# Ultralight Sounder: An Airborne System for Studying the Planetary Boundary Layer

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## Abstract

Until recently, investigations of the temperature structure of the planetary boundary layer have been confined to the use of balloon soundings (tethered balloon sondes, rawinsondes), disposable dropsondes, or high performance instrumented aircraft. These methods can be quite restrictive in their ability to obtain detailed temporal and spatial resolutions, especially in areas of limited accessibility. The operating cost of an instrumented aircraft also may be prohibitive. From this perspective, the use of an ultralight sounder—a meteorological sensor mounted on a motorized glider—is described, and its versatility is discussed. This system was employed in measuring the vertical temperature structure in mountainous terrain during the winter months of 1981–82. The system's capability to obtain detailed vertical temperature structure, as attested by the data gathered, renders it invaluable in the study of the planetary boundary layer in complex mountainous terrain.

## 1. Introduction

During the past several winters, a number of field experiments have been carried out, in conjunction with the Colorado Orographic Seeding Experiment (COSE) conducted by the Department of Atmospheric Science of the Colorado State University, to study the structure of the planetary boundary layer (PBL) in the mountainous region of northwestern Colorado. These field experiments were designed to develop an understanding of the physical processes that influence the transport and dispersion of ground-released seeding materials in complex, mountainous areas. To achieve this objective, it was necessary to monitor not only the temporal, but also the spatial, variations of the structure of PBL. In the absence of an extensive network of surface-based meteorological soundings, it would be necessary to measure the vertical structure at various locations in the experimental area by mobile platforms within a relatively short span of time. During the last field experiment, this was accomplished by the use of an instrumented ultralight aircraft. Information so obtained was essential to enable the investigator(s) to construct a coherent, encompassing 4-dimensional description of the overall features. The utility of the ultralight aircraft for these types of measurements will be discussed.

Until recently, *in situ* probings of the vertical structures of PBL have relied on rawinsondes, tethered balloon sondes, and airborne measurements via conventional instrumented aircraft. These methods can provide much of the needed information; however, they can become inadequate for some types of desired measurements. In the case of rawinsondes, the spatial resolution and the representativeness of the data would depend in some measure upon the extent of lateral movement and the rate of ascent of the balloon. While this might not impose a serious constraint on investigations in which one's primary interest is that of the mean large-scale structure, it could become a critical factor when knowledge of the details of small-scale variations are necessary. The time constraint involved in the operation of rawinsondes also could become a limiting factor when continual monitoring of temporal variability is needed. These problems can be overcome partially by using a tethered balloon sonde in which the balloon is confined to a given space. Under some conditions, the rates of ascent and descent, and hence the spatial resolution of the data, are controllable. Repetitious soundings also can be performed relatively easily. However, the use of a tether, with its added weight and its dragging effect in the wind, often hinders the rise of the balloon. Most commercially available tethered balloon sondes have a maximum operating ceiling of about 1000 m. Safety considerations with regard to air traffic also can restrict the use of tethered balloon sondes in certain locations. Another major obstacle in using tethered balloons for soundings is their limited portability and mobility. The primary difficulty is in gaining access to some locations in complex terrain. This handicap greatly reduces their applicability in studies dealing with mesoscale meteorology in complex terrain. In order to study horizontal variability, it is necessary to use two or more tethered balloon sondes concurrently. Human power requirements and operating costs can become prohibitive.

Instrumented aircraft have the advantage of being highly mobile, and thus can provide the 4-dimensional information desired. Again, due to the limitation of flight capacity and safety considerations, certain modes of operation are not feasible. Conventional instrumented aircraft also require a great deal of maneuvering space in which to operate. When the investigation of detailed mesoscale and microscale structures is required, as is often the case in studies involving monitoring PBL in complex terrain, certain sites may not be accessible by a conventional aircraft. Representative measurements in a specific locality and of a specific feature might not be possible. Furthermore, in low-level flight, the aircraft wing-tip vortices can cause mechanical mixing along the flight path, resulting in undesirable interference to surface-based measurements that are being taken concurrently in the vicinity.

