and regular recalibration leads to good performance stability. The method used for recalibration (Partial Glide method) is based on flying a certain altitude step with constant speed and measuring the time necessary to do so. With careful design of the flight path and location of the measurement interval relative to the prevailing wind field one is able to gain one point of vertical speed vs. airspeed. These measurements are performed in parallel and in addition of the glider comparisons to gain a statistically significant number of data points.

Typically the planes start the performance comparison at an altitude of 4000m and take measurements in an area of about 15km around the airfield (Figure 2). Each measurement (constant speed) takes about 90 seconds to complete and 2 to 5 flights are necessary to gather enough data

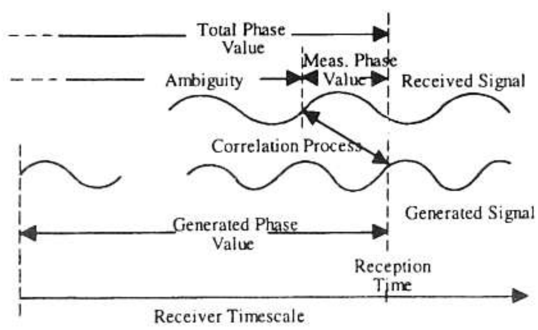

FIGURE 3. Carrier phase measurement principle.

points for a complete plot showing sink rate over airspeed (Figure 5). This plot is generated using the known values for the reference airplane and adding the measured vertical speed differences to obtain the polar for the sailplane under test.

The reduction of the weather errors from ±0,3 m/s for a single data point of the Partial Glide Method to ±8 mm/s for the Glider Comparison Method is impressive, but still a total measurement error of about 2,3% has to be accepted, essentially due to incomplete compensation of pilot actions and errors due to the photographic technique (/ Dorn/). With glide ratios reaching 1/50 routinely today, this translates into a measurement uncertainty of up to ±1,5 glide points.

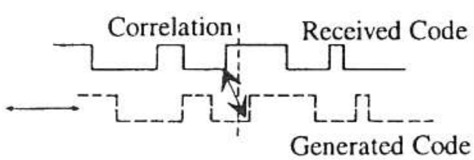

FIGURE 4. Code measurement principle.

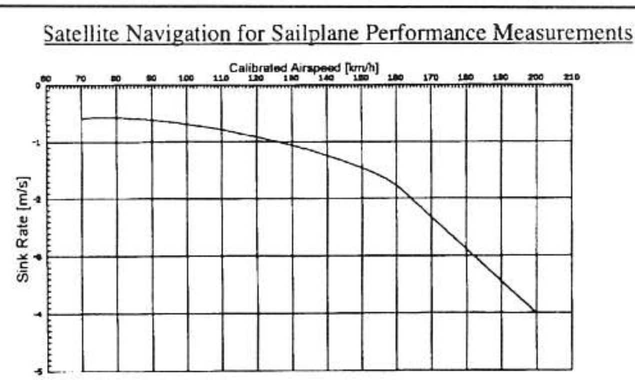

FIGURE 5. Typical glide slope diagram.

Satellite Navigation Systems and Carrier Phase Resolution

The information provided by a GNSS system can be used in several ways. For navigation a code modulated onto the satellite signal is commonly used to determine signal travel time. Due to receiver signal resolution limitations and the code frequency this limits achievable accuracy to 0.2-2m in the case of GPS C/A-code. As Figure 4 shows, this code can be correlated with a copy internal to the receiver, directly leading to the time difference and, with the speed of light - the distance to the satellite.

Carrier-Phase Positioning

To obtain higher accuracies, the carrier phase relationship between received and internally generated signal is measured. The carrier frequency is higher than the code frequency, leading to much higher resolution in the sub-millimeter range. Unfortunately, since all waveforms look similar, this is only possible to fractions of one full cycle. The unknown number of cycles between user and satellite is called "(full cycle) integer ambiguity" and must be determined before the information can be used for positioning (Figure 3).

