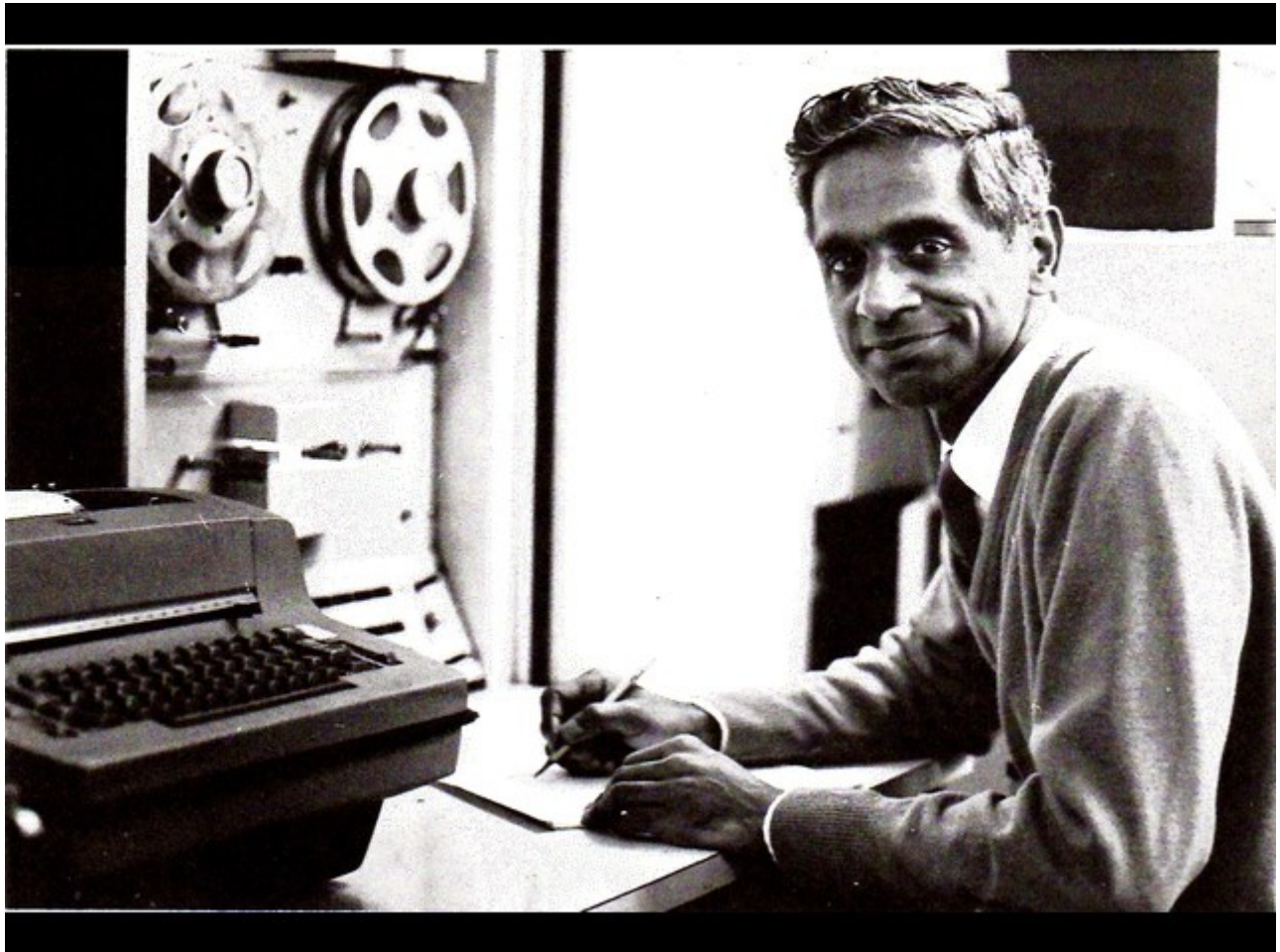


Applied Technologies, Inc.

ADVANCES IN METEOROLOGY AND THE EVOLUTION OF SONIC ANEMOMETRY

Written By:

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1. Introduction

Credit for the first sonic anemometer should be given to Carrier and Carlson (Croft Laboratories, Harvard University), who in 1944 described a “true air speed indicator” for use on a blimp. Wind velocity would be obtained from measurements of the phase difference between signals received by two microphones placed upwind and downwind from a continuous source of sound. The instrument was never completed. In the early 1950s the idea was extended to measure horizontal winds using a single sound source and four microphones, equidistant from it at four cardinal directions on the compass. Again, nothing came of those efforts. To scientists trying to explore the atmospheric boundary layer in the mid-1950s, the sonic approach had great appeal. The hot-wire and hot-thermistor bivariate techniques, available to them at the time, had serious limitations. The sonic anemometer offered rapid response, an open sampling volume and a calibration that could be calculated directly. It seemed especially suited for measuring the vertical wind component, badly needed for calculating turbulent transports of momentum, heat and water vapor near the ground.