During the field experiments of the winter of 1981–82, a new airborne measuring platform was tested and used to

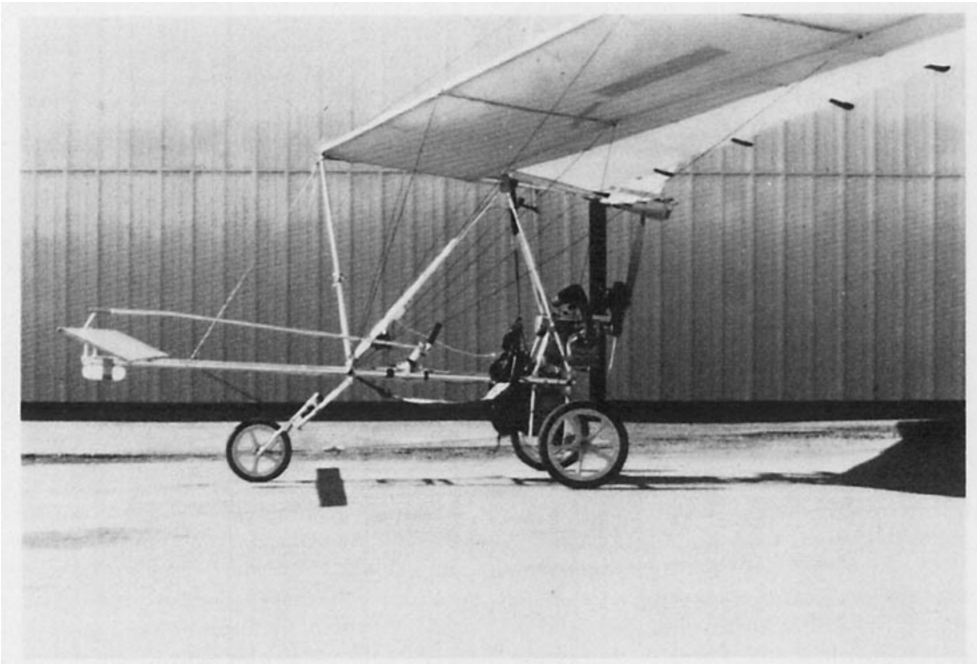

FIG. 1. Side view of ultralight with sensor mounted at extreme forward location on canard boom.

provide information on the vertical temperature profile. This new system consisted of an Airsonde™,[1] mounted on an ultralight aircraft (see cover photo and Fig. 1). The ultralight used was basically a motorized hang glider. The present article describes the results of the testing and operation of the ultralight system. Some of the data collected during the field experiment also are presented. We discuss the feasibility and the limitations of using the ultralight for various types of mesoscale and micrometeorological measurements and explore possible improvements that can be added to the system to enable it to meet more sophisticated needs.

## 2. Description of the system

### *a. Airborne platform—The ultralight*

Ultralight aircraft evolved from the hang glider, which became popular during the 1970s. Beginning with simply bolting an engine and propeller to a hang glider, ultralights now are designed entirely as powered aircraft. As a result of higher wing loadings and stresses associated with the additional weight, thrust, and torque loads of the engine, ultralights have stronger airframe components than a typical hang glider. All structural components are aircraft grade in the modern ultralight. Most ultralights are purchased as kits, which have components preformed, cut, and drilled for assembly. The degree of completeness varies from ultralight to ultralight, with assembly time ranging from an afternoon to several hundred man-hours. A short review of the history, construction, aerodynamics, and examples of several different models of ultralights currently available is presented by Markowski (1982).

Several models of ultralights are currently available from various manufacturers. The type used in the field experiment is known commercially as a "Pterodactyl Ascender."™,[2] In light of its new application, the ultralight has been referred to as the "Psounder." Its physical characteristics and performance are listed in Table 1. It should be emphasized that differ-

[1] Manufactured by Atmospheric Instrumentation Research, Inc., Boulder, Colo. 80301.

[2] Manufactured by Pterodactyl LTD, P.O. Box 191, Watsonville, Calif. 95076.

TABLE 1. Ultralight performance characteristics.

| | | |
|---|---|---|
| Wing span | 33 ft | (10 m) |
| Length | 11 ft | (3.4 m) |
| Empty weight | 200 lb | (91 kg) |
| Maximum weight | 425 lb | (193 kg) |
| Pay load (includes pilot) | 225 lb | (102 kg) |
| Glide ratio | 9:1 | |
| Stall speed | 20–25 mi/h | (32–40 km/h) |
| Cruise speed | 30–40 mi/h | (48–64 km/h) |
| Climb rate | 300–800 ft/min | (1.5–4.1 m/s) |
| Fuel consumption | 1.5 gal/h | (5.7 L/h) |
| Endurance (5 gallon capacity) | 3.3 h | |
| Takeoff roll | 100–150 ft | (30–46 m) |

TABLE 2. Sensor characteristics.

