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A REVIEW OF REMOTE-SENSOR POTENTIAL FOR WIND-ENERGY STUDIES

By
William H. Hooke

MASTER

March 1981

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FOR WIND-ENERGY STUDIES

By

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March 1981

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SUMMARY

This report evaluates a number of remote-sensing systems such as radars, lidars, and acoustic echo sounders which are potential alternatives to the cup- and propeller anemometers routinely used in wind energy siting. The high costs and demanding operational requirements of these sensors currently preclude their use in the early stages of a multi-phase wind energy siting strategy such as that recently articulated by Hiester and Pennell (1981). Instead, these systems can be used most effectively in the lattermost stages of the siting process--what Hiester and Pennell (1981) refer to as the "site development phase," necessary only for the siting of large wind-energy conversion systems (WECS) or WECS clusters. Even for this particular application only four techniques appear to be operational now; that is, if used properly, these techniques should provide the data sets currently considered adequate for wind-energy siting purposes. They are, in rough order of increasing expense and operating demands:

- optical transverse wind sensors
- acoustic Doppler sounders
- time-of-flight and continuous wave (CW)
Doppler lidar
- frequency-modulated, continuous wave (FM-CW)
Doppler radar.

Not all these instruments are presently commercially available. While the first two are, the latter two are not. Nor can such instruments necessarily be operated as simply, as reliably, or as economically as their in situ counterparts. Although in some instances this is the case, for the most part, these remote sensors are more expensive and demanding in their operating requirements than the most rudimentary in-situ capability for this siting phase (which for purposes of discussion can be taken to be a single tall tower with three

anemometers, mounted respectively at the bottom of the rotor disk, at hub height, and at the top of the rotor disk). Neither will the data sets obtained by these instruments necessarily be entirely free of shortcomings. In some cases, it is possible that the data may be biased as a result of variations in system performance under different meteorological conditions. However, it appears that these shortcomings could be tolerated in siting studies.

Despite these caveats, the use of remote-sensing systems in wind-energy applications may be viable in the next five years, if not now. Some of the instruments can operate virtually unattended for extended periods. The cost of their operation, while sometimes high, often falls within the rather large dollar limits determined by cost-benefit analyses to be available for site surveys, particularly for the larger WECS systems and WECS clusters. In addition, remote-sensing systems may prove quite useful, perhaps essential, in the development of certain specialized data sets for WECS design and for the advancement of WECS technology generally. As user requirements on wind-energy data sets become more stringent, as inflation increases the cost of conventional siting methods, and as improved technology reduces the cost of remote-sensing alternatives, these should continue to look increasingly attractive.

This report summarizes these findings. It describes briefly the principles underlying the operation of remote-sensing systems and discusses their advantages and limitations for wind-energy applications. The emphasis is on siting but some material on design work is included. Future data needs for wind-energy siting and design are projected and compared with the capabilities of the new instruments. Some lines of research and development that could be fruitfully pursued in order to increase the effectiveness of remote-sensing systems in wind-energy applications are indicated.

The views of several members of the remote-sensing community representing both the public and the private sectors were solicited to aid in preparation of the report; their responses are presented, essentially unedited, in an

appendix. A final appendix contains an extensive bibliography to published literature in remote sensing.

While the report provides no pat formulas for decision making, it does supply information that the Department of Energy, the Pacific Northwest Laboratory, and potential users will need to make intelligent, informed choices in their allocation of research dollars and in their selection of meteorological instrumentation for wind energy siting and design.

I. INTRODUCTION

Wind-energy siting is a methodology in its infancy. Until relatively recently, there have been few generally accepted procedures for executing a siting survey; instead there have been primarily rules of thumb. A number of these can be found in the Proceedings of the Conference and Workshop on Wind Energy Characteristics and Wind-Energy Siting 1979, held June 19-21, 1979 in Portland, Oregon, sponsored by the United States Department of Energy and the American Meteorological Society, and coordinated by the Pacific Northwest Laboratory. However, Hiester and Pennell (1981) have recently completed a major handbook on the siting of large wind turbines that assimilates and codifies meteorological aspects of the siting problem, and articulates a wind-siting strategy in some detail.

The Portland Conference and the Hiester and Pennell work bring out two points rather emphatically. First, existing data bases, originally developed for other purposes, such as archived data from the National Weather Service of NOAA or from the Federal Aviation Administration, are inadequate except as tentative guides in the very earliest stages of wind-energy resource assessment and the site selection process. Final site selection requires on-site data collection (see, e.g., Barchet and Elliott, 1979; Ginosar et al., 1979; Hiester and Pennell, 1979, 1981). Secondly, requirements for wind-energy siting studies are becoming increasingly demanding. Climatological data solely on mean surface winds, never considered very satisfactory, are diminishing in perceived utility. Demands for more detailed information on vertical shear, horizontal structure, gustiness and turbulence, and directional variability of the wind are increasing (e.g., Hiester and Pennell, 1979, 1980; Pennell, 1979a, 1980). Similar problems apply to the data required for WECS design (e.g., Connell, 1979). These trends are likely to continue.

Thus, although the most rudimentary in-situ sensing system used in siting studies of the past — a propeller- or cup anemometer on a tall mast linked to a data acquisition system recording one-hour averages of wind speed and direction and perhaps variances in these parameters — may have satisfied yesterday's view of WECS data requirements, there are very real questions as to whether the same system can adequately address tomorrow's needs. For example, Pennell (1980) points out that gathering information on wind shear across the WECS rotor disk will require wind-speed and direction data at not one, but three levels (the bottom and top of

the rotor disk as well as hub height), and at data rates of 0.5 - 1 Hz. Earlier, Pennell (1979b) had cited a need for data from arrays of towers, each instrumented at several levels, in order to estimate the mesoscale variability in temporal fluctuations in power output characterizing WECS clusters. Other participants in the Portland Conference, addressing aspects of WECS design, emphasized their interest in new kinds of turbulence data, such as the turbulence statistics actually experienced by the slowly revolving rotor, as contrasted with turbulence properties monitored by a fixed point sensor. It is widely recognized that mean flow and turbulent conditions experienced in the wake of a WECS system must be known in order to optimize the performance and economics of WECS clusters. Moreover, as a result of current DOE programs to build and test large-scale machines, such as the MOD-0, MOD-1, and MOD-2 series, there will be significant advances in our understanding of WECS performance and WECS failure modes over the next five to ten years. These tests should greatly clarify precisely which aspects of boundary layer airflow are most threatening to WECS operation and survival. In light of these anticipated advances in our knowledge, and given the long lead times required for planning and executing site evaluations (most appropriately measured in years rather than months), it is likely that those field studies contemplated today will have to archive fairly detailed data on site airflow in order to be judged adequate for performance evaluations and design decisions by the time of their completion.

Meeting the new data requirements implies radical increases in siting costs, particularly if conventional techniques are to be used. Multiple towers, multiple instruments on each tower, increased precision, responsiveness and sophistication of each instrument on each tower — these not only represent proportionately increased costs themselves, but require more sophisticated data processing and archiving systems to digest their outputs. This prospect has prompted a search for alternatives to these conventional methods for acquiring the data, including relatively exotic possibilities such as substitution of laboratory and numerical modeling for the field data themselves.

Remote-sensing systems provide another set of alternatives. As used here the term does not refer to satellite and aircraft photographic techniques for inferring wind climatologies from a careful examination of vegetation, snow cover, topographic and other features, as discussed by Hewson et al. (1977), Wade and Hewson (1979), or Rosenfeld and Maule (1979), and reviewed by Hiester and Pennell

(1981).. Instead the term denotes highly-diagnostic tools such as radars, lidars, and acoustic echo sounders. These offer a number of potential advantages relative to their in-situ meteorological monitoring counterparts. As Little (1972) points out, often a single device can

- obviate the need for a number of expensive towers or airborne platforms,
- monitor conditions in a large volume of the atmosphere,
- provide excellent spatial and temporal resolution throughout the volume of interest, and
- yield line-, area-, or volume averages more representative of prevailing conditions than point measurements.

In short, while the cost of a single remote sensor may be quite large compared to the cost of a single anemometer, its cost may be only somewhat larger than the cost of the anemometer plus the tower on which it must be installed. Also, because the incremental costs associated with monitoring the airflow at additional points distributed both horizontally and in height over the terrain of interest may be quite small for the remote-sensing system (requiring perhaps increased power to extend the usable range or modifications to the scanning procedures), remote sensors may prove to be quite cost effective compared with extensive arrays of towers and anemometers required to develop the equivalent data set.

Although these advantages are available in principle, they often fail to be achieved in practice for either technical or economic reasons. Accordingly, this study critically examines remote-sensor potential for wind-energy studies. In the spirit of the Hiester and Pennell siting methodology itself, it develops a framework which those responsible for WECS siting can use to make intelligent choices of wind-siting monitoring equipment. The report specifically examines such aspects of equipment performance as

- basic physical measurement capabilities, including range, velocity resolution, accuracy, spatial and temporal sampling, and all-weather operation,
- maintenance requirements,
- operating requirements, including power, environmental protection, installation, and training and expertise required for operation, maintenance, and servicing, and
- capital and operating costs.

Measured against the first of these standards, it appears that four techniques, if used properly, might provide data sets adequate for wind energy siting. They are

- acoustic Doppler sounders,
- FM-CW Doppler radar,
- time-of-flight and CW Doppler lidar, and
- optical transverse wind sensors.

Of these, only the acoustic Doppler sounders and the optical transverse wind sensors are available commercially at this writing. These also feature relatively simple and reliable operation. The optical wind sensors are inexpensive relative to conventional anemometers, but are most useful only for certain favorable topographies — primarily canyons. Costs for acoustic Doppler sounders are comparable to the costs of several anemometers plus a single tall tower (say 120-150 m in height). By contrast, the FM-CW Doppler radar and the lidar systems exist only as one-of-a-kind prototypes, primarily in government laboratories, are relatively (though possibly not prohibitively) expensive, and require substantially more training for operation, maintenance, and troubleshooting.

All these instruments provide, or could provide, if interfaced to appropriate data acquisition systems, considerable turbulence information to supplement the

mean wind speed data. However, at the small scales of turbulence this information is available primarily in the form of data on C_N^2 , the refractive index structure parameter (a measure of the turbulence intensity as reflected in refractive-index fluctuations). At present these can be related only indirectly to the turbulence statistics of interest to the WECS designer. Some information is additionally available from pulse-to-pulse variability in the Doppler shifts (and spreads in the Doppler shifts) of echoes detected by the radar, lidar, and acoustic-sounding systems. However, this is limited in spatial resolution by the pulse volume, typically some 10 m or more in linear dimension, and in temporal resolution by the pulse repetition frequency (which can be quite rapid for the optical or radar techniques, but is limited to 0.5-0.2 Hz for the acoustic methods). Thus, these particular remote sensors do not constitute a panacea for the need for turbulence information.

Moreover, it would appear a priori (although this has yet to be verified or denied by field tests) that the techniques may not be entirely free from observational bias as a result of outages that may occur preferentially under certain meteorological conditions. While acoustic Doppler sounders can be configured to measure velocity turbulence as well as thermal fluctuations, and thus operate effectively in near-neutral conditions, their operation is adversely affected by wind noise at the antennas, making data unreliable at wind speeds greater than 30 m s^{-1} . Optical techniques may be similarly vulnerable to the effects of high winds because windblown particulates may abrade delicate optical surfaces to the point they become unserviceable. Radar may be somewhat vulnerable, since the radar antennas pose a large cross section to the wind, precluding scanning under extreme wind conditions. And under certain meteorological conditions, FM-CW Doppler radars may fail to find humidity-associated refractive index fluctuations of amplitude sufficient for their operation. (On behalf of the remote sensors, however, it should be noted that in-situ anemometers have been known to fail under similar high-wind conditions.)

The four techniques cited above each provide, at best, only a single vertical profile of wind above the sensor; they do not provide area or volume coverage. In fact, the transverse wind sensors provide only line-averaged transverse winds; some profile information can be retrieved, as described in Section 3.4, but only by substantially augmenting the basic operating configuration. To study fully all aspects

of the spatial structure in the airflow over a broad area requires two or more pulse lidars or radars in order to provide all the wind components. Such multiply-coordinated, pulsed systems are more expensive and demanding in their operation; however, the equivalent network of in-situ sensors is correspondingly more costly. Thus, while pulsed radars and lidars may currently be uneconomical for siting studies, they may prove useful in design experiments, examining spatial structure of airflow over rough terrain, or of wakes in the lee of large WECS units. For these latter studies data gathered for relatively brief periods, perhaps the order of weeks, might be satisfactory.

Moreover, in five to ten years, the economics of wind energy siting may be more favorable to remote-sensing systems. WECS siting and design requirements continue to become more stringent. Five years from now, the connection between turbulent refractive-index fluctuations and the turbulent wind-gust data pertinent to WECS design will likely have been clarified and pinned down. Lidar and FM-CW Doppler radar systems may be available commercially. Also, we can expect general design improvements and cost reductions in the "price tag" of most remote sensors in response to advancing technology. Their operation will be correspondingly simpler. By contrast we can anticipate that the costs of in-situ sensors, for which the pace of technological improvement is substantially slower, will rise.

Some research and development would greatly improve the effectiveness of remote-sensing equipment for wind-energy applications. Six specific areas are extremely important:

- Operational "hardening" of research prototype instruments to the point where they can be operated by relatively untrained personnel with minimum attention. The hardening required includes mechanical systems, optical systems, and electronics.
- Studies relating parameters deduced from remote-sensing systems (such as C_N^2 , C_T^2 , C_V^2 , the spectral width of the Doppler-shifted echo returns, or ϵ , the rate of mechanical energy dissipation in the turbulence) to properties of the turbulence pertinent to WECS design.

- Improvement of filtering and computer software techniques for reducing the effects of ground clutter and permitting the pulsed remote-sensing systems to operate at low elevation angles out to long ranges.
- Reduction of the effects of wind noise and rain on acoustic sounder performance and the effects of precipitation and wind-blown particulates on optical system operations.
- Development of the technology and methodology required for optical studies of the turbulence that would be experienced by a rotating blade.
- Long-term comparison of remote-sensor performance with in-situ sensors in order to better understand and delineate any measurement biases introduced by remote-sensor volume averaging, system failure under certain meteorological conditions, etc. The evaluations of many of these aspects in Section II.3 are currently a matter of surmise rather than firsthand experience.

Table I.1 summarizes remote-sensor capabilities as they bear on wind-energy applications.

Table I.1. Remote sensor capabilities

	RANGE	SPATIAL RESOLUTION	VELOCITY RESOLUTION	ACCURACY	COMMERICAL AVAILABILITY	UNIT COST	DEPENDABILITY	LIMITATIONS
OPTICAL TRANSVERSE WIND SENSOR	1 100m-10km	same as path length in the along-path direction. tens of meters in the trans- verse direction. 2	$\pm 0.01 \text{ ms}^{-1}$	$\pm 0.1 \text{ ms}^{-1}$	yes	\$2k	little or no maintenance required; unattended oper- ation for long periods of time, limited by data logger	primarily able to measure only line- averaged winds; point measurements available only with difficulty and with limited resolution. For long paths, limited by visibil- ity. Best suited for canyon topography.
ACOUSTIC DOPPLER SOUNDER ∞	20m-500m	20m	$\pm 0.1 \text{ ms}^{-1}$	$\pm 0.2 \text{ ms}^{-1}$	yes	\$50-100k	minimal maintenance required	subject to wind noise at high wind speeds. Does not work well in rain. Slow pulse repeti- tion rates. Lengthy averaging times required.
FM-CW RADAR	10m 10 km (range) 3 km (height)	100m (achieved). 10 m (potentially achievable)	$\pm 0.03 \text{ ms}^{-1}$	$\pm 0.5 \text{ ms}^{-1}$	no	5 \$150k	prototype has operated reliably in numerous field experiments	operation is all- weather for ranges required by wind energy siting application
CW DOPPLER/ TIME-OF- FLIGHT LIDAR	20m-500m	3 10m (at 100m range)	$\pm 0.5 \text{ ms}^{-1}$	$\pm 0.5 \text{ ms}^{-1}$	no 4	5 \$30-100k	prototypes have operated reliably in numerous field experiments	resolution decreases with increasing range

1. refers to optical path length rather than range per se
2. a result of temporal averaging
3. proportional to range squared
4. a commercial prototype exists
5. estimated

II. REMOTE SENSING

II.1 Introduction

The 1960s and 1970s have seen the rapid development of a wide variety of remote-sensing systems for probing the atmosphere. In contrast with in-situ instruments such as anemometers, thermometers, hygrometers and barographs which measure atmospheric conditions at a single point, remote sensors take advantage of interactions between the atmosphere and radio, optical, and acoustic waves to deduce atmospheric conditions, including temperature, humidity, liquid water and particulate content, and winds over wide volumes or areas often far removed from the sensor location itself. Some of the more familiar instruments include radars, laser radars, called variously lidars or laser Doppler velocimeters (LDVs), and acoustic echo sounders, also referred to as echosondes or sodars. Other devices include radiometers and optical transverse wind sensors.

In principle, such devices should be superior in a number of respects for meteorological monitoring, relative to their in-situ counterparts. Little (1972) has pointed out the following advantages:

- Obviating the need for tall towers or aircraft to position the in-situ instruments in the region of atmosphere of interest. This results in cost savings and reduces hazard, such as when the required information is from aircraft glide paths on the approaches to airports, near tall structures such as power-plant stacks or cooling towers, and in regions of violent weather such as thunderstorms or tornadoes.
- Measuring parameters of the atmosphere along a line, or over an area, or throughout a volume, at small incremental costs (associated with sensor power or scanning capabilities and procedures). In-situ instruments can obtain such data only by means of (sometimes quite dense) arrays which are nearly always prohibitively expensive, and which may even severely modify the very flow properties of interest.

