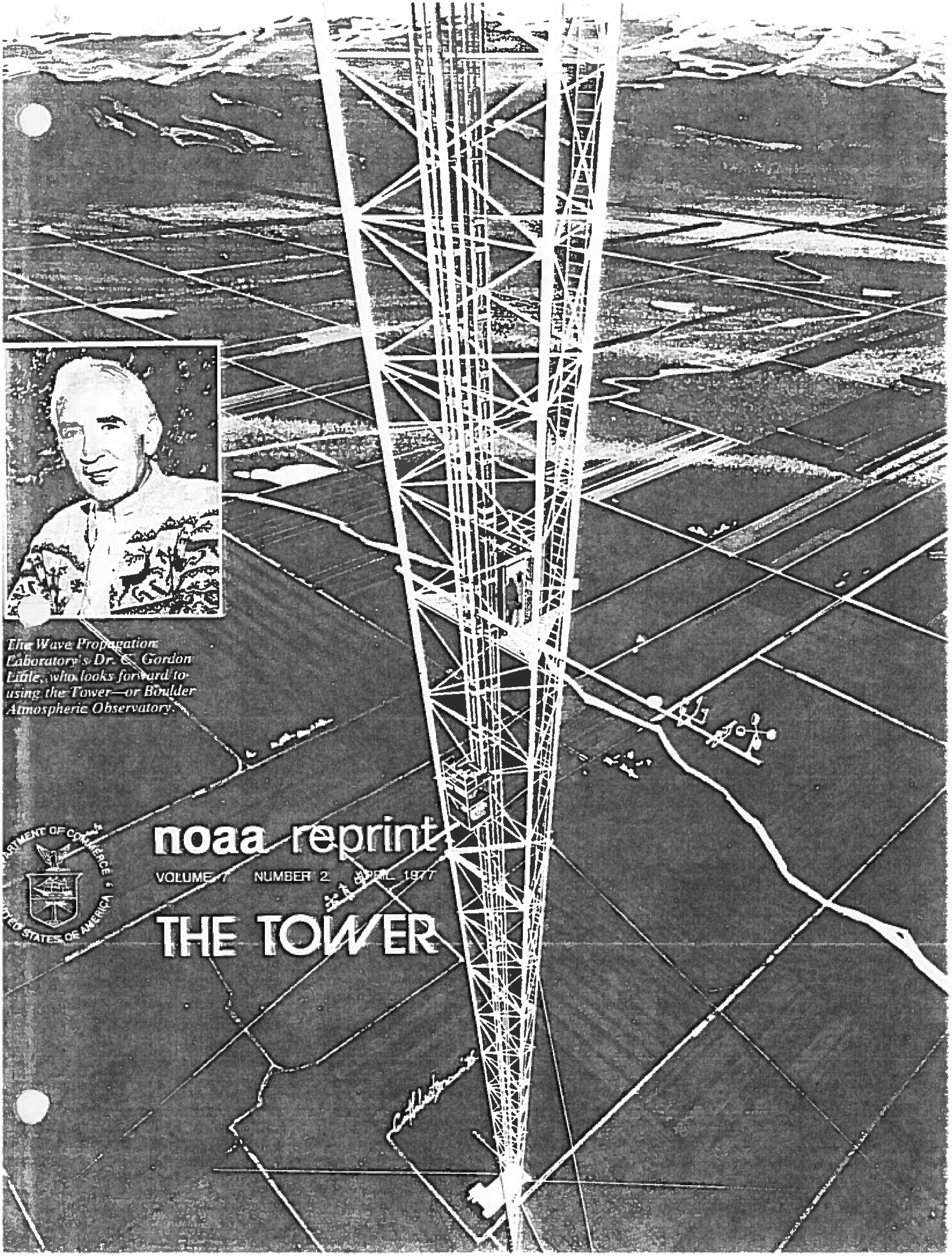

The Wave Propagation Laboratory's Dr. C. Gordon Little, who looks forward to using the Tower—or Boulder Atmospheric Observatory.

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THE TOWER

THE TOWER

By CARL A. POSEY

HE tower will rise 300 meters—nearly a thousand feet—from a section of farmland a few miles east of Colorado, a tiny town among several ıg the northern fringe of Denver's met-itan area. From the freeways, the tower have the vague, insubstantial look of steel structures seen at a distance, ren-l interesting to the eye by a flash of ıft-warning lights that flicker like small ıings at three levels on the structure. At , the lights will automatically dim, to me an unusual constellation upon the ınt Colorado night.

ellar analogies are fitting here, for the r will mark a watershed in a kind of 'on[illegible]al science that began in astron-—remote sensing, the ability to make titative measurements from a distance.

emote sensing. The term may be less a household word, but the techniques it esents are pervasively familiar. The stical powers we admire in whales and are remote sensing. When Mr. Spock unces, "Our sensors show a nitrogen ısphere similar to Earth's, Captain," he lking remote sensing. Historically, re-sensing is how we have tried to compre-the distant or inaccessible corners of the ical universe, fashioning telescopes to the heavens for objects the eyes cannot acoustic sounders to probe the light-uring world of the sea, radio-frequency ems to read the invisible changes of the sphere.

ow a small band of remote-sensing peo--specialists in wave and acoustic energet-electronics, optics, and a host of other ics-based skills—are turning their tech-es toward the more accessible, but still ling realm of the lower atmosphere. The r will be a functional instrument enabling ı to test their newly-developed remote ors. It will also be a promise of accom-ıments to come, for it is a centerpiece nd which will evolve many of the atmos-ic sensors of the next decades.

od[illegible] with the high plains settling toward mer, the tower is beginning to take shape. ge concrete footings have been prepared ıe Erie site. Massive prefabricated steel ıbers have arrived at the site and are g assembled into 30-foot (10-meter) sections. Erection of the tower will start this month, and should be completed by August, 1977. Then it will be instrumented to read weather elements from the surface to the 300-meter summit, and remote-sensing operations will begin at the Boulder Atmospheric Observatory, or BAO, as it is called.

The BAO, to be operated cooperatively by the Wave Propagation Laboratory of NOAA's Environmental Research Laboratories and the National Center for Atmospheric Research, will seem to be mainly the tower. It has the characteristic triangular cross-section of such towers, but is heavier and stronger. It was designed to accept conditions even an apocalyptic combination of Colorado winds and winter weather can hand out—it will withstand a wind loading of 65 pounds per square foot, when sheathed in half an inch of ice.

Inside the tower skeleton a personnel elevator will crawl up a rack-and-pinion track, like a cog railroad climbing a vertical grade. An instrument carriage outside the tower will also ride on a rack and pinion drive.

As operations begin at the BAO, strange-looking electronic devices will begin to appear in the grassy section of land the facility occupies: optical radars and their cannonesque telescope receivers, acoustic sounders that utter their signals in high-pitched beeps, radars of unparalleled sensitivity and ability, sensors that listen, sensors that see, sensors that probe with beams of light, or pulses of sound, or radio waves. At times, they have the look of swords beaten into plowshares—weather-sensing radars using surplused Nike-Hercules antenna dishes and trailers and miscellaneous tracking gear. Like many hybrids, they are unique.

The tower will be a vertical corridor of precise, continuous measurements from the ground to almost a thousand feet. The new sensors will be tested against the tower, and their evolution from their present hybrid form to the more polished systems industry can produce will be partly driven by how well they do in these comparisons.

Not all the sensors being tested at the BAO will look upward from the ground. The tower's column of accurate atmospheric measurements will also attract occasional visits by the versatile flying laboratories operted by NOAA, NCAR, and perhaps other universities and research institutions from around the country. For these, the BAO will provide the means of comparing in-flight measurements made during fly-bys past the pproaches of the tower with measurements made by sensors on the tower.

As the BAO evolves, the tower will be joined by a 21,000-square-foot laboratory building constructed by NCAR, which is upported by the National Science Foundaion. The NCAR building will house 30 to 40 permanent scientific personnel, and will complete the BAO's physical plant, providing the national facility anticipated by its enthusiastic proponents.

Chief among these, both in advocacy and nthusiasm, is NOAA's Dr. C. Gordon Litle, who directs the Wave Propagation Laboatory in Boulder. To him, having the BAO up and operating will mark the end of one ong trail—and the beginning of another.

“What the BAO gives us,” he says, in a voice that still carries the sound of northern England, “is a well-instrumented cubic kilometer of atmosphere in which we can measure weather conditions down to a very fine cale of time and space.

“Our primary use of the facility will be to est and evaluate the new remote sensing nstrumentation that appears to be at least part of the wave of the future in atmospheric esearch. Secondly, the BAO and its remote-ensing instrumentation will provide a unique ite for studies of processes in the lower atmosphere that still have not been thoroughly observed—evaporation, precipitation, urbulence, diffusion, air-pollution chemistry, and the like.

