Development of a measurement platform on a light airplane and analysis of airborne measurements in the atmospheric boundary layer

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Abstract
In the present paper we provide an overview of a long term research project aimed at setting up a suitable platform for measurements in the atmospheric boundary layer on a light airplane along with some preliminary results obtained from field campaigns at selected sites. Measurements of air pressure, temperature and relative humidity have been performed in various Alpine valleys up to a height of about 2500 m a.m.s.l. By means of GPS resources and specific post-processing procedures careful positioning of measurement points within the explored domain has been achieved. The analysis of collected data allowed detailed investigation of atmospheric vertical structures and dynamics typical of valley environment, such as morning transition from ground based inversion to fully developed well mixed convective boundary layer. Based on data collected along flights, 3D fields of the explored variables have been detected and identified through application of geostatistical techniques (Kriging). The adopted procedures allowed evaluation of the intrinsic statistical structure of the spatial distribution of measured quantities and the estimate of the values of the same variable at unexplored locations by suitable weighted average of data recorded at close locations. Results thus obtained are presented and discussed.

Key words *light airplane measurements – atmospheric dynamics – kinematic GPS positioning – Kriging*

1. Introduction

It is well known that in mountainous areas local valley winds arise, under fair weather conditions, as a result of different heating (during the day) or cooling (at night) occurring either between different parts of the valleys or between valleys and adjacent plains.

Solar heating of areas of the valley exposed to incoming radiation, varying during the day, and the overall cooling of valley bottom and sidewalls during the night give rise to thermally induced slope winds, due to the heating/cooling of air layers close to the ground. Combinations of these factors, reversing during the diurnal cycle, produce cross-valley flows which enforce the heat exchange occurring throughout the valley atmosphere. As a consequence greater diurnal temperature ranges occur within the valley than on the adjacent plains, and this different heating/cooling produces a horizontal pressure gradient that changes during the day and drives along-valley winds (fig. 1a-h).

Various physical factors, like valley shape, varied exposition to incoming solar radiation, ground nature and covering, surroundings and many others, have been identified in the literature as variously affecting the development of valley winds (Barry, 1981; Whiteman, 1990, 2000; Egger, 1990).

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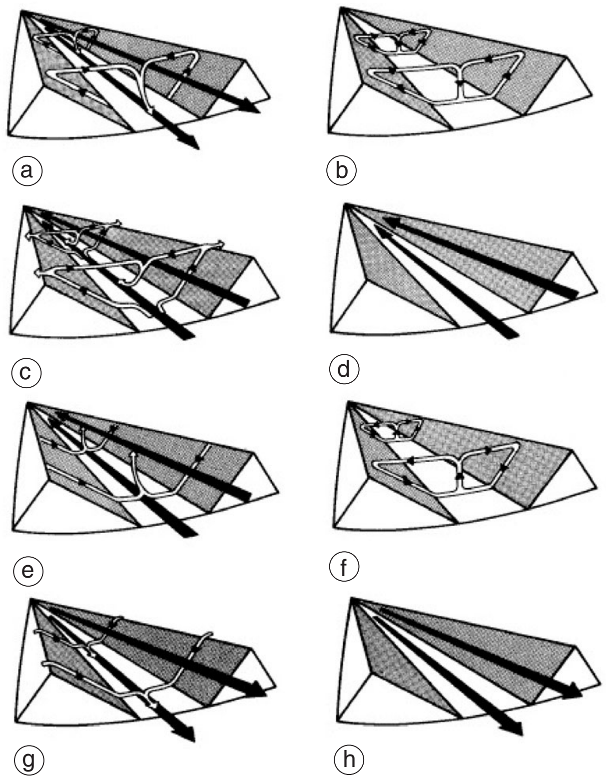

Fig. 1a-h. Diurnal cycle of valley winds (after Defant, 1949): a) Sunrise: onset of up-slope winds (white arrows), continuation of mountain wind (black arrows). Valley cold, plains warm. b) Forenoon (about 09:00): strong slope winds, transition from mountain wind to valley wind. Valley temperature same as plain. c) Noon and early afternoon: diminishing slope winds, fully developed valley wind. Valley warmer than plains. d) Late afternoon: slope winds have ceased, valley wind continues. Valley is still warmer than plain. e) Evening: onset of down-slope winds, diminishing valley wind. Valley slightly warmer then plains. f) Early night: well developed down-slope winds, transition from valley wind to mountain wind. Valley and plains at same temperature. g) Middle of the night: down-slope winds continue, mountain wind fully developed. Valley colder than plains. h) Late night to morning: down-slope winds have ceased, mountain wind fills valley. Valley colder than plain.

As a result, the development of the above valley winds is strongly dependent upon specific features of the atmospheric boundary layer dynamics (*cf.* Stull, 1988).

In particular, the attention of researchers has been recently concentrated on the understanding of some processes related to the formation or removal of thermal structures in the boundary layer (Whiteman and McKee 1982; Whiteman *et al.* 1996; Anquetin *et al.*, 1998; Sullivan *et al.*, 1998), also in connection with measurement campaigns performed within specific research projects, such as ALPEX, PYREX, ASCOT, MAP and many others (Whiteman, 1990).

To accomplish this purpose light airplanes provide a suitable platform for the investigation of many atmospheric boundary layer structures, in particular those displaying significant horizontal inhomogeneities, such as thermally driven flows associated with cross/along-valley winds.

The equipment developed at the University of Trento, Department of Civil and Environmental Engineering, includes instruments for measurement of standard atmospheric variables such as temperature, pressure and relative humidity and a Global Positioning System (GPS) device (antenna and receiver) for accurate determination of measurement locations.

The complexity of the atmospheric structures under investigation and the intrinsic difficulty of the measurements required particular care in the planning and execution of the flights and subsequent data analysis. In order to appreciate finer structures, instruments displaying higher accuracy than usually required in standard atmospheric measurements had to be adopted.

Further specific requirements about measurement accuracy are prompted by the mathematical and numerical algorythms developed to evaluate physical quantities at any point within the atmospheric domain, especially where not closely explored by airborne measurements. Such procedures for obtaining three dimensional mapping of variables like potential temperature or humidity, based on geostatistical techniques known as Kriging (Wackernagel, 1995), have been specifically developed for the analysis of airborne atmospheric measurement and will be only briefly described in the paper.