- Providing excellent spatial and temporal resolution (again through development of proper scanning capabilities). Stationary in-situ instruments can provide this only when deployed in arrays; airborne instruments are restricted in their sampling by the performance characteristics of the aircraft.
- Measuring a broad range of (sometimes novel) parameters, such as refractive-index structure function C_N^2 , or its thermal and velocity counterparts C_T^2 and C_V^2 . Sometimes these parameters may be directly related to atmospheric properties of interest, such as the turbulent eddy dissipation rate ϵ , whose estimation from conventional in-situ data can be quite involved.
- Not modifying the flow field and/or the specific parameter being measured. This problem is particularly serious with tall-tower and aircraft platforms, which necessarily introduce major perturbations in the flow in their immediate vicinity.
- Providing line-, area-, or volume averages of atmospheric quantities. These averaged values may often be more representative of atmospheric conditions over a region than the corresponding point samples, which are vulnerable to idiosyncracies of the instrument site selected.

While Little was careful to point out in 1972 that many of these potential advantages had yet to be realized in practice, and while that statement remains somewhat true today, a number of remote-sensing techniques have progressed to the point of useful application, both in research and operations. For example, acoustic sounders are now manufactured commercially by several competing firms and find use in a wide range of air-quality applications, such as monitoring inversion height and boundary-layer wind profiles, and in boundary-layer research where they provide not only flow visualization but also quantitative data. Optical transverse wind sensors have been tested by the military for use in measuring

crosswinds affecting artillery and tank fire. Microwave radiometers measure integrated atmospheric liquid water content in support of National Weather Service operations at the Denver Weather Service Forecast Office. A hybrid radar/acoustic sounder system operated at Dulles International Airport during the late 1970s to monitor low-level windshear under all-weather conditions (Hardesty et al., 1977). Under development now are satellite lidar systems that should be able to monitor global tropospheric wind fields with 300-km resolution, and a remote-sensing system including both radar and radiometric elements, which may replace the rawinsonde before the end of this century. Remote sensors are finding new applications continually.

In light of these advances in closely related fields, the question naturally arises as to whether remote sensors might not play a similarly useful role in wind-energy studies. An answer to this question first requires defining data needs for both siting and design. This is the task of Section II.2, which provides a consensus view within the community of these needs, indicates some of the uncertainty and controversy surrounding these, and anticipates trends in wind energy data requirements in response to hands-on experience gained at national field sites. Siting data requirements and design data requirements are treated separately in Sections II.2.1 and II.2.2 respectively. While this distinction is somewhat artificial in the sense that the two are necessarily intertwined, they are somewhat different in nature, and require — or permit — different approaches to their resolution. Finally, Section II.2.3 describes conventional in-situ techniques in use now for wind energy siting, indicating both outputs and costs. These figures provide a crude yardstick for evaluating remote-sensor performance.

This discussion lays a foundation for the descriptions in Section II.3 of the various remote-sensing techniques available today. We begin in Section II.3.1 with radar, which is perhaps the most familiar, and which serves well to illustrate a number of remote-sensing techniques common to all the devices. Section II.3.1.1 treats single- and multiple pulsed systems; then FM-CW Doppler systems are discussed in Section II.3.1.2. Other, more exotic systems are mentioned briefly in Section II.3.1.3.

Section II.3.2 deals with lidars. Relatively new arrivals on the remote-sensing scene, these systems offer advantages of resolution, and in some cases cost, over their radar counterparts, although the technology is not so uniformly well developed at optical frequencies as it is in the radio region of the electromagnetic wave spectrum. Section II.3.2.1 deals with pulsed lidar systems, which are functionally equivalent to the pulsed radars. Section II.3.2.2 describes the less expensive CW Doppler lidar technology, which has already been used for various boundary-layer applications, including measuring changes in planetary boundary layer (PBL) wind fields over the ocean and over land, monitoring airflows in the wake of buildings, and determining dust-devil and waterspout rotational velocities. Section II.3.2.3 describes time-of-flight lidar techniques for wind measurement.

Section II.3.3 treats acoustic methods of wind measurement. The approaches used here are equivalent conceptually to those used in pulsed radar and lidar systems. Both monostatic and bistatic operating geometries are used in the commercially available systems and research prototypes; these are both discussed.

Section II.3.4 treats optical measurements of transverse winds — winds normal to an optical line-of-sight path. The systems used in such measurements are quite inexpensive relative to the remote sensors described above; so cheap, in fact, that they are comparable in cost to some of the more sophisticated in-situ instruments.

Each separate discussion begins with an outline of the principles governing sensor operation, which leads rather naturally into a discussion of sensor performance, addressing such questions as: What is the system's range? Velocity resolution? Accuracy? Spatial and temporal sampling capability? Is it an all-weather device or does it fail to operate under certain weather conditions? This latter aspect is quite important in the wind-energy siting application, as a failure to operate under all weather conditions, including clear air, heavy precipitation, high-wind conditions or near calm may lead to significant biases in the resulting data set, perhaps severely degrading the system's potential usefulness. The current stage of development of each technique is also considered. Is the instrument available commercially? Or does it exist only in the form of research prototypes? If so, how many years are we away from commercial availability?

System operating requirements are also treated, responding to questions such as: What power is required? What environmental protection is needed? How costly are the automatic data processing (ADP) hardware and software required for the data processing and archiving? How easy or complicated is the equipment to install, operate, or maintain? Must the operators be highly trained? Can the system be operated unattended for long periods? What are the overall costs associated with the sensor, including capital, installation, operation and maintenance?

Section II.4 summarizes the conclusions and recommendations. Section II.4.1 indicates which systems look adequate now for application in wind-energy siting and design. Section II.4.2 attempts to forecast how remote-sensing capabilities are likely to evolve over five or ten years' time in response to improving equipment capabilities. Finally, Section II.4.3 lists a number of research efforts that could, if implemented, increase the effectiveness of remote sensors in wind-energy applications.

Section II.5 contains basic references, i.e., journal papers, articles, reports and conference proceedings that are referred to in the report proper. Appendix B contains a more complete bibliography for those who may wish to dig deeper into some specialized aspect of the field.

Members of the remote-sensing community responded to a brief questionnaire mailed to them during preparation of the report. Their responses are incorporated, essentially unedited, in Appendix A.

II.2 Wind Data Needed for Wind-Energy Resource Development

Wind data required for wind-energy resource development fall into two classes. The first encompasses those data required for assessment or estimation of the amount of wind energy or power extractable either at specific locations or over wide areas. The second class encompasses those wind properties that determine WECS design.

The two categories are defined and discussed in Section II.2.1 and II.2.2 respectively. Section II.2.3, considers briefly the basic in situ alternative currently in use for developing wind-energy data sets. This discussion lays the groundwork necessary for the assessment of the various remote-sensing systems that follows in Section II.3, and for the conclusions found in Section II.4.

II.2.1 WECS Siting Data Requirements

Wind-energy siting is a non-trivial exercise because of the spatial and temporal variability of the wind resource, which in turn arises because of global and local meteorological processes, topography, and seasonal and diurnal changes in solar heating. Wind characteristics vary not only horizontally but also vertically; there is substantial spatial structure in the wind in the height region accessed by WECS systems, particularly the larger ones. Prior to 1980, there were few formally articulated siting strategies for dealing with this variability. Recently, however, Hiester and Pennell (1981) have synthesized existing strategies into general siting methodology. While this methodology may change in detail over the next decade it is unlikely to alter in its broader aspects. Several aspects of the Hiester and Pennell strategy merit attention here.

First and foremost, existing data bases, such as the wind climatologies routinely archived by NOAA's Environmental Data and Information Service (EDIS) in Asheville, NC, are inadequate for wind energy siting. (There are many reasons for this, which stem primarily from the fact that national demands for wind information were far less stringent at the time that most of the present measurement and archival procedures were instituted. A number of inadequacies were documented during a recent workshop [Melita, 1979].) Thus on-site wind studies are generally required.

However, the expense of on-site data collection, by whatever means, is enormous, both from the standpoint of the capital costs and the implicit costs associated with the time required to carry out on-site studies. This time amounts to a minimum of one year in order to define the seasonal variations, and may extend to several years in order to delineate the interannual variability. Such studies are most economically carried out at a relatively few especially promising sites

which have themselves been selected by some other, more inexpensive screening process.

The result is a phased or staged strategy. In fact, Hiester and Pennell distinguish between two distinct strategies: (i) wind prospecting, in which potential sites are viewed initially with a completely open mind, contrasted with (ii) evaluating a predetermined site. The first approach includes:

- a large area analysis of a region perhaps $2 \times 10^5 \text{ km}^2$ in dimension, seeking promising mesoscale areas within that region perhaps 10^4 km^2 in size,
- a search for promising candidate sites possibly 100 km^2 in size within those mesoscale areas,
- a review of the candidate sites,
- an evaluation of the candidate sites, and
- an identification of the best locations for individual machines on a chosen site.

The latter approach begins with a preliminary evaluation of the wind energy potential; from that point on, the procedures are identical to those in the final two stages of the wind prospecting approach. Hiester and Pennell describe each of these phases in detail.

The high cost of conventional field siting studies has prompted the exploration of a number of alternatives, including the analysis of topographical indicators, biological indicators, and the use of numerical and laboratory simulations. While Hiester and Pennell (1981) review these at length, none of these techniques has yet demonstrated the reliability requisite for the final stages of the siting procedure. Instead these techniques are used to fill in gaps in NOAA climatologies in the preliminary site screening stages.

The final stage of the wind-energy siting process — the so-called site development phase — demands detailed wind measurements for a period of one to several years, at heights extending to the top of the proposed WECS rotor disk. For some machines either currently under development or contemplated this requirement can imply wind measurements to heights as great as 150 m. It is this lattermost phase that concerns us here. Hiester and Pennell (1981) and Pennell (1980) have summarized the data requirements for this phase, which are reproduced below:

- Wind data for energy production estimates are the most critical issue. The required sampling rates may be as rapid as a sample per minute in order to simulate such aspects of machine operation as start-up, shut-down, and yawing to follow wind direction changes, and corresponding machine control strategies.
- Wind direction measurements, as well as wind speed measurements, are required in order to assess directional variability in the wind (which adversely affects both system performance and rotor lifetime) and to properly orient cluster layouts.
- For energy production estimates, wind measurements representative of the flow through the entire rotor disk are needed. For one thing, diurnal characteristics of energy production cannot be determined from surface-level winds. For another, wind shear data across the turbine rotor disk is needed to ensure that the shear does not exceed the design limitations. This requires a measurement at a minimum of three levels: the bottom and top of the rotor disk and at hub height. For this purpose, the data rates required may be the order of 1 Hz.
- For WECS or WECS cluster siting over relatively flat terrain, only minimal spatial sampling in the horizontal may be required. However, for sites featuring substantial topography, a large number of measurements in both the horizontal and the vertical are needed to delineate topographical patterns and variability in the wind.

Conventionally, all these data are obtained by means of propeller- or cup-anemometers mounted on a tall tower or towers.

II.2.2 WECS Design Data Requirements

WECS design data requirements, both those pertaining to equipment survival and those relating to operating performance, remain somewhat ill-defined at this writing, primarily because of a lack of hands-on experience with large machines. The requirements should come in to much sharper focus during the next five years. Even now, however, we know that mean winds, vertical shear in the mean winds, and turbulent fluctuations in both the winds themselves and their shears, are all important factors in WECS design. And there are certain special considerations unique to the WECS design problem — specifically, the properties of turbulence experienced by a rotating blade as distinct from those at a fixed point in space, the properties of WECS wakes, and the influence of terrain on WECS cluster design. Each of these aspects is reviewed in more detail below.

Hourly mean winds and their seasonal and diurnal statistics influence WECS design in several ways. They affect the selection of threshold, or cut-in, or minimum operating wind speeds; they help the designer choose the maximum operating wind speeds; they determine the survival wind speed that the machine must endure. Thresher (1979) considers these aspects of WECS design. Vertical shear in the wind plays a major role since this determines the magnitude of the fluctuating stress the WECS rotor experiences with each revolution. Design interest in vertical shear has led to numerous studies of semi-empirical laws for predicting wind shear (e.g., Spera and Richards, 1979). However, interest also extends to short-term variability of the shear as well, and here power laws are of little aid.

Short-term and turbulent variability of the wind is a major factor in WECS design in general. Turbulent variations in wind speed cause WECS power output to fluctuate and also expose all WECS structural members, including the rotor itself, to a continued flexing, increasing the potential for structural failure. Turbulent velocity variations superimposed on large mean winds lead to the most dangerous conditions the WECS unit must be designed to survive. Turbulent variations in wind direction also affect both power output and system survival. The

larger WECS systems are particularly vulnerable to these deleterious effects. Unlike the smaller WECS units, which slew freely in response to changes in wind direction by means of vanes, the larger machines require yawing servomechanisms which respond only to slow wind direction changes because of the heavy loads involved in the yawing process.

Turbulent properties can be characterized in a wide variety of ways (e.g., Connell, 1979; Kaimal, 1979; Powell, 1979; Kareem et al., 1980) — in terms of turbulence intensity, maximum gusts, or spectra. Length scales and other turbulent properties are alternatively defined either by certain time-honored engineering rules of thumb or by direct measurement of correlation and coherence properties of the turbulence. Each of these approaches has its proponents and adherents; each by itself only partially addresses the design problem, so that in several respects the various approaches are complementary rather than redundant.

An important feature of WECS design is that it involves wind loading on a moving (rotating) blade or airfoil rather than a nominally stationary structure. Connell (1979) has described one approach to synthesizing such turbulence data, using a dense array of anemometers deployed in concentric circles on an array of towers. While practicable, this method is far from ideal, and a search for alternatives is underway. As we shall see in later sections, lidar may offer some particularly attractive and novel options. Another aspect of WECS design of particular interest concerns the character and properties of the airflow in the wake of a WECS unit. These properties help define the optimal configuration of WECS clusters, which involves tradeoffs between the high costs associated with sparse clustering and the power reduction and possible increases in turbulent loading resulting when one WECS lies in the immediate lee of another.

II.2.3 The In-Situ Alternative

Hiester and Pennell (1981) devote an entire chapter to measurements and instrumentation, examining a number of the options available for the in-situ sensors. These alternatives include hot-wire, cup-, propeller-, and sonic anemometers. Apart from sonic anemometry, however, which requires sophisticated electronics as an integral part of the basic instrument, it can safely be said that the cost of

all these instruments is minor compared with the cost of the tall towers required to situate them at the great heights of interest. This cost is a rapidly increasing function of height. The cost of short masts is negligible, but even inexpensive 60-m towers cost in the neighborhood of \$20K, while the 100-m masts used in some siting studies cost \$50K-70K. Installation of the larger towers can be somewhat involved. Instrumentation of the type required to carry out the simplest site development studies described above add perhaps \$10K to \$20K to these costs. By and large, the instrumentation works well; however, it has been known to fail in extreme wind conditions. Shafts bend, or propellers and vanes are blown off. Therefore, even in such simple systems, some maintenance is required. The above estimates do not include the cost of the data archiving systems used in the siting studies — not because these are unnecessary or inconsiderable, but rather because they should be virtually the same whether the data input is an array of anemometers or some other sensors providing the equivalent information.

II.3 Remote Sensor Capabilities

This section — which constitutes the main body of the report — describes the major remote-sensing techniques currently exploited for atmospheric monitoring in both research and operational contexts. This is not a text on remote-sensing per se; hence, a detailed description of the operation of the devices would be inappropriate here. However, to assess the potential of the various instruments for wind-energy siting and design studies does require some background. The text strikes the following compromise; it sketches the basic principles governing the operation of each device, and cites the major review papers and books which can provide deeper insights if needed. (For a more detailed review of remote sensing, the interested reader is referred to Derr [1972].) With the basic principles underlying the operation of each remote sensor in hand, there follows a discussion of its capabilities. These include: maximum and minimum range, velocity resolution, accuracy, spatial and temporal sampling, and ability to operate under a wide variety of meteorological conditions. A detailed investigation of the fundamental limitations imposed on these parameters was not performed. Instead, the report merely indicates capabilities representative of existing instrumentation. In many cases these do in fact reflect underlying limitations of a rather fundamental nature.) The text then considers the stage of development of each

technique, answering questions such as: Are the instruments commercially available? Or do they exist only as engineering protection required; the automatic data processing needed; installation, operation and maintenance; skills demanded of the operating personnel; and costs (capital, installation, operation, and maintenance). Because some of these instruments are engineering prototypes rather than fully operational units, direct operating experience is limited. Thus, to a considerable extent, some of the evaluations below reflect surmise rather than hard fact.

Radar, lidar, acoustic, and optical line-of-sight sensors are considered in turn. Radar (Section II.3.1) provides an appropriate starting point, both because it precedes historically the widespread use of lidar and acoustic echo sounding in atmospheric studies, and because it is the most familiar of the remote sensors. Since the principles governing radar operation can be applied generally to most of the other sensors described here, the introductory material in this subsection is rather lengthier and more detailed than that to be found in the subsections which follow. Lidar (Section II.3.2) operates in ways essentially similar to radar, and so is treated next. Because optical wavelengths are much shorter than radio waves, lidar offers potential monitoring advantages over radar (while at the same time posing some greater technological difficulties). Acoustic techniques are treated in Section II.3.3; these offer the relative advantage of low cost and commercial availability. Optical line-of-sight wind sensors, treated in Section II.3.4, are the least expensive of all. Their principle of operation is substantially different from the other methods described here and limits the usefulness of the technique to certain special topographies, primarily canyons. These occur sufficiently frequently, however, to make the technique particularly attractive; witness, for example, utility interest in the San Gorgonio Canyon east of Los Angeles and the Columbia River Gorge.