One method to enhance the resolution of the code is known as carrier smoothing. Here the code measurement is used to avoid the ambiguity. This method enhances resolution, but not absolute accuracy due to reliance on the code. More accurate results can be obtained by searching through a range of possible values, finally settling on the closest value by some statistical criterion. Many different techniques have been proposed for this search, within the scope of this paper it may suffice to illustrate the general principle.

Usually the code measurement is used to generate an approximate position and together with its uncertainty defines a search volume. In the two-dimensional case this results in a disk on which the search has to be performed. Assuming the true solution lies within this volume one can use the fact that the ambiguities are whole numbers to draw circles with distances of one wave length around each satellite. Due to the distance of the satellites relative to the size of the search volume these circles can be approximated as parallel lines as shown in Figure 6.

Two principles become evident from this figure - the greater the wave length, the smaller the number of possible solutions and the more satellites are usable (beyond the minimum two needed to generate the two-dimensional solution) the more solutions can be eliminated through redundancy. In the three-dimensional case a typical initial search volume of about 3m radius will encompass millions of possible solutions. In the example in Figure 4, eight possible solutions remain, two of which are almost outside

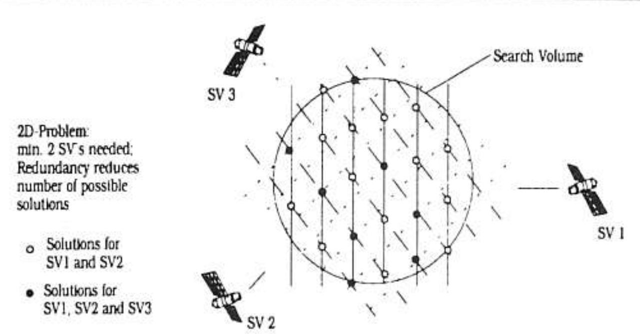

FIGURE 6. Ambiguity search at Time T_0.

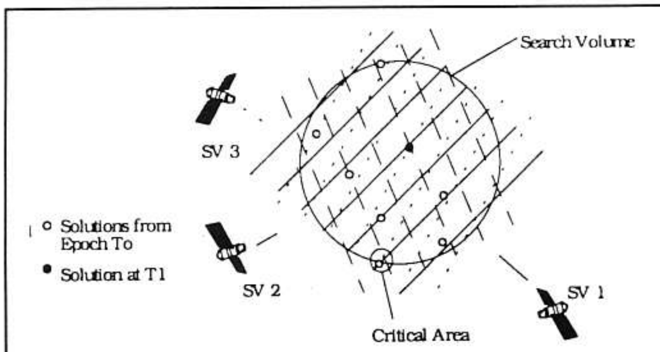

FIGURE 7. Ambiguity search at Time T_1.

of the search volume. One can now use the change of geometry caused by the movement of the satellites with time to eliminate further possibilities, until only the correct solution remains (Figure 7).

Obviously the solution quality depends on many factors and the method illustrated here is not optimal with respect to calculation time, use of the measurement information or application to a moving user. Therefore many modifications of the basic algorithm have been published in literature, as described in /Lipp/.

Issues of Solution Failure

Some of the problems associated with the search process can be found already in the example:

- The definition of the search volume is critical, since solutions outside this - more or less arbitrarily chosen - area will not be considered at all. Since large volumes are time-consuming to search and will contain more solutions of almost equal probability of success, a compromise must be found. Solution approaches that decrease the search volume with time are advantageous as long as no additional errors such as cycle-slips or multipath bias the solution with respect to the search volume.
- With unfavorable geometry and little or no redundancy a large geometry change is required to distinguish good and bad solutions, leading to a long search time independent of the type of algorithm.
- The example illustrates the stationary case. For a moving user both the search volume and the true position change. Errors in the user position estimate cannot be reduced by averaging as often done in the stationary case.

Up to now, no mention has been made of the other error sources common with GNSS systems. Three main causes of errors can be distinguished, namely the transmitting satellite (SA, clock and ephemeris errors), the propagation path (atmosphere, multipath, shadowing,...) and the receiver (clock, hardware delays).