| Dry and wet bulb temperature | | Barometric pressure | |
|---|---|---|---|
| Range: | −70°C to +50°C | Range: | 1050 mb–50 mb |
| Precision: | ±0.5°C (for +40°C to −40°C) | Precision: | 3 mb |
| Resolution: | 0.01°C | Resolution: | 0.1 mb |
| Response time: | Dry bulb—3 s | Sensor: | Aneroid capsule with moving diaphram capacitor, temperature compensated. |
| Sensor: | Bead thermistor | | |

ent models of ultralights perform differently, and that the performance also is dependent on the ambient atmospheric conditions such as wind, temperature, and flight altitude. This ultralight was selected because it has one of the best high altitude performance characteristics in the ultralight industry. During the field experiment, flights were conducted under conditions with temperatures ranging from 5°C to −20°C. Surface winds at the landing and takeoff site were generally less than 5 $m \cdot s^{-1}$. The boundary layer during this period generally was stable at low levels, became less stable at intermediate altitude, and near-neutral at higher elevations. Mild to moderate turbulence was encountered near the top of the surface-based temperature inversion and in regions with appreciable wind shear. The ultralight performed under these conditions with no difficulty. In one case, an ascent was made from about 2100 m MSL to 3500 m MSL, followed by a descent to the starting altitude. This sequence was completed in less than 30 min.

The low cruise speed, excellent climb rate, and small turning radius (less than 100 m in diameter) of the ultralight make it especially applicable to low-level flights in complex, mountainous terrain. The ultralight used does not require airport facilities for support and can be operated from unimproved fields where there is sufficient open space for safe landings and takeoffs. The entire ultralight can be disassembled and transported on top of a station wagon, in a van, or on top of a pickup truck. On a winter afternoon with near-freezing temperatures, it took two persons less than two and one-half hours to assemble the ultralight into its operational configuration. Disassembling it took even less time. Such portability, mobility, and maneuverability in flight permit a great deal of flexibility in using the ultralight for atmospheric research purposes. Finally, ultralights are relatively inexpensive, being in the price range of $4000–$5500. The low airspeed of an ultralight also permits the use of relatively inexpensive instrumentation and data acquisition systems.

### *b. Meteorological sensor*

An Airsonde™ was used as the meteorological sensor on board the ultralight. The battery-powered sensor and telemetry package are housed inside a streamlined styrofoam enclosure. Bead thermistors that measure dry- and wet-bulb temperatures are situated inside an open-ended tubular enclosure through which the airstream passes. A temperature-compensated, aneroid capacitance pressure transducer measures absolute pressure. In the field experiment, the enclosure with the sensor and telemetry package was mounted onto one of the canard booms on the ultralight. This ensures proper ventilation of the temperature sensor and minimized possible effects caused by the ultralight on the sensor. Because of the relatively low flight speeds involved, dynamic heating effects due to airflow are not a significant source of error for temperature measurements. The sensor characteristics of the Airsonde™ are shown in Table 2.

During operation, the Airsonde™ acquires a set of pressure and temperature data approximately every eight seconds. These data are multiplexed and transmitted at 403 MHz to a receiver. Signals received are stored on magnetic tapes by cassette recorder for future processing. Real-time printout of the data also can be obtained through interfacing the receiver with an HP-97 calculator-printer. During the field experiment, one set of data out of every six was printed on paper rolls. The Airsonde™ and the accompanying components of its ground-based unit are shown in Figs. 2a and 2b. The effective radius of operation of the Airsonde™ was found to be less than 5 km. Line-of-sight between the sensor-telemetry package and the antenna of the ground unit must be maintained. The alignment of the antenna is important to ensure good reception. After testing various configurations, it was found that orienting the antenna of the receiving unit near vertical and the antenna on the telemetry package at 45° to the vertical gave the best results.

## 3. Field experiment

The field experiment was conducted in the Park Range–Yampa Valley region in northwestern Colorado (see Fig. 3). The ultralight was, for convenience, based at the Routt County Airport. Testing of the system was carried out in mid-January 1982. The reliability of the system was verified by a series of extended tests on the ground. These were done by activating the system and allowing it to come to equilibrium with the environment. Then, over a long period, measurements obtained from the Airsonde™ were compared with measurements obtained from a reference thermometer and barometer. Data reliability also was confirmed by the close agreement and consistency of vertical soundings taken in the same location over a short interval of time. Several possible modes of operation also were explored. In the mode adopted for use, the entire ground unit was rendered mobile by placing its various components inside a van. The receiver was powered by a 12 V DC automobile battery inside the van; the calculator-printer and the recorder were powered by small dry cell batteries. In this way, the ground unit could be relocated, if needed, in accordance with the position of the ultralight. Thus, the relative location of the transmitter and re-