II.3.1 Radar

Battan (1973) provides an excellent and highly readable summary of radar applications in meteorology. Two types of radar are of interest to us here. The first is pulse radar, considered in Section II.3.1.1. Pulse radars are expensive,

have high power requirements, and except for the most powerful units, require natural precipitation or artificial chaff for targets. This would appear to preclude their use in wind energy siting studies. They can, however, scan large areas and reveal spatial structures in boundary-layer airflows — capabilities which make them attractive candidates for some of the WECS design studies mentioned in Section II.2.2. Because pulse radar techniques are the oldest historically, and their operation is the most familiar conceptually, they are treated first. Section II.3.1.2 turns to FM-CW Doppler radar. While FM-CW Doppler techniques exist only as a single engineering prototype, they offer clear-air capabilities, small minimum ranges, and relative freedom from ground clutter problems which render the method attractive for wind-energy siting. So-called "pseudo-noise" radars are considered cursorily in the final subsection (II.3.1.3). While these would appear to offer several interesting potential advantages over their more conventional counterparts, these have yet to be realized in practice; thus the technique receives only mention here.

II.3.1.1 Pulsed Radar

The principles of pulsed-radar operation are simple and straightforward. A pulsed transmitter excites an antenna, which radiates pulses of electromagnetic wave energy at radio frequencies. The range of radar frequencies available spans over six orders of magnitude, depending upon the application; for present purposes, however, we are interested primarily in frequencies between 3 and 300 GHz, corresponding to wavelengths between 10 cm and 1 mm. Usually the antenna is designed so that the bulk of the radiated energy is confined to a narrow beam a few degrees wide or less. The pulse propagates through the atmosphere in virtually straight lines at the speed of light in air, c . This is related to the speed of light in a vacuum, $c_0 = 2.998 \times 10^8 \text{ m s}^{-1}$, by

$$c = c_0/n,$$

where n is the so-called index of refraction of the air. The index of refraction depends upon atmospheric pressure, temperature, water vapor content and radio frequency. However, near sea level, a typical value of n is about 1.0003; small-scale structure in n amounts only to some parts per million. Hence refractive

effects, while detectable and important in some cases, can be neglected for purposes of our introductory material here. The radar pulses are typically 1 μ s or less in duration; this corresponds to pulse lengths of 300 m or less. Pulse repetition frequency (PRF) is typically 10^3 Hz; that is, about 1000 pulses are transmitted each second.

When the wave encounters a target, however, it scatters some or all of the wave energy in all directions. Some fraction of the scattered energy is returned to the radar receiving antenna. (As a matter of detail, the receiving antenna may or may not be identical with the transmitting antenna, depending upon the system design. For the radar systems considered here, the antennas are essentially collocated [monostatic operation]. Section II.3.3, which considers acoustic techniques, introduces bistatic systems, featuring separated receiving and transmitting antennas). Electronic measurement of the time delay between transmission and receipt of the echo yields the range of the target. For example, a time delay of 2 μ s corresponds to a total travel distance for transmitted and scattered radar pulses of 600 m; the target range is therefore half that, or 300 m. The antenna beam may be steered either mechanically or electronically to locate all the radar targets within an extended volume under surveillance. These points are illustrated in Figure 3.1.1.

The above concepts find their quantitative expression in the so-called radar equation, which can be written in the form (e.g., Battan, 1973)

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 r^4}, \quad (3.1.1)$$

where

- $P_r \equiv$ the power intercepted by the radar antenna
- $P_t \equiv$ the transmitted power
- $G \equiv$ the antenna gain, equal to the ratio of the power per unit area along the axis of the beam relative to the isotropic value
- $\lambda \equiv$ the radar wavelength
- $r \equiv$ the range to the target

Figure 3.1.1. The principles of pulsed radar operation.

and $\sigma_i \equiv$ the backscattering cross section, equal to the area intercepting the radar beam which, if it radiated isotropically, would radiate the same power in the backward direction as the target scatterer.

Thus, the problem is reduced to that of determining, for different targets, the appropriate cross section σ_i , which depends upon the target size, shape, and electrical conductivity or dielectric properties. As one might anticipate, the history of radar has seen its increasing ability over time to detect ever weaker targets of ever smaller cross section. The first targets to be detected by radar were aircraft, which by virtue of their high conductivity and large surface area scattered considerable radio wave energy. Improved radars, achieving greater peak powers, higher receiver sensitivities, and using higher-gain antennas, made it possible to detect atmospheric hydrometeors: rain, snow, and hail. Such radars are now used operationally by the National Weather Service to monitor precipitating clouds. Further improved versions operating at higher frequencies can detect and monitor clouds in their nascent, non-precipitating phase. Unlike the single, discrete targets such as aircraft, hydrometeor scatterers are distributed; that is, the radar echo consists not of the energy scattered by a single target hydrometeor, but rather the sum of the separate contributions from numerous targets filling the pulse volume. For these targets, the individual cross section σ_i appearing in the radar equation must be replaced by the pulse-volume sum of the contributions from the (n , say) individual scatterers, which can be expressed as

$$\sum_{i=1}^n \sigma_i .$$

Equivalently, one can introduce the so-called radar reflectivity η , defined by

$$\int_{\text{radar pulse volume}} \eta \, d\tau = \sum_{i=1}^n \sigma_i ,$$

where the volume integration is carried out over the radar pulse volume. As the distributed scatterers move relative to one another, the radar reflectivity varies with both position $\underline{r}$ and time t ; i.e.,

$$\eta = \eta(\mathbf{r}, t) .$$

Thus, for distributed targets, the radar equation becomes

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 r^4} \int_{\text{radar pulse volume}} \eta(\mathbf{r}, t) d\tau . \quad (3.1.2)$$

A good deal of research has been devoted to the deduction of hydrometeor properties — number density, size distribution, composition — from the echo returns. Battan (1973) summarizes this work. Atmospheric aerosols also scatter radio waves. Much smaller than a radio wavelength, they behave as so-called Rayleigh scatterers. The backscatter cross section of these small particles can be expressed as

$$\sigma_i = \pi^5 |K|^2 d^2 (d/\lambda)^4 ,$$

where d is the particle diameter and $|K|^2$ is a function of the particle's refractive index. What is of primary interest from our point of view here is that the backscatter depends upon the inverse fourth power of the ratio of the probing wavelength to the particle diameter. For radar wavelengths this scatter turns out to be quite small, although detectable by some very sensitive (and short-wavelength) instruments. For optical wavelengths, the scatter is quite a bit stronger, as seen in Section II.3.2.

The success of the radars in detecting hydrometeors and the unavailability of such natural targets under many meteorological conditions of interest has led to the development of artificial chaff that can be dispersed into the atmosphere and detected by the radars, thereby revealing atmospheric structure and motion. The chaff consists of fine, electrically conducting filaments, cut to one half the radar wavelength. These can be injected into the clear air by means of shotgun shells, small rockets, chaff cutters on board aircraft, or surface-based chaff cutters. During convectively active periods, atmospheric turbulence quickly disperses the chaff throughout the volume of interest, and the chaff cloud can remain aloft for considerable times. By contrast, at night the turbulence intensities are

typically lower, and turbulent mixing is then unable to maintain the chaff aloft against its fall velocity (some 30 cm s^{-1} in calm air).

Up to this point, the clear atmosphere itself has been treated as if it were incapable of producing radar echoes. However, from the very earliest days of radar, installations would from time to time detect echoes from "angels" — echoes of initially unknown origin in apparently clear air. With the passage of time, some of these were found to originate from birds and insects. Some, however, were found to be produced by regions of "strong" refractive index gradients in the atmosphere, which can be identified with air mass discontinuities and their associated turbulence. The word "strong" here is used in a relative sense. As indicated in the beginning of this subsection, the refractive index of the atmosphere exhibits only minor (parts per million) structure; however, this turns out to produce scattering that is detectable. The theory of radar-wave backscattering from refractive-index inhomogeneities in a turbulent medium is quite involved (e.g., Tatarski, 1961, 1971), but one finds that

$$\eta = 0.39 C_n^2 \lambda^{-1/3} \quad (3.1.3)$$

for radar wavelengths within the so-called inertial subrange of a Kolmogorov spectrum of turbulence. Here C_n^2 is the so-called refractive index structure function, related to the mean-square fluctuations of refractive index $\overline{(\Delta n^2)}$ by

$$C_n^2 = 5.20 \overline{(\Delta n^2)} L_0^{-2/3},$$

where L_0 is the outer scale of the turbulence (the largest scale at which the turbulence can be considered isotropic, usually some tens of meters in the earth's atmosphere).

Radar measurement of winds

With the preceding background, albeit sketchy, of how radars detect hydrometeors and atmospheric turbulent eddies in the clear air, we are ready to consider how properties of the radar echo returns permit us to deduce atmospheric wind speeds. The key to such measurements lies in the use of coherent radars that can monitor phase of transmitted and received pulses. Most operational weather radars, by contrast, use incoherent techniques that retain no information on the phase of the transmitted and received radio waves; they provide information on target position only. While they can monitor the progress of discrete targets such as aircraft and birds by detecting changes in the target position between successive pulses, they cannot accurately infer the velocity of distributed targets such as rain, snow, and turbulent eddies. For such measurements, the more powerful coherent approaches are required, which monitor changes in the phase of the scattered radiation. Assume that the radar target, or a region of distributed targets, is a distance r from the radar. If the electromagnetic wave emitted by the radar has phase ϕ_0 , the wave phase upon its return will be

$$\phi = \phi_0 + \frac{4\pi r}{\lambda} . \quad (3.1.4)$$

The time rate of change of this phase corresponds to the change in the angular frequency of the transmitted radio wave. Writing this change as $2\pi\Delta f$, and recognizing that the time rate of change of the radial distance is the radial velocity component u_r of the scatterer(s), we find

$$\Delta f = \frac{2u_r}{\lambda} . \quad (3.1.5)$$

Increases in the frequency of the emitted radiation result from scatterers moving toward the radar; decreases in frequency correspond to scattering by targets moving away.

The Doppler frequency shifts introduced by atmospheric motions are small. For a 3-cm radar wave ($f_0 = 10$ GHz), a 1-cm s^{-1} radial wind velocity produces

a 0.6-Hz shift Δf in the frequency (some six parts per one hundred billion). However, even such small changes are readily measurable, although the signal processing for coherent Doppler radars is more complex than for their incoherent radar counterparts. Figure 3.1.2 indicates the basic geometry of the pulsed Doppler radar approach and the additional system elements required in the signal processing. As in an incoherently pulsed radar, the transmitter excites the antenna at the operating frequency f_0 . Some power is, however, mixed with the output of a very stable local oscillator in a phase-locking device. The signal out of the locking mixer is at a substantially lower frequency (perhaps some tens of MHz); it provides phase information to a coherent oscillator at this lower frequency. In a similar way, the backscattered signal is also mixed with the signal from the local oscillator, producing an intermediate frequency wave now reflecting the Doppler frequency shift induced by the scatterer(s). A phase detector compares the phase difference between the signals. In the wind profiling application of interest here, the scatterers are distributed rather than discrete, and the pulse volume is finite. As a result, the scattered radar signal exhibits a spread in Doppler-shifted frequencies, as well as a mean shift in frequency corresponding to the pulse-volume-averaged radial velocity. This spread arises from

- spread of terminal velocities of scattering targets such as hydrometeors (these exhibit a spectrum of sizes, and hence terminal velocities, as they fall through the atmosphere),
- the turbulence spectrum of the air motions themselves,
- shear of the air motion within the radar pulse volume, and
- finite width effects of the radar beam. Different parts of the beam make different angles with the mean wind velocity vector, so that the radial component varies from point to point.

Measurement of more than one wind component

Since three wind components are required to specify the wind velocity vector, and since a given radial velocity component corresponds to only one of these, some

Figure 3.1.2. The principles of pulsed Doppler radar operation.

technique is required to determine the other two. The most straightforward approach (and also the most expensive) is to interrogate the volume of interest with two other radars, looking from (non-parallel) directions. This yields the three wind components without ambiguity (and is, strictly speaking, the only approach which does). There are other approaches, however, which serve sufficiently well for practical purposes. The first of these eliminates one of the radars by taking advantage of the fact that many atmospheric motions in circumstances of interest are in effect incompressible. Mathematically, this implies that

$$\nabla \cdot \underline{u} = 0, \quad (3.1.6)$$

which in component notation can be written

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \quad (3.1.7)$$

Using equation (3.1.7), measurements of the two horizontal wind components throughout an extended volume of atmosphere can be used to deduce the third, vertical component. The approach leads to some errors which increase in magnitude with height. It is widely claimed that achieving best results requires a careful treatment of the lower boundary conditions, even taking into account terrain features. While most of the existing literature skirts this issue, some work demonstrating this should be published shortly. The second approach eliminates two of the three radars by employing an azimuthally scanning beam to interrogate distributed scatterers and produce a so-called velocity-azimuth-display (VAD). Figure 3.1.3 indicates the geometry. When the radar is pointed upwind, the Doppler velocity u_r is given by

$$(u_r)_{\text{upwind}} = u \sin \alpha - w \cos \alpha,$$

where u is the horizontal wind speed component from left to right in the figure, w is the vertical wind speed component, and α is the zenithal pointing angle of the radar. By contrast, when the radar is pointed downwind, the effects of the horizontal and vertical velocity components add:

Figure 3.1.3. Variable-Azimuth-Display (VAD) scanning.

$$(u_r)_{\text{downwind}} = u \sin \alpha + w \cos \alpha .$$

Thus,

$$u = \frac{(u_r)_{\text{upwind}} + (u_r)_{\text{downwind}}}{2 \sin \alpha} \quad (3.1.8)$$

$$w = \frac{(u_r)_{\text{downwind}} - (u_r)_{\text{upwind}}}{2 \cos \alpha} . \quad (3.1.9)$$

Wind components in the orthogonal direction (in this notation, the v components) can be obtained by an analogous pair of equations governing the Doppler drift detected by radar look angles into and out of the figure. Data from different range gates fill in the height profiles. The technique presupposes that u , v , and w do not vary over the volume scanned by the radar; the method thus provides only a single, mean height profile. In the atmosphere, vertical velocities are smaller by an order of magnitude or more than the horizontal velocity components, except over irregular terrain. Over flat terrain, these assumptions are satisfied reasonably well.

With this general background, we are now ready to consider applications of pulse Doppler radars to the measurement of atmospheric winds. For recent reviews of meteorological radars and their applications in both research and operations, the interested reader is referred to Doviak et al. (1979), and the October 1979 special issue on radio meteorology of the IEEE Transactions on Geoscience Electronics. Here, however, we shall confine our attention to observation and measurement of boundary-layer wind fields by pulsed Doppler radars. For the most part these are dual-Doppler studies using the equation of continuity to supply the missing third wind component. While some results were obtained from clear-air echoes detected by very high power radars, the majority were obtained by radars of lower power using echo-producing chaff dispersed in the planetary boundary layer (PBL) by aircraft and dispersed by boundary-layer turbulence.

Radar studies carried out as part of the METROMEX experiment in St. Louis provide an interesting example (Kropfli, 1977; Kropfli and Kohn, 1978). Figure 3.1.4

Figure 3.1.4. One of a matched pair of WPL 3.2 cm pulsed Doppler radars, shown during METROMEX operations.

shows one of the two WPL 3.2-cm Doppler radars used in the study. Figure 3.1.5 shows where the two radars were situated relative to one another and to the St. Louis metropolitan area. Figure 3.1.6a shows the total wind field over St. Louis on one of the case days, 28 July 1975. The mean flow is from 20° east of north at about 4 m s^{-1} . The chaff had been released from an aircraft flying along the upwind edge of the wind field shown; at this time reliable wind measurements were possible over an area of some 250 km^2 with a resolution of about 500 m. Fine structure of the wind field is difficult to discern from Figure 3.1.6a, but becomes readily apparent once the mean velocity of the entire chaff cloud has been removed, as shown in Figures 3.1.6b,c, and d at altitudes of 0.3, 0.8, and 1.3 km respectively. The most striking feature is a line of convergence at low levels downwind of Granite City flanked by lines of divergence. At 1.3 km AGL, near the top of the PBL, this has become a line of divergence. Figure 3.1.7 shows vertical cross sections of the eddy wind field associated with this circulation. As Kropfli and Kohn (1978) discuss, the motion field apparently results from a heat island effect associated with the highly industrialized Granite City area. What is of more direct interest to us here, however, is that the dual Doppler radars successfully monitored this PBL flow at several heights, extending from 300 m to 1300 m AGL, developing a data set that would have required some 300 towers of 1300-m height (!) instrumented at three levels each. To obtain such a data set by in situ means is unthinkable. Subsequent studies, performed by WPL at its Boulder Atmospheric Observatory (BAO) in September 1978, have proved the radar technique able to obtain usable wind fields to altitudes as low as 100 m AGL and verified the wind estimates by comparison with data from instrumented aircraft and from the BAO 300-m tower (Kropfli, 1979; Kropfli and Hildebrand, 1980a,b). The capabilities of the radars for boundary-layer flow monitoring are rather remarkable, particularly considering the fact that the instruments were designed primarily for cloud studies and are by no means optimally configured for PBL research.

