The Design and Operation of a Microbarograph Array to Measure Pressure Drag on the Mesoscale

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ABSTRACT

During the ALPEX field program, pressure was measured along three Alpine cross sections. In order to attain high accuracy, pressure sensors had to be protected against the influence of wind-induced dynamic pressure effects and against gravity wave signals. Corrections based on pre- and postexperiment laboratory and on biweekly field calibrations enabled the compilation of a pressure dataset with an estimated absolute accuracy of 0.3 hPa and a relative accuracy of about 0.1 hPa. Time series plots and time–space plots of the data were generated for quality control purposes.

1. Introduction

In the Alpine Experiment (ALPEX), the last field experiment within the Global Atmospheric Research Program (GARP), the airflow over and around a mountain complex was studied. One of the objectives was the determination of the pressure field across the mountain range in order to allow the computation of drag forces (see ICSU/WMO, 1982). Additional aircraft measurements should further allow the computation of the different components of the drag (form drag; wave drag; possibly, drag due to trapped waves).

Drag measurements on a meso- or small scale have only been published by Smith (1978). In his paper he makes a number of valuable suggestions related to instrumental problems which were duly considered for the setup discussed here.

Three Alpine cross sections were selected for the ALPEX microbarograph subprogram. These were

i) Mali Losinj–Karlovac (Yugoslavia)
ii) Nurnberg–Brenner–Bologna
iii) Stuttgart–Gotthard–Genova.

The experiment design specified the required resolution and accuracy for the pressure data along the cross section according to Table 1.

A group consisting of scientists from Austria, Federal Republic of Germany, Italy, Yugoslavia and Switzerland designed and operated the microbarograph arrays in close cooperation. In order to obtain a reasonable spatial resolution for the pressure field, it was felt necessary to specify also a maximum horizontal separation between the stations. The value adopted was 25 km.

The specified “continuous” time resolution was interpreted to mean not to exceed one hour. Whenever available, temperature and wind data were collected together with the pressure data (see Richner, 1982). All data were collected, quality controlled and merged at the Special ALPEX Data Center (SADC) for microbarograph data in Zurich.

At most of the stations, pressure was measured with classical drum-recorder microbarographs equipped with a set of aneroid cells. In the Italian and Swiss portion of the Gotthard cross section, however, electronic sensors connected to a digital recording system were employed. Unless otherwise stated, the information given below relates to these electronic stations only. Figure 1 shows a map of the stations along the Gotthard cross section indicating the type of the system used. The lowest station was 199 m, the highest station 2949 m above mean sea level; a profile of the cross section is depicted in Fig. 7.

2. Station configuration

In Switzerland, data were obtained from the operational automatic network (ANetz) and from special purpose stations. In both cases, the same type of pressure sensor was used. Stations in Italy were all special purpose stations. Although they made use of a different type of sensor, calibration procedures were identical to those carried out for the Swiss stations.

The ANETZ stations are fully automatic weather stations which transmit meteorological and related data to a central computer every 10 min. via leased lines (see Roesli, 1981). The configuration of the special purpose stations is depicted in Fig. 2. A pressure and two temperature sensors—one for the outside temperature and one for the temperature of the pressure...
transducer—were interfaced with a Sierra Model 700 Field Data Station (the data acquisition system). Data were recorded on magnetic tape every 10 min. A set of accumulators which normally was charged continuously from the mains provided the power. In the case of station Gemsstock (located on a peak 2949 m above MSL), the batteries were recharged by an automotive alternator driven by the cables of an intermittently running cable car.

a. Instruments

The pressure sensors used in the Swiss part of the Gotthard cross-section were Rosemount General Purpose Capacitive-Type Pressure Transducers Models 1332A 10. Table 2 lists specifications which were computed from the values given in the data sheet of the manufacturer.

When comparing these performance specifications with the data requirements in Table 1, one notes that there are three areas in which special precautions are necessary to achieve the attempted relative accuracy among the different stations of 0.1 hPa: nonlinearity, temperature effects and long-term stability.

The figure specified for linearity is valid over the entire range of 339 hPa. In practice, the pressure variations at a given location cover typically 60 hPa, which is about one-fifth of the total range of the sensor. Consequently, it can be expected that errors due to nonlinearity are reduced substantially if the sensor is properly calibrated only in its actual operational range.

Errors due to temperature effects can be compensated for in two different ways: i) sensors can be put into an oven where they are operated at constant temperature or ii) the errors in pressure due to temperature effects can be determined in a climatic chamber and—provided the temperature of the sensor is monitored—compensated for in the data analysis.

Errors due to slow drifting of the sensor signal can only be prevented by frequent recalibrations. To minimize temperature inhomogeneities and their uncontrollable effects in the pressure sensor, the transducers were thermally insulated with 2 cm of styrofoam.