This was a time of great interest in the structure of the boundary layer. Scientists in different countries were conducting experiments with whatever sensors they could devise over the flattest open terrain they could find, to collect data they could analyze. In the U.S., the Defense Department needed a better understanding of turbulence in this layer, to predict flow patterns in case of missile launch

mishaps. Working through the Air Force Cambridge Research Center (AFCRC), they had supported research efforts in meteorology departments in many of our universities. In Australia the Commonwealth Scientific and Industrial Organization (CSIRO) was concerned about conservation of their water resources; in Japan the Japan Meteorological Agency had air quality to deal with; and so on. Waiting on the side were theoreticians and experimenters eager to verify some of the new ideas coming out of the U.S.S.R. In 1941 Kolmogorov had proposed a $-5/3$ power law for velocity spectra in the inertial subrange where the flow can be expected to be isotropic; Monin and Obukhov's similarity theory promised universal relationships when parameters of interest are properly non-dimensionalized. And the assumption of constant flux in the surface layer (the first 10-20 m above the ground) invoked by theoreticians needed to be tested.

2. Early efforts

Researchers at that time were facing enormous odds. This was still the age of vacuum tubes with no great options for recording and storing fluctuating signals. One had to be creative. Verner Suomi at the University of Wisconsin, working under contract with AFCRC, took a new approach. He used sound pulses, not continuous waves, traveling in opposite directions along a vertical 1-m path, to measure vertical wind and temperature. The difference between transit times would be a measure of the wind velocity and the sum of the transit times a measure of the air temperature along the path. The information would be displayed as horizontal scans on an oscilloscope and recorded by a continuous movie camera on 35-mm film. The film could later be processed and played back. Everything depended on the proper sequencing of the pulses and steadiness in the received signals.

This instrument was one of many sensors participating in the Project Prairie Grass field experiment of 1956. Organized by AFCRC under the direction of Morton Barad, it brought experimenters to a flat site in O'Neil, Nebraska, where they could test and compare their sensors and techniques. Suomi's sonic anemometer-thermometer did not fare well in these tests. It turned out that its measurements were badly compromised by mistrigging in the received signals. The receiver circuits could not handle the large turbulence-induced amplitude fluctuations in the received signals. (Laboratory tests may not have revealed this aspect of sound pulse transmission in the real atmosphere.) No later effort was made to fix this problem, but it started a chain of events that kept our interest in sonic anemometry alive for decades to come.

It must be mentioned here that sonic anemometers were being developed in the U.S.S.R. as well during that time. In 1959 A.S. Gurvich, at the Institute for Atmospheric Physics in Moscow, described a very small "micro-acoustic anemometer" using continuous waves. Mounted on aircraft, it provided evidence of a $-5/3$ power spectral drop within the frequency range of their analog spectrum analyzers. There were later reports of observations over land but details of their instruments have been scarce.

3. University of Washington-Kaimal sonic anemometer-thermometer

In the fall of 1958 Joost Businger joined the Meteorology Department at the University of Washington as a new faculty member. I was a graduate student there at the time, working on a hot-wire device as part of my M.S. program. Businger had spent some time at the University of Wisconsin with Verner Suomi trying to make sense of sonic data from Project Prairie Grass. He had in mind a mathematical model for the boundary layer but the recordings were too flawed and beyond recovery. He had brought with him ideas for a new sonic anemometer that could get around the limitations of the pulse approach. These ideas were provided by Peter Schofer, an engineering colleague at the University of Wisconsin.

The new sonic anemometer would send two continuous-wave signals in the audible range across a 1-m vertical path in opposite directions and would look for phase shifts in the signals picked up by receivers at both ends of the path. The phase shifts in the two signals could then be processed to yield vertical wind and temperature presented as analog signals that could be recorded on strip-chart or analog tape recorders.

The hand-drawn sketches looked promising and I took on the task of building a prototype, but implementation of the idea called for more complex circuitry and upgrading of my engineering skills. The two frequencies I chose, 7.5 kHz and 10 kHz, had to be stable and synchronized, the pass-through and rejection filters in the receiver circuits had to be sharp enough to prevent cross-contamination of signals, and the phase detection circuits accurate and linear. By 1960 I had a working instrument (Fig. 1a & 1b). Its development and deployment in the field evolved into a Ph.D. dissertation for me, with Businger as my thesis advisor.

