The Boulder Atmospheric Observatory and Its Meteorological Research Tower

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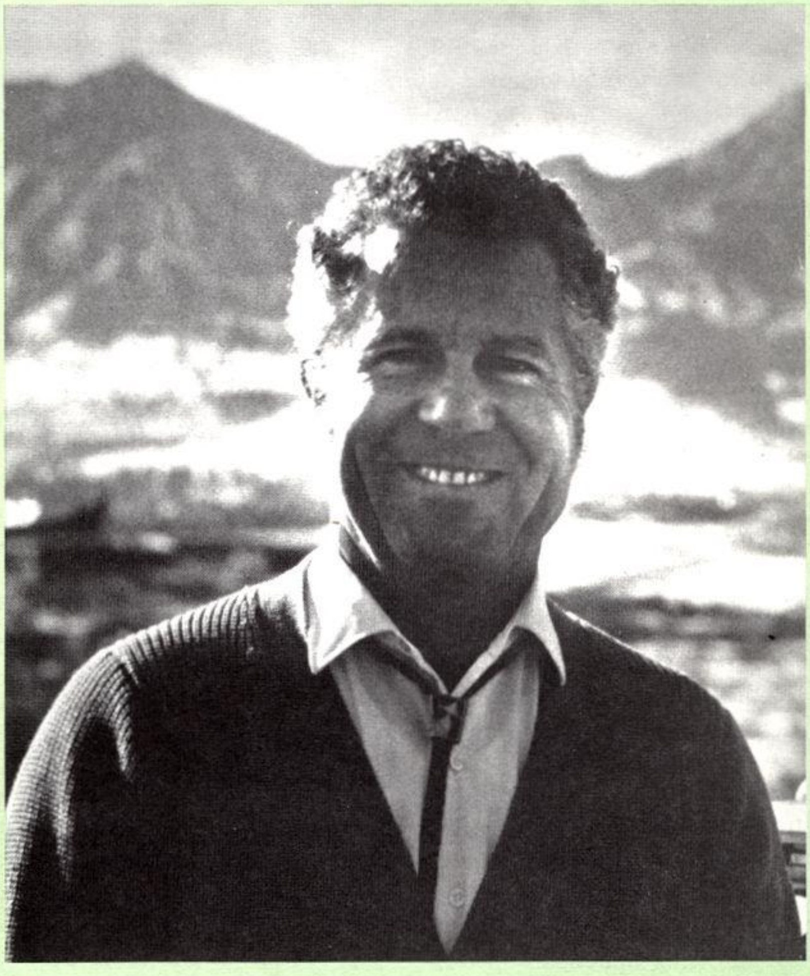

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Remote sensing of the atmosphere by optical, acoustical, or radar means is becoming increasingly important in the meteorological community. Yet those of us in remote-sensing development are frequently asked the question, "How do you know your interpretation 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.

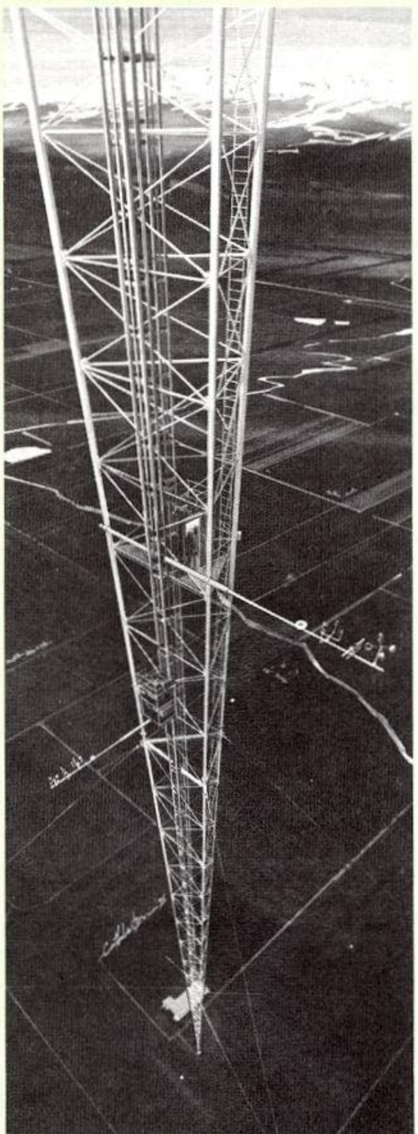

Figure 1. Artist's concept of the Boulder Atmospheric Observatory tower, located 25 km from the Rocky Mountain foothills.