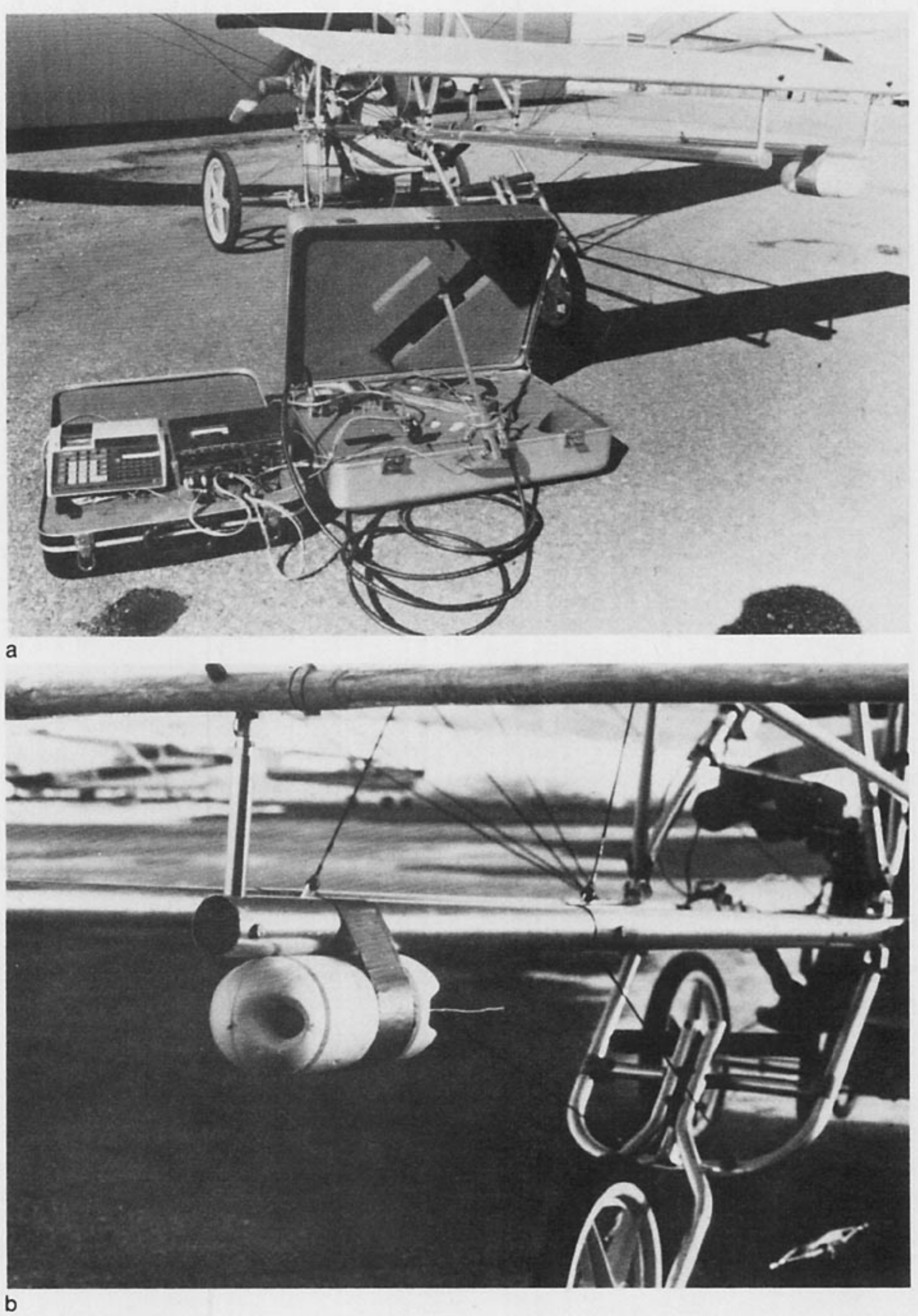


FIG. 2. a) Ultralight with sensor mounted on canard boom. In the foreground are the components of the Airsonde™ ground-based unit including printer-calculator, cassette tape recorder, and radio receiver. b) Close-up of Airsonde™ sensor mounted on the ultralight.

ceiver was ensured to be within the effective radius of operation and continuous contact was maintained. This allowed the mobility and flexibility needed for the ultralight to collect data. To avoid confusion and to simplify data-processing and analysis in the future, final flight plans and contingent flight plans were made before each flight and were strictly adhered to. A two-way radio provided a communication link between the pilot of the ultralight and the person in charge of the ground unit. The latter would monitor closely the performance of the sensor and would keep the pilot informed. Actual field measurements were carried out on 19–20 January and 24–26 February 1982.