The paper is structured as follows: in Section 2 an overview of various instruments used on the platform is presented; in Section 3 target areas where measurements have been performed are described; in Section 4 some preliminary results from the analysis of data are shown and discussed.

2. The measurement platform

2.1. *The airplane*

The platform developed for measurements described in this paper is based on a motorglider Scheibe Falck SF 25C (fig. 2) owned by the Trento University Sport Centre (CUS Trento).

The airplane has a single 80HP engine and allows a maximum speed of 150 km h^{-1} with a typical climbing speed of 1 m s^{-1}. The wing span is 16 m and the maximum gross weight is 650 kg.

One of the main advantages of this light airplane is its very low stall speed, which allows for high manoevrability and makes it particularly suited for detailed investigation of the whole valley volume to be explored. This can be achieved by planning a specific flight path with ascending and descending spiralling trajectories resulting in a spatial resolution of the collected meteorological quantities of about 30 m with a sampling rate of 1 Hz.

The motorglider is certified by the Italian Aviation Authority only for diurnal VFR (Visual Flight Rules). This drawback excludes exploration of the nocturnal boundary layer and morning transition before full sunrise. Therefore the earlier *pictures* of the thermal structure that we could take with our flights are those short after the sunrise when the sun starts heating the facing east valley slopes.

2.2. *Positioning techniques*

The use of the GPS resources for kinematic positioning of an airplane for environmental surveys needs specific setup for proper settings of all the receivers and the reference GPS network.

For this survey we adopted the continuous kinematic GPS technique with relative positioning. The so called OTF method (On The Fly, a technique for the determination of the GPS phase initial ambiguity without requiring a static initialisation) is used to process the data but, to prevent postprocessing problems, an initialisation period of about 10 min (where the plane stands still on the take-off strip) is required.

Using the OTF technique it is possible to process GPS data even with complete lock loss on all the satellites, provided a sufficient number of epochs with «clean» signal for at least five satellites: it is possible in this way to recover from

Fig. 2. The motorglider ready for take off at Trento airport.

lost locks due to external obstacles (mountains) or to sudden changes of direction.

2.2.1. GPS receivers

Two double frequency receivers have been used for the surveys:

Ashtech Z-XII - This receiver is mounted on the plane. It acquires simultaneously 12 channels for the C/A code on the L1 carrier, 12 channels for the P code on the L1 carrier, 12 channels for the P code on the L2 carrier, with automatic commutations on the *Z-tracking* method when the P code is encrypted. This receiver carries an internal memory of 3 Mb, which allows the recording of the data of 5 satellites for about 1.5 h with a 1 s recording interval.

Ashtech Z-Surveyor - This receiver is used as local reference station. It acquires simultaneously 12 channels for the C/A code on the L1 carrier, 12 channels for the P code on the L1 carrier, 12 channels for the P code on the L2 carrier, with automatic commutations on the *Z-tracking* method when the P code is encrypted. This receiver carries up to two PCMCIA cards to store the GPS data. The two cards currently available (4 and 10 Mb respectively) allow up to a 7 h recording with a 1 s recording interval.

The GPS data are processed with the post-processing software Spectra Precision Terrasat's *GeoGenius™* version 2.0 using the OTF technique.

2.2.2. Error reduction

Factors influencing the GPS positioning accuracy can be divided into different classes:

1) GPS system effects (satellite and receiver clock stability, ephemerides uncertainty, phase center variations and instrumental errors).

2) Environmental influence (ionospheric and tropospheric delay, multipath and electromagnetic interferences).

The first class of errors can be reduced using usual GPS techniques, in particular performing a relative positioning, *i.e.* use of two receivers at the same time, one aboard and the other at a fixed location whose coordinates are known with high accuracy.

In the present case, two reference stations have been used for each survey: a permanent GPS station, which has been chosen each time as the nearest to the flight zone, and a local reference station, whose coordinates are obtained via a static solution with respect to the permanent station. This local GPS station has been established according to the following criteria:

1) To make available a ground GPS station near the barycentre of the flight zone (for distances greater than 10 km from this barycentre, several effects influence the GPS solution and special care must be taken for data elaboration).

2) To give the possibility of choosing the reference station height to control the tropospheric effect.

3) To allow the acquisition of ground GPS data with the same rate of the flying receiver.

The influence of the ionosphere on the signal propagation can be modeled using a combination of two different frequencies, since the ionosphere is a dispersive (scattering) medium. This is not true for the troposphere since it is not a dispersive medium, therefore its effect must be modeled on other parameters such as temperature and pressure of water vapour. Moreover the troposphere influence depends on the incidence angle of the arriving signal, with a tropospheric delay of about 2.5 m at the zenith and of about 28 m at 5° elevation.

Several empirical models for the tropospheric delay are available in the standard GPS post-processing software, taking into account the influence of the dry tropospheric component.

The tropospheric delay can be written as

$$T_R^S = \int_{\text{trajectory}} c \cdot N_T \cdot dt \qquad (2.1)$$

where R and S refer to the receiver and the satellite respectively, c is the light speed in the vacuum and N_T is the tropospheric refraction index. The delay is

$$ds = c \cdot \left(1 - N_T\right) \cdot dt \qquad (2.2)$$

and, since usually $N_T \ll 1$, eq. (2.1) becomes

$$T_R^S = \int_{\text{trajectory}} N_T \cdot ds \,. \qquad (2.3)$$

The tropospheric refraction is usually computed by an empiric formula taking into account meteorological parameters such as

$$N_T = \left(77.624 \frac{P}{T} - 12.92 \frac{e}{T} + 371900 \frac{e}{T^2} \right) \cdot 10^{-6} \qquad (2.4)$$

where P is the atmospheric pressure in hPa, e the partial pressure of the water vapour in hPa and T is the temperature in K.

The above effect can be relevant when the reference station height is significantly different from that of the rover. This situation is common in airborne surveys, where the GPS reference station is usually at the valley floor.

For this reason some tests have been carried out processing the GPS of a flight against two reference stations at different heights in the surroundings of Trento.

