**2.6** THE EXTREME TURBULENCE (ET) PROBE FOR MEASURING BOUNDARY-LAYER TURBULENCE DURING HURRICANE-FORCE WINDS

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## 1. INTRODUCTION

While our understanding of hurricanes has increased over the last several decades through observations and modeling, there are still significant gaps. Many of these involve the atmospheric boundary layer, a region of well-known importance. Turbulent exchange between the atmosphere and ocean influences a hurricane's track and intensity. During landfall, air-surface exchange produces the wind damage and influences how quickly a hurricane weakens. Yet, very few direct boundary-layer observations of turbulence exist, primarily because they are so difficult to acquire. Most turbulence sensors function poorly, if at all, when winds exceed 20 m $s^{-1}$. Modern sonic anemometers are rain-tolerant, but only up to a point. We are developing a new extreme-turbulence (ET) probe which will acquire turbulent fluxes in the atmospheric boundary layer in heavy rain and hurricane-force winds.

A few studies have attempted to quantify turbulence in the marine atmospheric boundary layer during hurricanes and tropical storms. Gade and Scanlan (1977) installed three-component Gill anemometers on 10-m booms at five locations on the windward side of the Newport Bridge on the Rhode Island Coast. In August 1971, peak wind gusts of 33.5 m $s^{-1}$ were recorded during Tropical Storm Doria. Their data suggest a decrease in turbulence intensity, $\sigma_u/U$, with increasing mean wind speed $U$, where $\sigma_u$ is the standard deviation. Deploying three meteorological stations on the southern shore of Long Island, SethuRaman (1979) formulated some turbulence parameters from data acquired during the passage of Hurricane Belle in August 1976. The maximum recorded wind speed at the coast was 40 m $s^{-1}$ with a maximum friction velocity $u_*$ of 1.3 m $s^{-1}$. He found a shift toward higher frequency in the dominant spectral peaks as the hurricane approached the coast. Eddies encountered in the frequency range from 0.01 to 0.1 Hz contained most of the energy. The corresponding spatial scale at the mean wind speed of 20 m $s^{-1}$ ranged from 200 m to 2 km. A fivefold increase in turbulent dissipation $\epsilon$, reaching 130 $cm^2$ $s^{-3}$, was noted as the hurricane moved over Long Island. This corresponded to a peak in $\sigma_u$ of 5.6 m $s^{-1}$. The Humidity Exchange Over the Sea (HEXOS) Program, taking considerable care, achieved high-quality eddy-correlation measurements from a fairly sizable offshore platform (Smith et al. 1996; and Katsaros et al. 1994). In the process they developed techniques to protect the instruments from the harsh environment of water and salt. However, sonic anemometers were found to require considerable maintenance in such an environment. Also they did not observe winds in excess of about 22 m $s^{-1}$. Papers by Merceret (1976), Moss and Merceret (1976), and Moss (1978) examined turbulent fluxes acquired by aircraft in dry sectors of hurricanes. However, the lowest altitude achieved by these aircraft was usually no less than 150 m, too high to quantify air-sea exchange processes directly.

The relationship between wind stress and sea state as influenced by the turbulent structure of hurricane-force winds in the boundary layer is still poorly understood. Milestone research papers by Liu et al. (1979), Smith (1980), Large and Pond (1981), and Wu (1982) have developed various parameterizations for wind stress, drag coefficient, and friction velocity. However, all lacked data for winds in excess of 25 m $s^{-1}$. Thus, much remains to be learned about the turbulent nature of hurricane-force winds.

The new probe, intended to facilitate such studies, uses a pressure sphere, a standard for airborne turbulence measurements. Anemometer systems based on this approach have been around for at least 50 years (Martinot-Legarde et al. 1952; Wesely et al. 1972). We were motivated to use pressure-sphere anemometry for high-frequency wind measurement under harsh conditions, such as heavy rain and blowing spray. Pressure-sphere anemometry is rugged and responsive, and imposes minimal flow distortion. But in these early designs, the acceptance angle, over which incident winds could be measured, was limited. The bulkiness of the pressure sensors then available restricted sampling ports to one side of the sphere, which was directed into the wind by a vane. Sonic anemometers offered omni-directional acceptance and became the standard for near-surface turbulence measurement. Meanwhile, sensors of pressure and temperature have undergone the same miniaturization that has revolutionized computer use. A sphere of practical size may now fully enclose enough sensors to accept incident flow from any horizontal direction over a wide vertical range (±18°). Its design benefits from years of experience with airborne turbulence measurement. It exposes neither moving parts nor fragile projections to the wind flow since all of the sensors are internal. It can readily be hardened against harsh environments of sand, salt, wind, or rain.