For temperature measurements, YSI precision thermistors (type 44018 in probes No. 701) were used. The bead sensing the temperature of the pressure transducer was glued directly to its housing. The sensor for the air temperature was mounted on top of a 2 m pole. Five millimeters above the sensor, a flat, horizontal, round, chromium-plated metal sheet of about 150 mm in diameter served as radiation shield. Since the accuracy of the temperature measurements was not
crucial, no special calibration efforts were made. Occasional checks indicated that the overall accuracy was about 0.5°C.

b. Site selection

When making precise pressure measurements which should be representative for an area of one to several hundred square kilometers and for a period of one to several tens of minutes, two problems must be carefully considered:

(i) Winds at the measuring site can either increase or decrease the actual pressure through dynamic effects. In built-up areas, the resulting errors can amount to several hPa.

(ii) Atmospheric gravity waves and turbulence can cause pressure fluctuations with peak-to-peak amplitudes in the order of 1 hPa.

Two possible set-ups were studied to eliminate errors due to dynamic wind effects (see Fig. 3):

1) On top of the building, a self-supporting vertical tube samples the pressure in the undisturbed flow field. In order to eliminate noise in the subsonic frequency range, a filter or diffusor made of porous material must be mounted at the upper end of the tube; this diffusor can, at the same time, act as a shield against precipitation. The tube should reach at least out of the cavity zone which is established around a building under windy conditions. For houses with a more or less cubical shape, the total height of the cavity zone is about 1.2 times the height of the building (for details see Lord and Leutheusser, 1966). From the lower end of the tube, a hose is run to the pressure sensor.

2) From the middle of all major facades of the building, small hoses are run to a volume in which the pressure is equalized. The height of the inlets on the facades is uncritical; the individual inlets on a given building must, however, all be at the same height above mean ground level. The pressure in the equalizing volume then represents the mean pressure around the building and is fed directly to the pressure sensor.

For the ALPEX program, the second type of installation was chosen because it is significantly easier to install than the first one. In addition, by choosing a relatively large equalizing volume of 21 and hoses with an inner diameter of only 2 mm, an efficient attenuation of high-frequency pressure fluctuations was obtained. Thus, the pressure errors caused by turbulence and/or gravity waves were greatly reduced.

Alternatively, a high sampling rate (e.g., 1 per min or 16.7 mHz) and successive smoothing of the data by software could have been used to eliminate unwanted pressure fluctuations. (The dominant frequency is almost always near the Brunt–Väisälä frequency, i.e., about 1 per 5 min or 3.33 mHz.) Of course, in this case the space required for storing the data would have been much larger than in the case of the “hardware-smoothing” mentioned above. As mentioned in section 2, the sampling period chosen in the experiment was 10 min.

Pressure values from different sites can only be compared after they have been reduced to a reference level. Consequently, the station height is an important parameter associated with pressure data. The heights of the sites selected along the Gotthard cross section were leveled by the Swiss Federal Office of Topography. Because all but one station (Gemsstock) were very close
to a Swiss first-order leveling network, their height could be determined with a relative accuracy of less than 0.01 m; the height of the Gemsstock station was referenced to a fourth order network with an accuracy of about 0.1 m. As will be shown, the relative accuracy of pressure data was of the order of 0.1 hPa, corresponding to a height difference of about 1 m. Consequently, the accuracy of reduced pressure values will primarily be determined by the accuracy of the pressure measurements themselves and not by that of the leveling.

3. Calibration procedures

Calibration procedures were carried out in three steps:

(i) The sensors were calibrated in a climatic chamber over a pressure range of approximately 700 to 1050 hPa and a temperature range of 0° to 35°C.

(ii) During the operational phase, the sensors were calibrated in the field using a traveling standard. Field calibrations were repeated every 2 weeks.

(iii) After the field phase, the laboratory calibrations were repeated.

a. Linearity and temperature effects

Prior to and after the experiment, the sensors were calibrated in a climatic chamber in order to determine linearity and temperature errors. In the range from 665 to 1035 hPa, deviations were determined individually for each sensor at 0°, 10°, 15°, 20°, 30° and 35°C. Two pressure standards were used as reference: a Baromech (model M 1975, serial D 157) and a Thommen (model 2A4.611.02.2) aneroid type barometer. These had been calibrated against the national pressure standard. In repeated comparisons, the largest observed error of a single reading for both the intermediate standards with respect to the national standard was 0.5 hPa, their rms error was below 0.3 hPa. Mean errors, i.e., systematic deviations, were less than 0.1 hPa and were directly compensated. The Thommen instrument showed a slightly better linearity than the Baromech; consequently, this instrument served as the primary reference while the Baromech instrument was used as backup.