These tests have demonstrated that the planimetric effect of the relevant height difference of the reference and the rover station can be neglected, being at most a few centimeters. This effect cannot be neglected for the height component in precise positioning, since it can reach values around 10 cm. For more information on this topic see Ferrari *et al.* (1998) and Sguerso and Zatelli (1999a).

2.2.3. Planning

One of the most important aspects for a good GPS positioning is correct survey planning. In fact the geometry of the satellites constellation can change significantly with the hour or the day of flight. The parameters used to describe the quality of the satellites constellation are the DOPs (Dilution Of Precision), in particular the PDOP (Position Dilution Of Precision). This is a scalar quantity which represents the contribution of the geometric satellite configuration to the positioning accuracy

$$\sigma = \sigma_0 DOP \qquad (2.5)$$

where σ is the accuracy and σ_0 is the measurement accuracy (code or phase). The lower the PDOP, the better the accuracy.

The DOPs values in time can be predicted using the almanac data, which are acquired automatically by the GPS receivers and carry information about the satellite status and their ephemerides, although very roughly.

When planning a kinematic GPS survey the following parameters are taken into account:

– the number of visible satellite must be greater than four, whenever the number is smaller the positions are lost;

– the PDOP values should be smaller than six, otherwise poor accuracy is expected.

The presence of obstructions can change dramatically the number of visible satellite, for this reason the development of an automatic procedure for a realistic GPS planning is in progress at the Geodesy Laboratory of the Department of Civil and Environmental Engineering of the University of Trento. This project merges the available information about the satellite positions from the almanac with the morphologic information from a Digital Elevation Model (DEM) to automatically evaluate the number of visible satellites and the DOPs value (Sguerso and Zatelli, 1999a,b). It is possible to forecast the number of satellites and PDOP value along a full 3D trajectory of an object moving in time (Carli *et al.* 2000; Fruet and Sguerso, 2000).

2.2.4. Reference systems

Modern GPS receivers give point positions directly in the WGS84 reference system. To use of these positions in practical surveys it is customary to transform the coordinates from the WGS84 to the national reference system, which is used for instance for cartography and traditional surveys.

The transformation parameters were estimated in Italy with the IGM95 campaign by the IGMI (Italian Geographic Military Institute, the official Italian cartographic institute). These parameters retain only a local validity within a range of about 10 km.

For the Trentino-Alto Adige region the transformation parameters from WGS84 to the Italian National System 1940 were estimated by the Geodetic Office of local Land Registry and officially published on its bulletin (Bollettino Ufficiale della Regione Autonoma Trentino-Alto Adige, n. 19/I-II del 20/4/1999). These parameters are supposed to be used for the whole Region.

The coordinates obtained by applying the above transformation refer to the International ellipsoid locally oriented in Roma Monte Mario (Italian National System 1940): further transformation has to be applied to project planimetrically the survey over the cartography.

The heights are transformed using the geoid undulation

$$\Delta H = \Delta h_{\mathrm{GPS}} - \Delta N_{\mathrm{grav}} \tag{2.6}$$

where ΔN_{grav} is the geoid undulation which must be determined using a geoid model. This quantity cannot be neglected nor regarded as constant since this would introduce approximations of order of tens of meters. The Italian geoid model (Barzaghi *et al.*, 2002) is available from the IGMI.

2.2.5. External controls

In a continuous kinematic survey it is difficult to find external reference to check the obtained positions.

However some checks can still be done:

– For the *planimetric coordinates,* the trajectory can be superimposed to cartography and the real positioning verified. In particular the landing and the take-off trajectory can be checked against the position of the take-off strip. For the past flights the accuracy on the take-off strip shows a good accordance with the cartographic data.

– For the *altimetric coordinates,* it is possible to check the height of the plane taking off and landing against the take-off strip height. The height differences ranges from 1 cm to a maximum of 10 cm.

It is also possible to compare the heights from the GPS with the hydrostatic height as given by the measured pressure. The maximum difference of the two height determinations is of 40 cm.

2.2.6. The GLONASS tests

The GLONASS (GLObal NAvigation Satellite System) is a positioning system similar to the GPS developed by the former Soviet Union.

The main advantage of the GLONASS system is the possibility of using hybrid receivers which operate both the NAVSTAR GPS and the GLONASS. Using satellites of both systems it is possible to operate in situation where the sky obstruction are relevant since the total number of available satellites is nearly doubled with respect to the GPS alone.

The tests carried out in the Trento area with a hybrid GPS/GLONASS Ashtech GG24 receiver show a better reliability than the GPS alone: the number of lost positions due to insufficient number of satellites decreases from a few percent to an order of magnitude less. However a significant gain of precision (in the sense of standard deviation of the coordinates) has not been observed.

These tests have suffered from setup problems, in particular for the mounting of the antennas on the plane, therefore should be considered as preliminary.

2.3. *The meteorological sensors*

In all the measurements flights performed so far the platform has been equipped for probing scalar atmospheric quantities, namely air temperature, pressure and relative humidity. The list of the sensors used is reported in table I along with the device used for the calibration of the temperature sensors.

One of the major problems encountered when starting the setup of the measuring system was the positioning of the instruments on the airplane, taking into account various requirements due to measurement accuracy, sampling frequency, flight safety, and so on. Possible spurious effects induced by the front propeller on flow distortion and exhaust emissions on air temperature have been carefully evaluated. Also possible interferences of avionics on the signal acquired from the sensors has been considered and carefully filtered out.

Table I. Meteorological sensors used on the airplane and calibration equipment.

Sensor	Technical specifications
Barometer Vaisala Mod. PTB 101 B	Range: 600 ÷ 1060 hPa Accuracy at 20 °C: ± 0.5 hPa Long-term stability: ± 0.1 hPa/year
Temperature RTD sensor Hart Scientific Mod. 5627	Accuracy: ± 0.03 K Time constant in water (1 ms^{-1}): ≤ 4 s
Thermohygrometer Rotronic Mod. PT 101 A	Humidity: 0 ÷ 100% RH Temperature: – 40…+ 60 °C Accuracy at 23 °C: ± 1% RH, ± 0.3 °C
Thermocouple Type T (Cu-C)	Calibrated 0.127 mm diameter wires Cat. n. 2-ML
High Precision Calibration Bath Hart Scientific Mod. 7025	Temperature stability: ± 0.005 °C or better Temp. gradients ± 0.01 °C max in the work area

Accordingly, temperature and humidity sensors were mounted on the left-side leg of the undercarriage (fig. 3). This choice avoided the flow disturbances induced by the propeller and set the sensors at a suitable distance from the wing boundary layer.