“But we also see the facility as being an mportant national resource in the atmosheric sciences. We expect scientists from universities and other organizations to come o Colorado to participate in the kind of xperiments we will be able to conduct only t this observatory. The interaction between tmospheric scientists and remote sensing pecialists should be exceptionally strong, with many transfers of ideas and technologies occurring between the different disciplines.”

With the BAO developing into a technical eality, its potential less than a year from being tapped, the solf-spoken NOAA scienist has focused his attention farther into the uture, where he foresees exciting possibiliies for improved weather services. For it is ive, ten, fifteen years from now that he sees emote sensing in general, and remote sensing based at the BAO in particular, as having a major impact on the way we sense, analyze, eport, and forecast local weather.

To understand this impact we have to look at how weather is observed today. Currently, he only three-dimensional views of weather are the periodic profiles written by radiosondes, the small balloonborne radio-equipped instrument payloads which sense emperature, humidity, and pressure, and which can be tracked to obtain wind measurements from the surface to about 100,000 feet 30 kilometers). These balloons are launched from stations perhaps 400 kilometers apart, wice a day, on a scale of time and space which meteorologists call “synoptic,” a word that says we are comprehending a subject by viewing its principal parts in a general way. The technique works well for the global atmosphere, and for continental weather; it is also an important technical tradition in meteorology.

But the synoptic view inevitably fails to observe or predict the smaller-scale weather events that occur between these widely spaced observations.

This is a key problem in meteorology, and one on which progress comes very slowly. The reason for this slowness is the extreme difficulty of obtaining the large increase in weather data required to describe, understand, and predict small-scale weather phenomena. Using radiosonde spacing as an example, to take such profiles every 200 kilometers instead of every 400 requires a fourfold increase in the number of stations, and a twofold increase in the frequency of observation at each location. The difficulty lies in the eightfold factor. Then, because weather measurements are really measurements of *differences*, the accuracy of the measuring system must increase to detect smaller and smaller differences—again, a major problem. And then, with more measurements being taken more frequently, the time available to analyze the increased amount of data and shape it into a forecast is reduced, once more complicating things. Each significant descent to smaller scales of time and space carries something like a tenfold increase in complexity and cost. So progress is made, but it comes slowly.

Meteorologists now include the effect of the smaller scales by an averaging technique called “parameterization,” which permits inclusion within synoptic scale predictions of smaller-scale events using key terms instead of full descriptions to represent those events. There is no substitute for parameterization in solving the massive problems of global and continental meteorology. But the technique inevitably averages out some atmospheric processes that are important down at the people-sized end of the weather spectrum.

For forecasters working the operational shifts of the world's meteorological services, the barrier in scale is a recurring nightmare. They are able to use the radiosonde observations taken 400 kilometers apart. But their interest goes down and down, to 200-kilometer spacing, to 100, 50, 25, 10, 5, and—in the case of airport weather—down to a kilometer or two.

“There are at least seven octaves [factors of two] in the spacing of current radiosonde networks and the needs of airport meteorology,” says Dr. Little, whose excitement over the future of remote sensing and the BAO derives from his belief that his laboratory can do much to solve this problem of scale in meteorology.

“I think we offer a complementary approach,” he explains by way of emphasizing he is not leading a revolution against synoptic meteorology or even presenting alternatives to it. “While meteorologists using conventional in-place sensors work the upper end of the scale, we will be exploring ways to measure the atmospheric *micro*scale, where we're dealing in terms of a kilometer or two and processes lasting a few minutes to an hour. This is where current ground-based remote sensors tend to do their best work.”

Success in measuring microscale events remotely has been the major accomplishment of the Wave Propagation Laboratory, which, thus far in the 1970's, has taken an entire family of remote-sensing systems virtually from hypothesis to operating hardware. The laboratory has also begun to solve some of the difficult side-problems of applying remote-sensing technology to the atmosphere. Doppler radar, for example, has the unique ability to probe the interior wind fields of clouds. But to do this, it must operate at a data-acquisition rate that would blow fuses in today's operational weather-observing systems. Further, the technology of remote sensing as practiced in the Wave Propagation Laboratory presses hard upon the threshold of technical possibility—it is not merely advanced technology; it is *high* technology. It is to conventional weather instrumentation roughly what the *Concorde* is to the DC-3.

And yet—the time for a meteorological breakthrough of that magnitude may be at hand. The National Weather Service and the Environmental Research Laboratories are already discussing the Dopplerization of the new weather surveillance radars that are coming in to replace their less versatile predecessors at weather stations around the country. Weathercasters seem to look forward to using systems like AFOS (Automated Field Observing System) and AWANS (Aviation Weather and Notam System), both computerized handlers of massive quantities of weather data in tiny increments of time. These new systems are what meteorologists call four-dimensional, for they can move observations into the electronic pipeline any time, and are not constrained to the more traditional synoptic rhythms. Remote sensing has a place here. Witness the FAA technician in Atlanta talking about the experimental AWANS there: “This thing is great, but what it really needs is another way of getting data. I mean, we should have a bunch of remote sensors feeding the computer all the time. Then we could really get maximum use out of something like this.”

Because of this growing emphasis on four-dimensional systems, one also sees synoptic rhythms begin to fade in projects like the Global Atmospheric Research Program's First Global Experiment. In that experimental year of intensive weather-data gathering over the earth's entire surface, there is emphasis on research-quality synoptic measurements—and parallel emphasis on what is called four-dimensional data assimilation, the fourth dimension being time. Remote sensors that work continuously or almost continuously, most of them aboard earth-orbiting satellites, have pointed up the fact that today's technology does not require everyone to take the same observation at the same instant over the planet's surface. Computers can work out such temporal details. Better, if technology can develop systems capable of handling such a torrent of weather data, to take data continuously and develop the ability to spin out reports and forecasts at any point in the flow of time.

chniques like four-dimensional data assi-tion are one way the synoptic meteoro-l system can force progress to smaller of weather. And at the moment, it is to levelopment of such techniques that of the available meteorological support ad[illegible].

is means that while the world may make to your door for a better mousetrap, it ot for a better way of observing small-weather—not, at least, unless you help he path-making.

Little understands that an experimental e sensor operating in a Colorado wheat-is not ready to be assimilated by the tional weather-observing apparatus. understand that the kind of technology ensors require can be very difficult for average technician to use," he says. also understand that our microscale data e very hard to use operationally, at least ngs stand today. Still, I believe we can op systems through the BAO that will lement the synoptic observations, and ps relieve some of the pressure on con-nal meteorological tools to operate at er and smaller scales".

BAO will be the first step in a program at meeting conventional meteorological ving techniques somewhere around Dr. Little calls the "true mesoscale"—s about 100 kilometers on a side.

the BAO," he says, "we'll begin by oping our abilities to observe and pre-eather at what we're calling the airport rban scales—roughly 10 kilometers and ilo[illegible]rs on a side, respectively. The ssi[illegible]here would be first to perfect our to monitor, display, and describe the of the atmosphere around us. Then, this ability continuously to express the it state of local weather conditions over ea, we would work with the National ier Service to help them use this capa-in the preparation of improved short-ocal forecasts. However, because our ely sensed data exist on such a small we could forecast only for periods of an or two, though these detailed, short-orecasts would, of course, be comple-d by the standard, longer-range fore-of the National Weather Service."

three to five years he would expect A could have a research prototype of system working at the BAO, making r's the best observed and forecast met-an atmosphere in the world.

next step would be to the true mesos-where the earth's curvature makes it ary to install arrays of remote sensors. ittle sees another five years to proto-nstallations of this type.

some ways", he points out, "the that inhibit progress going from larger ller scales work for us when we go the way. Notice that when you want to be meteorological processes you need th[illegible]me number of data points, re-ss [illegible]e size—you need about as many oints to describe a thunderstorm as you describe a hurricane.

if you begin, as we are, at the micros-aking data of very high accuracy every l or two, and then go up to the larger scales, you find your life getting easier. The time available for your measurements expands instead of contracting. The phenomena you're measuring are larger and tend to last longer. You don't need the accuracies required at the airport scale. I don't want to say it's the difference between climbing up and walking down. But it *is* like first assaulting a rather difficult cliff, and then having an easier time walking on the plateau above."

In the conventional wisdom, the economics of remote sensing are viewed as an important part of that hypothetical cliff. Remote sensors of the type being developed by the Wave Propagation Laboratory are many times more costly than, for example, the tiny radiosonde transmitters and their balloons. On the other hand, remote sensors have a sensitivity and data rate that could fill a need that has gone unfilled thus far. "An airport is an expensive place, especially when you have an accident," Dr. Little notes. "I understand that the law suits associated with the Eastern Airlines crash at Kennedy Airport in June 1975 now total over $1 billion. I think our systems would be affordable at airports. At the urban scale—and urban implies something the size of Denver or Washington, D.C.—we have a lot of people who need a better view of local, short-term weather and air quality. I think we could be cost-effective there as well. At the mesoscale in densely populated regions we're talking about millions of people, and, again, it seems to me the arrays of remote sensors become affordable for that many consumers of weather information."