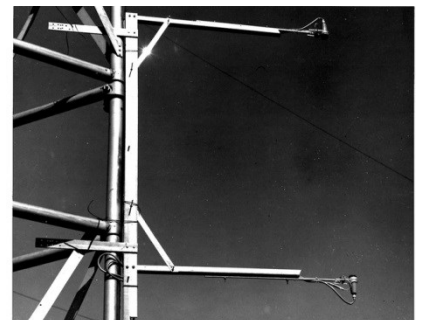


Figure 1a

Two field tests with this instrument were conducted at an experiment site operated by the atmospheric physics group at the Hanford Laboratories in eastern Washington. The terrain was dry and reasonably flat with scattered sage brush 1 m high. A 125-m high tower made routine measurements of wind, temperature and humidity. The sonic anemometer probe was mounted on a short mast with its mid-point 3.5 m above the ground. The path length was set at 1m for the first test and 0.5 m for the second.

The first test showed how vertical velocity and temperature fluctuations evolved as the stratification of the air changed from free-convection through neutral to stable. Side-by-side recordings of the two revealed for the first time how interrelated they are at that height and how dramatic that can be. The second test, two months later, with the shorter path length allowed us to examine more closely the structure of convective plumes, and with recordings on analog tape, to compute heat fluxes for selected periods.

Working with me on these field tests was Businger, with helpful advice and explanations of what we were seeing. His insights were critical to the success of the tests. By June 1961 I had completed my Ph.D. program and accepted a job as research scientist with Air Force Cambridge Research Laboratories (AFCRL), the newly reconfigured AFCRC in Bedford, Massachusetts. AFCRL, in a new strategy for the organization, was aiming to have their own scientists do the research in-house. I moved to the Boston area but the sonic anemometer stayed behind.

4. Modified Iowa State University sonic anemometer

I arrived at AFCRL just in time to take part in their new project: operating sonic anemometers at four levels on a 430-m TV transmission tower near the small town of Cedar Hill, southwest of Dallas, Texas. The tower had for several years been instrumented at 12 levels with wind and temperature sensors; 10-min averages of their outputs were recorded on punched paper tape in a building at the base of the tower. Operated by the University of Texas under contract with AFCRC, the profile data were used by many scientists to study the evolution and decay of nocturnal low-level jets, common over flat terrain and a hazard for pilots trying to land at night. What was missing was information on the turbulence profile across these jets. To address this AFCRC had a contract with Iowa State University to design and build four sonic anemometers based on the Suomi pulse concept, only smaller and more dependable. These were to be ready for testing at the Cedar Hill site soon after my arrival at AFCRL.

The first tests were conducted in the summer of 1962. Daunting as it was working at those heights (46, 147, 229 and 320 m) our problems came from an unexpected source. The radiation from the three powerful TV antennas on top of the tower was so strong it interfered with the operation of our sonic anemometers. The TV signals could not be separated from the sonic receiver signals and no dependable trigger could be obtained from them. Back at AFCRL, working on the problem, I successfully converted those instruments into continuous-wave anemometers for measuring the vertical wind component. The transducers used in the original device were designed for TV remote controls of that era. They were so highly directional and acoustically well-insulated from their housing that the entire probe could be adapted without much change. Being able to use the same ultrasonic frequency (40 kHz) on both channels was a help and my old phase-difference circuitry came in handy. To top it all, this system was not affected by the TV transmission signals on the Cedar Hill tower.

A full-scale experiment was conducted in the summer of 1963 with these modified sonic anemometers (Fig. 2a & 2b). Their outputs were recorded on analog tape in the same building at the base of the tower. The recordings showed us for the first time the progression of boundary layer turbulence through its morning growth and eventual decay in the evening. It included a well-defined low-level jet that lasted 8 hours. In all, 50 hours of data were collected over a 3-week period. An interesting finding was the behavior of vertical velocity spectra above 100 m under unstable conditions. The dominant peaks shifted little with height, suggesting they represented large convection cells that extended to the top of the boundary layer. We could see strong 4 m/sec updrafts 2 min in duration, appearing about every 5 min, separated by steady gentler downdrafts 3 min long, implying horizontal cell dimensions of 1.5 to 2 km. We now know those cells, scale with the depth of the boundary layer, not the height above ground.

