CALIBRATION AND USE OF A SAILPLANE VARIOMETER TO MEASURE VERTICAL VELOCITY FLUCTUATIONS

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Abstract. The calibration of a sailplane variometer to measure vertical velocity fluctuations in the atmospheric boundary layer is described. Its usefulness is demonstrated with typical results from a boundary-layer development study. The atmospheric calibrations gave the ratio of standard deviations of vertical velocity fluctuations measured by a standard tower-mounted turbulence instrument to the values measured by variometer as 2.5 m s^{-1} V^{-1}.

1. Introduction

Turbulence in the atmospheric boundary layer is an important parameter that varies with height and depends on several factors – atmospheric stability, terrain, wind speed, etc. Measurement from an aircraft is one method of studying the variation of turbulence at higher elevations in the boundary layer. Relative motion of the aircraft with respect to the wind requires an inertial navigation system or a doppler radar. Use of the aircraft motion itself to study vertical velocities is another method that has been used to measure updrafts in storms. In this method the pilot attempts to hold the aircraft pitch angle and thrust constant (Lenschow, 1976). In later experiments an inertial navigation system was used to measure pitch angle variations thus eliminating the need for maintaining constant pitch angle (Kelly and Lenschow, 1978).

This paper describes the use of a simple device called a variometer to measure vertical velocity fluctuations relative to the aircraft in the atmospheric boundary layer. The method consists of flying the sailplane variometer in a small aircraft and allowing the aircraft to be controlled by the atmospheric eddies in the vertical plane while maintaining control over the general direction of flight. This obviously precludes its use close to the ground in very unstable conditions, but it has operated satisfactorily at heights of 150 m over land and at 50 m over water. The variometer was calibrated in the atmosphere to obtain vertical velocities from its output. For atmospheric flows with no mean vertical motions, the vertical velocities measured by the variometer should approximate closely the fluctuations due to wind.

2. Variometer

A variometer (manufactured by Ball Engineering Company) senses small pressure changes with a diaphragm-capillary system and is commonly used on sail planes to determine the rate of ascent and descent. A photograph of the main assembly and the indicator panel is shown in Figure 1. A schematic sectional view of the device is given in Figure 2. When used with a pitot tube, the static pressure changes deflect the diaphragm. Variable inductors are used to measure the displacement of the diaphragm. There are three housings sealed by rubber O-rings (Figure 2). Inductors are held by two of the housings while an extremely thin plastic diaphragm is held between the inductors supported in a metal ring. Magnetic material in the middle of

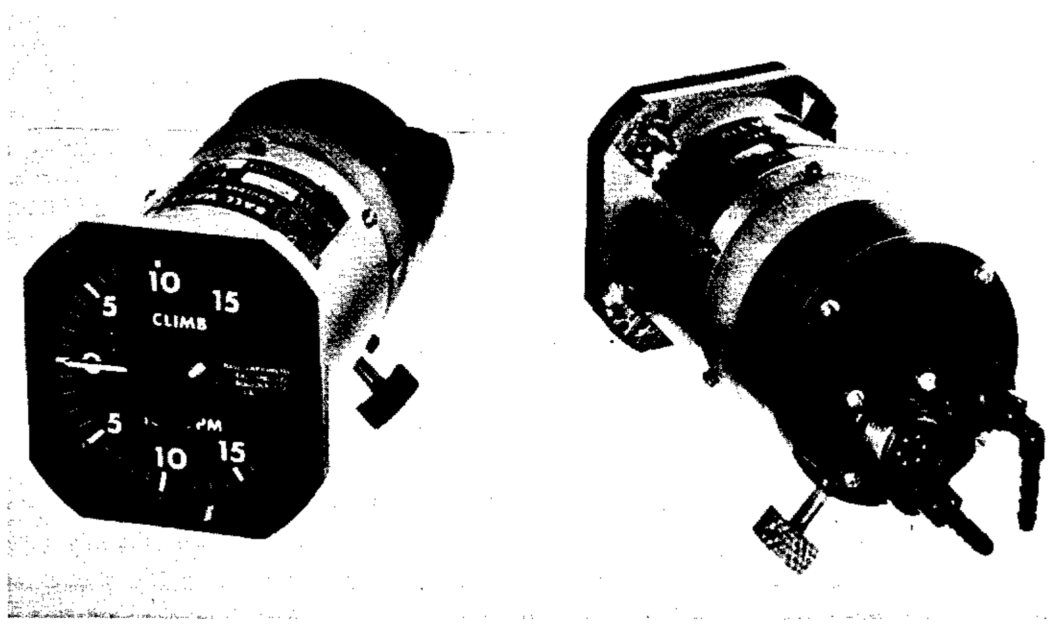

Fig. 1. Photograph of the variometer.