Moreover, the RTD sensor was properly shielded against direct solar radiation by means of a specific protection (fig. 4), which also assures an adequate ventilation of the sensor, introducing only a small perturbation of the airflow around the sensor. On the other hand the Rotronic thermohygrometer, whose sensing parts are thin and fragile under mechanical stress, were equipped with a specific cap aimed at obtaining a laminar flow close to the sensors. Indeed the manufacturer suggests the use of such a protection for wind speed greater then 20 ms^{-1}.

Finally the barometer is placed inside the cockpit near the GPS receiver and the datalogger, since it is a high-accuracy sensor and is not for a rough use in high stress conditions. This choice could in principle be responsible for some smoothing effects, but for the same reason it preserves the signal from being corrupted by possible dynamical effects induced by the flying speed of the motorglider.

In fact these effects were also investigated and a correction applied, even if its amount is

Fig. 3. A close look at the sensors outside the motorglider on the left undercarriage leg.

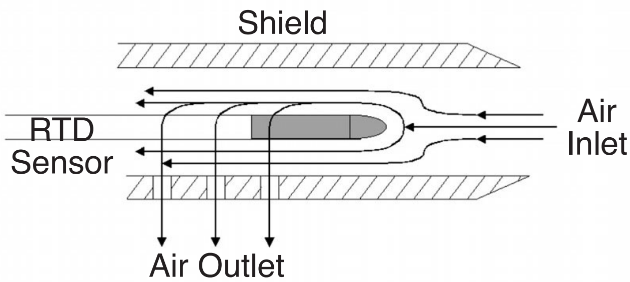

Fig. 4. Sketch of the shield protecting the RTD sensor from direct radiation.

quasi negligible and do not affect the overall accuracy of the pressure measurements.

2.4. *Data acquisition*

The data acquisition is done by a datalogger (Datataker Mod. DT600) which can acquire up to 10 analog channels (when operating in differential mode) with a temporal resolution of 1 s. Each channel has a sequential-type acquisition, and following steps are performed by the datalogger on each channel:

1) Exciting of the sensor connected to the channel (when needed).

2) Sensing of the response of the sensor.

3) Converting the analog signal into the requested physical variable when the proper linearization function is provided and enabled.

4) Storing of the obtained value.

Moreover 3 fast counter are available, which can control the scan sequence of the various channels.

For a secure storage of the acquired data a PCMCIA card with 1Mb of memory is used.

As previously mentioned, during the measuring sequence the datalogger is able to directly converting resistance, voltage and current signals into physical quantities, *e.g.* temperature data using internal conversion parameters stored for the most common sensors (RTD, thermistors and thermocouples). In our case this feature is used for the homemade thermocouple (type T, Copper-Constantan) for which a specific external reference temperature is used. By this way the accuracy is increased with respect to using the internal reference temperature of the datalogger which has an accuracy of ± 0.5 °C. On the contrary, for the Rotronic (temperature and humidity) and the Vaisala (pressure) sensors the conversion functions applied on-line by the datalogger before storing the data are those provided by the manifacturers, while the Hart Scientific RTD sensor's signal is stored as a measure of resistance and a complete post-flight conversion algorithm is applied using the original calibration certificate for a greater accuracy of the results.

In the whole data acquisition process a non-trivial step is represented by the synchronization of the datalogger channel scan with the position provided by the Global Positioning System. In fact, as mentioned in previous paragraphs, the GPS has its own internal storage unit and we need to couple each sensor scan to the correct position. This is realized by connecting the GPS open/close output to one of the fast counter channels of the datalogger. By this way the GPS sends a signal with a 1 Hz frequency which forces the scan of all the activated measuring channels of the datalogger. It is also important to notice that all the aforementioned steps for the sequential scan of the channels are fast enough to ensure an acquisition which can be considered as instantaneous.

3. Measurement campaigns

The work performed so far has allowed the execution of various flights for the investigation of thermal structures and their diurnal evolution (removal of the nocturnal inversion layer, subsidence of the stable core of the valley atmosphere, etc.) (de Franceschi *et al.*, 2000b). A specific feature of airborne observation is the capability of sampling a whole valley volume rather than a single vertical ascent, as in the case of standard meteorological upper measurements performed with balloons or other remote sensing instruments (sodar, lidar, etc.).

Measurements have been performed in the following target areas:

– Adige Valley close to the city of Besenello, about 10 km south of Trento.

– Laghi Valley and Sarca Valley, connecting Garda Lake with the Adige Valley north of Trento.

– Adige Valley close to the city of Bolzano.

– Isarco Valley from Trento up to the Brenner Pass (in connection with the Mesoscale Alpine Programme Special Observing Period).

3.1. *Adige Valley*

The area explored in the Adige Valley near the town of Besenello (fig. 5) is particularly narrow: the valley section is easily identified as a fairly regular trapezoidal shape at the lowest levels, as shown in fig. 6.