5. Bolt Beranek and Newman sonic anemometer

In 1964, having no luck with pulse-type sonic anemometers, we at AFCRL worked with Bolt Beranek and Newman (BBN) in Cambridge, Mass., to develop all-weather, 3-axis continuous-wave sonic anemometers, using current transducer technology and solid-state electronics. We came up with an array in which the horizontal axes were 120 deg apart and spatially separated to accommodate wind direction shifts normally expected in a 1-hr observation period. The vertical axis would be centered and set slightly upwind of

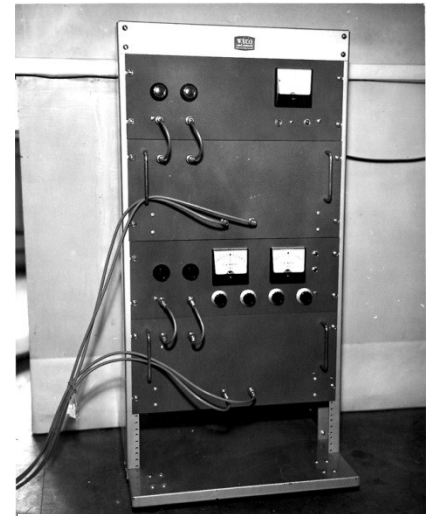


Figure 1b

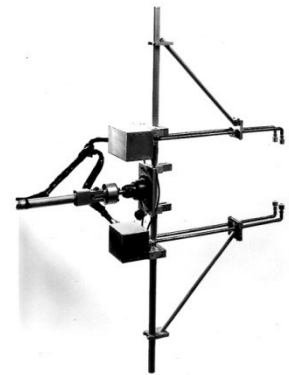


Figure 2a

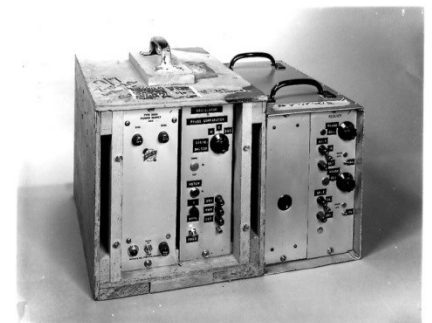


Figure 2b

the horizontal ones (Fig. 3). The paths would be 20 cm long for the vertical and 15 cm for the horizontal. BBN, a leader in the field of acoustics, had a wind tunnel in their building which we could use to test out our ideas. Herbert Fox, BBN's principal investigator on the project, hand-crafted the transducers, fine-tuning them on a lathe with selective shaving of the transmitter face to get the frequencies we needed. The electronic circuit was solid state, well-engineered and housed in compact boxes that could be mounted on a tower.

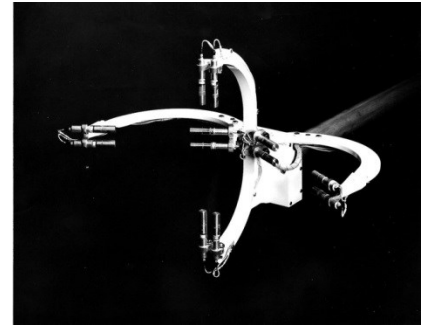


Figure 3

Two of these sonic anemometers were tested during AFCRL's 1965 Kansas Experiment. The probes were mounted on booms at 5.66 and 22.6 m (geometric means between 4 and 8 m and 16 and 32 m) on a 32-m tower. The tower was instrumented with wind, temperature and humidity profiling sensors at 1, 2, 4, 8, 16 and 32 m, and set in the middle of a mile square of very flat land. A computer-controlled data acquisition system housed in a 40-ft trailer parked not far from the tower sampled, digitized and recorded all the analog outputs from the anemometers. We were set up for winds from the south, the prevailing wind direction for the summer, and operated for 1 hour at a time. Between runs the sonic probes would be swung back into specially designed boxes for zero-wind adjustment. Despite all these precautions we found the readings drifted too much as the finely tuned transducers responded to changes in ambient temperature. The transducers needed to be fixed.

An improved BBN anemometer was operated again at the same heights in our 1967 Kansas Experiment. Some useful data were obtained: well-formed cases of convection plumes and a dust devil right through the tower. Businger and I were happy to study them, but the project was cut short by a severe thunderstorm with golfball-sized hailstones that damaged all our cup anemometers.

By this time our interest had shifted to a new pulse-approach being tested by Kaijo Denki Inc. in Japan. The BBN instruments had found a new home in Australia, where scientists at CSIRO in Canberra, using new transducers and a different probe configuration, operated them in forest canopies. The 120-deg array prompted our new colleague at AFCRL, John Wyngaard, to examine theoretically its consequences on the measurements we had made. He found they can be serious, but may be minimized by having the two horizontal paths cross each other with their centers just 0.6 times the path length apart. This would be a requirement in any new sonic probe.