## 4. Examples of data

Two sets of vertical soundings are shown in Figs. 4a and 4b. These soundings were taken in the general vicinity of the

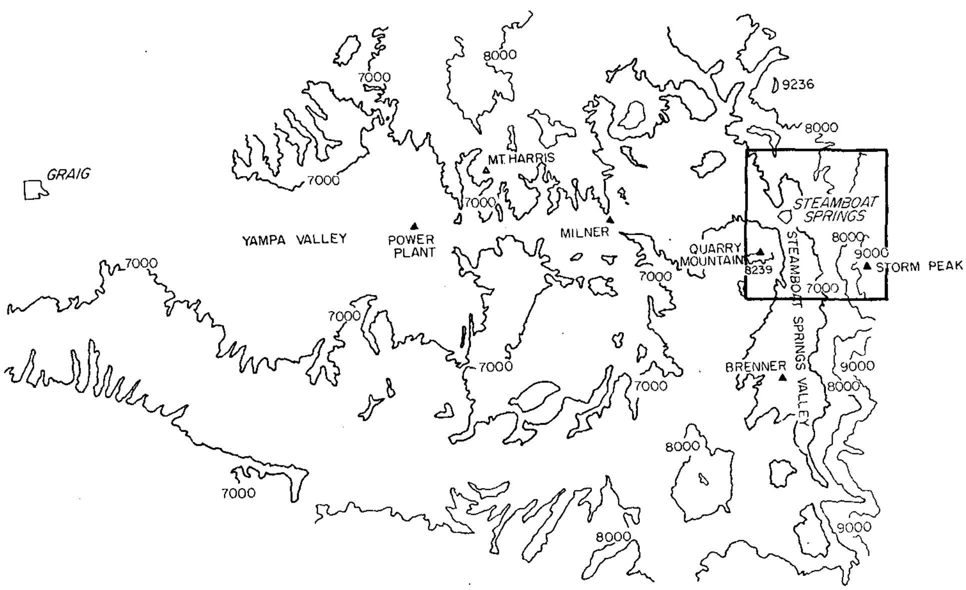


FIG. 3. Topographic map of Park Range–Yampa Valley. The box shows the location of the area of study shown in Fig. 5. The contour interval is 1000 ft.

Routt County Airport, at distances of about 6–8 km upwind (west) of the main ridge line of the Park Range. Each of these soundings consists of a successive ascent and descent. The 24 February soundings show a surface temperature inversion extending to more than 300 m above ground. This stable layer was capped by a near-neutral layer that extended to ridgetop level. A very sharp stable layer marked the transition to the upper layer. The greatest differences between the up- and down-soundings can be seen at approximately 703 mb and 765 mb. These differences might have been due to actual advective structural variations encountered in those regions. Also shown in Fig. 4a is a rawinsonde measurement of the vertical temperature profile. This sounding was taken at a distance of about 60 km west of the Routt County Airport. It is seen that above the surface temperature inversion and in the vertical domain where the local topographic effect would be minimal, the rawinsonde's measurements agreed very well with those taken by the ultralight system. The lack of spatial resolution, as shown by the differences between the rawinsonde and ultralight soundings, can certainly result in erroneous conclusions regarding the vertical temperature structure, as this example has shown.