It should be noted that comparing radar-derived winds (or winds measured by any remote sensor, for that matter) with measurements from an in-situ sensor is not a trivial matter. Ideally, what one desires are two independent means for sampling wind speeds in a common volume. The problem is that when the radar sample volume contains the meteorological tower required to mount an anemometer, radar echoes from the tower (with of course zero Doppler shift) mask the much weaker atmospheric returns of interest. The conventional means for sidestepping this

Figure 3.1.5. A map of the metropolitan St. Louis area indicating the location of the NOAA WPL dual Doppler pulse radars. The solid rectangular region is that displayed in Figure 3.1.6. Contours show 300-m potential temperatures measured by the University of Wyoming research aircraft. From Kropfli and Kohn (1978).

Figure 3.1.6a. The total wind field at 0.8 km above ground level (AGL) on 28 July 1975. The winds are determined by averaging 17 volume scans taken during the 70 minute period ending at 1557 CDT. The large black dot indicates the position of the Gateway Arch. From Kropfli and Kohn (1978).

Figure 3.1.6b. The eddy wind field at 0.3 km AGL, after the mean wind over the entire chaff cloud has been subtracted from the data. Fine-scale structure, difficult to discern in Figure 3.1.6a, is now readily apparent. From Kropfli and Kohn (1978).

Figure 3.1.6c. Same as Figure 3.1.6b except at 300 m AGL.

Figure 3.1.6d. Same as Figure 3.1.6b except at 1.3 km AGL.

Figure 3.1.7. Vertical cross sections of the eddy wind field through the vertical planes indicated in Figure 3.1.6a. From Kropfli and Kohn (1978).

difficulty involve measuring winds with the two techniques in adjacent, but not identical volumes, and accounting for the (fluctuating) differences in actual wind speeds in the two volumes by suitable averaging. Results of this procedure, as well as comparisons with instrumented aircraft, carried out at the BAO during September 1978, have been reported by Kropfli and Hildebrand (1980a,b). Sample comparisons are shown in Figure 3.1.8, which gives scatter plots for radar and tower-derived winds in the lowest 300 m of the atmosphere.

The requirement for artificial targets — chaff — in such studies is a restrictive one. In recent years, however, staff at NOAA's National Severe Storms Laboratory have established that their moderately powered Doppler radars are able to measure wind fields under convective conditions in optically clear air out to ranges of 50-60 km (Hennington et al., 1976; O'Bannon, 1978; Doviak and Jobson, 1979; Rabin, 1980). Rabin (1980) demonstrated the abilities of the radars to measure turbulence and estimate Reynolds stress and other turbulent parameters.

What do these studies imply about the near-term potential of multiple Doppler radar systems for WECS siting and design studies? Unfortunately, the prospect is not so unmitigatedly bright as the above discussion might make it appear. In what follows, we shall use the parameters of the WPL 3.2-cm radars as illustrative of the general capabilities. Given suitable targets, maximum range is not a problem. A function of the pulse repetition frequency, it typically extends many tens of kilometers from the radar. However, minimum range is a source of concern. Dictated by the recovery time associated with the decay of the large-amplitude transmitted pulse in the electronics and antenna that must occur before the radar can detect the relatively weak return signal, it amounts to some 300 m for the WPL 3.2-cm radars, a figure which is representative. To obtain wind measurements from the low altitudes corresponding to the lowermost point of the WECS rotor disk (a few tens of meters at the very most, perhaps) therefore requires very low radar antenna elevation angles. Depending upon the terrain and the radar signal processing, ground clutter may then become a serious problem. Most Doppler radars have been optimized for the study of severe convective storms, for which ground clutter is not an important limitation. While there is some room for improvement in ground clutter suppression, it is unlikely that the radar elevation angle can be usefully lowered below 5°. For pulse radars, maximum unambiguous velocity is dependent upon the pulse repetition frequency; depending upon the application, this varies from a

a) u-component

b) v-component

c) w-component

Figure 3.1.8. Comparisons of pulsed-radar and tower-derived winds (from Kropfli and Hildebrand, 1980b).

very low 10 m s^{-1} to a high value over 30 m s^{-1} for the WPL radars (corresponding to pulse repetition periods of $768 \mu\text{s}$ and $256 \mu\text{s}$ respectively; clearly these limits could be changed readily). The antenna beamwidth is 0.8° ; spatial resolution depends upon pulse length and range, but in typical operating conditions amounts to several hundred meters or more. This is too large for direct measurement of turbulent fluctuations. Instead turbulent information must be inferred from the properties of the spread in the Doppler spectrum from echo returns within the pulse volume.

Temporal sampling might appear to be quite rapid, given the high pulse repetition frequencies (short pulse repetition periods) cited above. However, usually some 64-128 samples are averaged to provide a single data point. Scanning large volumes takes time also: typically several minutes are required for the scans shown in the METROMEX data. And operation of these radars requires chaff, which in turn requires auxiliary means of injection into the atmosphere and FAA clearance in some cases. Chaff diffuses and remains aloft satisfactorily only under very turbulent conditions, typically confined to the daytime. While there are numerous such systems in operation for research purposes (at NOAA's WPL and NSSL, at the National Center for Atmospheric Research, at the Illinois State Water Survey, and at the University of Miami, for example), the systems exist only as research prototypes. No such systems are commercially available. Power requirements are substantial, in the neighborhood of 40 kW. Past operation has required a crew of two at each site (in part for safety reasons so that only one of these need be skilled). A single WPL Doppler radar features a replacement cost of perhaps \$250K. Data processing associated with the recovery of the wind fields from the raw Doppler echo spectra is typically a time-consuming, after-the-fact process, although single Doppler systems such as those currently being introduced for tornado detection in severe storms provide a real-time capability. Maintenance requirements are also demanding in comparison to other techniques reviewed below. Power requirements and costs for radars able to operate in clear air are higher still. All these factors work in concert to preclude the use of such systems in the field except for brief periods (the order of a few weeks). Any one of the above restrictions would make use of such systems in WECS siting difficult; taken together, they would appear to rule out such applications entirely. However, multiple Doppler radars might find some application in WECS design studies devoted to elucidating wind spatial and temporal structure. Here the data they can provide is virtually unique, and

field studies of limited duration, intended to merely sample the wind structure prevailing under a few representative wind regimes, may suffice.

II.3.1.2 FM-CW Doppler Radars

As the previous subsection indicated, high-powered, pulsed radars are limited in their applicability to WECS siting studies for several fundamental technical reasons, quite apart from economic considerations. They cannot resolve spatial scales smaller than 100 to 200 m. Additionally, they cannot examine the structure of the lowermost atmosphere because of the masking effects of ground clutter. Both these restrictions are surmounted by use of frequency-modulated, continuous-wave (FM-CW) radar systems, which offer the additional advantage of a peak-power-to-average-power ratio of unity. Even at relatively modest powers, the FM-CW radar is able to detect clear-air echoes. The principle of FM-CW radar operation is illustrated schematically in Figure 3.1.9. By contrast with a conventional, pulsed radar, which emits a pulse of constant frequency, the FM-CW radar, originally developed as early as World War II but adapted for meteorological study by Richter (1969), emits a pulse whose frequency increases linearly with time. The radar echo arriving at the receiver antenna therefore has a slightly lower frequency than that being transmitted at the same instant, because it results from a portion of the pulse transmitted at an earlier time. The difference or beat frequency f_b between transmitted and reflected signal is proportional to the range of the target. Because frequency measurements are among the most accurate in physics, it is possible to resolve ranges of the target to within 1 or 2 m. Multiple targets produce reflected waves that arrive at different time delays and, hence, produce different beat frequencies that are superimposed. Spectral analysis of the beat frequencies resolves the different targets. Minimum range is reduced by the use of separate transmitting and receiving antennas, and is determined solely by the lowest height or range at which the two antenna beams intersect. For the existing WPL unit this minimum range is about 15 m. Figure 3.1.10 shows the radar van and its antennas.

In light of the discussion at the beginning of this section about Doppler shifts of radar targets and their use in wind-speed determination, one might think that it would be impossible to measure atmospheric motions using FM-CW techniques. Indeed, the effect of target motion is to introduce errors in range estimation.

Figure 3.1.9. Principles of FM-CW radar operation.

Figure 3.1.10. The WPL 3.2 cm FM-CW Doppler radar.

In the past several years, however, FM-CW radar capabilities have been extended to include Doppler measurements of winds. Chadwick et al. (1976a,b), Strauch et al. (1976), and Chadwick and Strauch (1979) describe the FM-CW Doppler instrument, which recovers winds by measuring the changes in phase at the echo signal from sweep to sweep. Wind measurement is achieved at some expense to the spatial resolution, but for wind energy applications, this spatial resolution may have been excessive anyway. We note in passing that these features have made the FM-CW Doppler radar an attractive candidate for applications other than wind energy. For example, Chadwick et al. (1978, 1979) describe the potential of the system for detection of low-level wind shear at airports. Chadwick also indicates the system could be used to monitor meteorological conditions in the vicinity of nuclear power plants.

Maximum range of the existing FM-CW Doppler radar is some 3 km or less in clear air, but much greater in the presence of distributed targets such as hydrometeors, chaff, and insects. Chadwick et al. (1979) discuss the meteorology of the refractive-index fluctuations that determine this range, and conclude that the system should be operational virtually all of the time. For WECS siting purposes, where the interest is in height profiles of wind over a single location, this capability is clearly more than adequate. For studies of spatial structure in the wind over large areas, this is something of a limitation. When used in the range-only (no Doppler) mode, the WPL equipment provides some 500 range cells within this range, yielding a range resolution of 6 m or less. The beamwidth is 0.05 radians, so that at 3 km the beam is 150 m wide; hence the interrogated cells are shaped like thin discs. In the range-only mode of operation, the output displays regions of enhanced refractive-index fluctuations. The time history of such records reveals the evolution of PBL structure.

In the range-Doppler mode the antenna can either be aligned in a fixed direction or scanned in azimuth. Again the maximum range for clear-air measurements is 3 km or less. The number of range gates and the number of spectral points are variable; however, for the WPL system these are subject to the constraint that the product of range cells and the number of spectral points per range cell must equal 500, which is the number of points available at the output of

the present signal processor. This is not a fundamental limitation. Normally, ten range cells with 50 spectral points each are used, providing radial wind velocity measurements at equally spaced intervals out to the maximum range. The radar uses a VAD scan to obtain both mean wind components as well as convergence profiles and estimates of shearing and stretching deformation. Table 3.1.1 summarizes the FM-CW radar performance parameters. Figure 3.1.11 compares FM-CW wind profiles with those derived using tethered balloon instrument packages (Chadwick et al., 1976b).

TABLE 3.1.1 FM-CW radar performance parameters

average transmitted power	200 W
antenna diameter	2.44 m
wavelength	10 cm
receiver noise figure	2.2 dB
minimum range for wind measurement	15 m
minimum detectable signal	-155 dBm
range resolution (adjustable)	≥ 1.65 m
velocity resolution (adjustable)	≥ 3 cm s ⁻¹

The WPL FM-CW radar is a unique, one-of-a-kind unit. It is transportable and is housed in two trailers. Transportation and installation currently require about six man days. Operation and maintenance require skilled personnel. However, Chadwick (Appendix A) believes an operational unit could be developed which could be housed in a single van, and require minimal setup time and operator skill; he estimates the unit would cost some \$150K. These features would suggest that the FM-CW radar is a viable candidate for WECS siting studies, despite the fact it now exists only as a single engineering prototype.

II.3.1.3 "Pseudo-Noise" Radars

So-called "pseudo-noise" radars, or random signal radars, have been developed for use both at Purdue and in Johannesburg, South Africa. They differ from con-

Figure 3.1.11. FM-CW derived winds compared with tethered balloon data (from Chadwick et al., 1976b).

ventional pulsed Doppler radars in that the transmitted signal is random and non-deterministic. It happens that such techniques permit simultaneously very accurate range and velocity measurements, while other methods require tradeoffs between the two. The random signal radar also eliminates pulse-to-pulse range ambiguities, which severely limit the use of pulse Doppler radars in the study of distributed targets. However, there is only one of these units in operation, in South Africa; more importantly, while wind-sensing capabilities exist in principle, they have yet to be implemented in practice on this unit. We shall instead content ourselves with citation of pertinent references. They include: Chadwick (1970); Chadwick and Cooper (1971, 1972, 1974); Cooper and Gassner (1966); Cooper and McGillen (1967); Cooper and Purdy (1968); McGillen et al. (1969); Pasqualucci (1970, 1972).

II.3.2 Lidar

Lidar (laser radar, also known as laser Doppler velocimeter [LDV]) systems utilize essentially the same principles of operation as do their radar counterparts, with certain differences of detail. Most of these differences stem fundamentally from the fact that optical wavelengths are five to six orders of magnitude shorter than the wavelengths used in radar work. Since the resolving power of a radar or lidar system of given size increases proportionately with decreasing wavelength, this implies that optical antennas (mirrors) are typically quite a bit smaller in size than their radar analogs, while offering greatly improved beamwidth characteristics. Optical technology can be correspondingly more demanding, however, because of the small tolerances available.

Optical wavelengths are so short that they fall well within the viscous subrange of turbulence, where the clear-air refractive index fluctuations are quite weak. As a result, clear-air backscatter of optical radiation results primarily from the Rayleigh backscatter of the individual atmospheric molecules. On the other hand, atmospheric aerosols scatter optical wavelengths relatively strongly. The optical wavelengths are comparable to the particle dimensions in many instances, so the Rayleigh (small-particle) approximation has to be replaced by the more general Mie scattering theory. We will not review the theory here, but instead direct the

interested reader to the remote-sensing survey edited by Derr (1972) and the references therein. Suffice it to say that aerosol scattering competes with molecular (Rayleigh) scattering in producing optical echo returns.

Collis (1969), Hall (1974), and Derr et al. (1974) review lidar methods and their application to atmospheric measurements in general and PBL measurements in particular. Lidar has been used for quantitative monitoring of structure and circulations within the convective PBL (e.g., Kunkel et al., 1977), aerosol-loading in the polluted urban environment (e.g., Derr et al., 1976), and dispersal of plumes of pollutants from localized sources (e.g., Abshire et al., 1978). It is worth noting here that from the point of view of boundary-layer studies, lidar and radar data are complementary more than merely redundant. For example, clear-air radar studies of the convective PBL have been most effective in revealing structure near the PBL capping inversion, where strong ambient humidity gradients produce correspondingly large refractive-index fluctuations (e.g., Konrad, 1970; Hardy, 1972). Since lidar echoes result from dust and aerosols lifted from the surface by PBL winds, they tend to fill in the mixed-layer structure (e.g., Kunkel et al., 1977).

II.3.2.1 Pulse Lidar

Pulsed lidar systems operate in a manner exactly analogous to pulsed radars (Section II.3.1.1). They depend for their operation upon Rayleigh scatter from atmospheric molecules and upon Mie scatter from aerosols; usually the latter predominates. Incoherent systems, designed solely for studying properties of the scattering aerosols (number density, size distribution, and composition), are the more common. Figure 3.2.1 shows a schematic representation of the WPL incoherent pulsed lidar system. Only a few coherent systems for making wind measurements exist, dating back to work by Benedetti et al. (1972, 1974). In order to maintain pulse coherence despite the deteriorating effects of atmospheric turbulence, most of these lidar systems operate in the infrared, generally near 10 μm . As a side result of this, most such systems are eye safe, an important advantage in operational applications. It should be pointed out, however, that visible wavelengths offer increased resolution, and, for the short ranges involved in wind profiling for WECS installation, may remain sufficiently coherent to be useful.

Figure 3.2.1. Schematic representation of the WPL incoherent pulsed lidar system.

Very few systems exist, so it is difficult to define what operating parameters might be considered "representative." Here, however, we have adopted the performance parameters quoted by Bilbro and Vaughan (1978) for an airborne pulsed Doppler lidar system currently under development and testing for use in cloud studies. These are given in Table 3.2.1. While such a system should be able to operate under virtually all weather conditions, we can see immediately from the table that these optical systems suffer some of the same shortcomings for wind-energy siting (height profiling of mean winds) that plague pulse radar systems. Although the beamwidth is narrow indeed, the pulse length is too long to permit resolution of differences in wind speed over the WECS rotor disk. The minimum range extends beyond the height of most of the WECS under consideration. As a result, the lidar beam must be scanned nearly horizontally if it is to develop wind information at the low levels required for WECS applications. Here, however, the short wavelength of the optical system reveals its advantages. Optical beamwidths are sufficiently narrow to present excellent height resolution in this configuration. Moreover, ground clutter effects are not so serious. Optical systems can be operated readily within a few degrees of the horizontal. In addition, the optical systems require no artificial chaff. Therefore pulsed optical systems offer considerable potential for WECS siting and design applications, particularly those where areal coverage is required. Because of the small size of the

TABLE 3.2.1 NASA airborne Doppler lidar system parameters

wavelength	10.6 μm
pulse length	1 μs
peak power	5 kW
pulse repetition frequency	200 Hz
beamwidth	30.54 cm
horizontal range coverage	$\sim 1/2$ -10 km
data point resolution	~ 150 m
vector component measurement	up to 40 m s^{-1}
vector component threshold	$\sim 1 \text{ m s}^{-1}$

components and their high resolution, they are already being used in the study of WECS wakes; further studies, including some novel approaches to the study of turbulence encountered by rotating WECS blades, have been proposed.