Figure 4 shows a typical result of the calibration of a Rosemount sensor in the climatic chamber. Generally, the deviations from the reference were within the specifications. While the errors for some of the sensors were significantly larger than for others, there was a general behavior pattern: The pressure readings became too low as the temperature increased, the error being larger at low pressure values. There was only 1 sensor out of 15 for which this pattern did not apply.

![Figure 4](image)

FIG. 4. Typical calibration curve for a Rosemount electronic pressure sensor. The sensors were cycled through temperature and pressure; in each cycle about ten readings were taken. Each point in the graph for a given temperature-pressure combination represents a mean of these readings. Different points for identical temperature-pressure combinations originate in different cycles. For clarity, only three temperatures are depicted. Please note that the sensors are not specified below 745 hPa by the manufacturer.
The results of this calibration were used to determine coefficients for a correction polynomial for each of the sensors. The form of this equation was

$$\Delta p = a_0 + a_1 p + a_2 p^2 + a_3 p^3 + bT$$

where

- $\Delta p$ the correction to be added
- $p$ the indicated pressure
- $T$ the temperature of the sensor

Originally, it was planned to include a time-dependent term in the correction polynomial for compensating any drift that might occur. However, the recalibration after the field phase yielded essentially the same results as the calibration prior to the experiment, indicating that drift is negligible. Consequently, pre- and postcalibration data were averaged before the coefficients of the correction polynomial were determined.

b. Field calibrations

Once the stations were in operation, the pressure sensors were recalibrated at the site approximately every 2 weeks. A so-called traveling standard was used as a reference.

The traveling standard DRUKA is an instrument capable of generating defined pressure calibration values within about 50 hPa of the station pressure. A block diagram of the instrument, which was developed by the Swiss Meteorological Institute, is shown in Fig. 5; for details see Joss et al. (1981).

A Rosemount pressure sensor 1332A (selected for good linearity and small temperature error) measures the pressure in a small test volume. Its output signal is compared with a preset value, the comparing circuit producing a difference signal which, by means of a compensated proportional controller, acts on a vibrating membrane pump. With the help of two three-way valves, this pump either reduces or increases the pressure in the test volume with respect to ambient pressure. A third on-off valve controls a calibrated leak which speeds up the equilibrating process if pressure in the test volume is near the ambient pressure.

In order to attain high accuracy and stability, the pressure sensor is kept at a constant temperature of about 40°C, and the air within the instrument is circulated by a small fan. Therefore, a warm-up period of about 30 minutes is required before a calibration can be performed.

The nominal pressure value in the test volume can be preset by a 10-turn potentiometer calibrated in hectopascals. With each of two three-position switches, 20 hPa can either be added or subtracted from the value indicated on the dial. This arrangement allows calibration points at $p1 - 40, p1 - 20, p1, p1 + 20,$ and $p1 + 40$ hPa; $p1$ is the calibration value set with the potentiometer within, say, 10 hPa ambient pressure. The time required to obtain stable reference pressure depends, of course, on the volume of the sensor to be calibrated. With a buffer volume of 1 L, the time required for a change of 20 hPa is about 5 s. For comparison purposes, an external reference barometer can be connected.

Although the pressure stations were calibrated quite frequently, no adjustments to the instruments were made during the field phase. Differences between indicated pressure and reference pressure were recorded along with the sensor temperature for corrections to take place after the experiment.

c. Correction of pressure data

As it turned out, the sensors were very stable. Allowing for temperature and linearity effects based on the laboratory calibration, corrections for a given pressure and sensor obtained in the field calibrations were usually within 0.1 hPa. For two stations, one field calibration produced differences outside this limit; these were later explained by not having allowed the reference instrument to attain stable temperature. At another station, correction values shifted after replacing an A/D converter which had been destroyed by lightning. Finally, for one station, data of a field calibration had to be dismissed because it was inconsistent with data from previous and successive calibrations for unknown reasons.

Correction procedures consisted of first applying the corrections for temperature effects and nonlinearities which were based on the laboratory tests. As already mentioned, no allowance had to be made for drift because of the good agreement of the calibrations prior to and after the experiment. For each sensor, the two sets of the laboratory calibration data were combined as to produce only one correction polynomial. In a second step, the differences between the observed and the corrected values were compared with the differences obtained in the field calibrations. Based on this analysis, a constant was added to the polynomial so as to produce corrected values which were consistent with the values from the field calibrations. Thus, the shape of the correction polynomial (based on laboratory tests only) was not changed; however, it was shifted along the pressure axis to produce values which deviated minimally from the field calibration values. These shifts exceeded 0.1 hPa only in about 10% of the cases; they were always within 0.25 hPa.