In many algorithms some common errors are eliminated by differencing data between satellites and between the user and a fixed reference station, essentially eliminating the errors caused by the satellite and the receivers. Propagation path errors are strictly only equal if the antennas are at the same position. With increasing separation first the multipath errors (signal deformations due to reflections at nearby structures) become decorrelated, then the tropospheric and finally the ionospheric errors. Errors of the satellite position (ephemeris) will decorrelate as well, but to a lesser extent.

Examples for the residual errors due to multipath are found in /Schänzer/. The carrier solution is only slightly (less than 5cm) influenced, while the code solution shows several meters of error. Since carrier-phase based systems typically operate on short baselines, mainly the tropospheric error remains. Most of this error accumulates in the densest part of the atmosphere, near the ground. Experiments have shown, that even for a typical airport traffic pattern with vertical distances between receivers of not more than 400m can result in residual errors of up to 4cm if no atmospheric error correction is performed. Using a simple tropospheric model may reduce these errors to less than one centimeter. In dynamic positioning errors due to receiver accelerations may arise and must be compensated for in some applications.

Not included at all in the simple model above is the noise floor due to receiver design and measurement noise (increased for instance by differencing). This noise may differ in size and distribution depending on receiver design as illustrated in Figure 8 and Figure 9.

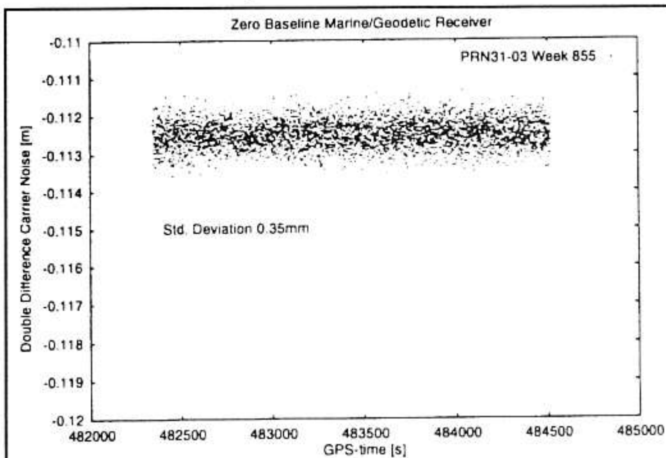

FIGURE 8. Marine/surveying receiver.

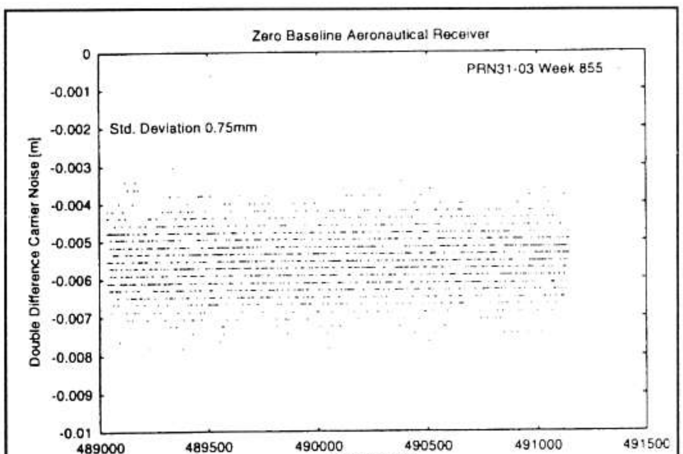

FIGURE 9. High quality aircraft receiver.

Both receivers shown contain high-quality clocks, for low-cost receivers the noise may increase significantly. Also, satellite elevation has some influence on the values shown - below 15° of elevation it may increase up to a factor of two due to propagation path noise and reduced signal strength with the signal' s longer path through the atmosphere.

Despite the difficulties outlined in the preceding paragraphs carrier-phase positioning has been successfully demonstrated for precision positioning and even in automatic flight of a model aircraft. For the work described in the following an algorithm was chosen based on /Chen/ and further optimized in /Schänzer/.