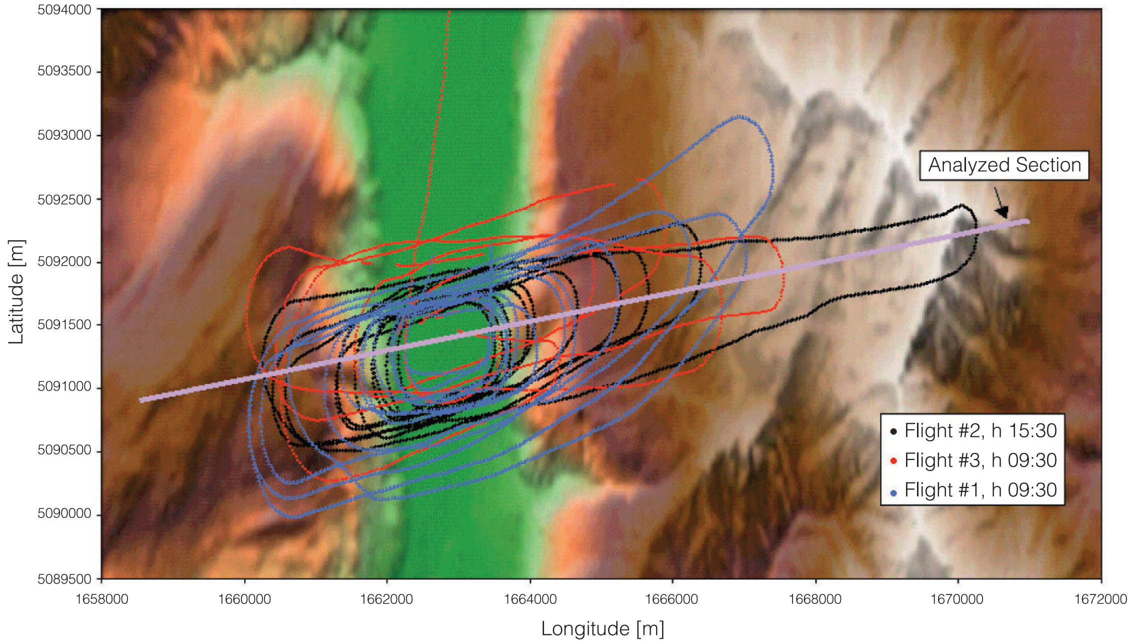

Fig. 5. Plan view of flight trajectories of subsequent flights over target area «Besenello». The straight line indicates the vertical cross section used for mapping in figs. 9 to 11.

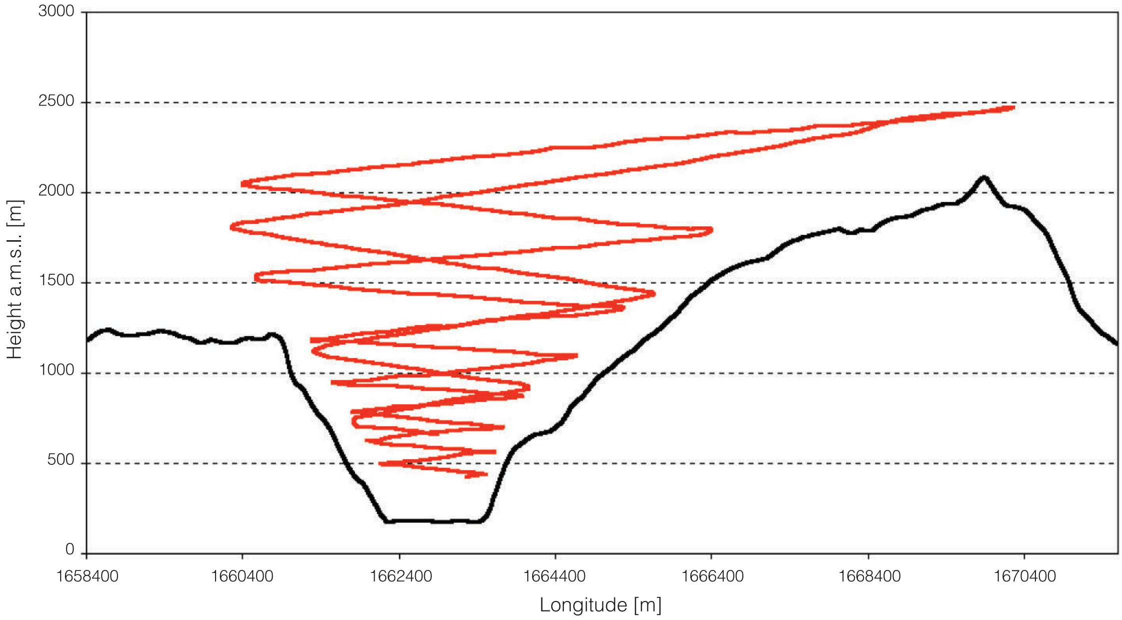

Fig. 6. Vertical projection of the flight trajectoriy over Besenello.

The flight plan included 3 flights, the first in the early morning, then the second at noon and the third in the early afternoon. The airplane took off at the airport of Trento and, once reached the area under investigation, performed an ascending spiralling path up to a height of about 2500 m above ground followed by a descending path variously crossing the previous one. A picture of the flight trajectories is also reported in figs. 5 and 6.

The same kind of flight path has been performed close to the city of Bolzano in connection with ground based measurements held during different seasons from July 1999 to March 2001. The measurements were aimed at studying the atmospheric dynamics affecting the transport of pollutant emitted from a waste incinerator and a waste disposal in the area (de Franceschi *et al.*, 2000a).

3.2. *Laghi Valley and Sarca Valley*

The two valleys have been explored to identify the thermal structure of the so-called «Ora del Garda» wind, which flows regularly on sunny days during the summer season, when thermal forcing is strong enough to produce an appreciable pressure gradient throughout the valleys connecting the area north of the Garda Lake to the Adige Valley (Daves *et al.*, 1998). The wind originates along the shoreline of Garda Lake (65 m a.m.s.l.) in the late morning, as a typical coast breeze, and then channels along the adjacent Sarca Valley and the Laghi Valley till it reaches the Adige Valley (whose floor is about 200 m a.s.l. high) north of Trento, flowing over an elevated saddle (about 600 m a.s.l.).

The flight paths were four cross sections (like those described in the previous paragraph) regularly displaced along the valleys allowing an estimate of the thickness of the «Ora del Garda» during its flowing towards the Adige Valley.

3.3. *Isarco Valley*

This flight was aimed at exploring the vertical structure of the atmosphere from Trento to the Brenner Pass during a Foehn event. The flight path was different from those commonly performed during previous investigations, and consisted in straight lines flown at constant ascending and descending rate along the Adige and Isarco Valleys. The reason for this flight strategy is mainly due to the nature of the phenomenon under investigation, occurring in an elongated domain, and limited endurance of the motorglider (about 4 h).

In the following section we will concentrate on the results of measurements performed in the «Besenello» target area.