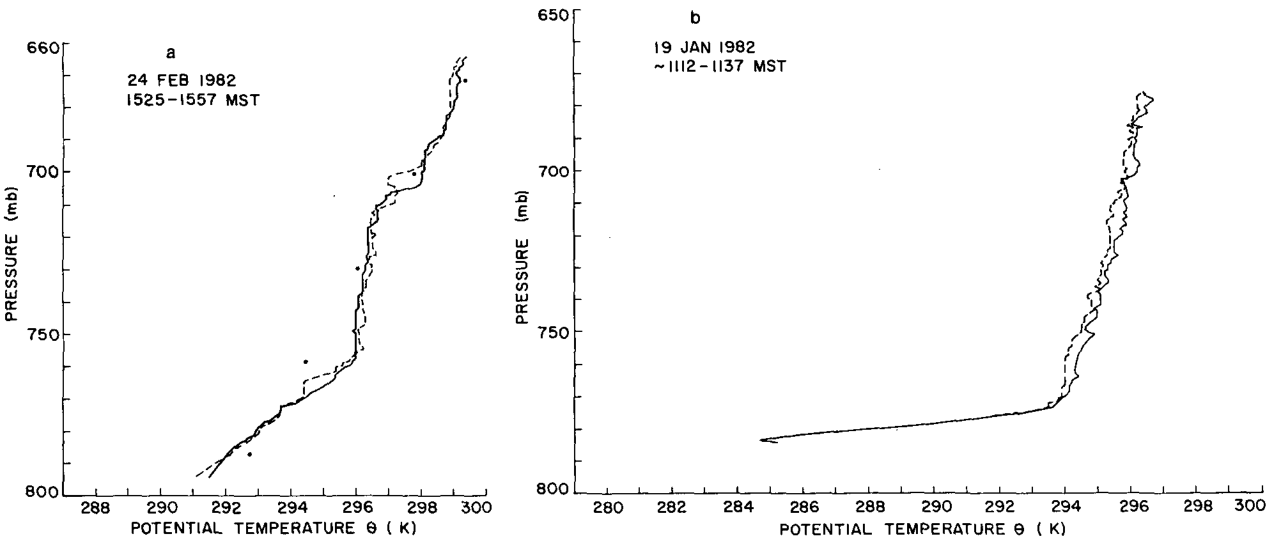


FIG. 4. a) Ultralight soundings taken at Routt County Airport on 24 February 1982. Solid line indicates up-sounding; broken line indicates down-sounding. The rawinsonde data taken at Craig, Colo., 60 km to the west, at 1600 MST are indicated by dots. b) Ultralight soundings taken at Routt County Airport on 19 January 1982. Solid line indicates up-sounding, broken line indicates down-sounding.

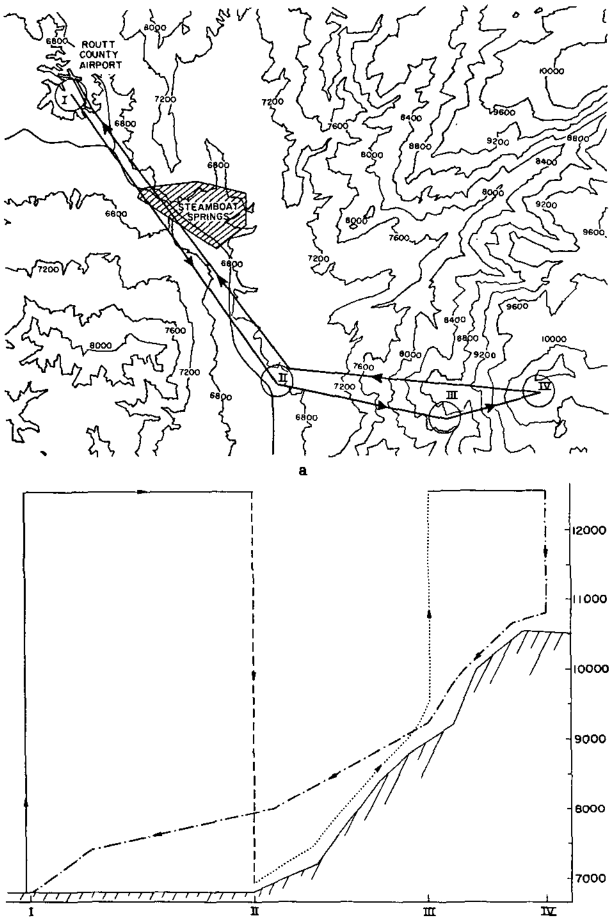


FIG. 5. a) Ultralight flight track of 26 February 1982 and the detailed topographic features of the area of study. Circles indicate the locations where vertical soundings were conducted by the ultralight. The contour interval is 400 ft. b) The east-west cross section of the flight track shown in Fig. 5a. Vertical scale in feet.