Oost (1983) reported a pressure anemometer configured in three mutually perpendicular rings. Because this anemometer is not a sphere, the relation between the sensed pressures and the velocity is not simple. Calibration requires a wind tunnel. Oost et al. (1991) improved the design, with a different head geometry, simpler to manufacture and capable of operation in light winds. The calibration remained complex, however, and the acceptance angle is 180°. We have chosen a

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spherical configuration with internal pressure sensors to simplify the calibrations and to allow full 360° operation.

The ET probe currently under development is a robust pressure-sphere anemometer capable of sampling fluxes of heat and momentum under high winds and heavy rain. Special consideration will be given to the need for self-sufficient operation, ease of deployment, and hardiness in the harsh environment. It will carry its own power source and transmit data via a satellite telephone system to a safe location far from the storm. As a backup it will also store data on rugged flash-memory cards. It is adapted from NOAA's Best Aircraft Turbulence (BAT) probe (Crawford and Dobosy 1992; Hacker and Crawford 1999), but configured as an omni-directional spherical sensor with pressure ports regularly distributed over its surface. The theoretical basis is well-established and underlies the algorithms currently in use with the BAT probe. The 40-cm sphere is constructed of fiberglass-epoxy composite, highly resilient, corrosion-free, versatile, and lightweight. Resistance to rain will be achieved by pneumatically back-flushing all pressure ports.

## 2. APPLICATIONS AND SIGNIFICANCE

The ET probe is designed to address objectives of two research programs that share a focus on understanding high-wind air-surface exchange processes and their influence on hurricanes' intensity, size, and track. The Office of Naval Research sponsors a Departmental Research Initiative named Coupled Boundary-Layer Air-Sea Transfer (CBLAST). CBLAST has identified a critical need for innovative instrumentation capable of measuring surface-layer turbulence in hurricanes. The U. S. Weather Research Program sponsors the Hurricanes at Landfall Program, seeking to reduce the vulnerability of life and property.

The ET Probe will create exciting opportunities for new observations benefitting both programs, first at hurricane landfall, later in the wave boundary layer during hurricanes and other strong winds. Landfall is a critical period when the hurricane undergoes rapid change and inflicts particularly severe wind damage. Measurements facilitated by this new probe directly address the large gap in knowledge of boundary layer structure and surface fluxes during this period.

## 3. ET PROBE DESIGN

The basic design goal is to develop a simple, low-cost probe which is robust, easy to calibrate, and accurate for high-frequency eddy-flux applications. The probe must be easily mounted and must operate in an environment of salt, heavy rain, and high wind.

The pressure-sphere design has proved rugged in airborne applications (Brown et al. 1983; Crawford and Dobosy 1992). Resistance to rain and salt can be provided in several different ways. Since dynamic pressure increases as the square of wind speed, the device becomes more sensitive with increasing wind. The mathematical expressions relating the pressure distribution to the direction and speed of the incident flow are simple and well-validated. Thus, calibration of the probe need only consider the pressure sensors themselves. Airborne experience shows extensive wind tunnel calibrations of the whole system to be unnecessary. The probe's small size, light weight, and low power requirements allow flexibility in deployment in harsh environments with questionable power availability.

### 3.1 Theory of Operation

Wind velocity is most conveniently measured by pressure sphere in terms of its speed $U$, with two angles, elevation $\alpha$, and azimuth $\beta$, giving its direction. From these, one determines the rectangular components of the wind velocity through the usual coordinate transformation.

$$u = U \cos\alpha \cos\beta \tag{1}$$

$$v = U \cos\alpha \sin\beta \tag{2}$$

$$w = U \sin\alpha \tag{3}$$

The speed $U$ of the incident airflow is determined by solving

$$q = \frac{1}{2}\rho U^2 \tag{4}$$

where $q$ is the dynamic pressure, and $\rho$ is the local density of the air. Dynamic pressure is the difference between the pressure at the stagnation point, where the flow strikes the sphere directly, and the ambient pressure, far from any flow disturbance. The set (1) - (4) plus the equation of state are solved for the three components of wind, yielding the ambient pressure and temperature as byproducts. Five independent measurements are required.