6. Kaijo Denki sonic anemometer

Y. Kobori, chief engineer at Kaijo Denki, working with Yasushi Mitsuta at Kyoto University and Businger at University of Washington, had, since 1964, been trying to come up with a dependable pulse system that would work in the field. They brought along a few single-axis versions to our 1965 Kansas Experiment and we were impressed.

Kobori found the limitations of the continuous wave system: zero-drift and inadequate range, too serious for an operational device. He could get the pulse system to work by using highly damped ultrasonic transducers to make sure their ringing times stayed short and locking onto the second positive zero crossing in the received signal for a reliable trigger pulse. By 1967 Kaijo Denki had designed a 3-axis system with a probe that was compact and accommodated our need for a 120-deg acceptance angle and Wyngaard's spatial separation criterion (Fig. 4). AFCRL placed an order for their first three units, which were delivered in time for our 1968 Kansas Experiment. These units did not measure sonic temperature; we used platinum-wire thermometers mounted within the Kaijo Denki probe to get temperature fluctuations. Mounted on remotely controlled antenna rotors at 5.66, 11.3, and 22.6 m on our tower, they performed dependably; we came back with enough data to keep us busy for years.

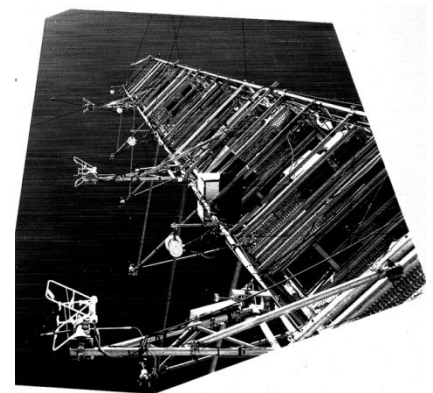


Figure 4

Participating in the 1968 Experiment was Businger, who had stayed in close touch with us through the years. On a year's leave from the University of Washington, he spent that time at AFCRL as a Senior Research Fellow, taking a lead in the analysis of our data. We knew it held many of the answers we were waiting for. A long series of papers followed and we still continue to be intrigued by some of the findings.

There were hurdles to overcome before we got there. We needed to correct the data for transducer-shadowing that we had discovered in earlier BBN wind tunnel tests. This we could do as we started working with the data points. The second error was unexpected and more involved. We found evidence of misalignments in the probe geometry that showed up as non-zero vertical velocity means and anomalies in the calculated momentum flux. We could determine the alignment offsets in our machine shop and correct the data, point-by-point, to create new data sets. We asked Kaijo Denki if they could do their future assembly more precisely. At that point they were in no position to do it. At AFCRL we were looking for new sonic anemometers to carry out experiments planned for the early 1970s. We needed ten 2-axis (horizontal) anemometers for an experiment at Edwards Air Force Base in California, and three 3-axis

ones in addition for a full-scale boundary layer experiment in Minnesota. We needed a manufacturer who could meet an alignment accuracy of 0.1 deg.

7. EG&G sonic anemometers

Arthur Bisberg and his team at EG&G Environmental Equipment Division in Waltham, Massachusetts, were well positioned to respond to our needs. They could meet our alignment requirement and had some experience with operational versions of a sonic anemometer developed by David Beaubien, who had founded Cambridge Systems Inc., which later became a division of EG&G. They seemed to have figured out how to make dependable transducers, the most critical component in a sonic anemometer. The active element was a small cylindrical piezo-electric cylinder mounted inside an aluminum cylinder 0.9 cm in diameter and 1.25 cm long. These were held together with a silicone compound that filled the radiating end of the cylinder. Having no metal diaphragm at that end greatly contributed to its directivity and efficiency. The silicone provided all the damping that was needed. The other end of the cylinder held a microdot connector that screwed on to an acoustic isolator on the frame. Here was a transducer that could be replaced in the field.

Fig. 5 shows the 2-axis probe with its 25-cm paths and separate transmitters and receivers at each end. It was designed to operate under the control of the computer in our mobile data acquisition system. The probe electronics accepted 100-Hz pulses by cable from the precise clock in the system and sent back stable trigger pulses derived from the received signals. Up-down counters in the system measured the transit times and constructed 0.1-sec block-averages for transfer to computer memory. The computer system did the rest. This integration was the work of Duane Haugen, who headed our Boundary Layer Branch at AFCRL. He had conceived the mobile data acquisition system a decade earlier and kept us updated with new custom software as the parameters changed with every experiment.