There is a kind of proof of affordability in the laboratory's experience: where a remote sensor has reached a point where it can be applied operationally, it has found an interested clientele.

Acoustic remote sensing is a case in point. In 1969, Dr. Little told an interviewer that as his organization (then one of the Environmental Science Services Administration's Research Laboratories) moved into the remote sensing area they were exploring the possibilities of electromagnetic waves (radio, light, infrared)—and adding *acoustic* sensing to the picture. As development of this innovative acoustic approach went forward, according to Dr. Freeman Hall, who leads the laboratory's acoustic program and is directing BAO construction for NOAA, it soon began to draw interest from outside the government. "Back in 1972," Dr. Hall remembers, "we held a conference on acoustic sounders and what they could do. One of the attendees thought sounders looked like something his company might want to manufacture, and they began putting one out. Now they're the principal supplier of these units". About 150 of the sounders produced by private industry have been sold. In four smelting plants in the American northwest, acoustic sounders tell plant managers when atmospheric conditions are right for smelting—and when they are such that the plant should shut down, or modify operations. Highway departments are using acoustic sounders to determine whether new routes will encounter persistent, pollution-concentrating atmospheric conditions. Lumber mills use acoustic sounders to determine when slash burning will not cause low-level air pollution. "It's a very good example of technology transfer", says Dr. Hall.

Technology transfer determines where remote sensors go when they grow up.

Another family of acoustic sensors—a Doppler acoustic sounding system that can detect velocities and altitudes of wind shear above an airport—was developed by the laboratory with support from the Federal Aviation Administration. It is a large system, requiring great horn-shaped listening antennas in buried bunkers, a minicomputer, and other expensive gear, and for a while there was some question as to how important real-time wind shear information really was to aviation.

Then the 1975 crash at New York's John F. Kennedy International Airport made wind shear, always a familiar hazard to pilots, an aviation hazard everyone knew something about. Another jetliner crash at Denver's Stapleton International later in the year reinforced the point. The acoustic wind shear detector became more than an interesting technical development—it became a way to save lives and property at an airport. That technology, along with some other remote sensing techniques from Boulder, is now in the process of transferring to the world of aviation safety.

"The fact is," Dr. Little explains, "at this time we have more other-agency support than NOAA support for these devices. I think part of this at least comes from our former Central Radio Propagation Laboratory connection. (The Central Radio Propagation Laboratory, which Dr. Little directed, was one of three major elements combined in 1965 to form NOAA's predecessor agency, the Environmental Science Services Administration). While the CRPL background enabled us to bring new remote-sensing talent and experience into meteorology, it worked the other way too. We're also viewed as meteorological *arrivistes*: we don't really speak the language, and it's difficult to bridge between what we do and the operational world of meteorology. But if NOAA is to make maximum progress toward weather reporting and prediction at these small scales, it is absolutely essential that we develop a joint Wave Propagation Laboratory—National Weather Service program to exploit the advantages of remote sensing for the monitoring and forecasting of local weather conditions.

It may be that people think of remote sensing as a new concept, but it isn't at all. I began in radio astronomy, he explains, referring to his graduate days at the University of Manchester, "which is *really* remote sensing. Then I went to remote sensing of the upper atmosphere and ionosphere, which we sensed remotely because we couldn't get there to measure things in place. Now we're in a more accessible part of the environment, not because remote sensing is the only way to measure events there, but because it permits us to measure events there extremely well."

For the coming decade, his laboratory's remote sensors will be doing what they do so well at the Boulder Atmospheric Observatory near Erie, so that those twenty-first century weathermen will have the kind of tools they'll need to do the kind of jobs they'll have to do. ▫

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NOAA INSTRUMENTATION AT THE BOULDER ATMOSPHERIC OBSERVATORY

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1. INTRODUCTION

The Boulder Atmospheric Observatory (BAO) is a new research facility operated jointly by the Wave Propagation Laboratory of NOAA and the National Center for Atmospheric Research (NCAR). It is located 20 km east of Boulder (see Fig. 1) on gently rolling terrain. Installations at the site include an instrumented 300 m tower, a variety of remote sensors, and a highly interactive computer system controlling the acquisition and processing of data. The in-situ and remote sensors installed at the site by NOAA are designed to provide basic data for atmospheric studies and testing of other atmospheric sensors. These data will be archived for future use and will be made available to the scientific community. For major experiments these standard measurements will be augmented through the deployment of NCAR's Portable Automated Mesonet (PAM) system and instrumented aircraft, extending the range of the tower measurements over wider horizontal and vertical scales. Other instruments will be operated for specific periods to meet the needs of in-house and visiting scientists.

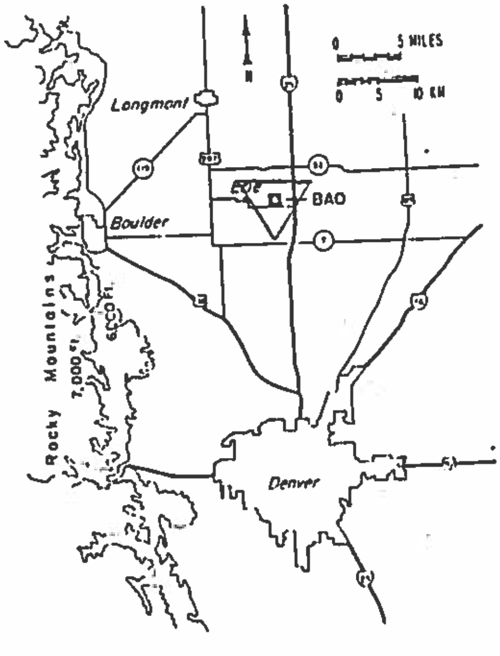

Figure 1. Map showing the location of the Boulder Atmospheric Observatory (BAO) with respect to Boulder, Colorado, and the Rocky Mountains.

This paper will describe the standard instrumentation at the BAO site and discuss briefly the sampling considerations and processing techniques used to minimize tape storage requirements.

2. TOWER INSTRUMENTATION

The tower is a guyed, open-lattice structure of galvanized steel, with three legs spaced 3 m apart. A two-man elevator inside the tower provides access to the eight instrumentation levels while a moving carriage on the southwest face permits continuous profiling or fixed level operation at any desired height. Details of the tower design have been given by Hall (1977).

The standard instrumentation levels on the tower are distributed linearly with height, except for the two lowest levels (see Fig. 2). All levels have identical instrumentation; two booms are available at each level for switching sensors so that the data are not compromised by unexpected changes in wind pattern. Special sensor mounts permit quick transfer of all probes from one boom to the other. Prevailing winds at the site are from the southeast during the summer and from the northwest during the winter. At the very least the sensors will have to be moved twice a year to insure proper exposure.

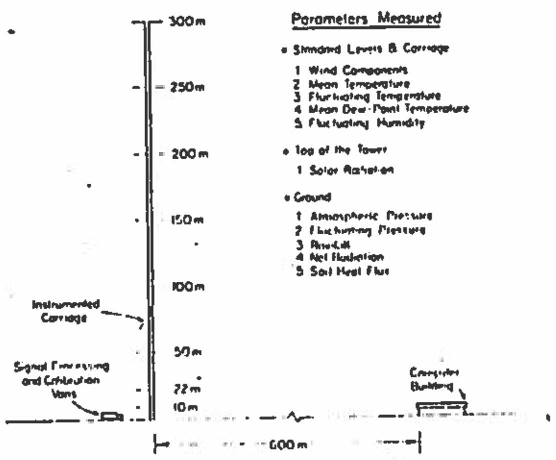

Figure 2. Schematic of the instrumented level on the tower and parameters measured at BAO.

The booms are specially designed for convenience of handling and easy access to the sensors for servicing. Each consists of a 4-m telescoping boom (R. M. Young model 35260-12A) attached to a hinged support with fine adjustments for leveling. If the lateral support member is loosened (see Fig. 3), the entire boom can be swung toward one face of the tower and retracted to bring the sensors within easy reach of the platform.

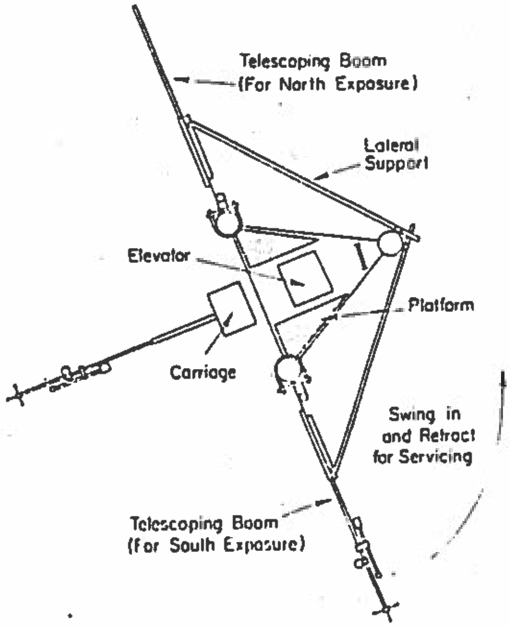

Figure 3. Plan view of an instrumented level on the tower showing the dual boom configuration in relationship to the boom on the movable carriage.