System Design for Sailplane Measurements

In order to apply this technique to sailplane measurements, an estimate of possible performance has to be undertaken. An analysis has to be performed in order to obtain the correlation between the desired accuracy and the measurement quantities. In this case the final quantity is the glide ratio or its inverse - the glide point number. Measured are the differences in altitude between the two gliders over the measurement interval - they must be corrected for air density and aircraft weight as in /Schmerwitz/, which will not be discussed here. The relationship between these quantities is given by:

$$w_S = \frac{\Delta h + \Delta h_{ref}}{\Delta t} = -V \sin \gamma = -\frac{V}{E} \quad \text{and} \quad \Delta w_S = -V\left(\frac{\Delta E}{E(E+\Delta E)}\right))$$

with W_S the vertical speed calculated from the height difference Δh, the altitude loss of the reference plane, V the airspeed, $\gamma = \frac{1}{E}$ the glide ratio and the glide point number E.

Assuming a worst case scenario for the current system and neglecting weather and piloting error components one arrives at

Glide Number E	(-)	30		40		50	
Airspeed V	km/h	60	80	60	80	60	80
Instrument Error Photograph (0,5%)	(ΔE)	0,15	0,15	0,2	0,2	0,25	0,25
Δw_s	m/s	0,010	0,013	0,007	0,010	0,006	0,008
Meas. Length Δt	s	60	60	60	60	60	60
Necessary Resolution	m	0,6	0,78	0,42	0,6	0,36	0,48

The expected accuracy of code-based positioning of 0,7-1,5m would therefore be marginal, but carrier-phase systems with expected values of 0,05-0,1m would provide sufficient reserves for a reference system.

In order to allow a standard-class glider to be calibrated in one flight the typical 2600s flight time from 4000m altitude must be sufficient. Experience from past campaigns shows that about 20 points are necessary and about half of the flight time can be spent gathering data. This allows for the 60s time interval for one data-point as used above.

In principle, the satellite navigation techniques therefore are suitable for the task and there are reserves for improvements as confidence is gained in the procedure. Weather errors cannot be influenced except for a suitable length and orientation of the flight path, but by adding additional sensors airspeed variations and thus piloting errors can be corrected to some extent. Furthermore altitude and temperature information can be used to calculate air density; thereby improving the above-mentioned corrections. One drawback with reference to current techniques is the loss of attitude information since the photograph with aircraft and horizon as attitude reference will not be present. Whether this can be compensated must be the object of further study.

Severe size and weight limitations have to be observed though, necessitating the development of a sensor suite specially adapted to the purpose. In this application low-cost 12-channel Ll receivers with raw data output were used. Due to the relatively large receiver noise (Figure 10) the traditional technique with a fixed reference station on the ground had to be abandoned and the positioning solution was formed directly between the two aircraft receivers. This allowed to reduce the atmospheric errors and retain a very short baseline. Unfortunately, since both stations are moving, this necessitated the use of a SA-influenced position for defining the horizon-aligned coordinate system and estimation of the errors resulting from this simplification. As can be seen from Figure 11, the resulting error is negligible. In the typical flight pattern bank angles are small and satellite visibility excellent during the entire time. Therefore the ambiguity search has to be performed only seldomly and search time is not critical.

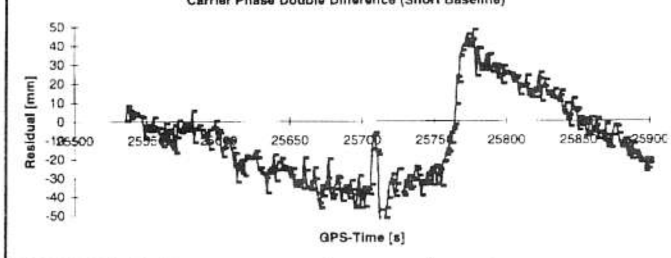

FIGURE 10. Low-cost receiver carrier noise.