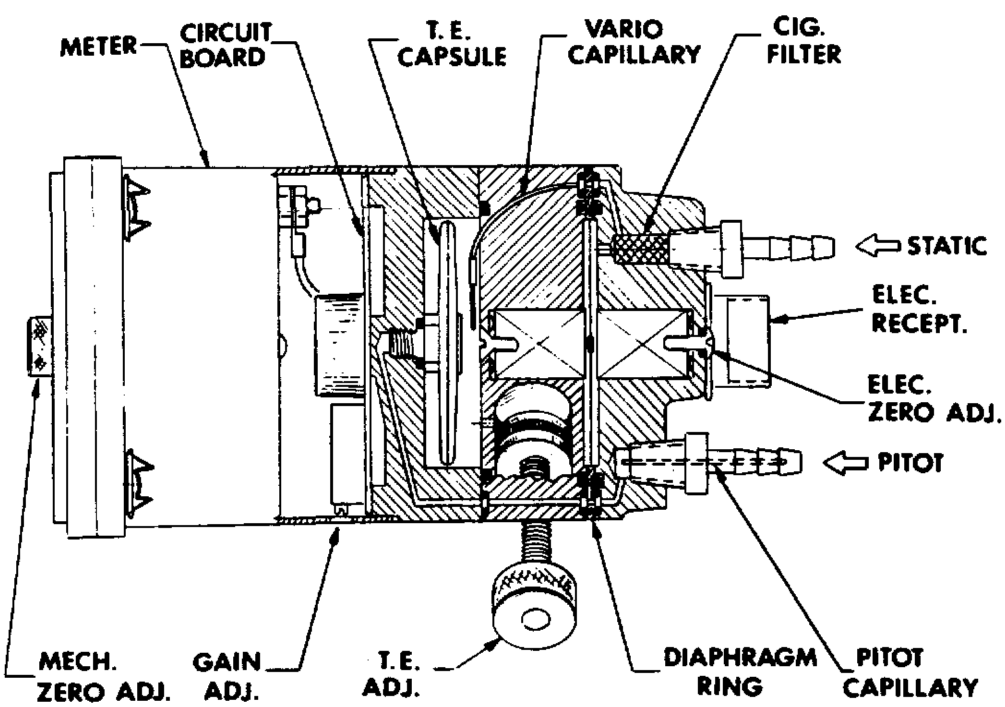

Fig. 2. A schematic sectional view of the variometer.

the diaphragm causes the inductance to change when the diaphragm moves. The reservoir or air bottle is contained in the third housing and this volume is connected to the static pressure line through a capillary tube. During climb, air flows out of the volume, causing a pressure drop which deflects the diaphragm. A small metal pressure capsule called 'total energy capsule' is connected to the pitot pressure line and it compensates for the variations in air speed.

The d.c. output from the variometer was recorded in analog form with a cassette data recorder. The information was also obtained on a chart recorder with a drive speed of 7.5 cm min^{-1} as a backup. The analog data were then digitized as two samples per second and analyzed.

The pitot tube was gimbal mounted and was provided with a styrofoam tail to maintain its horizontal position during flight. The entire assembly was mounted on the wing of a single engine aircraft.

3. Calibration

The readings indicated by the variometer can be used directly for a qualitative analysis of turbulence. In order to get quantitative values for the vertical velocity fluctuations in the atmosphere, several tests were conducted to compare the variometer observations with those obtained with a conventional meteorological sensor. The tests consisted of making flights past a 126-m high meteorological tower at Brookhaven National Laboratory. A vector vane (manufactured by Meteorology Research, Inc.) was mounted at the highest level of the tower and used to measure the longitudinal, lateral and vertical velocity fluctuations. The outputs were recorded on a magnetic tape recorder in analog form and digitized after passing through a low-pass RC filter. Other measurements included vertical temperature profiles with another aircraft during the experiments to determine the atmospheric stability. Wind speeds and directions aloft were computed from pibal soundings.