Only a handful of pulse Doppler lidar systems either exist or are under development. These are being designed by and large with larger-scale applications in mind. Lead-time for this development promises to be fairly lengthy. Until then, it can be safely assumed that power requirements, environmental protection requirements (which are stringent in order to protect delicate optical surfaces from the deleterious effects of abrasion by aerosols in high wind-speed conditions), and demands on operating and maintenance staff will be so stringent as to preclude their use in wind-energy siting. Again, however, for brief experiments in support of WECS design work, pulse lidars look attractive.

II.3.2.2 CW Doppler Lidar

Continuous-wave (CW) Doppler lidars determine range by beam focusing techniques rather than by range-gating the lidar pulse. Like the pulsed lidars, they are virtually all-weather devices. However, unlike pulsed lidars, which provide uniform range resolution with range from the instrument, these focusing techniques yield a range resolution that deteriorates with increasing distance in the same way (and for precisely the same reasons) that "depth-of-field" increases with distance on a camera. Using the WPL system developed by Schwiesow as an illustration, we find a minimum range of about 20 m, at which the range resolution is less than half a meter. For a range of 100 m, range resolution is 10 m, while at 200 m it has deteriorated to something like 40 m. However, this need not be a disadvantage, since over the height range of interest the dominant turbulent eddy scale sizes are also increasing. The systems have been used successfully to measure wind fields in atmospheric vortices such as dust devils and waterspouts (Schwiesow and Cupp, 1976; Schwiesow et al., 1977); they have also been used to study changes in boundary layer airflow passing over water and encountering land. Figure 3.2.2 shows the system mounted in a small camper while observing turbulent airflow in the wake of a building. Post et al. (1978) have compared wind speeds deduced by tower-mounted propvanes with such a lidar system; results are shown in Figure 3.2.3, taken from

Figure 3.2.2. The WPL CW Doppler lidar studying turbulent airflow in the wake of a building.

LIDAR-Anemometer Comparison

27 February 1976

Figure 3.2.3. CW Doppler lidar measurements of wind speed compared with measurements made using a propvane anemometer mounted on a nearby tower. The lidar sampling volume was a cylinder some 20 m long and 3 cm in diameter centered one meter below the propvane. From Post et al. (1978).

that paper. Here, because of the small width of the optical beam, the sampling volumes of lidar and anemometer are quite close together, and the comparison is seen to be eminently satisfactory.

CW Doppler lidars exist only as engineering prototypes. The existing units require considerable attention from highly skilled operators and maintenance personnel. Power requirements for the WPL unit do not exceed 750 watts, including the data processing system and the cooling system. Schwiesow estimates the cost of a transportable unit (without the truck) to be some \$30K. At such prices, it might prove feasible to use two units for measuring both horizontal wind components, rather than resorting to VAD scans. These CW Doppler lidar attributes make them attractive for WECS wind siting (see also Schwiesow's contribution to Appendix A). Schotland (Appendix A) describes an intriguing dual-frequency Doppler lidar (DFDL) for remotely measuring wind velocity.

II.3.2.3 Time-of-Flight Lidar

Figure 3.2.4 shows the geometry for time-of-flight lidar measurement of a single wind component. The technique makes use of two beams that overlap at small ranges, but focus in small, disjoint volumes at some height h above the lidar. Each beam will sense any aerosols that happen to be blown through the beam in this focal plane. Measurement of the time delay required for the particle to move from one beam to its neighbor yields the mean wind-speed transverse to the beams in the plane of the beams. Use of a third beam permits determination of the second horizontal wind component. Bartlett and She (1977) and Lading et al. (1978) describe the technique.

The time-of-flight lidar systems offer several potential advantages. For one, they do not, strictly speaking, require coherent light sources, except as these provide sufficiently narrow and stable wavelengths to permit optical filtering of background sky radiation. For another, they require only relatively inexpensive components. Costs and operating requirements are comparable to those cited above for the CW Doppler lidar systems. For further remarks the reader is referred to the contribution by Schwiesow in Appendix A.

Figure 3.2.4. Geometry for time-of-flight lidar measurement of a single wind component.

II.3.3 Doppler Acoustic Sounding

Acoustic sounding of the atmosphere is analogous to radar or lidar probing except for the use of acoustic waves instead of electromagnetic waves. Acoustic waves propagate with the speed of sound c_s relative to the medium, where

$$c_s^2 = \gamma RT/M. \quad (3.3.1)$$

Here $\gamma \equiv$ ratio of atmospheric specific heats (c_p/c_v)
 $R \equiv$ the universal gas constant,
 $T \equiv$ the absolute temperature, and
 $M \equiv$ the molecular mass of air.

There are three major points of interest here concerning the speed of sound in air. First, whereas the speed of light $c = 3 \times 10^8 \text{ m s}^{-1}$, the speed of sound is some six orders of magnitude slower; in the troposphere, $c_s \approx 340 \text{ m s}^{-1}$. Second, the speed of sound is much more variable spatially and temporally than is the speed of light. The sound speed is proportional to the square root of the temperature, and thus varies the order of ten percent from the base of the troposphere to the tropopause and from season to season. This variability is orders of magnitude greater than that experienced by electromagnetic waves. Turbulent fluctuations in refractive index for sound waves are correspondingly larger than for electromagnetic radiation. Sound speed also varies as a result of changes in atmospheric moisture content through associated changes in the average molecular mass M of the air (although these changes are relatively small). Third, and finally, sound waves are materially advected by atmospheric winds. Whereas the speed of light is essentially unaffected by atmospheric motions, the speed of sound as given in equation (3.3.1) is that measured by an observer moving with the local mean flow. An observer stationary with respect to the ground measures different sound speeds for waves propagating with and against the wind, respectively. In fact, this dependence is the basis for wind measurement by means of sonic anemometry (e.g., Kaimal, 1978 and the references therein). As we shall see, all these differences between acoustic waves and their electromagnetic counterparts manifest themselves in certain operating differences.

The block diagram for an acoustic sounding system does not look significantly different from that for its radar and lidar analogues. Figure 3.3.1, taken from Brown and Hall (1978), shows the basic operating configuration for the instrument, variously referred to as an acoustic radar, a sodar, an echosonde, or an acoustic sounder. Transmitters and receivers are now, however, audio oscillators and audio amplifiers. Loudspeakers are used to radiate the acoustic energy. Figure 3.3.2 shows several acoustic antennas deployed in a recent WMO-sponsored comparison of low level sounding systems held at the Boulder Atmospheric Observatory (Kaimal et al., 1980), and serve to indicate something of the variety of approaches currently taken in acoustic antenna design. Brown and Hall (1978) provide an extensive and relatively up-to-date review of the technique.

The radar equation (3.1.1) holds for acoustic sounding systems as well as radars. Here, however, the "targets" not only include the temperature fluctuations in the clear air induced by turbulence, but also velocity fluctuations as well. Tatarski (1961, 1971) and others have worked out the theory. One finds that the inertial-range scattering cross section for acoustic waves is given by

$$\eta(\theta) = 0.055 \lambda^{-1/3} \cos^2 \theta \left[\frac{C_v^2}{C_s^2} \cos^2 \frac{\theta}{2} + 0.13 \frac{C_T^2}{T^2} \right] \left(\sin \frac{\theta}{2} \right)^{-11/3}, \quad (3.3.2)$$

where $\eta(\theta)$ is the scattered power per unit solid angle of the scatter angle θ , per unit volume, per unit incident flux, and C_v and C_T are the turbulence structure constants for velocity and temperature, respectively. Most acoustic probing wavelengths fall within this inertial range, since the same viscous effects that serve to dissipate the turbulence at smaller scales also act to damp the higher-frequency acoustic waves to an extent unacceptable for atmospheric probing. Acoustic probing frequencies are typically 1700 Hz, corresponding to wavelengths $\lambda \approx 20$ cm. For backscatter,

$$\eta(\theta) = \eta(\pi) = 0.0072 \lambda^{-1/3} \frac{C_T^2}{T^2}. \quad (3.3.3)$$

Several features of equations (3.3.2) and (3.3.3) are worthy of note. First of all, there is no scattering of acoustic waves at $\theta = 90^\circ$. Second, for backscatter

Figure 3.3.1. Basic operating elements for an acoustic echo sounder (from Brown and Hall [1978]).

Figure 3.3.2. Several acoustic echo sounding antennas deployed during the 1979 WMO Boulder Low-Level Intercomparison Experiment. The main elements visible on each system are actually the cuffs designed to minimize wind noise effects on the antennas proper.

($\theta = 180^\circ$), there is no contribution from turbulent velocity fluctuations. This is significant here for the following reason. When wind speeds are high, a case of considerable interest for WECS siting applications, the background atmosphere may become well mixed and therefore neutrally stratified or nearly so. In such instances, it may happen that turbulent temperature fluctuations will be insufficient to yield detectable acoustic echoes. Monostatic sounder systems (collocated transmitting and receiving antennas, $\theta = 180^\circ$) may be unusable in such circumstances. However, bistatic systems (separated receiver and transmitter antennas, $\theta \neq 180^\circ$, $\theta \neq 90^\circ$) will continue to provide usable wind profiles under such conditions.

Like pulsed radars and lidars, acoustic echo sounders measure wind speeds by measuring the Doppler shifts of the acoustic echo returns from turbulent scatterers, as described in Section 3.1.1. For monostatic sounding techniques, the formulation is exactly that described in that earlier section. For the bistatic geometry, however, the problem is slightly more complicated, as illustrated in Figure 3.3.3, which shows sound emitted from an antenna T, scattered and Doppler shifted by turbulent scatterers moving with vector velocity $\vec{u}$, and detected at receiving antenna R. Describing the transmitted wave by its wave vector $\vec{k}_t$ and the scattered wave by its wave vector $\vec{k}_s$, we have

$$\Delta f = \frac{1}{2\pi} (\vec{k}_s - \vec{k}_t) \cdot \vec{u} . \quad (3.3.4)$$

This equation shows that the bistatic system monitors that velocity vector component parallel to the difference vector of the incident and scattered acoustic waves.

A number of geometries can and have been employed for acoustic Doppler monitoring of all three components of the wind. In Figure 3.3.4 we reproduce three of the most popular operating configurations. Figure (a) shows the monostatic configuration — three units oriented in three nonparallel directions (one vertical and two off-vertical axes). The advantage of this configuration is that it requires the least real-estate; the sounder antennas can be essentially collocated. This was the configuration used by WPL acoustic sounders on board the NOAA research

Figure 3.3.3. Doppler shifts for the bistatic sensor geometry.

Figure 3.3.4. Three Doppler acoustic echo sounder configurations for measurement of the three wind components. (a) three monostatic sounding units. (b) two fan-beam transmitting antennas and one vertically-pointing transmitter-receiver. (c) two fan-beam receiving antennas and one vertically pointing transmitter-receiver.

vessel OCEANOGRAPHER during the GARP Atlantic Tropical Experiment (GATE), for example. The disadvantage, as implied above, is that the approach requires strong temperature fluctuations to provide the necessary acoustic echoes. Configuration (b) is a truly bistatic geometry. Fan-beam slave transmitters illuminate the vertical beam of a vertically looking transmitter-receiver system. This approach offers the advantages of providing echo returns from velocity turbulence eddies as well as turbulent temperature fluctuations. Its primary disadvantages are the increased real estate required and the possibility that the fan-beam transmitters may prove bothersome to any people in the test area. Configuration (c) removes this latter disadvantage by transmitting only from the vertically-looking antenna; this can normally be heard only by standing quite near the antenna. The tradeoff here, however, is signal-to-noise ratio. Just as the fan-beam transmitters emit sound of high-intensity at ground level, fan-beam receiving antennas receive noise from all sorts of natural and man-made sources.

During the past ten years, acoustic echo sounders have become popular instruments for a number of boundary-layer meteorological applications. They are in use by dozens of groups around the world. As with radar, the majority of these units are not Dopplerized. Likewise, the majority of the instruments are used for air-quality monitoring. However, they have been used for other applications, including detection of low-level wind shear at airports.

Several commercial manufacturers offer Doppler acoustic sounders. A number of these commercially-available as well as several one-of-a-kind research instruments were compared as part of a recent WMO-sponsored comparison of low-level sounding systems. Kaimal et al. (1980) describe the results. A sample comparison between the WPL acoustic Doppler sounder and sonic anemometry on the 300-m Boulder Atmospheric Observatory tower is shown in Figure 3.3.5. This is just one of a number of tests that have led to considerable confidence in acoustic Doppler techniques.

Minimum range for the acoustic systems is usually some 10-30 m. Maximum range for both monostatic and bistatic systems extends to the top of the planetary boundary layer at night and the early morning. Bistatic systems should receive usable echoes to the height of the top of contemplated WECS rotor disks under virtually all meteorological conditions. Acoustic waves propagate very slowly, so

Figure 3.3.5. Scatter diagrams comparing horizontal wind components measured by the WPL acoustic Doppler system with winds measured by BAO tower instrumentation during the 1979 WMO experiment. Wind speeds range from $\pm 10 \text{ m s}^{-1}$.

that wind profiling to heights of 170 m requires pulsing at rates slower than 0.5 Hz. Rain and high winds produce noise that is a significant factor in reducing signal-to-noise ratio and limiting the utility of the technique. While Neff of WPL asserts wind noise should not be a limiting factor at speeds below 30 m s^{-1} , even over rough terrain, others note problems at lower wind speeds. Note that acoustic-sounding systems provide only single height profiles of the wind; they are unable to provide the area coverage achieved by pulsed radar and lidar systems. There are two reasons for this. First, acoustic pulses propagate so slowly that scanning of large volumes requires prohibitively long times. Second, beamwidths are typically rather large, several degrees or more, and echoes from sidelobes become a problem for low-elevation angles.

The commercial units require several kilowatts of power and a single technician for system operation. Cost of the three-component units run something like \$60K. For further details the reader is referred to the responses found in Appendix A.

II.3.4 Optical Transverse Wind Sensing

During the past decade, the Wave Propagation Laboratory has developed a line-of-sight optical method for measuring atmospheric winds. Basically, the system observes scintillation patterns induced in an optical beam by atmospheric turbulence and monitors the advection of the patterns across the beam. The geometry is shown in Figure 3.4.1. In this way it provides a line-average estimate of the winds transverse to the beam. Figure 3.4.2 compares optical measurements of the transverse wind with the average winds measured by a series of propeller anemometers spaced along the optical path. The agreement is excellent. Lawrence et al. (1972) describe the basic technique. Under strongly turbulent conditions over long paths, scintillation-saturation effects may enter; Ochs et al. (1976) discuss the modifications and extensions of the theory required under these conditions. While Figure 3.4.1 indicates the use of a laser, coherent light sources are not required, and working units have used light sources such as lasers, incandescent lamps, and even light-emitting diodes (LEDs). Figure 3.4.3 shows sample equipment. Clifford et al. (1975) have demonstrated that it is possible to make such measurements by using passive observations of a natural scene. Stars have been

Figure 3.4.1. Principle of operation for optical transverse wind sensing.

Figure 3.4.2. Winds measured optically compared with transverse winds measured by several anemometers spaced along the optical path.

Figure 3.4.3. Optical transverse wind-sensing equipment, featuring an incoherent light source.

used as the light source, providing some information on winds aloft, but this is sufficiently unreliable as a result of cloud cover that it will not be considered further here. Ochs et al. (1974) give details.

In principle, the technique can be extended to profiling of the wind along the path. Figure 3.4.4 indicates the geometry. Two transverse wind-sensing systems monitor paths that intersect at one point. By analyzing only that component of the scintillations that correlates between the two beams, the user can deduce wind speeds at the point of intersection. The method is somewhat awkward, however, provides only limited resolution, and has not seen extensive use. Accordingly it shall not be pursued further here. Wang et al. (1974) provide details.

We are left, then, with the basic technique of measuring line-averaged transverse winds. The technique would appear to be quite suitable for the measurement of wind speeds within canyons, where the canyon walls provide excellent sites for mounting light sources and receivers, and where the major axis of the canyon provides a prevailing wind direction. Several canyons meeting the requisite conditions are currently under either development or consideration (including the San Geronimo Canyon and the Columbia River Gorge). Laser-driven versions of the instrument are available commercially, costing roughly \$3K-4K. Power requirements are minimal, particularly for the engineering prototype IR LED systems, which consume the order of a few watts and may be battery operated in the field, or operated from solar panels. For the basic (non-profiling) systems, spatial sampling is limited to the line average along the path; the transverse dimension is much smaller. Minimum path length is some 100 m. Temporal resolution can be as fine as 1 Hz. The main limitation is visibility along the path. On longer paths, heavy snow, rain, or fog can obscure the beam. Small, commercially built data loggers suffice for data acquisition. A technician need monitor the units only infrequently, every few days — a time interval comparable to that required to service and reinitialize the data loggers. For more details, the reader is referred to the contribution from R. B. Fritz in Appendix A.

PATH PROFILE EXPERIMENT USING TWO LIGHT SOURCES

Figure 3.4.4 Geometry for wind profiling using optical transverse wind sensors (from Wang et al., 1974).

II.4 Conclusions and Recommendations

II.4.1 Present Remote-Sensing Capabilities

As asserted in the executive summary, and indicated in passing at appropriate points in Section II.3, there are four remote-sensing approaches to wind measurement that would appear to be adequate, although not necessarily ideal, alternatives to in-situ devices for WECS siting studies. This subsection considers each of these in turn.