The standard measurements on the tower are listed in Fig. 2. A three-axis sonic anemometer measures wind velocity along three orthogonal directions. This particular configuration provides a wider azimuth coverage for both the vertical component probe and the fast-response temperature sensor nestled in it (see Fig. 4). Non-orthogonal arrays of the type used in past surface layer measurements (Kaimal et al., 1974; Mitsuta, 1974) are not suitable for unattended operation on tall towers since they require periodic reorientation into the wind to accommodate changes in wind direction. They offer unobstructed exposure for the acoustic paths, but only over a limited azimuth range. However, this new configuration has its own limitations. The larger separation between the vertical path and the horizontal paths has the effect of lowering the high-frequency response in the Reynolds stress cospectra. An underestimation in the 10-m stress is expected but little, if any, error should occur at the higher levels. Another limitation (inherent in any fixed array) is the underestimation caused by the blocking effect of the upwind transducer when the wind blows directly along one of the horizontal axes. Correction for this velocity defect is made in the data processing software with a first degree approximation to the wind direction.

The sonic anemometer probes used at BAO include two-axis probes made by EG&G (model 198-2) and by Ball Brothers Research Corporation (model 125-198), and one-axis probes, all made by Ball Brothers Research Corporation (model 125-197). The probe electronics are of the EG&G (model 198-3) type; the computer interface unit (Kaimal et al., 1974) was originally developed at the Air Force Cambridge Research Laboratories for their boundary layer research. The probe electronics located on the tower fire the transmitters on receipt of a signal from the interface unit and select the proper triggering point on the waveform picked up by the receivers. Coaxial cables connect the probe electronics to the computer interface circuit in the van at the base of the tower. The latter contains the timing circuits needed to fire the transmitters and the counters, and holding registers to measure the interval time between pulses arriving at the receivers. To insure proper synchronization in data sampling, the transmitters at all levels are fired simultaneously at a 200 Hz rate. The actual sampling rate for these and other fast response sensors is 10 Hz, so each sample is an average of 20 successive transmissions. This block-averaging is provided to minimize aliasing effects in spectral computations.

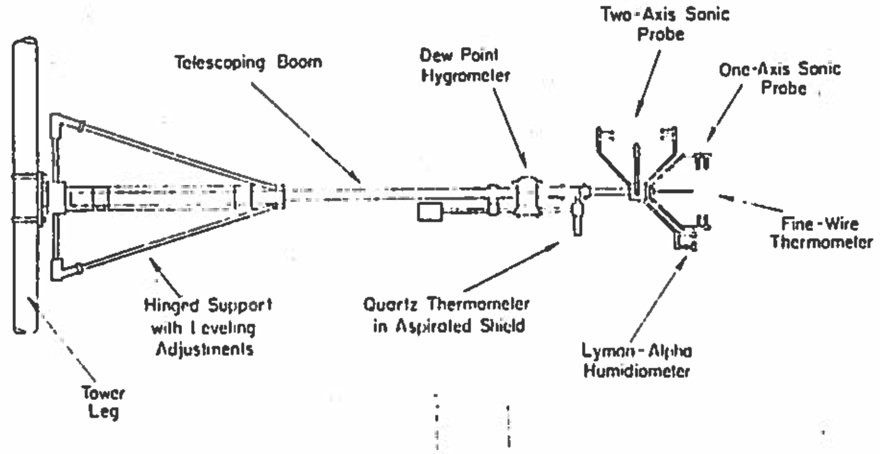

Figure 4. Sketch showing retractable boom and arrangement of sensors on it.

Fluctuating temperature is measured by a platinum wire thermometer (Atmospheric Instrumentation Research, model DT1A) specially engineered for use with the vertical sonic probe. Its frequency response very closely matches the path-averaged response of the sonic wind measurements. The sensor consists of a simple bridge circuit with a length of 12-μ platinum wire (nominally 150Ω at 20°C) on one leg. The wire is wound on a helical bobbin of the author's design attached to the end of a 10-cm rod (see Fig. 4). The mechanical support provided by the bobbin adds considerably to the useful life of the wire without affecting its frequency response in the 0-5 Hz range. Unless hit by debris or exposed to freezing rain, the wire will last for days if not weeks.

The low-noise, low-drift electronic circuitry in the temperature probe has an output range of ± 10 v corresponding to a temperature range of ± 50°C. The wide temperature range makes range switching unnecessary, but shifts the burden of performance to the multiplexer and A/D converter. A 15-bit A/D converter should provide more than adequate resolution in the temperature fluctuation measurements.

An attractive feature of this circuit is its simple calibration scheme which adjusts for probe-to-probe variations in wire resistance and insures proper relative calibration in the output signal. The data acquisition software uses the observed mean temperature reading at that level to correct for the nonlinearity in the platinum temperature-resistance curve.

The Lyman-Alpha humidiometer shown in Fig. 4 represents a modified version of the commercial device made by Electro Magnetic Research Corporation (model BLR). Plans are underway to develop a more compact probe with better exposure of the sampling volume to the airflow. Mean temperature and dew point measurements made at each tower level are used by the data acquisition software to keep the humidiometer in calibration as its sensitivity changes through aging and contamination of the windows.

The other two sensors on the boom are slow-response devices for measuring mean temperature and mean dew point. A Hewlett Packard quartz thermometer (model 2850A) housed in an R. M. Young aspirated shield (model 43404) measures the temperature. An absolute accuracy of ± 0.005°C is maintained by using a single reference oscillator for the probes at all levels, by periodically calibrating all probes at the same time in a precision temperature bath, and by using that information to scale the readings at each level. The dew point is measured with a Cambridge Systems hygrometer (model 110-SM), calibrated in the manner prescribed by the manufacturer. On top of the tower, attached to a vertical mast, is mounted an Eppley pyrheliometer for measuring incoming solar radiation. The outputs of these sensors are sampled once a second by the data acquisition system. Signals from all sensors on the tower are transmitted to the data acquisition system through cables installed in conduits on the tower. Additional signal cables and power outlets are provided at each level to accommodate visitor equipment.

The boom on the carriage is designed to handle the full complement of standard level instrumentation. The carriage can take loads up to 1200 kg so that a large number of other sensors may be added at a later date. For convenience of data transmission all sensors on the carriage yield analog outputs. Transmission of the signals to the data acquisition system is handled through a cable and trolley arrangement which connects to a terminal box at the 150 m level. The carriage sensors are sampled by the same multiplexer used for sampling all other analog sensors on the tower. As new sensors are added, alternate telemetry systems will be used. For the present, however, the direct cable link offers the simplest means for sampling the fast-response channels on the carriage.

3. GROUND-BASED SENSORS

These fall into two categories:

(1.) *In-situ sensors* measuring atmospheric pressure, rainfall, net radiation, and soil heat flux. The raingauge, net radiometer, and soil flux plates are located at a spot removed from the tower and other structures at the site. The barograph for measuring absolute atmospheric pressure is installed in the signal processing van. In addition, a spatial array of eight microbarographs distributed over a 2 km radius around the tower senses small pressure fluctuations signaling the advance of gust fronts and gravity waves (Hooke et al., 1973). Signals from all these sensors are sampled once per second by the analog multiplexer.

(2.) *Remote sensors* such as the laser triangle, the FM-CW Doppler radar, and the acoustic sounder. These remote probes, developed at the Wave Propagation Laboratory in recent years, measure parameters that complement the in-situ measurements on the tower. The laser triangle consists of three crosswind anemometers (Lawrence et al., 1972) spanning the distance between the outer guy wire anchor points. Instantaneous measurements of wind convergence at the base of the tower are computed from the average cross winds measured along the three legs of the triangle. The FM-CW Doppler radar (Chadwick et al., 1976) measures winds to heights up to 1 km in clear air and operates continuously in an unattended mode. The measurements are not degraded by clouds or precipitation. The three acoustic sounders, one at each corner of the laser triangle, document the heights of the boundary layer, the presence of convective plumes, and stably stratified layers. One of the sounders will have bistatic Doppler wind sensing capability through the addition of two fan-beam transmitters.

In addition to these remote probes other WPL devices (e.g., passive microwave radiometers, infrared Doppler lidars, optical heat flux sensors, pulse dual-Doppler radars) will be operated at the BAO as needed. Also, new techniques, as they are developed, will be tested against the in-situ measurements on the tower. Arrangements will be made for intercomparison of remote sensors developed in-house and by visiting groups.