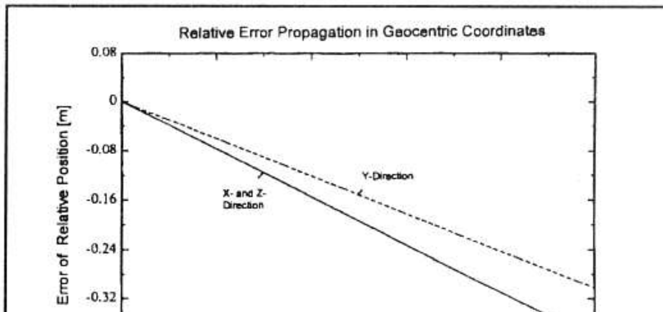

FIGURE 11. Relative positioning error due to reference position uncertainty (from/Bredemeyer/).

Implementation of the Sensor Package

The receivers used are identical to those used in soaring flight recorders and allow acquisition of raw GPS-data at a 1s rate. The antenna is suction mounted on the canopy. Solid-state barometric sensors for airspeed, altitude and

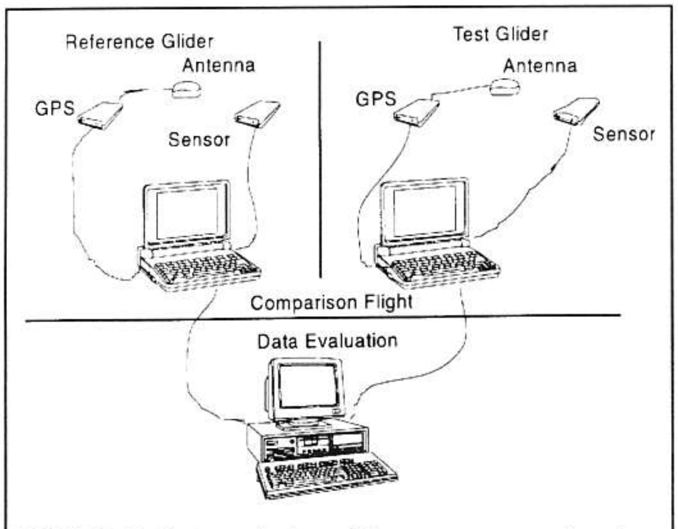

FIGURE 12. System design of the measurement system.

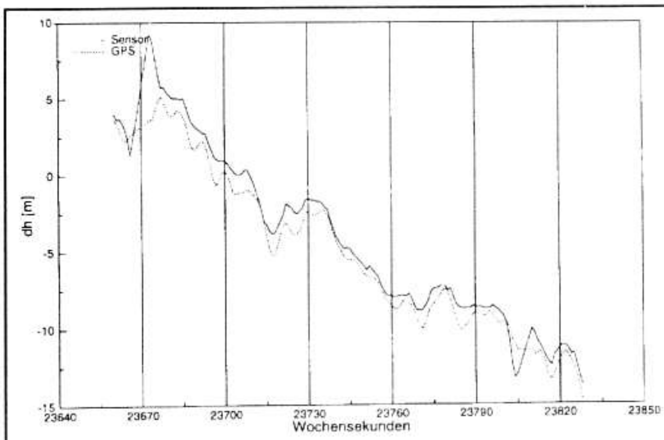

FIGURE 14. Altitude differences as measured by barometric and satellite navigation sensors.

temperature are employed to calculate true airspeed and compensate for altitude and speed changes during the measurement. The barometric sensors are attached to the aircraft pitot and static lines and the temperature probe is mounted on the canopy outside. Its size does not impair glider performance. All data are time-stamped and saved on a miniature laptop with hard disk (Figure 12). The entire measurement equipment has the size of a cigar box and is powered through a standard 12V battery (Figure 13). Data evaluation was performed off-line after the flight.

First Results and Validation

Using this technique in parallel to the classical measurements during the Idaflieg summer meetings of 1995 and 1996 allows direct comparison of the results, as detailed in /Wehnert/, /Bredemeyer/ and /Schroeder/. As shown in Figure 14 the measurements of barometric and GNSS-sensors compare well.