For the calibration flights, the variometer was mounted on a single engine Cessna-172 aircraft and connected to a standard pitot-static tube attached to the wing. The pitot tube was provided with a tail and a gimbal mount to isolate it from the pitch and roll of the aircraft. The aircraft was flown at a near constant speed of 33 m s^{-1}. The flight time for each run averaged about 15 min. Several flights were completed for each day to obtain a representative value. Eleven flights past the tower were made during neutral, stable, and unstable atmospheric conditions at a height of about 126 m. The mean wind speeds for these tests ranged from 2 to 8 m s^{-1}. The results obtained from these tests are shown in Table I. Mean wind speed $\bar{u}$, the turbulence level $\sigma_u/\bar{u}$ and the standard deviation of the vertical velocity fluctuations σ_w are also given in Table I. The simultaneous values obtained by the vector vane and the variometer indicated the reproducibility of the calibration within reasonable limits. The ratio R for each test was obtained as

$$R = \sigma_w \text{ (vector vane)}/\sigma_w \text{ (variometer)}.$$

TABLE 1

Variometer Calibration Results

Test No.	$\bar{u}$ (m s^{-1})	$\sigma_u/\bar{u}$	Tower σ_w (m s^{-1})	Vario. σ_w (V)	Ratio* R	Atmospheric Stability
1	4.64	0.04	0.15	0.052	2.87	Stable
2	3.97	0.09	0.15	0.050	3.00	Stable
3	2.42	0.21	0.68	0.282	2.40	Neutral
4	2.42	0.21	0.68	0.285	2.37	Neutral
5	2.42	0.21	0.68	0.281	2.41	Neutral
6	2.42	0.21	0.68	0.287	2.36	Neutral
7	6.68	0.24	1.40	0.476	2.94	Unstable
8	7.27	0.22	1.13	0.514	2.20	Unstable
9	7.65	0.24	1.37	0.483	2.84	Unstable
10	6.12	0.25	1.07	0.520	2.06	Unstable
11	8.05	0.22	1.17	0.534	2.19	Unstable

* (m s^{-1} V^{-1})

The value of r varied between 2.06 and 3.00 with a mean of 2.5 m s^{-1} V^{-1}. The standard deviation of R was found to be 0.36.

The variance spectra of the vertical velocity fluctuations measured by the bivane (or vector vane) and the variometer for one of the tests is shown in Figure 3. The units for the ordinate for the vector vane are in m^2 s^2 and for the variometer in V^2. Both spectra show peaks at about the same frequency. The values for the vector vane are about 2.5 times the values for the variometer at a given frequency up to about 0.5 Hz beyond which the energy falls off rapidly for the variometer spectra. A rough computation using the indicated air speed of 33 m s^{-1} and this frequency gave a wavelength of about 11 m which corresponded to the wing span of the aircraft.

4. Typical Applications

The variometer will be highly useful where quick and reasonably accurate measurements of atmospheric turbulence are needed (Raynor *et al.*, 1975; Raynor *et al.*, 1978a). Due to its adaptability to commercially-available small aircraft, its operation is economical. It is best suited for boundary-layer studies (Raynor *et al.*, 1978b). Development of the internal boundary-layer over Long Island with on-shore atmospheric flow is being studied at Brookhaven National Laboratory (Raynor, *et al.*, 1977). A schematic diagram of the development of the internal boundary layer is shown in Figure 4. The sailplane variometer was flown at several heights to study the change in turbulence caused by the formation of internal boundary layers. The flight path at one such height is also shown in Figure 4. The measured vertical velocities as the aircraft flew at 33 m s^{-1} towards the Atlantic ocean at a height of 335 m are shown in Figure 5. An abrupt decrease in the turbulence can be seen as the aircraft experienced marine air. By analyzing the observations independently for within and outside the boundary layer, the increase in turbulence inside the boundary layer can be estimated.

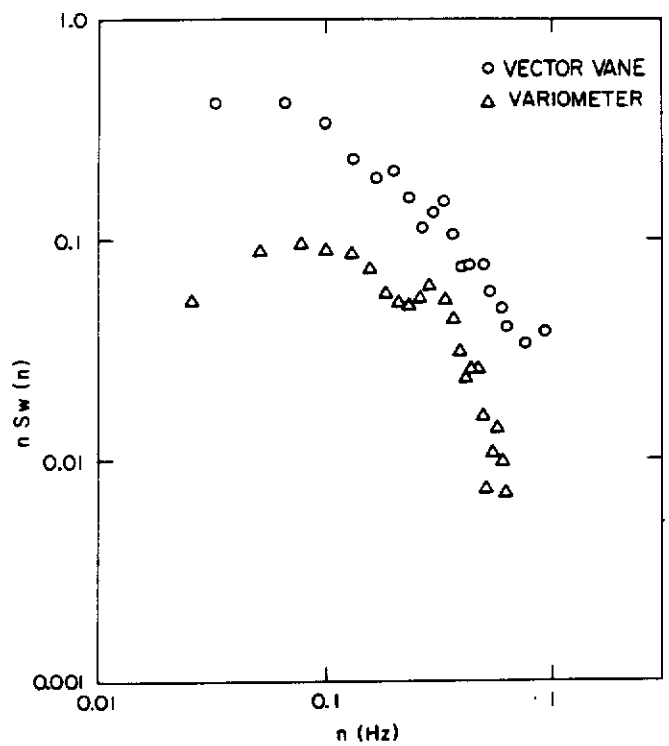

Fig. 3. Variance spectra of the vertical velocity fluctuations measured by the vector vane and the variometer for one of the tests. The units for the ordinate are $m^2 s^{-2}$ for the vector vane and V^2 for the variometer. Note the rapid drop in energy for the variometer beyond 0.5 Hz.