4. Data analysis

4.1. *Vertical profiles*

A preliminary step in the analysis of collected data is the evaluation of vertical profiles of virtual potential temperature θ_v irrespectively of horizontal coordinate. The vertical profiles of θ_v for the three flights of the lst October 1999 are shown in fig. 7.

Notice the development of a convective boundary layer and erosion of the stable core of the valley atmosphere as outlined in the well known paper by Whiteman and McKee (1982).

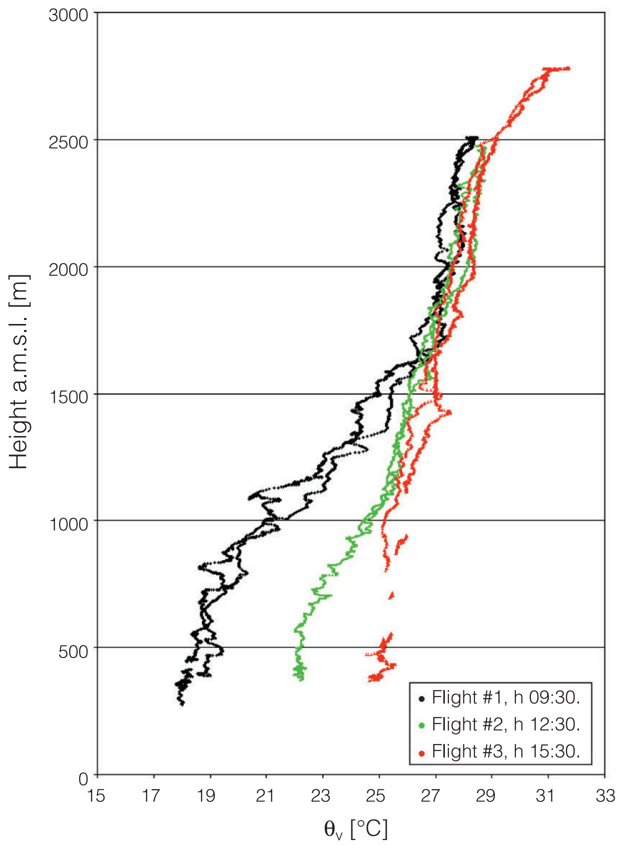

Fig. 7. Profiles of virtual potential temperature θ_v during subsequent flights performed in the Adige Valley over Besenello, 1.10.1999 at times reported on the figure.

4.2. *Mapping of temperature and humidity fields*

Further progress in the analysis of airborne data can be made by evaluating fields of potential temperature or water vapour content through suitable interpolation of the measured variables in the whole explored valley section (Rampanelli and Zardi, 2000). This can be performed with different techniques, but the application of kriging techniques is highly recommendable due to the specific advantages it provides, such as the possibility of evaluating the estimation variance of krieged data, the preliminar statistical analysis data in order to obtain suitable variograms of the variables (see below) and the property of being an exact interpolator (Wackernagel, 1995), *i.e.* an interpolator which provides exactly the measured value of the variable when applied in the measurement location. Further details about specific applications of the above technique are reported in more detail in Rampanelli (1999) and will be the subject of a forthcoming paper. Maps of potential temperature over a cross section where the flight has been performed are shown in figs. 9, 10 and 11.

The first analysis of collected data is the calculation of the vertical profile of virtual potential temperature. This can be done using the temperature, pressure and relative humidity data. These profiles can be used to obtain the five parameters describing the average vertical atmospheric structure. The three flights explored the same valley section and the results show a good agreement to the theoretical models of CBL growth.

Given a space dependent scalar variable Z evaluated at N fixed location $\boldsymbol{x}$, it is possible to define the so called dissimilarity between values at two different points $\boldsymbol{x}_\alpha$, $\boldsymbol{x}_\beta$

$$\gamma\left(\boldsymbol{x}_\alpha, \boldsymbol{h}_{\alpha\beta}\right) = \frac{\left(Z\left(\boldsymbol{x}_\alpha, \boldsymbol{h}_{\alpha\beta}\right) - Z\left(\boldsymbol{x}_\alpha\right)\right)}{2} \tag{4.1}$$

where $\boldsymbol{h}_{\alpha\beta} = \boldsymbol{x}_\alpha - \boldsymbol{x}_\beta$. The experimental variogram is obtained by dividing the set of all possible distances between couples of points into statistically significant subsets of growing distances and calculating an average value of the dissimilarity over each subset. The resulting number will