4. DATA ACQUISITION AND RECORDING

A digital computer at the BAO site controls data acquisition from the tower and ground-based sensors. The Mobile Micrometeorological Observation System (MMOS), which performed the data handling in past boundary layer experiments (Haugen et al., 1971; Kaimal et al., 1976), is now used for this purpose. A new system built around NCAR's PDP 11/34 computer will soon take over the data acquisition and recording functions. This system is in a temporary building about 600 m southwest of the tower (see Fig. 2). The system will be housed in more permanent quarters when NCAR's Field Observation Facility moves to the BAO site. Underground cables link the computer to the signal processing circuits at the base of the tower.

The sequence of data handling operations is shown schematically in Fig. 5. This sequence may undergo modification as our requirements evolve. Nevertheless, the block diagram highlights our basic approach to data storage. It was clear from the outset that recording of all sampled data (fast-response data at 10 Hz and slow-response data at 1 Hz) would place an unacceptable burden on the BAO operation. The problem of retaining all relevant information in the bandwidth of our measurements, operating on a continuous mode, is solved by storing the high-frequency information in the form of smoothed spectral and cospectral estimates and the low-frequency information as time series. The high-frequency data are needed for computing dissipation rates (ε) and temperature structure parameters (C_T^2) at the different heights and for a wide range of studies where the inertial subrange behavior of various parameters is of interest. A 1024-pt fast-Fourier transform (FFT) spectrum is computed every 2 min. Successive spectra obtained over a 20 min period are first averaged in time and then block averaged over non-overlapping frequency intervals (the first few estimates excluded) to provide a roughly equal spacing of center frequencies on a logarithmic plot. A density of approximately 10 frequency blocks per decade (shown schematically in Fig. 6) provides a smooth inertial subrange spectrum with more than adequate resolution (Kaimal et al., 1972). Thus the high-frequency information in each 20 min period (synchronized with the line-printer output of data summary) is compressed to roughly 24 data words per channel.

The low-frequency information is contained in two parallel time series. For computations of the low-frequency portion of the spectra, the original 10 Hz data are block-averaged in 10 sec (100-pt) non-overlapping blocks. The block averaging reduces aliasing and confines the mismatch with the real-time high-frequency spectrum to the region of overlap (0.01 to 0.05 Hz). In reconstructing the entire spectrum only spectral estimates below 0.01 Hz are used, while the entire bandwidth of the real-time spectrum is retained.

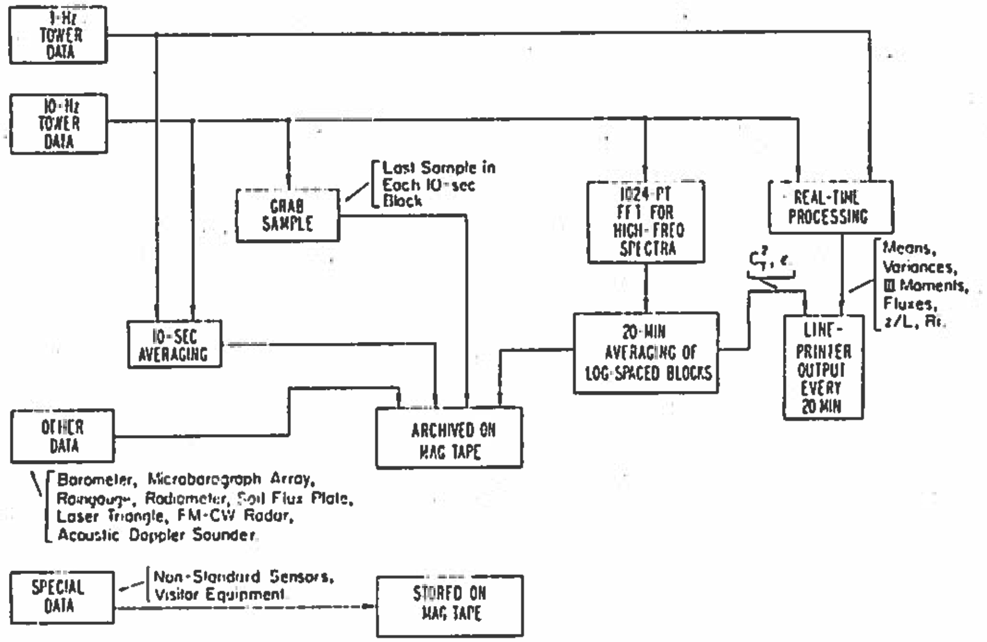

Figure 5. Schematic of data handling for archiving and real-time line printer output.

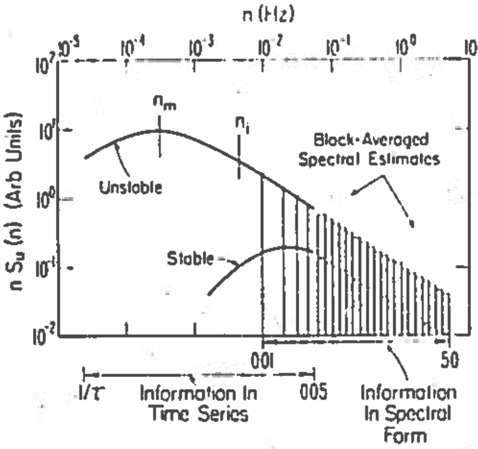

Figure 6. Typical spectra showing bandwidths covered by the smoothed high-frequency spectral estimates and the block-averaged time series. n_m and n_i are the frequencies corresponding to the spectral peak in the logarithmic spectrum and the onset of the -5/3 region, respectively.

The other time series recorded is a grab sample every 10 sec (last sample in each 10 sec block). This time series contains the turbulence information needed to compute variances, fluxes, third moments and other turbulence parameters. Important high-frequency information is lost in the block-averaging, which renders the first time series useless for turbulence calculations. Haugen's (1978) analyses show that the errors in estimates of variances and fluxes with these 10 sec grab samples are of the same order as the deviations from the ensemble average determined by the properties of the turbulent flow (Wyngaard, 1973).

Typical spectra for unstable and stable stratifications are shown in Fig. 6 to illustrate the approximate range covered by the high frequency spectrum. The daytime spectral peak, n_m, corresponds roughly to a wavelength equal to $1.5z_i$ (Kaimal et al., 1976) over flat terrain, where z_i is the height of the lowest inversion base. Also, for heights above $0.1z_i$, the onset of the -5/3 region in the spectrum (seen as a -2/3 slope in the logarithmic spectral representation), indicated by n_i in Fig. 6, corresponds to a wavelength equal to $0.1z_i$. Under typical daytime conditions at the BAO, the real-time velocity spectrum above 100 m should have much of its -5/3 region covered by the high-frequency spectrum. The relationships for the stable spectra above 22 m have yet to be established but preliminary indications are that n_m will fall roughly in the region where the low and high frequency spectra overlap.

The 1 sec samples from the slow-response sensors are also averaged in 10 sec non-overlapping blocks. Included in this slow-response category, besides the mean profile sensors on the tower, are most of the ground-based sensors at the site. The acoustic sounder and FM-CW radar outputs, which do not lend themselves to the same treatment as the other outputs, are the exceptions. Their outputs are not currently included in the archived tape.

In addition to the recordings on magnetic tape, hard copy outputs are available on the line printer every 20 min listing such parameters as means, variances, fluxes, third moments, dissipation rates, structure parameters, Richardson number and z/L. These outputs serve as a quick summary of meteorological conditions for observational periods on hand, but even more important, they are useful for monitoring sensor performance during experiments. All the data from the sensors (see Fig. 5) are used in the real-time computations for the line printer output.

Non-standard data from special sensors and from visitor equipment installed for the duration of an experiment will be recorded not on the archived tape, but on a separate magnetic tape. It should be pointed out that the system design permits parallel recordings of non-standard sensors as well as other groupings of data from the standard sensors. During episodes of concentrated data gathering all the sampled data may be recorded.

5. FUTURE PLANS

Several experiments have been scheduled at the BAO for the coming year. They range from small experiments verifying new sensor performance against routine tower data to two large cooperative boundary layer experiments involving other agencies and university groups. A site evaluation experiment in April will determine how well the boundary layer at the BAO site approximates boundary layers over flat homogeneous terrain. NCAR's aircraft and PAM system will be in operation at the site for the duration of the experiment. In August a more ambitious boundary layer experiment utilizing several dual-Doppler radars and radiosondes in addition to the aircraft and PAM systems will attempt to study the evolution of the planetary boundary layer and the role played by the boundary layer in the initiation, development, and maintenance of convective storms.