The remote-sensing technique that appears to be most readily able to replace its in-situ counterpart in WECS siting studies appears to be the optical transverse wind sensor. Its output is similar in nature to that from a cup- or propeller anemometer, so that it would interface relatively directly to an equivalent data logger or data acquisition system. Some forms of the instrument are available commercially, and power requirements are minimal, permitting battery-powered operation or solar-panel operation if required. It has the disadvantage of not providing as much resolution in the line-of-sight direction as the in-situ sensor, so that it effectively filters out the smaller-scale turbulent fluctuations, some of which may be important from the standpoint of WECS design (Section II.2.2). It has the additional disadvantage of sensing only the cross-beam components of the wind. However, in some canyon geometries, the terrain determines a single usable wind direction: airflow parallel to the canyon axis (Hiester and Pennell [1980] provide an extensive discussion of airflow in passes, canyons and gorges). Moreover, the optical wind sensors offer the major advantage of requiring no towers in the canyon geometry. The instrumentation is so inexpensive that it might even find some application in WECS siting over regular terrain. Once a single tall tower was erected to carry in-situ instrumentation at the site of interest, light sources could be mounted atop the tower and monitored by the optical devices at various surface locations around the tower. This might prove a more inexpensive method of obtaining area information than the method suggested by Hiester and Pennell (1980) involving erection of satellite towers. However, to evaluate the usefulness of the optical devices in this way might require some further testing (as mentioned in passing in Section II.4.3).

Acoustic Doppler sounders also offer a viable alternative to in-situ measurement. Units are commercially available from firms having some experience in their use. They have been operated in the field for extended periods, in both regular and irregular terrain. They have a fairly substantial, though not perfect, all-weather capability. They do require, however, some attention, at fairly frequent intervals, from a technician. And because of the low sampling rates afforded by the acoustic pulses, wind information in most current systems is available in the form of averages over periods of minutes rather than seconds. As indicated in Section II.2 there is some interest in turbulent motions occurring on time scales the order of a second or a few seconds. However, some of this information might be inferred from the acoustic inferences about the turbulence, including the intensity of the turbulence, spreads in the Doppler shift of the acoustic echo, velocity differences measured in adjacent range gates, etc. And the cost of the commercially available, three-component Doppler acoustic systems is comparable to the cost of the towers they would replace.

Continuous-wave (CW) Doppler lidar (or possibly time-of-flight lidar, or dual-frequency Doppler lidar) offers a third alternative. At present, it is available only as a research prototype. However, little further development work is needed. Suitably housed, it provides all-weather capability. An operational three-axis system might cost as little as \$100K. Operating requirements (personnel, maintenance, power, data processing) should prove comparable to those for the commercially available acoustic systems. Use of electromagnetic waves rather than sound waves also permits a better look at high-frequency turbulent fluctuations in the wind.

The fourth and final remote-sensing alternative for WECS siting is the FM-CW Doppler radar. This also exists only as a research prototype, but is attractive because of its ability to probe at short ranges and under virtually all weather conditions. Chadwick of WPL indicates that little further development should be required to produce an operationally "hardened" unit. The chief disadvantages are its cost (estimated to be perhaps \$150K for a prototype unit) and its reliance on a VAD scan. To acquire turbulence information will require analysis of the echo returns, as in the case of acoustic Doppler sounding techniques.

The four instruments cited above appear to be suitable for WECS siting. As mentioned in Section II.2, remote sensing instruments offer some potential for

WECS design work. Pulsed Doppler radar and pulsed Doppler lidar systems would permit detailed study of PBL airflow structure on the meso- and microscale pertinent to the design of WECS clusters; CW Doppler and time-of-flight lidars offer capabilities for studying (a) the turbulence experienced by rotating WECS blades and (b) airflow in the WECS wake.

II.4.2 Remote-Sensing Capabilities That can be Expected in Five Years

I am personally discomfited by projections into the future, but following repeated and specific requests for this, I offer the following:

- The cost of remote-sensing equipment relative to in-situ counterparts will decline during the next five years.
- Engineering prototypes of (perhaps multiple) pulsed Doppler lidar systems will be available for planetary-boundary-layer studies.
- Operationally "hardened" versions of FM-CW radar and CW Doppler lidar systems will be available within five years, and commercial firms will be evaluating their marketability. These may or may not be optimized for the wind-energy application, however. Alternative applications, such as monitoring meteorological conditions near nuclear reactors or low-level wind shear near airports are being considered.
- Much more will be known about relating radar, lidar, and acoustic echo sounder echo properties (amplitude, Doppler spreads, etc.) to properties of atmospheric turbulence.

II.4.3 Recommendations for Research and Development

There exist a number of fruitful areas for future research. Some of these recommendations, if implemented, would have the effect of making the forecasts of the previous subsection self-fulfilling. The recommendations listed below are not necessarily in order of importance.

- Funding should be advanced to support "hardening" of research prototype instruments (specifically the FM-CW Doppler radar, CW Doppler lidar, and time-of-flight lidar) for operational use. The hardening required includes mechanical systems, optical systems, and electronics. Such hardening would result in better environmental protection for the units and less stringent demands on operator (maintenance) expertise.
- Studies should be funded relating parameters (deduced from FM-CW radar, acoustic sounder, and lidar systems) such as C_N^2 , C_T^2 , C_V^2 , spectral width of the Doppler-shifted echo returns, and turbulent kinetic energy dissipation to turbulence parameters of importance in WECS design.
- Efforts should be made to improve the performance of pulse lidar and pulse radar systems in scanning large areas of the planetary boundary layer by reducing the effects of ground clutter through various computer techniques and antenna design.
- Funding should be used to remove some of the observational biases threatening the utility of existing remote sensing systems; for example, the effects of wind noise and rain on acoustic sounder operation, and the effects of precipitation and wind-blown particulates on optical surfaces.
- Funding should continue for efforts to study, through the use of lidar, turbulence effects experienced by a rotating blade.
- Funding should be provided to compare remote-sensor performance with in-situ sensors, to better delineate and understand measurement biases in the remote-sensing techniques, to evaluate the costs of field use of remote-sensing equipment, etc. Past comparisons have been brief and have emphasized measurement accuracy as opposed to other aspects of system performance. What is needed are longer-term studies, lasting for months or perhaps years. A particular target of opportunity that comes to mind would involve installation of optical wind sensors in the San Gorgonio canyon for comparison with tower anemometer results currently being acquired there. Much of the material in Section 3 concerning operating requirements is based on surmise rather than direct experience. In order to be more confident of the tradeoffs between use of remote sensors and in situ sensors, we require more actual field tests.

II.5 References

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APPENDIX A

In December 1979 we polled members of the remote-sensing community for their views of the state of the art of remote sensing as it applied to wind-energy studies. A copy of our form letter appears here as Section A.1. The mailing list we used attempted to be representative rather than all-inclusive; it did, however, reach members of both the public and private sectors. The mailing list appears as Section A.2. In disseminating the questionnaire it was our purpose to broaden the range of points of view available in this report, and to provide the interested reader with some names and addresses for further inquiry. In this goal we feel we have succeeded. As we promised our correspondents, their replies would be incorporated in the report without editing; the replies constitute Section A.3. We thank each of the respondents for his thoughtful attention to what may have been an unwelcome task.

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George E. McManus
U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80302

R45/R45X7:WIII

A1

December 17, 1979

Dear

We have been asked by the Department of Energy (through the Pacific Northwest Laboratory) to review remote-sensor potential for wind-energy studies. A two-page work statement (copy attached) from the inter-agency agreement covering this work describes the task in more detail.

To meet this obligation, we plan to (a) develop a bibliography, and (b) poll members of the remote-sensing community for their views on the state-of-the-art.

This letter is a first step in that process. We are hoping that you, or perhaps your designated representative, might find time to respond to the issues described in the attachment in a short, written statement, as viewed from the perspective of your own research and development (or operational systems) and/or those of your parent institution. We also hope that you can provide us a complete bibliography of your relevant journal articles, available reports, and brochures. If possible, we would appreciate reprints or copies of these.

We will use your responses in two ways. First, we will take all responses into account in developing our own synthesis and summary, to constitute the main body of our final report. All suitable references will be included in the master bibliography. Second, we will append all responses we receive to the final report, without modification, for Department of Energy inspection and use.

At this time we also invite your telephoned responses and comments (call William H. Hooke, (303) 499-1000, Extension 6378). Our Department of Energy budget does not permit us to travel and

interview all investigators and principals in person, but if your travel during the next few months will bring you to the Denver area, we will appreciate your paying us a personal visit. Some of you we may telephone or visit at our initiative.

Please give this matter your serious attention. We know that you are busy but we hope that you see in this an opportunity to put forward your remote-sensing capabilities for Department of Energy consideration in a most favorable light.

Thank you.

Sincerely yours,

Duane A. Haugen (PROFS)

William H. Hooke (WPL)

Attachment

MAILING LIST FOR "A REVIEW OF REMOTE-SENSOR POTENTIAL FOR WIND ENERGY STUDIES

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80503

February 4, 1980

To: Bill Hooke, R45x7

We have shown in past boundary layer experiments that 3-D wind fields can be accurately measured with the NOAA dual-Doppler radar system. Measurements within 100 m to 200 m of the surface have been made over several hundred square kilometers, with a resolution of several hundreds of meters, and with errors less than .3 m/s. It would take less than 1 minute to scan the 200 m layer nearest the surface. These X-band radars require the presence of hydrometeors or chaff to provide a suitable echo.

This research tool could be used to measure the quality of a proposed wind power site in a wide variety of weather situations as well as to establish the validity of boundary layer models used in site evaluation. A high level of expertise is required to set-up, operate, and maintain this system.

Two-identical X-band radars are mounted on flat-bed trailers and are easily transportable. Set-up and check-out are usually accomplished by a crew of 2 or 3 in less than one day.

Bob

R. A. Kropfli, R45x6

(2) Attachments

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80303

Date: August 14, 1980

To: William H. Hooke, R45x7

From: Fausto Pasqualucci, R45x6 *F.P.*

Subject: Remote Sensing Potential of 8.6 mm Radar

1. Backscattering from small hydrometeors or other atmospheric particles (seeds, insects, pollutants, etc.).
 2. Sensor is capable of detecting clouds which are optically visible at ranges of the order of 10 km and precipitation (rain, snow, etc.). The detection of other atmospheric particles is strongly related to the condition of the atmosphere. For example a strong inversion layer will tend to accumulate pollutants and insects in the lower part of the atmosphere, increasing the possibility of using them as wind tracers.
 3. Typical maximum range of the sensor is of the order of 60 km and the range resolution is 37.5 m.
 4. The antenna pointing accuracy is about 0.1 degrees. The accuracy in the velocity measurements depends on the measurement conditions (type of target, dwell time, etc.). Typically 0.1 m sec^{-1} should be easily achieved.
 5. Maximum mechanical scanning speed of the antenna is $30^\circ/\text{sec}$ with maximum angular acceleration of $40^\circ/\text{sec}^2$. With a complete data system the maximum sample rate is 16000 range gates/sec.
-
1. The sensor will be operational by September 1980. The complete data system will be ready by May 1981.
 2. A radar operator familiar with the equipment is needed. Such operator could be trained in a few days.
 3. a. Electric power requirements:
120/208 VAC 3 ϕ 4 wires 100A-60 $\pm$ 1 Hz
b,c,d. Environmental protection and data processing (hardware & software) is provided with the sensor.
 4. Purchase cost $\approx$ 150K
Installation 3-5K
Operation: 2 trained operators are required.

JHR:gep
9 January 1980

Dr. William H. Hooke
R45x7
WPL/ERL/NOAA
Boulder, CO 80302

Dear Bill:

This is in response to your letter of 17 December 1979 requesting information on remote sensor potential for wind energy studies. The only wind sensing we have done is with the Xonics acoustic sounder described in Technical Report 1997. The Xonics device never worked well because of ambient noise (manmade, biological, wind). Only under very quiet conditions were we able to measure winds. I am enclosing another paper dealing with wind measurements (Atlas, Harris, Richter, 1970) for curiosity. The rest of the articles are enclosed because they either deal with certain aspects of wind measurement or wind effects (e.g. shear induced waves).

Hope the material is of help to you.

Sincerely yours,

JUERGEN H. RICHTER

FM-CW Clear Air Radar

The FM-CW (frequency modulated-continuous wave) Radar is specifically designed to make short range measurements in the boundary layer. Usually the backscatter is from clear-air refractive-index inhomogeneties and the radar has measured radial winds from ranges of 15 m to 10 km in the clear atmosphere. Under rain or snow conditions, the backscatter is from hydro-meteors and much greater ranges can be obtained. The radar is an all-weather device for wind measurement.

Because of equipment considerations, the range resolution available depends on the elevation angle. At low elevation angles the range resolution is greater than 100 m and at high elevation angles the range resolution is greater than 1.5 m. The division between high and low elevation angles depends on the ground clutter and is therefore site dependent. Of course, at 5° elevation angle a 100 m range resolution translates into 8.7 m height resolution. The velocity resolution is independent of elevation angle and is greater than 3 cm/s.

The radar beamwidth is about 2.5° and this beam can be scanned over a hemisphere. The maximum scanning rate in azimuth is $3^{\circ}/s$ and the maximum scanning rate in elevation is $0.5^{\circ}/s$. The radar acquires a new estimate of the spectrum of the radial wind at each range gate every second or greater.

The FM-CW radar should be especially useful for wind energy studies because it measures wind over a volume rather than at a point. This is important because a wind energy machine operates over an area rather than a point. In addition, since the radar measures the wind spectrum, potentially useful information relating to turbulence would be available. The amount of turbulence across the surface of a wind energy machine would be an important design parameter.

The present WPL radar is a research device, and would not be appropriate as an operational device useful in wind energy studies. It requires experienced

operators and is contained in two trailers which require 6 man days plus travel time to move. If this radar concept appears useful in wind energy studies, the optimum approach would be to use the present research device to demonstrate this usefulness and then design and build a mobile radar especially for wind energy studies. This radar would be contained in a standard van and one trailer; it would be such that one person could move it in as little as a few minutes. Also, inexperienced personnel could be trained to operate it in one hour. It would be capable of remote, unattended operation. A prototype of this device could perhaps be designed, and built for \$150K. The operating costs of this system would be small.

For further information, contact Dr. R. Chadwick, FTS-323-6318.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80303

R45X2

December 17, 1979

Dr. William H. Hooke, Chief
Atmospheric Studies, R45X7
Wave Propagation Laboratory
Environmental Research Laboratories
National Oceanic & Atmospheric Administration
Boulder, CO 80303

Dear Bill:

Since my travel plans at this time do not include a trip to the west end of RB#3, I shall reply to your inquiry R45/R45X7:WHH, dated Nov. 27, 1979, by letter. As you are probably aware I have been associated with two different remote sensing techniques while at the Wave Propagation Laboratory, Atmospheric Acoustics and Infrared Doppler Lidar. Since the acoustics responsibility now rests in your program, I shall assume you are more or less familiar with acoustic sounders and, especially, Doppler capabilities as they might apply to wind energy studies. Therefore, I shall concentrate on the capabilities of infrared Doppler lidar for wind energy studies.

Following the format of DoE 1A#D1-A106/91 123051, Attachment 1, Statement of Work, Task 1:

(1) Infrared Doppler lidar depends on the backscatter of infrared electromagnetic radiation from scattering centers advected with the wind in the atmosphere. These scattering centers are usually the naturally occurring atmospheric aerosols; although they may be artificial aerosols as from smoke generators or from other man-made pollution sources.

(2) The number of naturally occurring aerosols varies widely with atmospheric turbidity; however, in the planetary boundary layer, with a modestly powerful lidar with an average 1 watt of output power, enough turbidity exists to obtain winds at ranges of several hundred meters in the planetary boundary layer under almost all conditions. Because coherent propagation of the infrared radiation is required and because of turbulence in the boundary layer, Doppler lidars for such ranges must operate in the wavelength region near 10 μm . In this spectral region, penetration of heavy dust and of fog over ranges of

several hundred meters is no problem. Thus the sensor can be viewed as all-weather except possibly for extremely heavy snowfall conditions.

(3) The ranges of infrared Doppler lidars are dependent upon the instrument design. The low power, CW lidars, which achieve range resolution by focussing the transmitted beam, to enhance coherent detection scattered back from the probed volume, have ranges limited to about 500 m. Range resolution is a few meters at about 100 m from the lidar but with poorer range resolution as the distance from the sensor increases. The angular dimensions of beamwidth for lidars are always extremely narrow, much less than any radars and usually measured in a few one-hundredths to less than a tenth of a milliradian. For pulsed lidars, the new high-powered TEA lidar that we are acquiring, for example, will have a range of ten to twenty km but the range resolution limited by the pulse length to about 100 or 200 m. Again the beamwidth will be measured in small fractions of a milliradian.

(4) If by accuracy of the sensor the question means wind measurement accuracy, then this is highly dependent on the Doppler processing scheme used. For most IR Doppler lidars the accuracy will be on the order of $\frac{1}{2}$ ms⁻¹ when signal to noise exceeds 1.0 by a comfortable margin. At longer ranges, our new pulsed TEA lidar, for example will have an accuracy of about 2 ms⁻¹ at its extreme range beyond 10 km.

(5) Space and time sampling rates are highly dependent upon the data processing schemes used. With the focussed CW lidars velocity data is usually only acquired for the particular range gate where the focussing occurs. Most on-line processors (such as surface acoustic wave devices for analog processing) are typically sampled once every 25 microseconds and with resolutions of about 100 KHz or $\frac{1}{2}$ meter per second. Thus independent wind measurements can be made about 40,000 times per second. There is no technological reason that sampling could not be done at much higher rates and our A to D converter in our TEA lidar has a bandwidth of 10 MHz. Of course, with a pulsed device information is available in a number of range gates so generally this data will be tape recorded and processed later for an off-line, but equivalent, bandwidth of, perhaps, 100 MHz.