The dynamic pressure and the angles $\alpha$ and $\beta$, which locate the stagnation point, are found from the distribution of pressure over a sphere in potential flow

$$p_\gamma - p_s = q\left(1 - \frac{9}{4}\sin^2\gamma\right), \tag{5}$$

where $p_\gamma$ is the pressure on the sphere's surface at angular separation $\gamma$ from the stagnation point. The ambient pressure $p_s$ and dynamic pressure, represent the strength of the incident flow. Applicability of (5) to fully turbulent flow for $\gamma < 60°$ has long been established (Schlichting 1968). Pressures $p_\gamma$ are measured at $m$ known locations on the sphere, the measurements identified as $p_{i\gamma}$, $i = 1,..., m$. Angles $\gamma_i$ between point $i$ and the stagnation point of the incident flow are unknown, as are $q$ and $p_s$.

Solving for these unknown quantities is facilitated by recasting (5) as

$$p_{i\gamma} = \frac{9}{4}q(\mathbf{n}_{i\gamma}\bullet\mathbf{n}_0)^2 + p_s - \frac{5}{4}q \tag{6}$$

Here $\mathbf{n}_0$ and $\mathbf{n}_{i\gamma}$, $i$=1, ..., $m$ are outward-normal unit vectors on the sphere. They are located at the (unknown) stagnation point and at the $m$ points, fixed and known, where pressures $p_{i\gamma}$ are measured. Note that $\mathbf{n}_0 \bullet \mathbf{n}_{i\gamma}$ is the cosine of $\gamma_i$. Taking a difference between pressures measured at two points eliminates the unknown ambient pressure $p_s$ (and, incidentally, the $5q/4$ term). The remaining unknowns are $q$ and the two angles, α and β, which locate $\mathbf{n_0}$ on the sphere. These three quantities may be found from three independent pressure differences $\Delta_i p_\gamma$, $i = 1, 2, 3$ among four ports at known positions on the sphere. The specific algorithms depend on the configuration of the ports, and may vary with conditions. Adding measurement of air temperature and of absolute pressure at one of the four ports allows determination of ambient pressure $p_s$ and of density ρ for wind speed from (4).

In the process, ambient temperature and pressure are made available as well, for computation of turbulent heat flux and other terms of the turbulent kinetic energy budget (Stull 1988). In our airborne applications we use nine pressure ports. This provides considerable redundancy in the measurements at the expense of a restricted acceptance angle. A small acceptance angle is not limiting in airborne applications.

For the omni-directional sensor, we are reformulating the algorithms from the first principles given above. Initially we will set ports every 36° around the horizontal great circle of the sphere (i.e., equator). Pressure differences will be sensed between adjacent pairs of these ten ports, with every second port also sampled by an absolute pressure sensor. These measurements will provide information on the azimuth angle β and on the dynamic pressure. Two additional rings of ports around horizontal circles (i.e., latitude) at 18° above and below the equator will give the elevation angle α. The final design may be modified from this.

If we were seeking maximum sensitivity, we would locate the upper and lower ports at ±45° from the equator. There is, however, a tradeoff between the sensitivity and the acceptance angle. With 45° spacing, the angle of attack may be only ±15° before the angular separation from the more distant port exceeds the 60° limit of applicability. With 18° the limits are ±42°, though the capacity of the pressure sensors imposes more severe limits than this. Sensitivity as used above is in any case less important with the high wind speeds involved.

In contrast to a sonic anemometer, the pressure-sphere system functions increasingly well as the wind speed increases. Stronger wind increases the strength of the pressure field's pattern over the sphere, allowing it to be more readily sampled. Stronger wind also increases the Reynolds number, ensuring fully-developed turbulence over the sphere's surface, a requirement for validity of the theory.

### 3.2 Mechanical/Electrical Design

Our aircraft BAT probes can readily be configured to measure incident flow well beyond 100 m s$^{-1}$ in flight. (Crawford and Dobosy 1992; Hacker and Crawford 1999). The ET probe will be a full sphere, able to accept winds from any azimuth, and containing all necessary sensors. The current port arrangement, described in the previous section, will use twenty differential pressure sensors, and five absolute sensors.