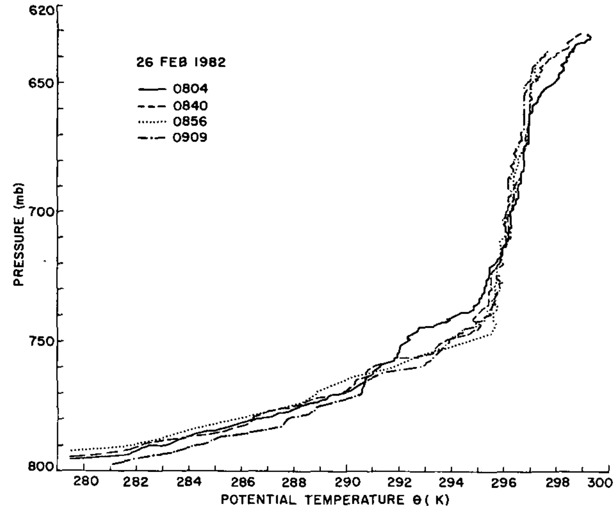


FIG. 6. Ultralight soundings taken on 26 February 1982. The nature and location of these soundings are indicated in Figs. 5a and 5b. For example: the sounding plotted as a solid line here was obtained along the flight path indicated by a solid line in Fig. 5b. This same correspondence applies to the other soundings.

The soundings of 19 January show a pattern generally similar to that of 24 February. The surface temperature inversion was capped by a less-stable layer that extended well above the ridgetop level. There was an indication that a shallow near-neutral layer also separated the two. A thin superadiabatic layer had evolved at ground level as a result of the heating of the ground by solar insolation and the ensuing vertical mixing. In both of these sets of soundings, the close agreement between the up- and the down-soundings was quite remarkable.

One of the objectives of the field experiment was to define the temporal and spatial variations of the vertical temperature structure in mountainous terrain. In this regard, the ultralight-Airsonde™ system was employed in a monitoring scheme that required the system to make consecutive vertical soundings at different locations and to take airborne measurements of temperature along mountain slopes. Figure 5a shows a typical flight track of the ultralight used in this scheme and the topography of the surrounding terrain. Figure 5b shows the corresponding west-east cross section. One set of measurements taken on the morning of 26 February using this scheme is shown in Fig. 6. The sequence and locations of these measurements are indicated in Figs. 5a and 5b. For example, the sounding taken on the flight path indicated by the solid line in Fig. 5b is plotted as a solid line in Fig. 6. The same holds true for the other soundings. These soundings showed the heights of the top of the surface temperature inversion at different locations away from the slope. Of particular interest are the lapse rates and the relative lateral temperature differentials at various heights, as indicated by the soundings. Such information is needed to deduce the 4-dimensional structure of PBL in mountainous terrain and to understand how the flow fields in PBL are generated or influenced by the temperature gradients at different points. As is evident from these soundings, in the absence of external forcing, pressure gradients resulting from horizontal temperature gradients would lead to downslope flows with a general east-to-west flow direction inside the surface-based temperature inversion. Such a layer of thermally-driven easterly drainage flow would extend to more than 300 m above ground in the area covered by the ultralight. In the layer above it, the lapse rates would diverge and the horizontal temperature gradients would reverse their directions. This would suggest that in the absence of a large, dominant synoptic-scale pressure force, a thermally driven return flow having a general flow direction opposite to that of the drainage flow below would be present. Observations of such return flows or compensating flows have been reported in the literature (Thyer and Buettner, 1962; Whiteman, 1980). In the present case, investigation of the spatial pattern of the temperature structure shows that such a system could be driven by mesoscale pressure gradients caused by horizontal temperature gradients. Since heat exchange is a major and dominant process in the surface layer, a knowledge of the details of temperature differentials and lapse rates is very useful in the understanding of the physical processes taking place in PBL.

## 5. Discussion

In its present form, the ultralight sounder system has a number of limitations. The ultralight proved to be a safe airborne platform in fair weather. However, its light weight and structural simplicity, which allow it great maneuverability and ease of operation, also make it unsuitable to be flown under turbulent or poor weather conditions. Extreme caution must be exercised when operating the ultralight on a day when PBL may become unstable, turbulent, or windy. While the ultralight is simple to fly, it takes experience to operate it proficiently and effectively for research purposes in complex mountainous terrain.

As of 2 October 1982, the Federal Aviation Administration (FAA) has incorporated as law Part 103 of the Federal Aviation Regulations (FAR) specifying the minimum standards for the operation of ultralight aircraft. The ultralight cannot exceed an empty weight of 254 pounds, cannot carry more than 5 gallons of fuel, and must have a maximum level cruise speed of 55 knots and a power off stall speed of not more than 24 knots. The FAA can request to inspect any ultralight. The pilot does not have to be licensed nor does the ultralight have to be registered. The FAA is fostering the idea of self-regulation within the industry, which has been successful with hang gliders. The national organization of the Aircraft Owners and Pilots Association (AOPA) has begun setting up programs for ultralight pilot training and licensing and ultralight aircraft registration, as well as safety programs. Participation remains voluntary.