As schedules for future experiments are being drawn up, steps are being taken to link the BAO data acquisition system to a larger computer system at the Wave Propagation Laboratory in Boulder. This larger system, designed around NCAR's PDP 11/70 computer, will have multi-user terminals where several scientists can perform a number of independent computations and analyses of recent data stored in disc memory. The two computer systems are marked Station A and Station B in Fig. 7. When the two stations are linked by dedicated phone lines all standard data will be transmitted to Station B for archiving. Eventually, as the link to NCAR's computing facility is also established, the BAO data will be accessible to an even wider group of users through terminals at NCAR and phone links to other computers across the country.

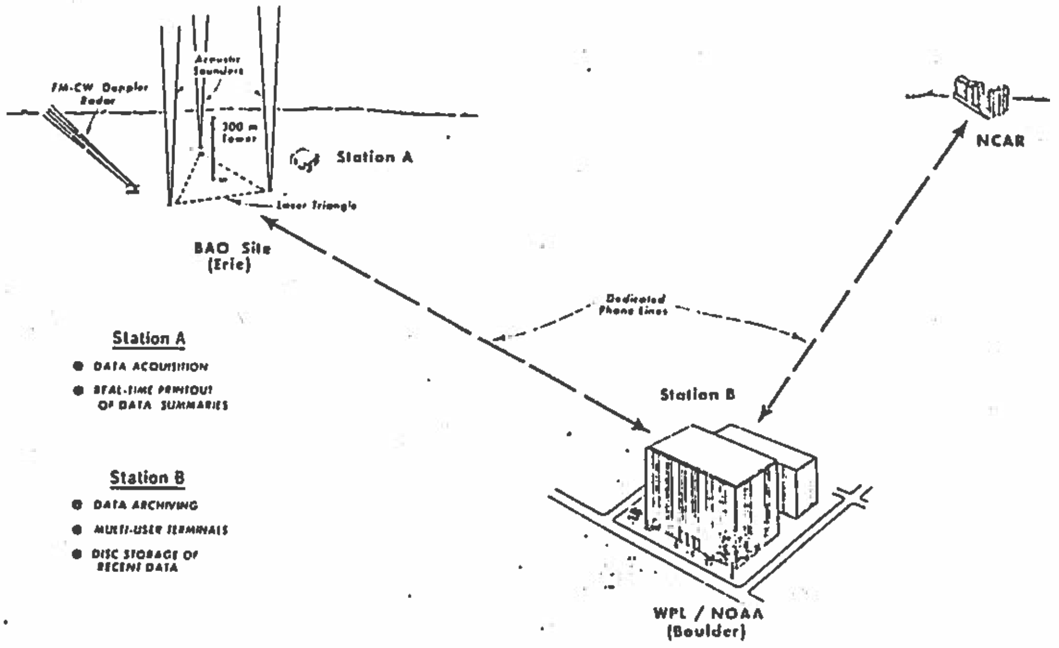

Figure 7. Bird's-eye view of the BAO site indicating data links planned with computer systems at WPL and NCAR.

6. ACKNOWLEDGMENTS

The author is happy to acknowledge the contributions of the BAO staff, Messrs. Robert W. Krinks, Jim T. Newman, Norbert Szczepczynski and Daniel Wolfe to the development of the Boulder Atmospheric Observatory. Drs. John C. Wyngaard and Duane A. Haugen played critical roles in the evolution of the data processing scheme. Mrs. Mildred F. Birchfield prepared the manuscript.

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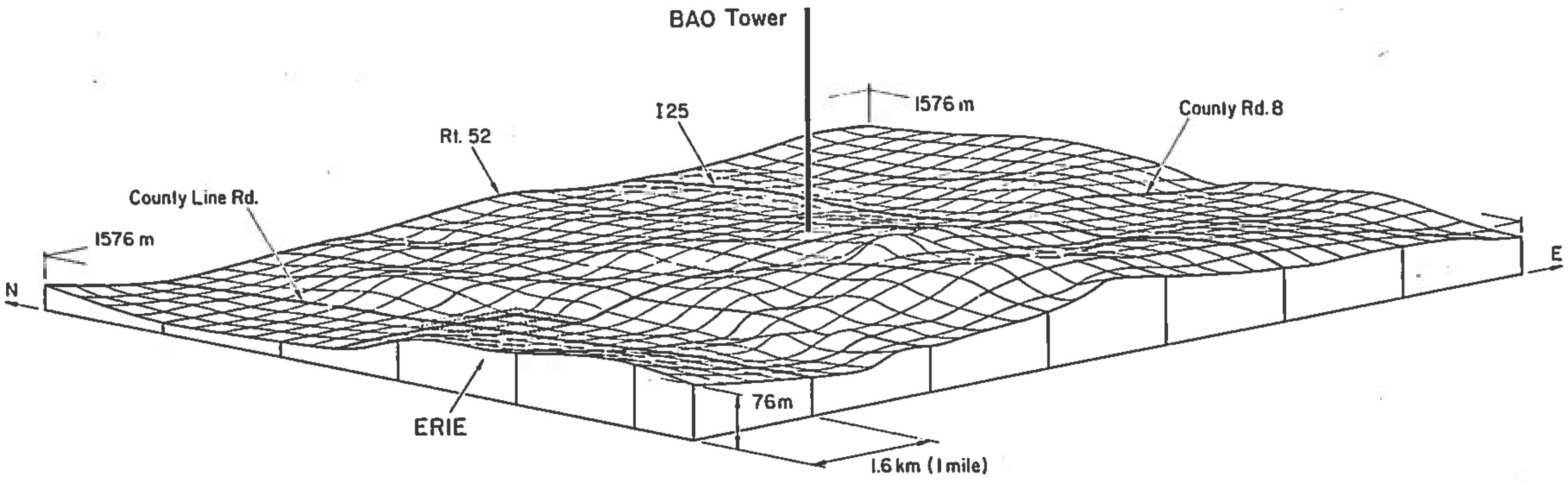
BAO Tower
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1576 m
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1.6 km (1 mile)

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The Boulder Atmospheric Observatory and Its Meteorological Research Tower

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Remote sensing of the atmosphere by optical, acoustical, or radar means is becoming increasingly important in the meteorological community. Yet those of us in remote-sensing development are frequently asked the question, "How do you know your interpretation of the probing wave interactions with the atmosphere is correct?" Indeed, providing the independent verification of remote sensor performance has always been a challenge.

For the past ten years, the NOAA Wave Propagation Laboratory at Boulder, whose mission is remote-sensor development, has operated an instumented 150-m tall tower at Haswell, Colorado, in the southeast corner of the state. Many short-term but definitive atmospheric remote-sensing experiments have been conducted at this site. By 1969 we were aware of the limitations of the Haswell site because of the travel expense in operating so far from the home laboratory, because its intermittent use did not justify significant improvements in the instrumentation there, and because of the limited tower height. During the past four years we have been working hard to define the requirements for an improved tower and site and to obtain the monetary support to build such a facility. Now in 1977 we are constructing the tower. The purpose of this paper is to familiarize the optical community with the tower, its instrumentation, and its potential impact on atmospheric remote sensing. Possibly you, the reader, have in mind some atmospheric tests or experiments you would like to conduct at the site or use the tower instrumentation to support. The procedure for accomplishing such tests will be described.

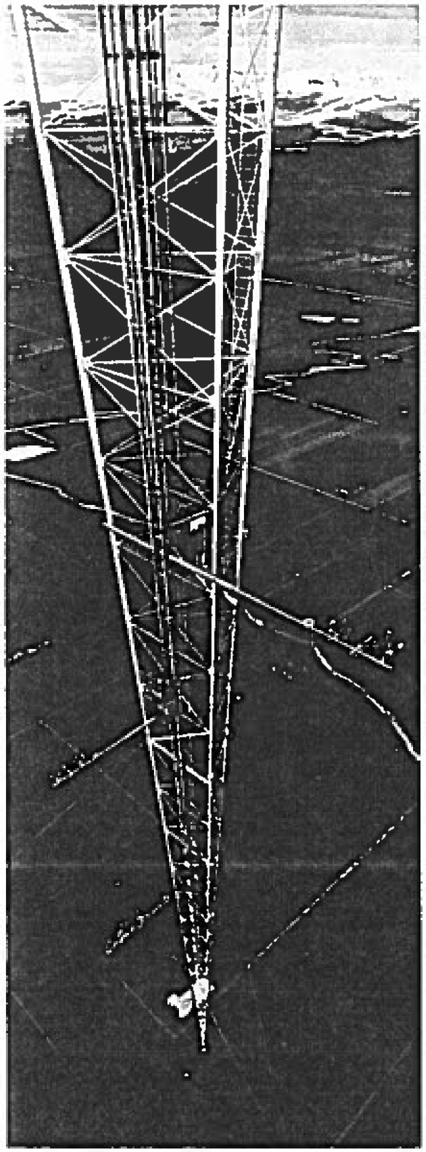

Figure 1. Artist's concept of the Boulder Atmospheric Observatory tower, located 25 km from the Rocky Mountain foothills.