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

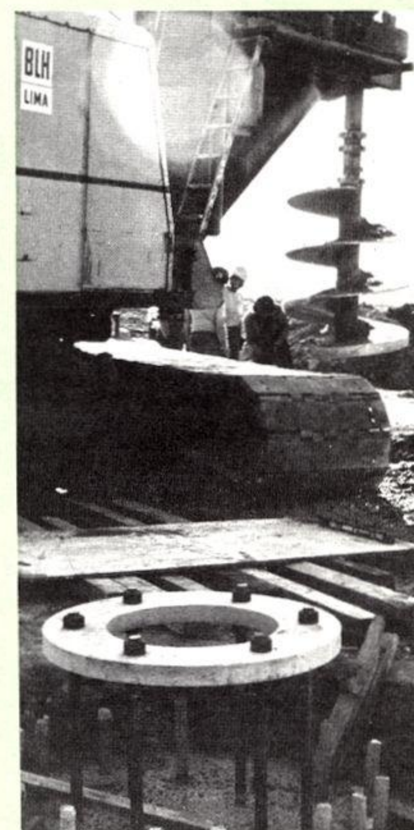

Figure 2. Drilling for the tower foundation piers, November, 1976.

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.

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.

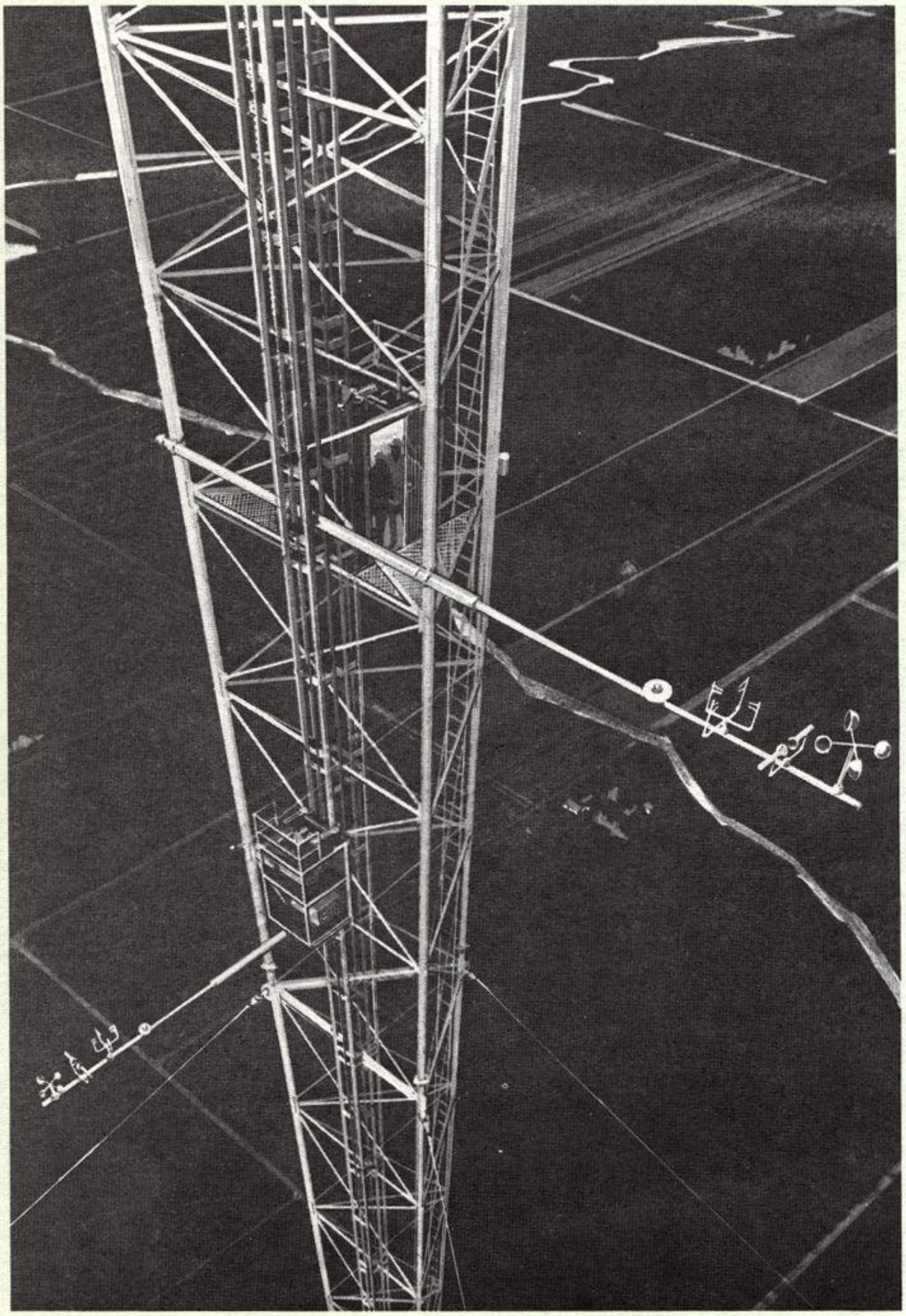