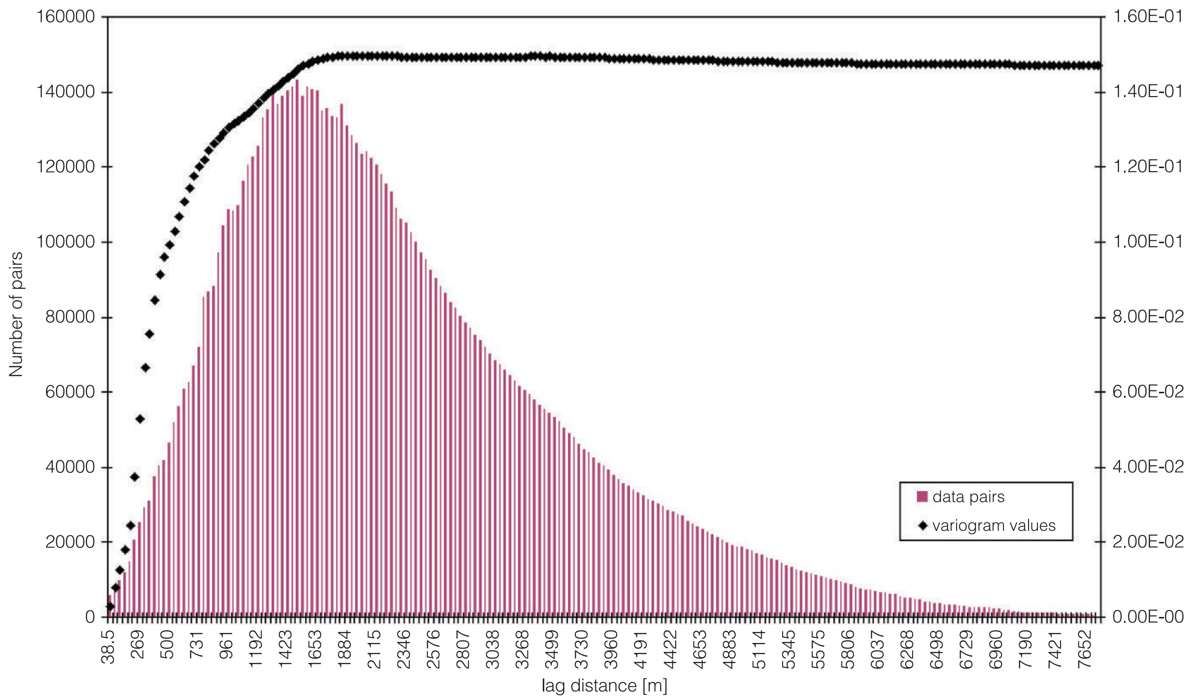

Fig. 8. Isotropic experimental variogram (after geometric scaling) and best fit curve (Gaussian) for the flight #2.

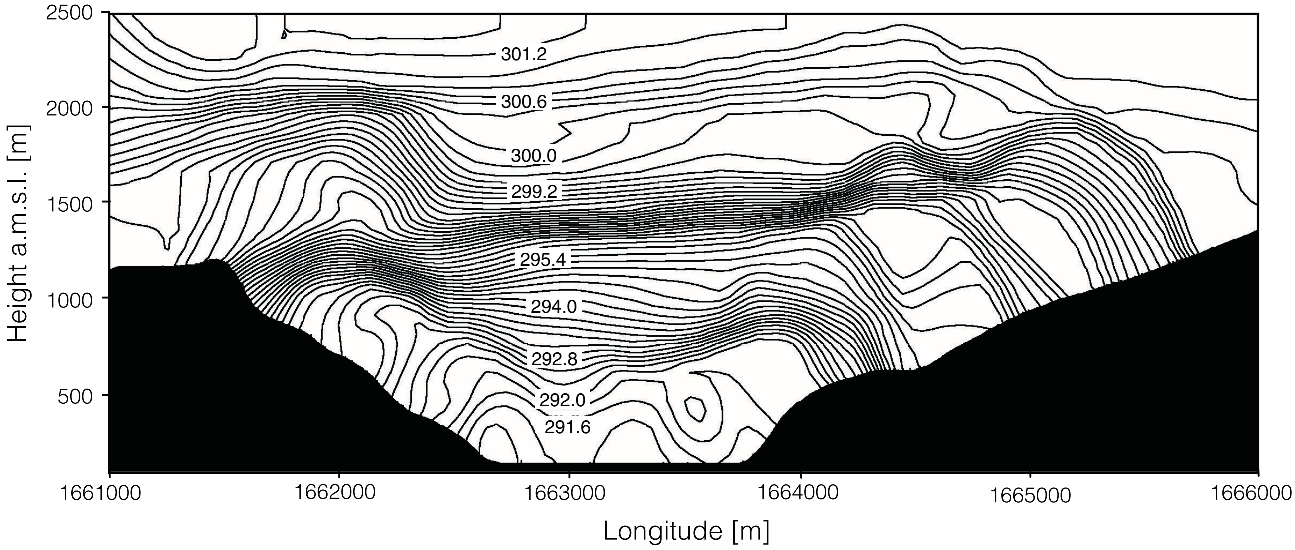

Fig. 9. Mapping of virtual potential temperature θ_v over a valley cross-section (over Besenello fig. 5) from measurements collected during the flight #1.

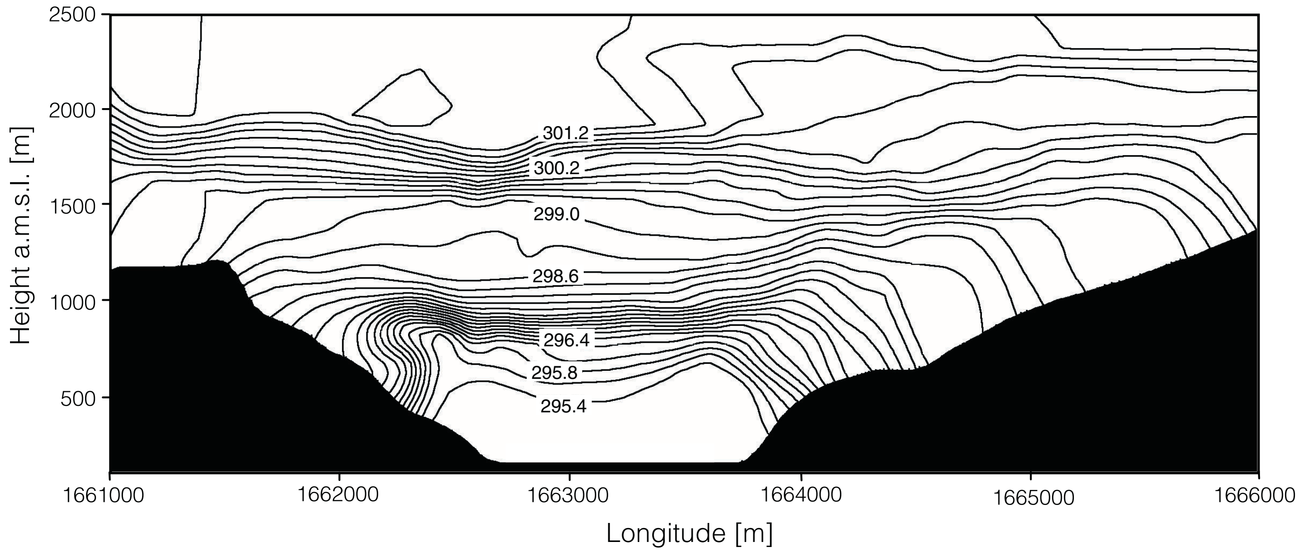

Fig. 10. Mapping of virtual potential temperature θ_v over a valley cross-section (over Besenello fig. 5) from measurements collected during the flight #2.

be associated with a characteristic distance vector $\boldsymbol{h}$ representative of the subset.