THE TOWER STRUCTURE

The Boulder tower will be a guyed, open-lattice design 300 m tall. The structure will be galvanized steel with the three legs spaced 3 m apart. Flashing strobe lights will operate night and day to warn low-flying aircraft of the tower presence. A two-man elevator, internal to the tower, will allow access to the eight instrumentation levels while a movable carriage on one face of the tower provides for profiling or an intermediate platform between the fixed levels for sensing instruments. An artist's concept of the tower, showing these features and the general appearance of the facility, is illustrated in Fig. 1. The site is some 25 km from the nearest foothills of the Rocky Mountains so that the planetary boundary layer will be largely unaffected by the Rockies, except when strong downslope winds sweep over the prairie to the east of the mountains. The 300-m height of the tower will ensure that the instruments extend above the nocturnal planetary boundary layer most of the time during all seasons. As the boundary layer depth is increased by convective mixing during the daytime, the capping inversion typically found at the top of the boundary layer will lift past the tower top by mid-morning. By afternoon the boundary layer may be one or two kilometers deep, so that it is not feasible to build any tower tall enough to sample this turbulent region continually. The planned 300-m tower is designed to allow extension to 500-m should the necessity for doing this be strongly apparent and the funding identified.

The location of the tower close to the mountains requires that special care be given to its design to withstand the winds and occasional icing conditions that can occur. The specification used was devised by the Electronic Industries Association and calls for the tower to withstand a

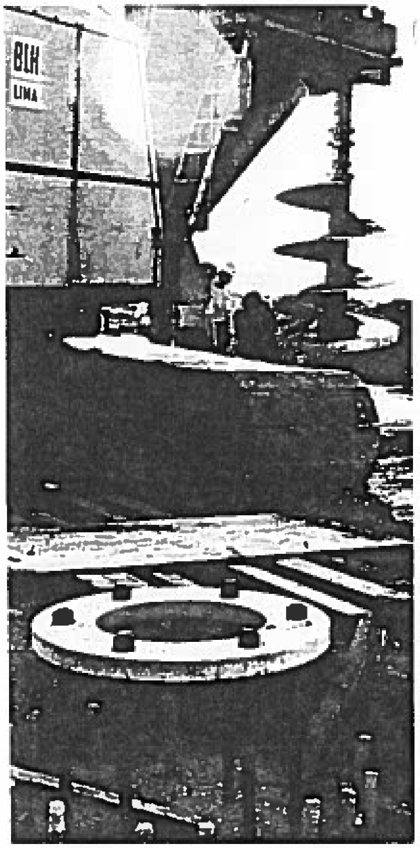

Figure 2. Drilling for the tower foundation piers, November, 1976.

wind loading of 3123 Nm^{-2} with 1.3 cm of radial ice on all members. At the altitude of Boulder, this is equivalent to a wind speed of 77 ms^{-1}. Safety factors of 2.5 were used in designing the tower structural members and guys.

The tower foundations must support not only the dead weight of the tower but also the pull-down tension of the guys. This required three concrete piers under the foundation cap, each pier 1.5 m in diameter and 17 m deep. Figure 2 shows the drilling rig on the site in November, 1976 preparing the holes for the foundation.

One of the operational goals was to place the tower close enough to the atmospheric sciences community in Boulder to keep the travel time from town less than 30 minutes. This was achieved when we identified an undeveloped section of land in Weld County, two miles east of the town of Erie, which was available for lease from the Colorado State Land Commission. The terrain is gently rolling prairie overlaying the Boulder-Weld Counties coal field. Many of the surrounding sections of land have been undermined during the past 80 years, and an operating mine is still worked on the adjoining section of land. Fortunately, we were able to locate a block upthrust or horst area which had not been undermined, wide enough to accommodate the tower guys. Coal deposits are generally thinner in such horst regions, explaining the lack of mining. Because the surrounding land is subject to subsidence over the old mines, there is little danger in future years of housing or commercial developments that might interfere with the low-level airflow past the tower. Most of the surrounding land is now used in alternate-strip, dry-land wheat farming.

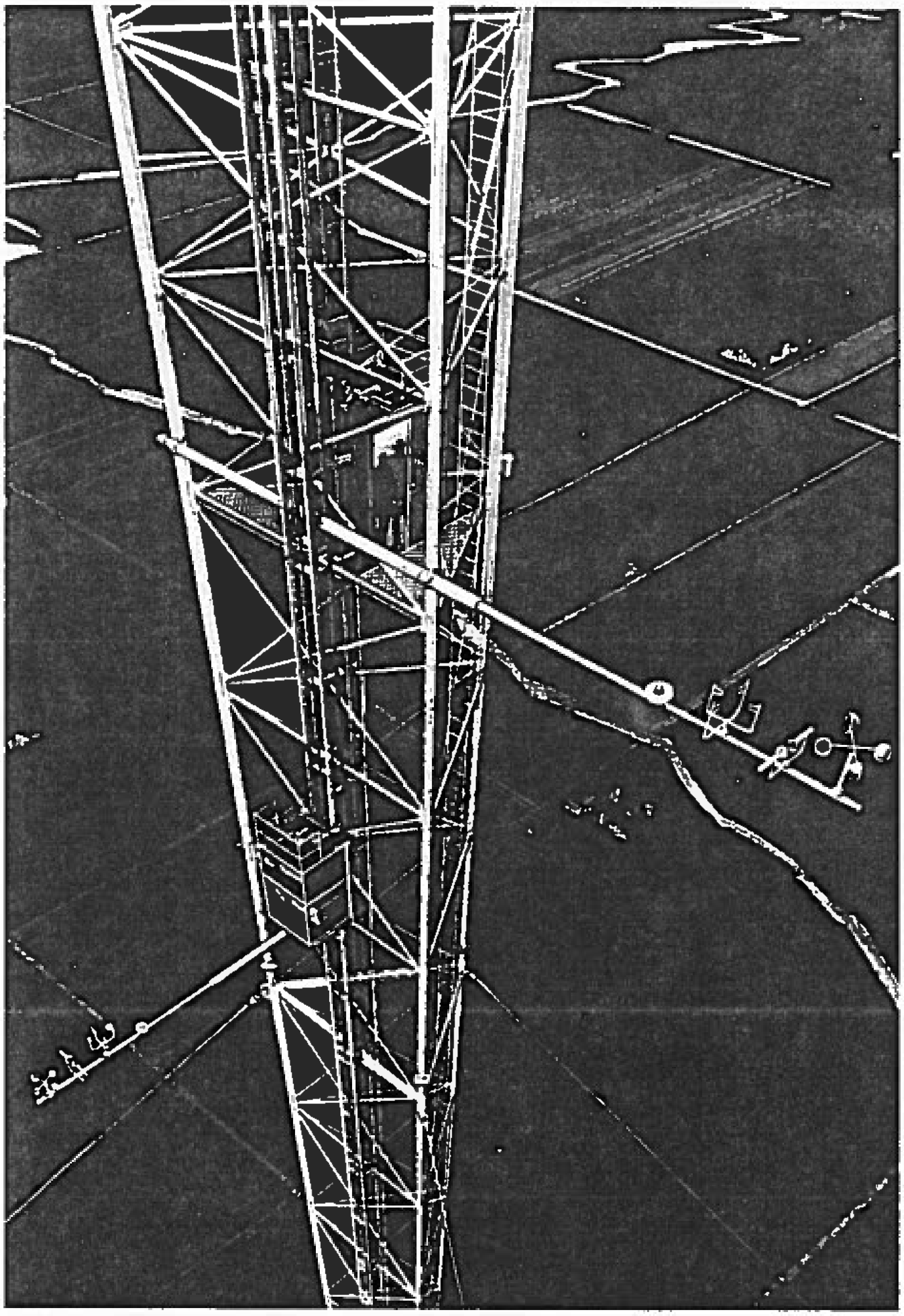

Figure 3. Details of an instrument level, showing the elevator landing platform, instrument boom, and external carriage.

Besides the NOAA investment in the tower and much of the instrumentation to be placed on and around it, the National Center for Atmospheric Reseasrch (NCAR), also located in Boulder, plans to move its Field Observing Facility to the site sometime in the future. The combined operation will be known as the Boulder Atmospheric Observatory. Through NCAR, we hope that many of the university groups in the atmospheric sciences will participate in experiments at the site.

INSTRUMENTATION ON THE TOWER

Prevailing winds at the tower site are from the southeast during the summer months and from the northwest during winter. For this reason, the tower instrumentation will be located on booms which can be extended 5 m from the tower to measure winds optimally from either the summer or winter prevailing direction. Instruments will probably need to be moved twice a year to ensure proper exposure. Figure 3 is a blow-up of the earlier illustration to show one of the instrumentation levels. The elevator will stop at the steel grating platforms to allow access to the instruments. The booms can be cranked inward for instrument calibration and servicing, then repositioned away from the tower so as to reduce the effects of the structure on measurement accuracy. The booms will be located at 10, 20, 50, 100, 150, 200, 250, and 300 m heights. At each level we will have three-axis sonic anemometers, which can measure the three components of the wind independently twenty times per second. Conventional cup or propeller anemometers may be located at several levels for independent, average wind-speed measurement. Fast-response, platinum resistance thermometers will be colocated with the sonics to provide 10-Hz bandwidth temperature measurements. Slower response quartz crystal thermometers will provide averaged temperatures accurate to within 0.01 K.