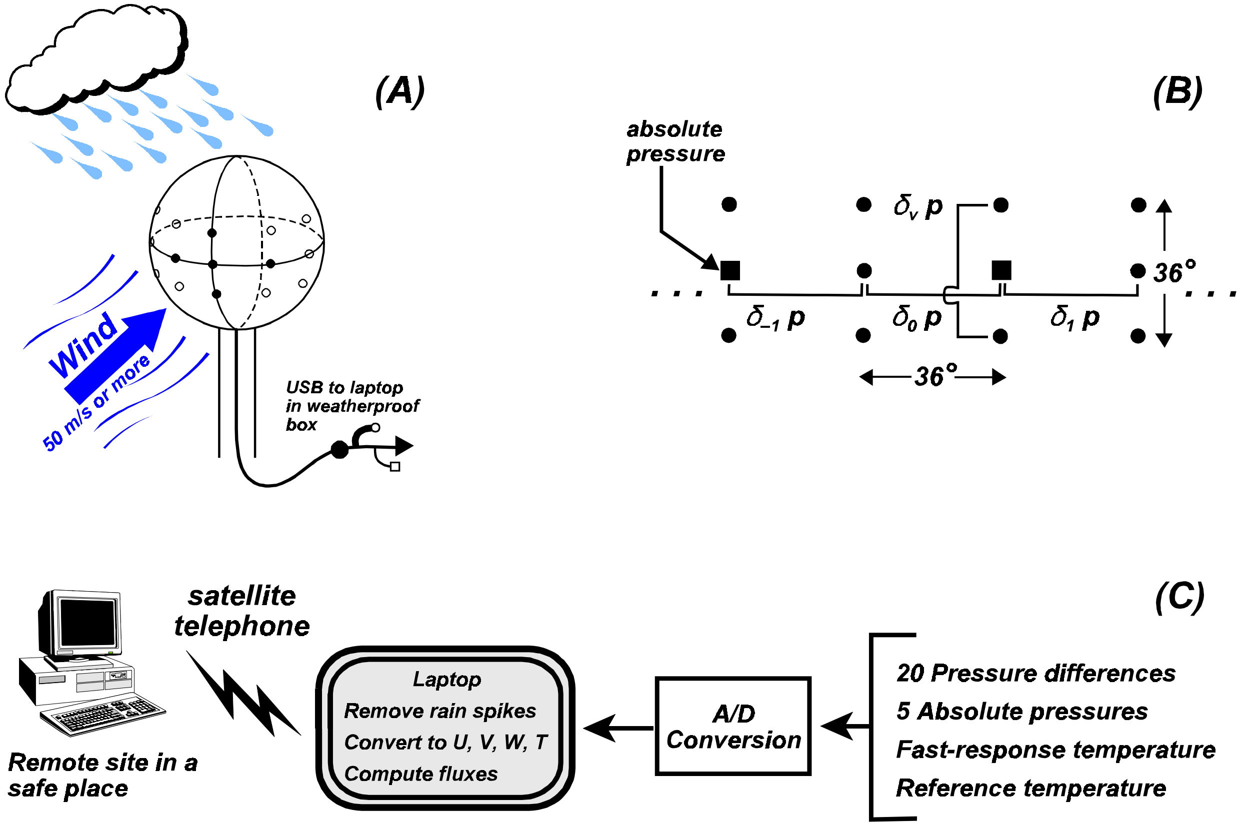
A prototype is under construction. At this writing the design of many features is still in development. Such features will be discussed in the future tense. The figure sketches the concept of the probe. The sphere is constructed of fiberglass-epoxy composite, as used in the BAT probe. This material is highly resilient, corrosion-free in salty environments, versatile, and lightweight. Its 40-cm diameter houses the necessary sensors and maintains sufficiently high Reynolds numbers to ensure turbulence. To avoid fouling by spray and rain, we will back-flush all pressure ports. Back-flushing has proved successful in similar designs (e.g., Oost et al. 1991). Pressure spikes due to raindrop strikes will be mitigated by software rejection techniques during the data reduction.

Modern solid-state pressure sensors have small size, low cost, fast response, and high reliability. All of these characteristics are necessary for our application. A ±12 mb range for differential pressure is appropriate for wind velocities and turbulence up to 50 m s$^{-1}$. Sensors having a range of ±50 mb will handle winds up to 100 m s$^{-1}$, sufficient for a hurricane of category five. In general, the solid-state sensors have good repeatability, low hysteresis (0.25%), and inherently very low noise.

Since the pressure differences increase with the square of the wind speed, the probe becomes more sensitive to fluctuations as the wind speed increases. This is beneficial for a high-wind probe, but becomes problematic for light wind measurement. A practical lower limit for the mean wind speed appears to be about one fifth of the maximum measurable. At this lower limit the dynamic pressure is 4% of the full scale of the sensor. Thus, an error of 0.25% of full scale is 6% of the dynamic pressure and a considerably higher fraction of the pressure differences from which the wind direction is determined. An important design goal is to expand as much as possible the useful range of mean wind speeds. Using sensors having two different ranges, as noted in the previous paragraph is one approach. We are also considering alternative port arrangements, and experimental protocol specifications, that may include use of other types of instruments for that portion of the storm in which the mean winds are too light for the ET probe.