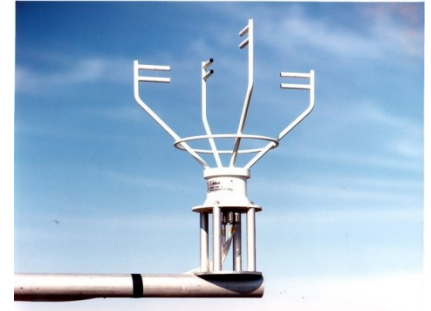


Figure 5

The Edwards AFB Project positioned ten 2-axis sonic probes along their 2-mile runway. It was flat, open terrain on the edge of the Mojave Desert. The experiment was designed to address a frequent complaint from pilots that they often encountered 180-deg shifts in wind direction within that distance. It was hoped that the sonic anemometer, with its ability to sense wind directions accurately, could shed some light on the subject. The experiment, which lasted for weeks, did offer a clue: large convection cells 1-2 km in horizontal dimensions were filling the boundary layer with wind patterns that made the pilots' observations entirely plausible.

The 1973 Minnesota Experiment aimed to finally look at the entire Planetary Boundary Layer (PBL) with all the sensors we could bring together. Our site near the northwestern corner of Minnesota was chosen for its extreme flatness. The 32-m tower was there, instrumented with five of the EG&G 2-axis sonic anemometers and two new EG&G 3-axis anemometers (Fig. 6). To reach above the tower height to the top of the PBL and beyond, we sought the expertise of the British Meteorological Office in Cardington, UK, where a team of scientists, under Christopher Readings, had perfected the art of sending up special packages of turbulence sensors attached to the tethering cable of huge kite balloons (the barrage balloons of World War II). Their sensor package was an ingenious assembly of a wind vane, a damped pendulum, some hot-wire sensors and a vertically oriented light cup anemometer. With careful calibration, the package provided data comparable in accuracy to our tower sensors.



Figure 6

The British team came with five of these packages and participated in an experiment that lasted several weeks. The enormously complicated task of inflating the balloon with helium, unreeling the steel cable, attaching the sensors and monitoring the tethered balloon for six hours at a stretch, was handled by a team from the U.S. Air Weather Service. (They also operated slow-ascent radiosondes every two hours to inform us where the capping inversion was during our runs.) The Cardington sensors were flown at heights of 60, 300, 600, 900 and 1200 m above ground and the data were sent to a base station by radio transmitters and to our data acquisition system.

Much can be written about our findings from this experiment, but I will limit myself to the question we had been after for so long: what controls the length scale of the large eddies in the so-called mixed layer, the top 9/10 of the PBL. The horizontal dimensions of these eddies turn out to be about 1.5 times the PBL depth (as found decades ago in laboratory studies by James Deardorff), which we see as the height of the capping inversion. In the bottom 1/10 of the PBL, that scaling is controlled by the height above the ground as had been predicted.

8. EG&G-Ball Brothers sonic anemometer

By 1976 the landscape had changed for atmospheric studies. The push for basic research had given way to the need for a fully instrumented all-year test facility where the new remote sensors being developed in places like the Wave Propagation Laboratory (WPL) at NOAA's Environmental Research Laboratories in Boulder, Colorado, could be tested and calibrated. In 1975 the core of the boundary layer group at AFCRL, with their data acquisition system and inventory of sensors, moved to Boulder to be part of WPL and take part in creating an experiment facility 25 km east of the city. It came to be known as the Boulder Atmospheric Observatory (BAO). A 320-m tower was built at the site and all the former AFCRL hardware fitted right in. The terrain was open and rolling, not ideal for surface layer work, but good for a lot of other studies.

The tower was instrumented at eight levels, from 10 m to 300 m, with fast-and slow-response sensors. We needed eight 3-axis sonic anemometers on the tower operating all the time. Working with Herb Zimmerman at Ball Brothers Research Corporation (BBRC) in Boulder we had eight of our EG&G 2-axis probes converted to 3-axis probes by attaching a vertical axis of matching design (Fig 7) directly in front. A small platinum-wire thermometer attached to the front of the vertical array, supplied by AIR in Boulder, measured temperature fluctuations. The three axes would remain fixed in space and transducer-shadow corrections would be applied in real time during data acquisition. The sampling of fast-response sensors at a 10-Hz rate and the slow-response sensors at a 1-Hz rate, their processing and recording on large magnetic tapes, and printing of real-time data summaries every 15 min were carried out by Haugen's efficient software, which kept the facility running smoothly for years.