Figure 3. Details of an instrument level, showing the elevator landing platform, instrument boom, and external carriage.

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

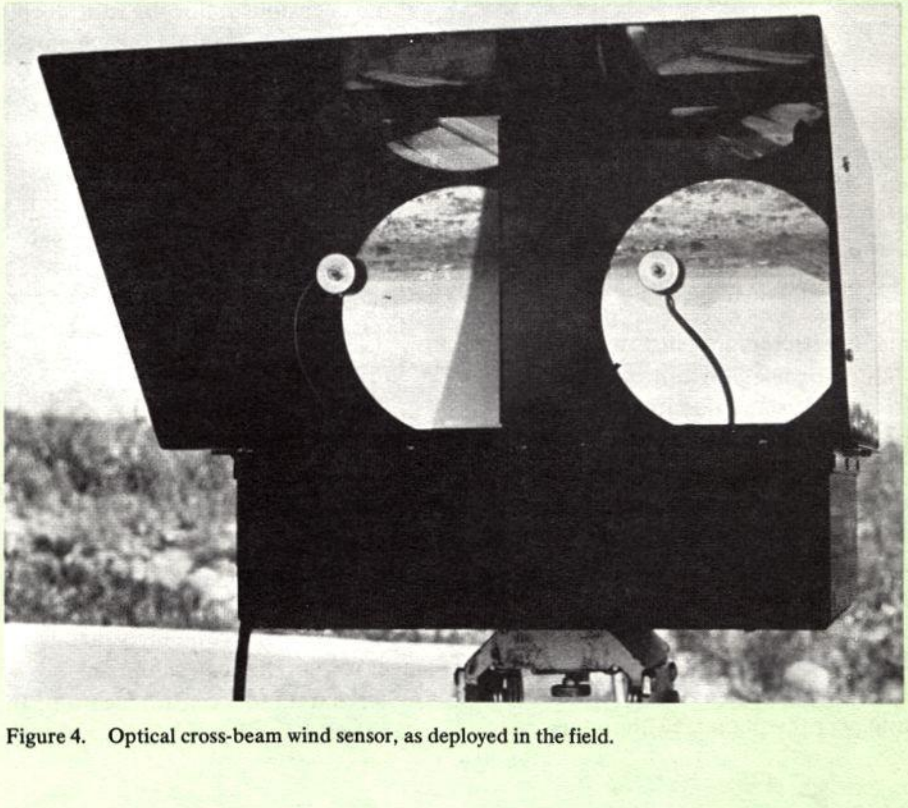

Figure 4. Optical cross-beam wind sensor, as deployed in the field.

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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