Here it should be recalled that the laboratory calibrations were performed over a pressure range of 370 hPa while the field calibrations were restricted to about 120 hPa (see section 3b). Thus, field calibration data served solely to improve the fit of the correction polynomial in the pressure range in which the sensor was actually operated.

It could be argued that a more exact calibration could have been carried out by using laboratory calibration data only in the pressure range in which the sensor was actually operated at a particular station. By this, the validity of the calibration polynomial for a given sensor
would be restricted to its operational range, at the same time reducing the necessary corrections based on the field calibration data. The reason for not choosing this procedure was the impression (which was actually confirmed after the experiment) that an increase in accuracy thus obtained would be less than the envisaged final data resolution of 0.1 hPa.

Based on careful estimates for the different contributing factors, Pike (1984) has shown in a recent paper that the realistic total uncertainty of a pressure sensor is about 0.25 hPa. This figure corresponds well with the 0.3 hPa absolute uncertainty estimated for the ALPEX microbarograph stations. The obtained relative accuracy of 0.1 hPa for the stations is also comparable to the value for repeatability of 0.08 hPa stated by Pike.

4. Results of quality control

As a first step, the time series of all parameters for all stations were plotted and visually inspected. The very few spikes were removed and replaced by values obtained from cubic spline interpolation. Data were merged to form a uniform dataset which is now available from the SADC for microbarograph data in Zurich.

The plot of the 10-min data for a station in Fig. 6 gives an impression of the data resolution. The weather situation allowed a very clear recording of the semi-diurnal oscillations of the pressure. The occasionally occurring noise on the signal indicates the presence of gravity waves whose effects on pressure were not completely filtered by the setup.
For a more thorough assessment of the data quality, mean pressure and mean temperature values were computed for each of the stations over the 2-month ALPEX period. For each combination of two stations, pressure values from the one station were reduced to the height of the other station. For the reduction, it was assumed that the mean layer temperature was the average of the mean temperatures observed at the two stations involved, plus a (climatically determined) virtual temperature addition of 0.5°C. The difference between the pressure reduced in this manner and the actually observed pressure value was arranged in a matrix. (For more details see Phillips, 1984).

Before interpreting the results, it is important to realize that such a procedure cannot provide a very good quality control; on the other hand, it is about the only possibility for a quality assessment apart from the direct calibration of the stations as described in section 3. The assumptions that the temperature measured at any station is representative for the whole air mass at that height and that the profile between any two stations is linear are quite bold. In addition, it must be hoped and expected that there really is a horizontal pressure gradient—its detection was, after all, the purpose of the experiment.

The results of this spatial consistency check reflect very accurately these limitations; for adjacent stations with a vertical separation of less than 250 m, pressure differences were always within 0.1 hPa; mountaintop stations separated as far as 45 km yielded differences of less than 0.05 hPa while the pressure difference between two stations separated only by 3 km horizontally but 1.26 km vertically amounted to about 2 hPa. Of course, it is not feasible to compare data from stations located on one side of the Alps with data originating from the other side; here the differences were always in excess of 1.5 hPa.

Even more qualitative information on data reliability can be obtained when analyzing the data with regard to a specific application. Since it is normally known how the atmosphere behaves, an improperly operating station can be readily identified when its data do not fit in with the values from the rest of the platforms. Phillips (1984) has carried out some analyses by producing time-latitude plots of reduced pressure data and static energy data; Fig. 7 shows an example. The inclusion of the static energy allows an additional testing of the consistency of the temperature data. Please note that in these analyses the German stations (which used classical drum-recorder microbarographs) were also included while the Italian stations (which came into operation only toward the end of the ALPEX Special Observing Period) were omitted.

5. Conclusions

Provided that the necessary precautions are taken, it is possible to obtain pressure data which are, to a high degree, free of noise from the effects of wind and/or gravity waves. For the particular sensors used in the experiment described, drift and hysteresis did not limit the data accuracy. However, errors due to nonlinearity
Fig. 7. Example of a time-latitude plot of pressure (in hPa) and static energy (in Kelvins) for a 3-day interval. Pressure was reduced to the mean height of the instrument array. The plot is based on hourly data, each data point being the mean of five 10-min values centered about the full hour. Above the plot, the profile of the Gotthard cross section is depicted. The three stations in the north (HECH, KLP and WEIS) used classical drum-recorder microbarographs, and for their calibration a slightly different scheme was followed (from Phillips, 1984).

and—to a lesser degree—due to temperature effects could only be eliminated with substantial calibration efforts and, subsequently, tedious correction procedures. On the other hand, the consistency of these corrections, which were based on a fair number of independent calibrations, raised the confidence in the overall data accuracy. The estimated values correspond well to those obtained in other experiments.

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