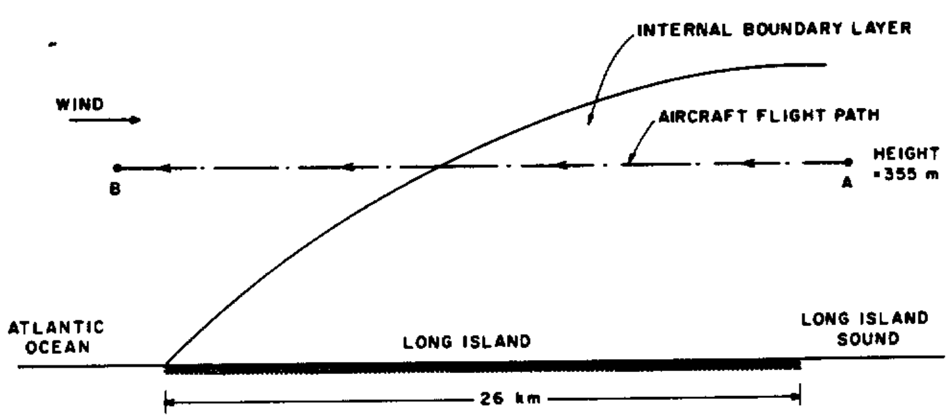

Fig. 4. A schematic diagram indicating the internal boundary layer development over Long Island and the flight path of the aircraft at a height of 355 m from position A over Long Island Sound to position B over Atlantic Ocean.

5. Conclusions

A variometer that senses small air pressure changes with a diaphragm-capillary system was calibrated with flights past a meteorological tower equipped with a meteorological instrument to measure vertical velocity fluctuations. Tests conducted during different atmospheric stability conditions produced a consistent value for the

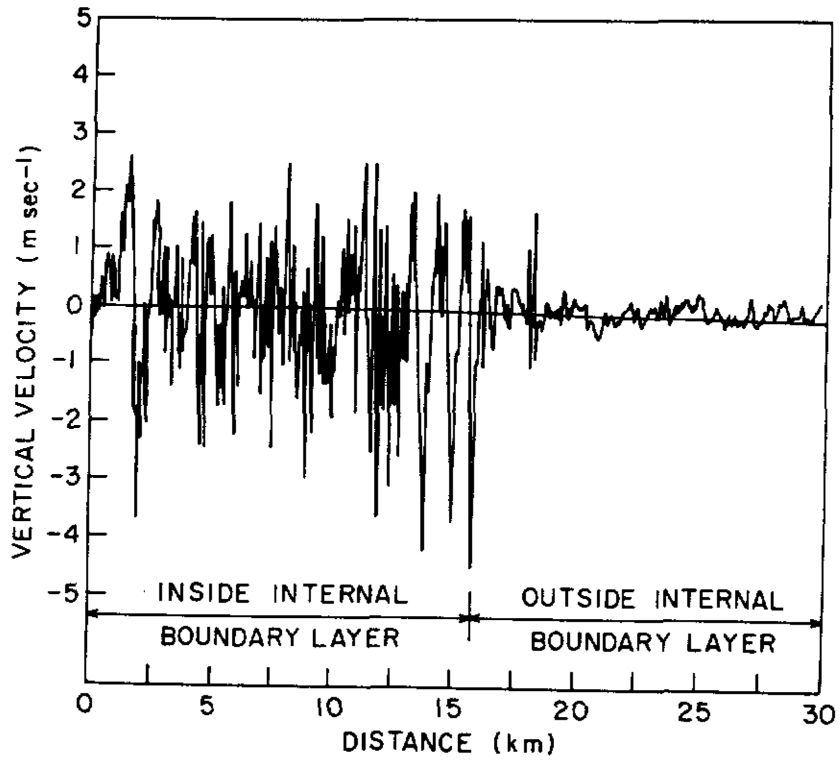

Figure 5. Vertical velocities measured by the aircraft at a height of 335 m along the flight path indicated on Figure 4.

calibration constant. The advantages of this system include its simplicity, ease of operation, ruggedness and economics; but one should be aware of the human errors that can be introduced if the aircraft is controlled excessively during its ascent and descent.

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