On the status of the sensor, all of the infrared Doppler lidar systems used to date must be viewed as research tools. Two devices developed for the Transportation Systems Center and used by the FAA for wind and vortex studies near airports are semi-operational in that they are transportable and put quickly into operation by the equipment developers, Lockheed Aircraft. Therefore the level of expertise required to install and operate the sensor is at the skilled and knowledgeable technician level, not necessarily that of a research scientist, at least for some of the equipments. Operating requirements are nominal for van-mounted equipment:

several kilowatts of 110 V line power, near laboratory equivalent shelter and protection and air conditioning for the data processing equipment. Many versions of the data processing hardware and software have been developed and are available as state of technology accomplishments. Cost of the lower power CW equipments, complete with data processing and a mobile van can run close to \$250,000 (the price of the EPA General Motors camper van equipment that WPL is calibrating at this time.) The replacement costs for a more simplified system without on-line data processing capability, such as the WPL pickup truck-mounted equipment would be about 100 K. Longer range, pulsed infrared Doppler lidars might run 400 to 500 K.

The following list is a bibliography of publications describing infrared Doppler lidars and their capabilities.

Sincerely,

A handwritten signature in dark ink, appearing to read "Freeman F. Hall". The signature is fluid and cursive, with a large, sweeping initial "F" and a distinct "H".

Freeman F. Hall, Chief
Infrared Doppler Lidar

Attachment

- Biernson, G., and R. F. Lucy (1963): Requirements of a coherent laser pulse-Doppler radar. *Proc. of the IEEE*, 51, p. 202.
- Huffaker, R. M. (1970): Laser Doppler detection systems for gas velocity measurement. *Appl. Opt.*, 9, no. 5, p. 1026.
- Huffaker, R. M., (Winter Issue, 1974-75): CO₂ laser Doppler systems for the measurement of atmospheric winds and turbulence, *Atmos. Tech.*, NCAR, p. 71.
- Huffaker, R. M., H. B. Jeffreys, E. A. Weaver, and J. B. Bilbro (1975): Development of a laser Doppler system for the detection, tracking and measurement of aircraft wake vortices. FAA Report FAA-RD-74-213.
- Kingston, R. H. (1977): Coherent optical radar. *Optic News*, 3:27.
- Lawrence, T. R., M. C. Krause, L. K. Morrison, C. E. Craven, 1973: A study on laser Doppler velocimeter atmospheric wind interrogation systems. Final Report. Lockheed Missiles and Space Co. Inc., Huntsville, Ala. LMSC-HREC TR D306888, October 1973.
- Murty, S. S. R. (1975): Atmospheric transmission of CO₂ laser radiation with application to laser Doppler systems. NASA Tech. Memo. TMX-64987.
- Schwiesow, R. L., R. E. Cupp, M. J. Post, R. F. Abbey, Jr., P. C. Sinclair (1977): Velocity structures of waterspouts and dust devils as revealed by Doppler lidar measurements. AMS, Proc. of Tenth Conf. on Severe Local Storms, Omaha, NE.
- Siegman, A. E. (1966): The antenna properties of optical heterodyne receivers, *Proc. IEEE*, 54:1350.
- Sonnenschein, C. M., and F. A. Horrigan (1971): Signal-to-noise relationships for coaxial systems that heterodyne backscatter from the atmosphere. *Appl. Optics*, 10:1600.
- Teich, M. C., R. J. Keyes and R. H. Kingston (1966): Optimum heterodyne detection at 10.6 μ m in photoconductive Ge₁Cu, *Appl. Phys. Lett.*, 9:357.
- Teoste, R., and R. N. Capes (1978): High-altitude infrared radar measurements. *J. Appl. Meteorol.*, 17.
- Thomson, J. A. J., and M. F. Dorian (1967): Heterodyne detection of monochromatic light scattered from a cloud of moving particles. Tech. Report GDC-ERR-AN-1090. Convair Div. of General Dynamics, San Diego, CA.
- Thomson, J. A., and J. C. S. Meng (1975): A feasibility study for the detection of upper atmospheric winds using a ground based laser Doppler velocimeter. Physical Dynamics, Inc., Berkeley, CA Report PD-75-042, Contract NAS8-28984.
- Thomson, J. A., and F. P. Boynton (1977): Development of design procedures for coherent lidar measurements of atmospheric winds. June (Revised November 1977). Final Report, Contract No. NOAA-03-7-022-35106, Physical Dynamics, Berkeley, CA.

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812

Reply to Attn of: EC32

January 11, 1980

Mr. Duane Haugen
PROFS
Environmental Research Laboratories
Boulder, CO 80302

Dear Mr. Haugen:

I am pleased to be able to respond to your request for information concerning our work in remote sensing. I have enclosed a bibliography and a short description of our systems in which I attempted to address the specific questions contained in the attachment to your letter.

I hope that this information is satisfactory for your purposes. If I can be of any additional service please do not hesitate to contact me or Mr. E. A. Weaver, (205) 453-1597.

Sincerely,

A handwritten signature in cursive script that reads "James W. Bilbro".

James W. Bilbro

2 Enclosures

cc:

EC31/J. L. Randall/F. W. Wagnon
EC32/C. O. Jones/E. A. Weaver

CO₂ DOPPLER LIDAR

The Marshall Space Flight Center has been actively involved in the development of CO₂ Doppler lidar systems since the 1960s. Two distinct systems have been the result of this research - one, a continuous wave, short range, high resolution device and the other a pulsed, long range system with less spatial and velocity resolution. The application of these systems has been exceedingly varied resulting in measurements of: aircraft wing tip vortices, dust devils, vertical wind profiles, smokestack exit velocities, wind shear, clear air turbulence, and severe storm outflow. Airborne mapping of the flow field around severe storms is planned for the spring of 1981. Both types of systems have been operated as ground based trailer mounted units and as airborne measurement systems. In responding to the specific questions of the survey the two systems will be addressed as one where common features exist.

a. The CO₂ Doppler lidar system rely on electromagnetic propagation at a wavelength of 10.6 micrometers.

b. The lidar coherently detects light backscattered by naturally entrained aerosols in the atmosphere. These aerosols follow the motion of the atmosphere and as such measurement of their velocity provides a reliable measurement of the ambient wind velocity. The particular wavelength used is subject to absorption by water vapor and consequently cannot be considered an all weather system. The range capability of the lidar is seriously limited during rain storms - the limitation being determined by the concentration of rain along the desired measurement path. This problem can be somewhat alleviated by the selection of another wavelength.

c. The range of the continuous wave unit is limited to approximately 1 km by the size of the focusing telescope. The range resolution is a function of range from the telescope. Typically, the resolution (as defined by the half power points of the coherent return) varies from a few centimeters at a range of a few meters to several hundreds of meters at a range of 1 km. The velocity resolution is dependent upon the type of processing employed and is currently approximately 0.5 m/s.

The range limitation of the pulsed system is set by the pulse energy which varies from approximately 10 mJ to 30 mJ depending on pulse width selection. Maximum ranges at ground level have been on the order of 13 km. The range resolution is selectable, being 0.3 km, 0.6 km, or 1.2 km with accompanying velocity resolutions of 2.65 m/s, 1.33 m/s, or 0.66 m/s.

d. The accuracy is primarily SNR dependent. The present systems are accurate to within less than 0.25 m/s. No attempt has been made to measure the absolute accuracy beyond this point.

e. The continuous wave unit obtains a complete spectral distribution with selectable integration times from 1/2 ms to 64 ms. The pulsed unit uses an estimation technique to provide the first three moments of the spectrum in selectable integration

periods of 20 to 95 pulses. The PRF is typically 140 pps. Spatial sampling is dependent upon scan rate. Limitations are determined by the resolutions covered in item 3.

f. Both systems are in the category of research tools. Continuous wave systems have been built which are very close to being considered as an operational resource.

g. Installation and operation requires at least one engineer in concert with a highly trained technician in the continuous wave case and at least two technicians in the pulsed case.

h. Approximately 20 kw is required for each of the systems. This figure is greatly dependent upon the amount of support equipment.

i. Both units are trailer mounted and require temperature and humidity control.

j. Continuous wave unit utilizes surface acoustic wave delay line signal processor. Pulsed unit utilizes conventional filter bank and polypulse-pair signal processor.

k. Both units use a PDP 11-35 on-line computer with 64K of memory, magnetic tape recording, disk storage, and a Tektronix 4014 display terminal.

l. Costs are extremely variable depending upon the level of sophistication. For the continuous wave system costs will range from \$20K to \$500K. Costs for the pulsed unit are estimated at approximately \$2.5M. The major portion of this cost is related to necessary laser development.

PUBLICATIONS

1. Robert M. Huffaker, Harold B. Jeffreys, Edwin A. Weaver, and James W. Bilbro, et al, "Development of a Laser Doppler System for the Detection, Tracking, and Measurement of Aircraft Wake Vortices," FAA Final Report, FAA-RD-74-213, NASA TMX-66868, March 1975.
2. James W. Bilbro, Harold B. Jeffreys, "Development of a Laser Doppler System for the Detection and Monitoring of Atmospheric Disturbances," Paper Presented at the Electro-Optical System Design Conference, November 1975.
3. Harold B. Jeffreys and James W. Bilbro, "Development of a Laser Doppler System for the Detection and Monitoring of Atmospheric Disturbances," NASA TMX-64981, November 1975.
4. J. W. Bilbro, H. B. Jeffreys, E. A. Weaver, R. M. Huffaker, G. D. Craig, R. W. George, and P. J. Marrero, "Laser Doppler Velocimeter Wake Vortex Tests," FAA Final Report, FAA-RD-76-11, NASA TMX-64988, March 1976.
5. L. Z. Kennedy and J. W. Bilbro, "Remote Intensity Fluctuation Measurements With a Laser Doppler Radar," Applied Optics, Vol. 15, No. 9, p. 2008, September 1976.
6. Harold B. Jeffreys, James W. Bilbro, Charles DiMarzio, Charles Sonnenschein, Douglas Toomey, "The Remote Measurement of Tornado-Like Flows Employing a Scanning Laser Doppler System," Paper Presented at the 17th Conference on Radar Meteorology, October 1976.
7. E. A. Weaver, J. W. Bilbro, J. A. Dunkin, H. B. Jeffreys, "Laser Doppler Technology Applied to Atmospheric Environmental Problems," Paper Presented at the NASA Aviation Safety and Operating Problems Conference, October 1976.
8. James W. Bilbro, Harold B. Jeffreys, Edwin A. Weaver, and John W. Kaufman, "Laser Doppler Measurements of Dust Devils," NASA TN D-8429, November 1976.
9. J. W. Bilbro, G. D. Craig, R. W. George, H. B. Jeffreys, P. J. Marrero, E. A. Weaver, M. Krause, T. Dunn, C. DiMarzio, C. Harris, C. Sonnenschein, and D. Toomey, "Laser Doppler Vortex Measurements at John F. Kennedy International Airport," Paper Presented at the Transportation Systems Center Conference on Aircraft Wake Vortices, March 15 - 17, 1977.

ABSTRACT

Dual-frequency Doppler lidar (DFDL) is a new method to remotely measure wind velocity. In DFDL, the laser output is modulated to create two superimposed beams of differing frequency ν_1 and ν_2 , where $\alpha = \nu_1 - \nu_2$ is in the microwave region. The dual-frequency beam consists of a set of sinusoidal interference fringes traveling at the speed of light c in the direction of the beam. Aerosols, moving with the air, backscatter and Doppler shift energy from both beams to collecting optics incorporating a high-speed photodetector. The difference $\Delta\alpha$ in the Doppler frequency shifts from the two beams is extracted from the signal of the square-law detector by a microwave Doppler receiver. The component of wind velocity V_L parallel to the beam (normal to the fringes) is obtained from the relation $\Delta\alpha = -2V_L\alpha/c$.

Laser Doppler methods of wind measurement can be hampered by atmospheric scintillation effects which degrade the requisite coherence of the laser signal. Application of scintillation theory to DFDL shows this method is relatively insensitive to optical turbulence since the frequency separation of the beams is small compared to the optical frequency and the beams travel a common path. Atmospheric scintillations can alter the irradiance profile across the beam, but the relative coherence of the beams is hardly altered, and the fringe pattern along the beam is well maintained.

A variation of this technique is the hybrid DFDL, which can measure the component of velocity at a selectable skew angle normal to fringes which are slanted with respect to the composite beam. This fringe pattern is formed by crossing the two beams at a small angle ($\sim 10^{-5}$ rad in the experimental DFDL instrument). The hybrid DFDL combines features of the DFDL with the crossed-beam laser Doppler anemometer. The hybrid DFDL concept can in principle be utilized to remotely measure the three-dimensional wind velocity at a point in space from a single instrument site.

In this study the power spectrum of the differential Doppler signal is derived for the case of a Gaussian beam profile and multiple target particles within the probed volume. Expressions for the signal-to-noise ratio in the presence of shot and thermal noise are obtained. Methods to optimally calculate the correct velocity from the Doppler spectrum, which is generated by the randomly positioned aerosols and contaminated by the random noise, are discussed.

An experimental DFDL instrument, based upon an acousto-optically modulated laser, was constructed and operated. It was capable of real-time wind measurement, utilizing a minicomputer for data analysis and recording. Laboratory tests, including operation in a wind tunnel with seeded flow, confirmed the predicted differential Doppler shift. The functional dependence of signal-to-noise ratio on equipment variables of the DFDL instrument were also verified in the wind tunnel. Outdoor wind measurements in both pure and hybrid DFDL configurations, with natural aerosols as targets, were performed. Good agreement was

found between the lidar and a conventional anemometer adjacent to the sensed volume. Concurrent measurements of aerosol size distributions provide a basis for predicting performance under different aerosol conditions.

In harmony with the investigative nature of this project, the range capability of the experimental DFDL was modest. With 0.3 W transmitted power and a 42 cm diameter primary mirror on the receiving telescope, wind velocity measurements were routinely accomplished at a distance of 20 m with a sampling rate of approximately once each 1.5 seconds. A range capability of 1 km can be projected for an upgraded DFDL incorporating existing technology.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80303

January 10, 1980 R45x1:RS

TO: Wm. H. Hooke, Chief R45x7
Wave Propagation Laboratory

D. A. Haugen, PROFS

FROM: R. L. Schwiesow, R45x1
NOAA/ERL/WPL

R. L. Schwiesow

SUBJECT: Wind Measurement by Short-wavelength Lidar for DOE Review

Two kinds of short-wavelength ($0.3 \mu\text{m}$ to $1.2 \mu\text{m}$) wind-sensing lidar are particularly applicable to the measurement of winds in the first few hundred meters of the atmosphere. One technique is the time-of-flight laser anemometer and the other is Doppler lidar. The two kinds of measurements are complementary in many senses. I will first consider some of the distinctive characteristics of each of the wind sensing lidars and then discuss some common features and comparison with other remote wind sensors.

1. Time-of-flight laser anemometer

Time-of-flight lidar senses the wind component perpendicular to the lidar line-of-sight in the plane of two slightly-separated beams. By using three beams, both transverse wind components are determined.

Each aerosol particle that is large enough to produce a measureable signal gives an independent measure of V_T . The time difference between backscatter sensed in channel 1 and channel 2 gives the signed velocity component. Lading et al. (1978) have shown that single-particle velocity determination is practical.

In its present state of development, the time-of-flight anemometer is useful to a range of 100 m in a daytime environment. Temporal resolution or sampling period is the order of a few ms per measurement, depending on the ambient aerosol loading. The spatial resolution is a few mm transverse to the line-of-sight and approximately 10 m along the beam for a range of $r=100$ m with a CW system. The measurement accuracy is controlled by the uncertainty in separation of the two beams. This separation can easily be determined to $\pm 1\%$, so that the accuracy in wind estimate depends on the fluctuations in the measurements caused by turbulence.

The time-of-flight approach has a growth potential to perhaps 500 m. Beyond that range it is possible that single-particle data processing will no longer be applicable, so more experience is required to make longer-range estimates. Some slight increase in range resolution is possible with larger optics, but present systems are close to the maximum effective aperture permitted by the atmosphere. A better way to increase range resolution is to use short-pulse lasers (a well-developed technology) with pulselengths between 10 ns and 100 ns.

A vertically-pointing time-of-flight anemometer is ideally suited to measuring vertical profiles of the horizontal wind. Because of excellent cross-wind spatial resolution, it may be used to measure in the wake of wind turbines.

2. Doppler Lidar

A Doppler lidar measures the wind component along the lidar line-of-sight, or the radial (longitudinal) wind component.

Light scattered from a moving scatterer is frequency-shifted from the incident frequency by the Doppler effect. A Doppler lidar in the visible part of the spectrum has been used by Benedetti-Michelangeli et al. (1972 and 1974).

These authors use their system primarily at night to a range of approximately 1 km with a 300 m range resolution. Spatial resolution is a few mm transverse to the beam. With a scanning interferometer, 3 s is

required to produce one velocity estimate at many range gates in parallel. The measurement accuracy is $\pm 0.3 \text{ ms}^{-1}$ for a single measurement, and estimated at $\pm 0.03 \text{ ms}^{-1}$ for an average of 100 measurements.