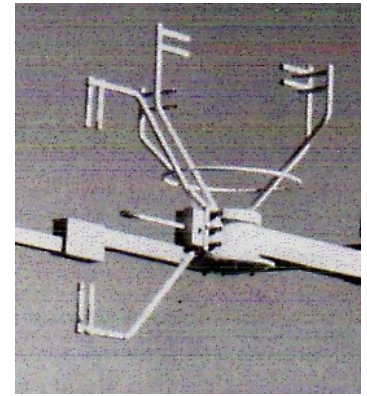


Figure 7

The BAO became a magnet for scientists around the world. Many came to study special events in the archived data such as mountain waves and high winds coming from the Rocky Mountains. Others came to perform their own experiments, making use of the supporting data the BAO provided. The presence of the National Center for Atmospheric Research (NCAR) close by made the interactions even more productive. Sonic anemometry appeared to have reached a point where we could sit back and just focus on the data.

9. ATI sonic anemometers

At the same time that BBRC was converting the EG&G probes, they also acquired the transducer technology from EG&G and started perfecting the 25-cm path 3-axis system, since EG&G was not interested in continuing. BBRC also redesigned the style of probe, using their own design, but keeping the 4 transducers and the 25-cm path lengths (Fig 8). In 1978, BBRC decided to discontinue their involvement in the environmental business and the principals involved with the department decided to start Applied Technologies, Inc.(ATI). They continued to build the 25-cm path version of the sonic.

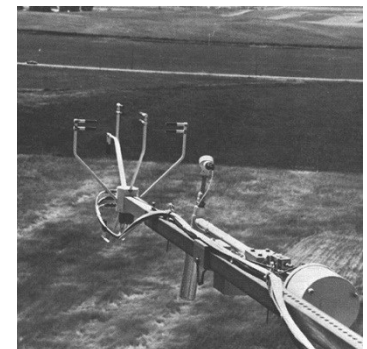


Figure 8

In 1987, with the advent of the microprocessor, ATI designed a new version of the sonic anemometer, using a 15-cm path length, a single pair of transducers in each path, and all three axes measuring orthogonally with each other. This new version allowed the microprocessor to control

the switching of the transducers into a transmitting and receiving operation. This was the first time the size of the instruments could be reduced. The first production model was a design suggested by me and was named the 'K' Probe. This K-probe took a different approach (Fig. 9), sacrificing common volume for minimum interference to the flow. The spatial separation between the axes can be justified on practical grounds for use above 5-m heights. Eddies the size of the separation distance could, in those applications, be well within the inertial subrange where the flow is isotropic and would not be contributing in any significant way to the calculated variances and fluxes.

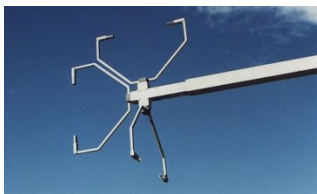


Figure 9

Much testing was done at the BAO to verify this assumption. K-probes were lined up with the BAO 3-axis probe, upside-down (Fig. 10) and also at odd angles to the wind. The results showed remarkable agreement regardless of orientation. The processing unit for the ATI probe used integrated circuits and microprocessors that offered a whole range of real-time processing options not possible with our BAO electronics. After that, several other designs were incorporated, to meet the needs of different types of science requests.

One other design had all axes intersecting orthogonally within the same sampling volume (Fig 11). The slim supporting structure did get in the way of the paths, but left the opening clear directly in front. Called the Vx probe, it attracted users who were looking for a small

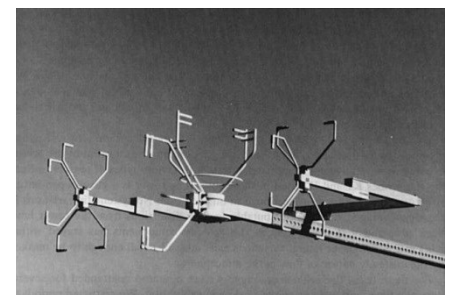


Figure 10

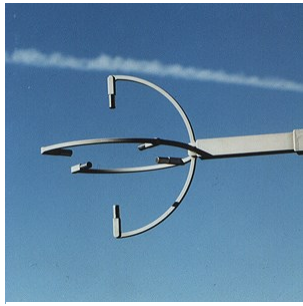


Figure 11

common volume and were using it in turbulent locations such as within and around plant canopies where the supports were not that much of a problem. Sonic anemometry seemed poised for a new era of greater availability and broader applications.