In order to eliminate a significant error source of previous measurements not the actual airspeed was used for determining the vertical speed on the plot, but a simple correction for total energy was performed, using a one-point model of an ideal glider. This allows for some pilot reactions during the measurements, but still assumes a quasi-stationary process. In addition the airspeed was not calculated based on pilot observations but rather using the air data combined with the GNSS-based ground speed to estimate wind influence.

As Figure 15 shows, the new technique compares well to current methods in accuracy, showing practically identical sink rates and only slightly different speeds for the data points due to the compensation performed with the barometric sensors. After first field trials in 1995, where only a limited number of flights were performed, in 1996 the system was used on all measurement flights. 57 data points were evaluated for 4 different sailplanes and only one data point was lost, due to technical reasons. Differences between both measurement techniques do not exceed 2.5% and are well within the expected measurement accuracy.

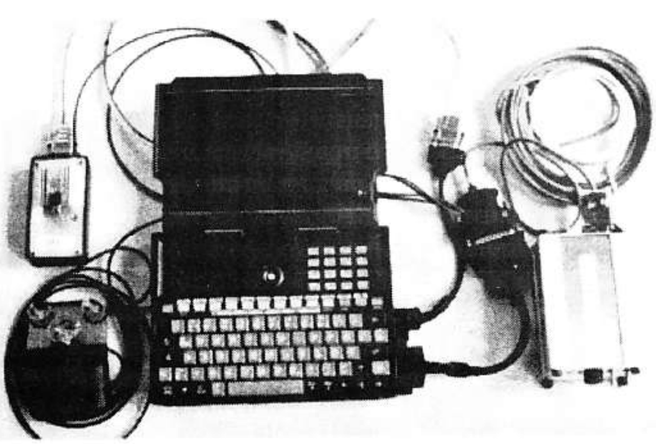

FIGURE 13. The entire measurement system.

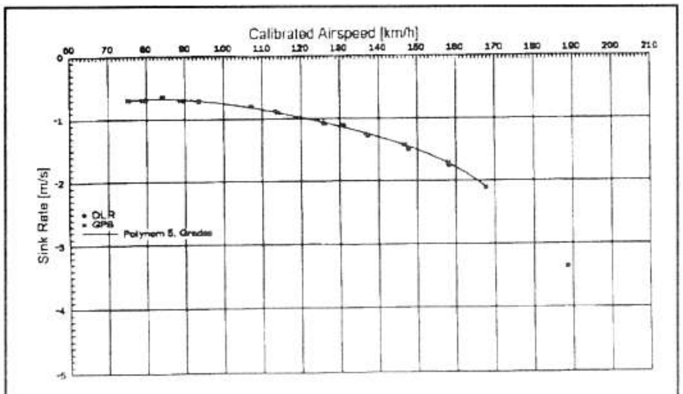

FIGURE 15. GPS measurements as compared to classical technique (/Schroeder/).

Conclusion

The GPS measurement technique is comparable in accuracy to the classical techniques, but has the potential to reduce necessary manpower, time and cost in performing and evaluating the measurements. The next step will be to use telemetry for a real-time solution in order to give the pilots an information whether a given measurement was successful. This allows the measurement time to be shortened, reducing the number of flights necessary. Automation of the measurements helps speed up time for processing, allowing discussion of the results on the day of the measurement and thus faster evaluation of improvements. In addition pilot training for such tests can be improved by providing pre- and post-flight briefings with precise flight track displays and the currently stringent procedures for flight patterns can be somewhat relaxed, thus reducing the pilot error component in the measurements. Estimation of the local wind field helps improve the reduction of weather errors due to better siting of the measurement track relative to the prevailing flow as detailed in / Albat/. Up to now the reliability of the system has been excellent, although sensor calibration and time stability will yet have to be improved for an operational system. Better software handling and automation will allow a wider range of pilots to use the technique, allowing more data to be collected for further improvements of the system.

Acknowledgments

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