The law has several restrictions regarding the operation of ultralights. They cannot be flown over congested populated areas, restricted areas, or prohibited areas. To operate an ultralight in an airport traffic area or control zone, a terminal control area, or in positive controlled air space (greater than 18 000 ft MSL), the pilot must receive prior permission from an appropriate air traffic control facility. Airports without an operating control tower do not fall into these categories. In general, above an altitude of 1200 ft MSL and below an altitude of 10 000 ft MSL, the pilot must have a visability of 3 mi and maintain a distance of 2000 ft horizontally from, and 500 ft below, clouds. Below 1200 ft AGL (above ground level), the pilot must have a visibility of one mile and stay clear of clouds. Above 10 000 ft MSL and below 18 000 ft altitude MSL, the pilot must maintain a horizontal distance of one mile from, and 1000 ft below, clouds and have a visibility of 5 mi. These are part of the standard visual flight rules (VFR), as outlined in FAR Part 91.105. Ultralights cannot be flown after dark. They may be operated 30 min before sunrise and 30 min after sunset if they have an approved anticollision light. In addition, the pilot must maintain visual reference to the ground, which prohibits flight above or within cloud. The ultralight must yield right of way to all other aircraft, and must be operated for sport or recreational purposes only. This limitation is a grey area as far as use of an ultralight for research purposes is concerned and is open to some interpretation according to FAA at this time. However, all FARs will be enforced. If one wishes to operate an ultralight under conditions other than those just indicated, or for commercial purposes, the ultralight can be registered as an experimental aircraft. In that case, the pilot must be a federally licensed pilot.

Insurance, both personal liability up to $500 000 and for hull or airframe damage, is now available from several sources.

One drawback of the ultralight sounder lies in its mode of data acquisition. The data telemetry link presently used restricts the ultralight to flying within less than a 5 km radius of the ground unit. During field testing, an attempt was made to operate the entire Airsonde™ system airborne by mounting the various components of the ground unit on board the ultralight. It failed because the ambient air was too cold for the recorder and the electronic components to operate. There are two simple methods to overcome the problems related to the transmission and reception of data: 1) increase the signal strength of the transmitter or improve the performance of the receiver and 2) eliminate telemetry by using a direct on board data acquisition system, designed and insulated to ensure proper functioning under cold conditions. Most ultralights have about 100 W of 12 V DC power available. In view of this, the second method is quite feasible and more preferable than the first.

By far, the most useful and needed additions to the ultralight sounder would be a radio altimeter and a system to measure wind. The former is almost indispensable for measurements in which information on the actual altitude above ground is needed. Inclusion of wind-measuring capability is more difficult. A feasible way would be to deduce the wind speed and direction by combining airborne measurements of air speed and flight heading with a measurement of the ground speed of the ultralight determined by a dual ground-based, automated radio-theodolite tracking system.

In addition to the application illustrated previously, an instrumented ultralight aircraft also is suitable for a variety of other micrometeorological studies under low wind conditions (i.e., less than $9 \text{ m} \cdot \text{s}^{-1}$). Floats can be purchased for ultralights in the price range of $600–$800 that would permit safe, low-level temperature, moisture, and wind profiles to be made over lakes or ocean coasts. The ultralight also can be equipped with pollution-sampling devices, such as aerosol detectors and specific gas samplers, for low-level plume tracking studies. Applications are limited only by ingenuity and aircraft performance.

## 6. Conclusion

Based on our field experiment, the ultralight has proven to be a reliable airborne platform for taking measurements in the planetary boundary layer. It is inexpensive to operate and easy to maintain. Its transportability, low cruising speed, tight turning radius, high climb rate, maneuverability, and accessibility to remote locations otherwise not reachable by a land vehicle make it uniquely suitable for use in complex mountainous terrain.

In our field experiment, an Airsonde™ that measured temperatures was attached to the ultralight. The ultralight sounder was employed to take vertical soundings and to measure temperature profiles along mountain slopes.

The experiment was successful and the result has provided valuable insight regarding the temperature structure in mountainous terrain. The versatility of the system can be improved by including sensors for wind, altitude, aerosol, and gas measurements. With such additions, the ultralight sounder can meet the needs of more sophisticated studies that require information on all of these parameters.

From this experience in the field, the potential of the ultralight sounder is promising. Continued improvement in instrumentation and further exploration of its application are intended. The full analysis of the data is being integrated with other surface and boundary layer data. A technical report of the result of the analysis will be submitted to an appropriate journal.

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