A dewpoint hygrometer will be the standard humidity measuring instrument at each level with averaging times of several seconds for each reading. Lyman-α humidiometers will be added later to take advantage of the much faster response of these optical instruments. Pyroheliometers will be located at the base and the top of the tower to measure boundary-layer turbidity influence on solar flux.

The instrument carriage will be capable of handling loads of 1200 kilograms so that even the largest aerosol impactors or spectrometers can be profiled through the boundary layer. To avoid the necessity of trailing wires, we plan to telemeter the data from the carriage, probably utilizing an optical link for this purpose. At times, we may locate several three-axis sonic anemometers on the carriage together with high-frequency temperature and humidity instruments, thus requiring a communication bandwidth of a megahertz or more. We are now working out details of the carriage instrumentation and telemetry.

Several remote sensors will also operate routinely at the tower. Surrounding the tower base will be a triangle of laser beams to measure the transverse wind across each leg of the triangle.[1] With the three independent transverse measurements we will be able to determine the wind convergence at the tower base. A typical instrument for such measurements is shown in Fig. 4. Three acoustic sounders, one at each corner of the laser triangle, will document the heights of the boundary layer and the presence of convective plumes or the occurrence of stably stratified layers. Sensitive microbarographs will also aid in the interpretation of gravity waves in the atmosphere propagating across the site.[2]

DATA ACQUISITION AND PROCESSING

The tower instrumentation, the laser triangle, and the microbarographs will be under the control of a digital computer housed at the base of the tower. The carriage telemetry receiver and the other instruments will be hard-wired to the computer through analog-to-digital converters with data being recorded on seven-track digital tapes. An XDS 920 computer, which has demonstrated its versatility through many years of field experiments, will be used initially. It will perform such chores as recording the raw or appropriately time-averaged data from each sensor, multiplying together the wind, temperature, and humidity fluctuations to provide averaged turbulent fluxes of momentum, heat, and moisture as well as performing other statistical manipulations of the data, printing out longer-period wind averages and variances, and correlating vertical velocities with the laser-triangle convergence measurements. We are working now on the formatting of the digital tapes and studying the optimum data-recording frequency and averaging times to provide a completely defined microclimatology of the boundary layer, and hope to limit

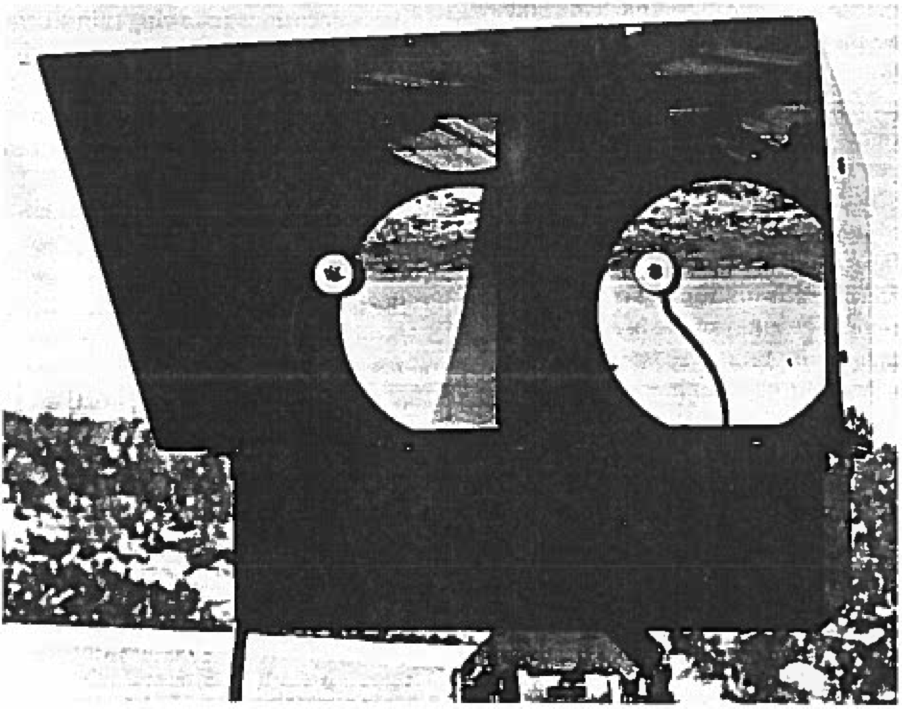

Figure 4. Optical cross-beam wind sensor, as deployed in the field.

tape utilization to one or less per day. In addition, we will incorporate a more modern computer, at first for specialized, perhaps high-data-rate but short-time-period experiments, with the eventual goal of tying together the new tower computer with the Boulder Laboratories computer. This will allow experiments to be controlled in the future by scientists in Boulder without their even visiting the tower site. Eventually we may be able to link computer control to other users hundreds of miles away from the facility.

SOME SPECIFIC GOALS OF THE TOWER MEASUREMENT PROGRAM

The primary purpose of the tower, as previously stated, is to provide the *in situ* verification of atmospheric measurements made with remote sensors. The reliable comparison between remote sensors, which average over finite scattering volumes in the atmosphere, with the *in situ* instruments, which are essentially point sensors, requires the accumulation of significant statistics, something that the tower will be able to do since we plan to keep it in continual operation for a number of years. As the interaction of optical, acoustical, and radar waves with the atmosphere becomes better understood, we will be able to "virtually" extend the height of the tower past its 300-m limit through use of the remote probes. Indeed, one of the eventual goals is to replace many of the *in situ* instruments with remote sensors, eliminating the need for conventional instruments and possibly even for balloon-borne instruments.

With the information available at the tower from remote and *in situ* sensors, a unique data set on atmospheric dynamics will become available. By operating the tower continuously for an extended period, say five years or more, we will finally obtain a detailed microscale climatology of the planetary boundary layer. We will have a reliable grasp on the statistics of turbulent heat, momentum, and moisture fluxes. We will be able to verify the importance of wave dynamics in boundary-layer processes and be able to understand the scattering mechanisms by which remote sensors record these events. For opticists, understanding the turbulent heat flux will permit better modeling and predicting of the effects of the turbulent atmosphere on optical wave propagation. We already have a good understanding of turbulent heat flux and optical index-of-refraction fluctuations under dry daytime convective conditions.[3] Better models are needed to help us to understand the stably stratified, nocturnal boundary layer, and we need to know the correlation between moisture and temperature fluctuations at different heights in the boundary layer so that the contribution of the latent heat fluxes on the optical index can be properly understood. Of course, this will require instrumenting the tower with fast-response humidity sensors, which we plan to do within the first year or two. Although the dry, high plains in Colorado are usually characterized by low moisture fluxes, on those occasions following rain storms we will be able to study the convariance of moisture and temperature fluctuations and should be able to extend this understanding to tropical or marine atmospheres by proper scaling. The improved understanding of moisture flux is also of great importance in understanding how the upward transport of water vapor through the boundary layer occurs. After all, this moisture is the source of clouds and large-scale weather in the atmosphere.

When the NCAR Field Observing Facility moves to the site, the measurement capability will be extended by the occasional deployment of its Portable Automated Mesonet (PAM) system, forty instrumented surface layer towers that can send telemetered data to a central location. In addition, NCAR and NOAA aircraft will use the tower for calibration and be able to extend the range of tower measurements over wider horizontal and vertical scales.

The investment of tax dollars in the NOAA tower is significant. The data collected there will be of value not only to the Wave Propagation Laboratory in our mission of developing remote sensors, but to the entire atmospheric sciences community. It will be NOAA policy to treat the tower as a *national facility*, where others in the government, in universities, or in the private sector will be welcome to come and perform cooperative experiments with the NOAA personnel. The digital data tapes on which the routine tower data will be recorded will be available for anyone to duplicate, study, and evaluate for the cost of making the tape copy.

Eventually we hope that by obtaining better measurements and modeling of the boundary layer in its mesoscale (10–100 km) extent, we will be able to deduce better forecasting schemes for local weather. This goal, one of the most important in NOAA's list of priorities, will be continually kept in mind as this new national facility comes on line and as we gain experience in its first several years of operation.

Do you have an experiment you would like to conduct at the Boulder tower? After construction is completed in June, 1977, it will take several months to install the instruments and shake down the data acquisition system. We will then be ready for experiments on the tower. Get in touch with Dr. William H. Hooke at NOAA in Boulder, (303) 499-1000, X6378, and inform him of your experiment requirements.

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