The formulation of Li and Lake (1994) for the variogram estimator is

$$\gamma(|\boldsymbol{h}|) = \frac{1}{n}\sum_{i=1}^{n}\left\{\frac{1}{2m}\sum_{j\in D_{i,h}}\left(Z(\boldsymbol{x}_i)-Z(\boldsymbol{x}_j)\right)^2\right\}. \quad (4.2)$$

This procedure provides important information on how the variable values depend on the reciprocal distance between couples of points. When an isotropy assumption can be made for the field, the variogram will depend only on the modulus of the distance. In the case of anisotropic field (as in the present case) one can find some scaling factors so that the data field

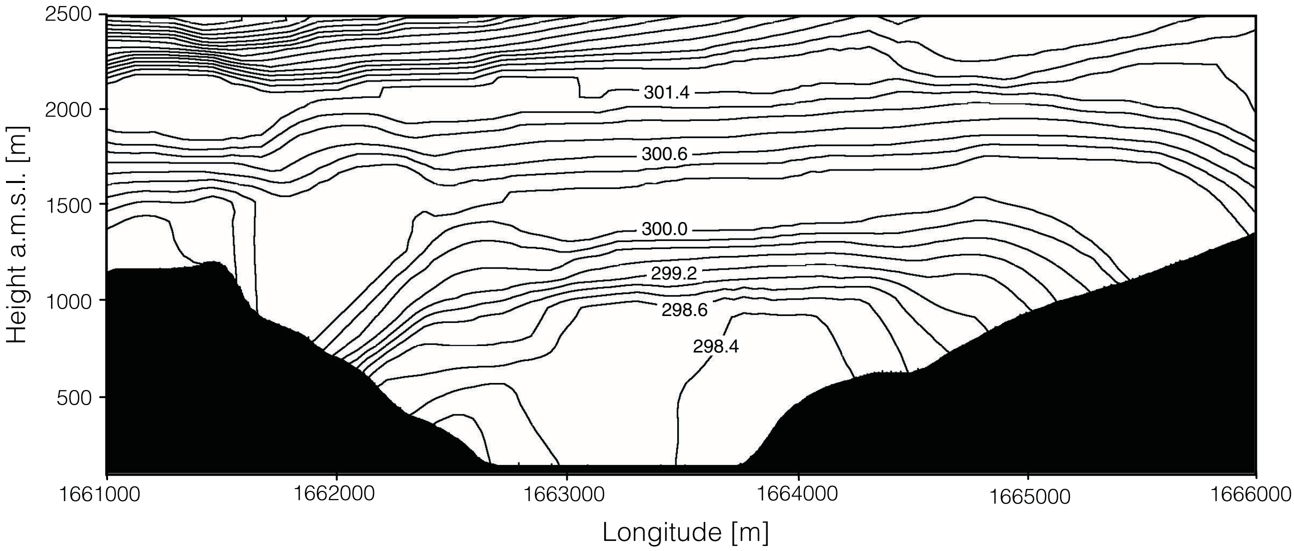

Fig. 11. Mapping of virtual potential temperature θ_v over a valley cross-section (over Besenello fig. 5) from measurements collected during the flight #3.

will be isotropic after a geometric scaling. For our problem the directions are naturally defined as: vertical, along-valley, cross-valley. The lag value for which the variogram function has reached the 95% of its asymptotical value is the *practical range* of the model. This range, evaluated for a single directional variogram, can be chosen as scaling factor for the direction in exam.

A best fit curve of such pointwise determined function (fig. 8) allows one to obtain the best estimate of the theoretical variogram, which is the analytic function supposed to underlie the statistical distribution of the random variable under analysis.

Further steps in the theory lead an estimation of the value of the variable in a location $\boldsymbol{x}_0$ where no measurement is available evaluating it as a linear combination, or rather a weighted average, of available data

$$Z(\boldsymbol{x}_0) = \sum_{\alpha=1}^{n} w_\alpha Z(\boldsymbol{x}_\alpha). \qquad (4.3)$$

A crucial point is therefore to determine weights: the kriging procedure allows that to be done by requiring the variance of the estimate to be a minimum. The net output is that weights w_α are finally given as the solution of a linear nonhomogeneous algebraic system whose coefficients are defined in terms of the variogram evaluated for couples of positions.

Complete lack of information about temperature along slopes (which cannot obviously be reached directly by the motor-glider) makes the estimated values of temperature in the adjacent region very questionable.

It is well known, in fact, that along a heated slope a convective layer develops along with upslope flow and a steep temperature gradients in the cross-flow direction. To fill this gap, ground measurements have to be taken along slopes during flights.

5. Conclusions

An overview has been provided of results recently obtained by the Atmospheric Physics Group at the University of Trento with use of a small airplane.

Interest in this field has increased in recent years and various research groups have pursued airborne measurements with light airplanes. The need of stronger cooperations among small research groups working with similar tools in different countries has stimulated the establishment of a Network of Airborne Environmental Research Scientists (NAERS), in which the Group at the University of Trento is involved.

The results summarized in the present paper show that measurements with light airplanes are not only feasible but also particularly indicated for the detection of special structures of the atmosphere and dynamics of the atmospheric boundary layer, especially over complex terrain. As opposite to other instruments for vertical profiling of the atmosphere, airplanes allow a detailed investigation over full 3D domains at selected locations, according to the specific nature of the phenomenon under investigation. Furthermore suitable data analysis allows identification of thermal structures over 3D domains, even in regions not directly probed by the measurement flight.

Unfortunately one of the main limitations of the equipment in the present configuration is the absence of a device for measurement of wind velocity. Since wind velocity is obtained by the difference between indicated airspeed and absolute airplane velocity with respect to the ground, this kind of measurements imposes two main requirements:

1) Accurate and high resolution sensors for air speed.

2) Suitable device (advanced GPS, accelerometer, etc.) for determination of instantaneous position, pitch and roll angles of the airplane with high accuracy and sampling frequency.

Successful experiments in this field have already been achieved by various research groups by means of special probes specifically designed for airborne wind velocity and turbulence measurements, like the so called BAT-Probe (Best Air Turbulence, *cf.* Hacker and Crawford, 1999).

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