10. University of Washington non-orthogonal sonic anemometer

In the early 1980s, at the University of Washington, Joost Businger and his graduate student Steven Oncley started working on a 3-axis non-orthogonal sonic anemometer system. They used parts from our two remaining EG&G 2-axis anemometers and some ATI components, to come up with a new way to measure wind fluctuations. The axes

would all be tilted 60 deg from the horizontal and intersect in the middle to present an open aspect to winds from all directions (Fig. 12). A careful study of the response characteristics of such a probe by S. F. Zhang, also a graduate student there, came out in 1986. In the same year Oncley and colleagues took two “custom-made” 20-cm path, 2-transducer versions of the instrument to a surface layer experiment in Carpenter, Wyoming, where they were able to collect plenty of useful data and evaluate the performance of this new instrument.

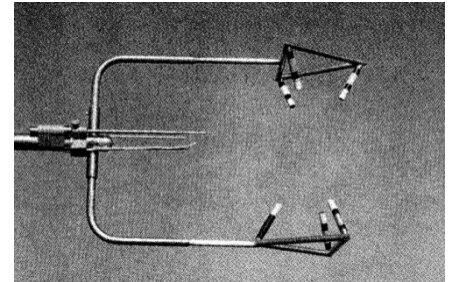


Figure 12

By 1989 Oncley was working at NCAR, having received his Ph.D. at University of California, Irvine. Also working there were Businger and Wyngaard, veterans of past surface layer experiments. In his 1996 paper with other participants in the Carpenter experiment, Oncley describes the extraordinary efforts that went into ensuring the vertical axis in the processed data was truly vertical and into tracking down all sources of errors. No transducer-shadowing corrections were made, but the blocking of paths by adjacent transducers was considered. His paper offers a thorough analysis of the data they collected.

The openness of the non-orthogonal array and its potential for a wide range of applications attracted immediate interest. Soon there were three manufacturers with their own different designs: R.M. Young’s and Gill Instruments’ probes have aspects in common (Figs. 13 and 14), but Campbell Scientific’s probe managed to come up with less clutter (Fig. 15). They all claim good accuracy for small inclinations of the wind vector. These designs were appealing to the next generation of sonic anemometer users, agricultural and forest meteorology scientists, who needed to measure turbulent fluxes and look at energy balance over a variety of surfaces and ecosystems. A large majority opted for the non-orthogonal devices.

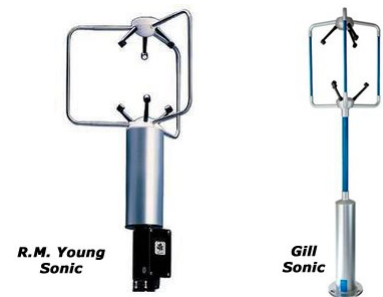


Figure 13 & 14

11. Where we stand now

Looking back at the data collected over the years, investigators are finding a pattern that needs explaining. Energy balance calculations from sites that used non-orthogonal probes are showing a deficit that matches a possible 10% underestimation in vertical velocities and heat fluxes measured at those sites. Are the two linked? A 10% difference had been observed in past comparisons between orthogonal and non-orthogonal sensors, but the orthogonal ones were then thought to be overestimating. This has led two groups to conduct exhaustive side-by-side tests against ATI’s Vx probes. In tests with R.M. Young probes, John Kochendorfer of NOAA and colleagues found the underestimation to be real and have proposed angle of attack corrections for fixing old data and the addition of a vertical axis for just the vertical winds in new probes. John Frank of US Forest Service and his colleagues compared the ATI sensor against Campbell Scientific’s probes oriented in many different ways to isolate the source of the problem (Fig. 16). They have come to the same conclusion and propose the possibility that the underestimations might not be manufacturer-or sensor-specific, but rather a fundamental difference between orthogonal versus non-orthogonal design.



Figure 15

At this writing (July 2013) Frank and his colleagues are in the middle of another experiment at their field site in Wyoming. This time, they are evaluating the performance of a new Campbell Scientific version of its non-orthogonal sonic and ATI's non-orthogonal probes against the orthogonal ATI K-Probe, looking for the source and nature of differences in their outputs. It is important to find out whether the vertical wind component constructed from three tilted sonic measurements can be as dependable as a single direct vertical measurement. A lot of manufacturers and users would like to know.

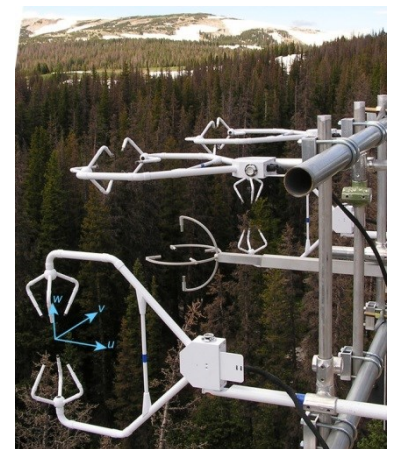


Figure 16