Temperature will be measured by thermistors attached to a port or set of ports at the bottom of the sphere. This orientation is normal to the incident flow, affording protection from flying water or sand. It has the additional advantage of being approximately at ambient pressure, not elevated by impact of high-speed air. Additional protection may be provided by baffles or other structures, if necessary. A fast-response sensor will track the temperature fluctuations for flux calculations, while a low-drift sensor will serve as a reference for absolute temperature measurements.

The temperature and pressure sensors reside on custom-designed circuit boards, directing their analog output to two commercial 16-channel data-acquisition modules. These modules digitize the signals to 16-bit resolution, taking up to 3000 samples per second per channel (3 kS/s) from as many as 32 channels. The high sample rate and high precision (1 part per 64K) virtually eliminate alias components and provide accurate reporting of both high and low pressures and temperatures. The digital signal passes to a relatively inexpensive laptop computer through a USB interface. The laptop computer for data acquisition and processing will




**ET probe concept:** A. General appearance. B. Schematic of port arrangement and pressure measurement. Absolute pressure, along with pressure difference, is measured at squares. Vertical pressure differences skip the "equator", reducing the required number of sensors. C. Schematic information path from sensors in hurricane to receiver in safe place.

be housed in an enclosure designed to protect against wind-blown dust, rain, and splashing salt water (National Electrical Manufacturers Association, type 4X) located below the spherical probe in a protected place. A satellite telephone in the enclosure will normally transmit the processed output to a remote site in a safe location. The computer will also record locally all raw (50 S/s) and derived data on a high-capacity flash-memory card. This allows postprocessing and provides backup if communication is lost.

### 3.3 Operational Software

Software to record reliably the high volume of measurements, correctly tagged with their precise time, is fundamental. The 3 kS/s signal from each channel will be filtered and subsampled, probably at 50 S/s to be stored as alias-suppressed raw data for flexibility in postprocessing. However, an important additional goal is real-time availability of meteorologically relevant information, including fluxes and spectra. Mathematical algorithms are being developed, from the fundamental principles stated in Section 3.1, to determine the incident wind from the measured temperatures and pressures. Since the theory is straightforward, the primary development focuses on optimization. The objective is to use the fewest sensors to provide the required accuracy. In our aircraft experience remarkably little tuning has been necessary to adjust the ideal theory to the actual device. One important new issue is the influence of rain. Though the pressure ports' diameter is 0.1 mm, occupying a tiny fraction of the surface area of the sphere, the heavy rain will guarantee strikes. A strike directly on a pressure port will appear as a spike. On detecting a spike in the 3 kS/s signal, we may select a alternate port, if we choose to provide them, or we may remove the spike mathematically.

The time series of wind and temperature measurements will be ingested by software adapted from our long-standing deployments of boundary-layer instrumentation on towers. This software computes the covariance matrix among the three wind components and temperature, providing estimates of fluxes of momentum and heat. Also computed are the power spectra of temperature and wind components. Additional statistics can be determined as appropriate for other purposes such as estimating stress on structures.

## 4. TESTING AND RESEARCH DEPLOYMENT

Recognizing the general acceptance of sonic anemometers for high-quality turbulence measurement, we plan operational intercomparisons between the ET probe and standard sonic anemometers as an important part of the acceptance tests.

Initially we plan to deploy three to five probes during the 2002 hurricane season on a shoreline in advance of hurricane arrival. We are developing a collaboration with NOAA's Hurricane Research Division (HRD) to draw on HRD's experience with safe and effective operations. Stationary installation simplifies logistics, allowing multiple-unit deployment anywhere a hurricane may land. Multiple-unit deployment increases the likelihood of observing the maximum winds, provides additional information on the hurricane's horizontal structure at landfall, and gives redundancy.

The necessary design tasks to meet this goal are well defined and understood. The new challenge lies in extending our proven BAT probe design to omnidirectional operation in heavy rain. However, we are convinced that this is a tractable development task.

The difficulty of sampling fluxes of heat and momentum under high winds and heavy rain has limited understanding of the atmospheric boundary layer beneath a hurricane. The ET probe's rugged design, fully autonomous operation, and ability to transmit wind and turbulence information in real time to remote locations are important assets in such an environment. Storage of raw data on flash-memory cards allows additional post-processing and provides backup if communication is lost. We expect this new system to facilitate greatly the understanding of boundary-layer dynamics during hurricanes and other severe weather events.

## 5. ACKNOWLEDGEMENTS

This work is supported under a contract from the Office of Naval Research (N00014-00F-0511) under the Coupled Boundary Layer Air-Sea Transfer (CLAST) Departmental Research Initiative (DRI) and by NOAA's Office of Oceanic and Atmospheric Research (OAR).

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