The Doppler lidar technique can be improved by using shorter laser pulses and more powerful, narrow-frequency lasers than were available for Benedetti-Michelangeli et al. These improvements should increase range to a few km and increase the range resolution, especially if longer averaging times are used. In an optical Doppler lidar the range and velocity resolution are linked because of the frequency broadening introduced by pulsing. The uncertainty product goes as

$$\Delta V \Delta r \approx c\lambda/4,$$

which shows that for a velocity uncertainty of $\pm 0.5 \text{ ms}^{-1}$ a total range gate of approximately 38 m is appropriate for a $0.5 \mu\text{m}$ (green) lidar. It is obvious that visible (rather than infrared) wavelengths are appropriate for a pulsed Doppler lidar on the scale of wind energy studies. At very short ranges, a CW (focused-range) lidar may be more appropriate than a pulsed lidar.

For many applications, for example profiling the flow over a terrain feature, a 40 m range gate is adequate. Range-height display of a single wind component is among the capabilities of a Doppler lidar configuration.

3. Common Features

Both remote sensors are single-ended devices. They measure one or two components of the wind, range-resolved along the line-of-sight. The signal on which they depend comes from aerosol scattering, where the aerosol particles in the range of $0.1\text{ }\mu\text{m}$ to $5\text{ }\mu\text{m}$ radius serve as flow markers. Aerosol particles are conservative tracers in the sense that they are not generated internally by the flow. Acoustic and radar wind sensors rely on scattering from nonconservative refractive index inhomogeneities, particularly temperature fluctuations. In general, aerosol particle tracers are distributed more uniformly in the lower atmosphere than temperature inhomogeneities. This distribution characteristic gives the lidar a spatial-sampling advantage over remote sensors relying on inhomogeneities that may cluster near shears and/or inversions. In addition, the interpretation of signals from scatterers that are created and destroyed in the flow is more difficult than analysis of returns from conservative tracers.

Because they rely on optical transmission, the short-wavelength lidar wind sensors will work at ranges approximately limited by the visibility. They are not limited by wind or rain noise. The high angular resolution (mrad or less in azimuth and elevation) of the lidar is associated with negligible antenna sidelobes, so wind measurements may be made close to machinery or terrain features.

Short-wavelength wind-sensing lidar is more highly developed in Europe than in North America. It is a demonstrated research tool, possessing development potential for extended range and sampling rate. It is not likely that a lidar wind-measurement system will be useful as an unattended, continuously-operating system within the next two or three years. Present laser technology requires a semi-skilled operator to check mirror alignment as well as to ensure the eye safety of workers in the target area if beam steering programs malfunction.

A near-visible-wavelength lidar has significant advantages over an infrared ($10.6\text{ }\mu\text{m}$) Doppler lidar, in addition to the resolution advantages for pulsed systems already mentioned. Aerosol scattering near $0.69\text{ }\mu\text{m}$ is stronger than at $10.6\text{ }\mu\text{m}$ by factors ranging between 690 and 1900 in recent comparative experiments. Although coherent (optical heterodyne) processing has not yet been successful in short-wavelength lidars as it has been in the infrared, both visible and infrared lidars can operate near the quantum noise limit. Quantum noise limitations favor the infrared over the visible by a factor of approximately 20 for equal transmitter powers, but this factor is much less than the backscatter coefficient difference.

Present lidar experience and technology allows us to build a mobile (truck-mounted) remote wind sensor. Although power and cooling requirements are a few kW, such a system can operate independently. It is best suited for short-term, intensive studies that require the capability for single-ended, high-resolution velocity measurements. Although not yet demonstrated, it should be possible to combine the two types of short-wavelength, wind-sensing lidars to produce a true three-component wind measurement with a single basic system, at least in a time-shared mode. Such a measurement of the vector wind at a point is applicable to problems involving flow around obstructions, wind profiles in horizontally inhomogeneous situations, and flow around turbines, for example.

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February 1, 1980

Dr. William H. Hooke
ERL/WPL
National Oceanic and Atmospheric Administration
Boulder, CO 80302

Dear Bill:

I have been asked to respond to your letter of 17 December to Ron Collis. Although our Center is engaged in a variety of remote sensing activities, our activities in the area of remote wind measurement have been very limited. We do have a small effort funded by the Army Research Office to develop and test an acoustic angle-of-arrival wind sensor. This work is still in the hardware development stage, and we have made no actual wind measurements yet. As a consequence, we have not produced any publications. However, the principles of the technique and some experimental results produced by a German system are described in a paper by Gerhard Peters et al., "Acoustic Doppler and Angle of Arrival Wind Detection and Comparisons with Direct Measurements at a 300 m Mast," J. Appl. Meteor., 17 (1978) 1171-1178.

It is certainly true that the operational capabilities of acoustic doppler wind-sensing systems currently exceed those of angle-of-arrival systems. However, our continuing pursuit of the angle-of-arrival techniques is based on a feeling that a properly functioning and optimized angle-of-arrival system might have significant advantages over a comparable doppler system. However, this remains to be demonstrated, and I do not expect this to occur for a year or so.

Sincerely,

Philip B. Russell
Senior Physicist
Atmospheric Science Center

PBR/jl
cc: R.T.H. Collis
W.B. Johnson
E.M. Liston

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Mr. William H. Hooke
U. S. Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
Boulder, Colorado 80302

Dear Mr. Hooke:

I am responding to Duane Haugen's letter of December 17th addressed to Paul. I would like to apologize for the delay but it arrived just as we were taking the holidays off and since returning, things have been quite busy.

I believe that the enclosures will be quite helpful in satisfying your request and particularly, the most recent paper which describes the Doppler System as it was used for the Boulder tests, covers all of the first five questions under Task 1 of attachment 1. I believe it is worthwhile speaking directly to the latter points of Task 1.

- (1) The current Doppler is basically the same as the one used for the inter-comparison tests in Boulder during the late summer of 1979. The design has been fixed and there are currently orders for several units. We consider it to be usable on an operational basis and the operator does not require any special skills beyond those of the average instrument technician who would work with electronic meteorological data gathering systems.
- (2) A manual exists which covers many details regarding installation and operation. If someone is reasonably familiar with setting up instrumentation, they should have no difficulty following the information in the manual. Nevertheless, it must be kept in mind that a doppler is a very sophisticated piece of equipment and we do recommend participation from a member of the AV staff to assist with site selection and to make final checkout in the field at the time of installation. It is felt that this is not unusual since the equipment would be totally new to any customer as there is essentially no way that he could have previous experience with it.

As stated in (1) above, it is felt that any reasonably competent instrument technician could operate the system in the field.

31 January, 1980

- (3) Most of the answers to the operating requirements are contained in the document which answers the first five questions but perhaps a few comments are worthwhile. The power requirement for the system is basically 110 volts AC, 60 Hz 8 amps. If the system is in a climate which experiences severe winter weather, ice and snow, then a 110 volt heating system for the dishes is commonly employed. If this is used, an additional 20 amps are required to heat two antenna dishes.

All of the electronics and recording equipment must be maintained in an environmentally controlled shelter or building. The primary reason for this is that the basic components which make up the electronics and recording equipment are fundamentally designed for a very limited temperature range.

I'm not really certain what is meant by items C and D as the basic hardware and software is part of the system. This can be determined from the system description. Most commonly, the data is recorded on half-inch magnetic tape at 800 BPI. An example of the format of the data is shown in the printout. From this, a standard program can be written to summarize the data as may be desirable.

- (4) Basic cost for a system including assistance with the installation will be approximately \$50,000 for a two-component system and upwards of \$60,000 for a three-component system. No allowance for operation is made as the only costs are power, magnetic tape, and a few minutes of someone's time, typically once a week, to check that everything is working properly and occasionally change tapes.

I hope that this takes care of most of your questions. In any case, I hope you know that you are most welcome to call or visit us. Just let me know if I can help.

Sincerely,

George P. Ettenheim
Vice President, Products

GPE:jo
Enclosures

A-32

**Model 2000
Doppler Acoustic Sounder**

AeroVironment Inc.

DOPPLER ACOUSTIC SOUNDER

MODEL 2000

INTRODUCTION

The Model 2000 is a two- or three-component monostatic Doppler acoustic wind profiling system. The result of a collaborative effort between AeroVironment Inc. and the University of Melbourne, it is based primarily on techniques developed by Dr. Ian Bourne of the University.

In simple terms, the antenna sends out a pulse of sound energy at a particular frequency. The pulse echoes back from atmospheric scatterers caused by thermal or mechanical turbulence. The returning signal is picked up by the antenna. If the scatterers are moving towards the antenna, the echoed signal will be a higher frequency. If the layer is moving away, the echo will be a lower frequency. This change in frequency is called the Doppler Effect.

The Doppler Acoustic Sounder consists of two antennas in its basic form. One measures the north-south component of the wind, the other the east-west. A typical printout includes the two wind components for each level (every 30 meters) and the resultant wind speed and wind direction. An estimate of the reliability of each value is also printed. An optional third antenna may be added to measure the vertical component of the wind.

Speeds are printed out to 0.1 m/s resolution and directions to 3° . Nominal accuracy during periods of strong signals is 0.2 m/s.

APPLICATIONS

Since field use of the Doppler is in its infancy, this section touches on only those applications either currently employing the Doppler, or where it is expected to be used in the immediate future. Please do not hesitate to contact the factory to discuss other possible applications which may not be covered here.

System Flexibility

The monostatic configuration permits usage in numerous situations where mobility is highly important. When it is desirable to evaluate the meteorological characteristics of a site for almost any purpose, this mobility makes it possible to take measurements for a short period of time — hours or days — and then move the Doppler to another site in a matter of minutes. Where extreme mobility is required, it is possible to use a vehicle, such as a van, to house the electronics and

tow the trailer. Once at the site, the trailer can be set up and the cable connected from the electronics to the antennas. If commercial power is not available, the system may be operated from storage batteries using a high-quality inverter.

Where a limited space is available for the instrumentation, a significant cost savings may be realized as an area of approximately 25' x 25' is all that is required for the antennas of a three-component system.

Surveys

The collection of wind data may be supplemented by adding a third antenna to the two-component system. This provides vertical winds and a direct measure of the vertical mixing properties of the particular atmospheric region of interest. The two-component or three-component configuration may be used for the study of:

- o Site climatology
- o Power plants
- o Refineries
- o Smelters
- o Airports
- o Cement plants

Operations

In a number of applications, the Doppler may be used to optimize plant operation while complying with air pollution regulations. Its capabilities make it useful for other special tasks as well.

In the case of power plants, refineries, smelters, or other specialized plant operations, the data may prove helpful for identifying time periods when it would be necessary to burn a low-sulphur fuel, control emissions because of the limited mixing capability of the atmosphere, or because of particularly troublesome wind directions and speeds.

For airports, the system can provide a direct indication of whether there is wake turbulence or wind shears in the approach area which might be hazardous to safe operations. Wind data above surface level can also be available to flight control personnel.

Studies & Research

Over the years, investigators have used pilot balloons, radiosondes, tether sondes, instrumented aircraft, and instrumented towers to collect meteorological data to support their work. In most applications the data was less than desirable, but methods were not available to yield the quality and quantity which was sought. Often the Doppler satisfies these needs, permitting 24-hour a day monitoring without interference of other investigative activities. Its portability and ease of installation reduce setup and teardown time, thus producing significant cost savings.

Output

The system's most common output will provide the user with time-averaged wind direction and wind speed at height intervals of 30 meters above site elevation.

Data is available as averages of 10, 15, 20, or 30 minutes. Hourly summaries may be calculated off-line from these averages. Shorter sampling times of two or five minutes may be desirable where short distance trajectory analysis is important.

If the data is to be used in plume modeling, it is highly desirable to have a third antenna to obtain the vertical component of the wind. Although this component will average near zero, the instrument will calculate the variation of the vertical component about zero velocity. This value may prove very useful as an input for model calculations of downwind dispersion.

Data interpretation is so closely tied to the goals and needs of the program for which the data is being collected that it is difficult to write a broad explanation which will cover most applications. For this reason, it is important to point out that AeroVironment Inc. is staffed with numerous meteorologists and other scientists who are trained and willing to assist you with your particular application. Please do not hesitate to contact us so that we can be of maximum help to you.

SYSTEM THEORY

The three-component Doppler Sounder is comprised of three adjacent pencil-beam antennas. One tilts 30° north (or south) from the vertical to observe the north-south wind, one tilts 30° east (or west) to observe the east-west wind, and one points vertically to observe the vertical component. Each antenna is operated sequentially in the monostatic mode.

The sound pulse for the two 30° antennas (100 watts electric) is at a frequency of approximately 1500 Hz, with a duration of 180 ms for the tilted beams. A somewhat longer pulse duration is used for the vertical antenna. The received echo is heterodyned and then processed through an electronic comb-filter with 31 teeth which continuously yields the full spectra.

The spectra are input to a microprocessor-based computer which performs all computational and data output functions and controls the operation of the entire instrument. For each altitude range gate (30 m), the entire spectrum is sampled, baseline trends are removed, and a preliminary estimate of the spectral peak is computed. The data is tested for background noise level, peak placement, amplitude, and signal-to-noise ratio. Accepted spectra are stored in an averaging buffer. At the same time, a histogram of peak locations is updated. At the end of the selected averaging period, the averaged spectra and the corresponding histogram are smoothed, and interpolation techniques are employed to locate the peak in each data set. Finally, the best estimate of Doppler shift is ascertained together with a reliability factor for that data set.

0E SAMPLE INTERVAL 08/03 14:46 TO 08/03 15:00 THREE COMPONENT MONOSTATIC

00005 F=15 N+00W+00 MAN AGC:27N30E30V 20HTS SMCD45 TEST3

001/0/000

SITE1 SPECTO HISTO

HT	NS	R	NO.		EW	R	NO.		VERT	R	NO.	SD		VEL	ANG	R	NO
20	6.0	0	46	♦	-4.5	0	46	♦	-0.1	2	46	0.2	♦	7.5	324	0	46
19	5.2	0	26	♦	-4.6	0	34	♦	0.2	0	44	0.3	♦	7.0	318	0	30
18	4.8	4	14	♦	-4.9	0	29	♦	0.3	0	45	0.3	♦	6.8	315	4	21
17	4.3	0	14	♦	-5.9	0	32	♦	0.3	1	45	0.3	♦	7.2	306	0	23
16	4.3	0	12	♦	-6.3	0	34	♦	0.3	0	44	0.3	♦	7.7	306	0	23
15	4.4	0	18	♦	-6.2	0	33	♦	0.2	0	45	0.3	♦	7.6	306	0	25
14	4.4	0	23	♦	-6.7	4	35	♦	0.2	0	46	0.2	♦	8.0	303	4	29
13	4.4	0	39	♦	-7.1	0	39	♦	-0.2	3	45	0.4	♦	8.2	300	0	39
12	4.2	0	40	♦	-7.2	0	42	♦	0.2	0	45	0.3	♦	8.3	300	0	41
11	4.2	0	40	♦	-7.1	1	45	♦	0.0	2	46	0.2	♦	8.2	300	1	42
10	4.2	0	41	♦	-7.2	0	46	♦	-0.2	0	44	0.2	♦	8.3	300	0	43
9	4.2	3	41	♦	-7.2	3	45	♦	-0.1	2	44	0.3	♦	8.4	300	3	43
8	4.1	1	45	♦	-7.2	0	46	♦	-0.1	5	44	0.3	♦	8.3	300	1	45
7	3.9	0	46	♦	-7.2	0	45	♦	-0.1	0	43	0.1	♦	8.2	297	0	45
6	3.7	3	46	♦	-7.3	0	46	♦	-0.2	0	42	0.3	♦	8.3	297	3	46
5	3.4	2	45	♦	-7.0	0	46	♦	-0.3	0	42	0.5	♦	7.8	294	2	45
4	3.3	0	44	♦	-6.9	1	46	♦	-0.4	3	37	0.4	♦	7.8	294	1	45
3	3.3	2	45	♦	-5.8	3	46	♦	-0.1	0	36	0.4	♦	6.7	300	3	45
2	3.0	1	43	♦	-6.1	0	42	♦	-0.1	3	32	0.3	♦	6.9	297	1	42
1																	
6	1.2	0	46	♦	-3.2	0	46	♦	0.2	1	46	0.0	♦	3.4	291	0	46

The left column gives height ranges, in this case in units of 30 m (Range 2 = 60 m, Range 3 = 180 m, Range 10 = 300 m, etc).

Sample data printout.

The resulting wind profiles for each period are printed out on a Texas Instruments Model 743 printer. Each printout includes: the north-south horizontal component, the east-west horizontal component, the vertical component, a turbulence estimator (which is the variance of the vertical component), and the resultant horizontal wind as a single wind speed and direction. This is done for every range gate, starting with 60 meters and continuing to the maximum height selected, up to 50 range gates, or the maximum height observed. Ground level wind data is input from propeller anemometers, which are supplied with the system.

An automatic frequency alteration for the transmit pulse is provided as a part of the system. On the basis of the wind during the previous integration period, the frequency is adjusted for the next period to keep the measured quantity in the mid-range of the comb-filter. This extends the working range of the filter to component speeds of ± 25 m/s. Therefore, in some directions, wind speed and direction can be covered to vector speeds of 35 m/s. This technique permits the total frequency band evaluated to be narrow, minimizing the acceptance of spurious noise.

The altitudes to which data are obtained vary widely with meteorological conditions and show a marked diurnal variation with nighttime and low wind conditions being generally more favorable.

SYSTEM DESCRIPTION

Basic

The basic system consists of an outdoor portion with essentially no moving parts, and the electronics and related control and recording equipment, which must be kept in an environmentally controlled shelter or building. The antennas are usually located 200' from the instrument shelter with the primary control and signal cable running between the antennas and the shelter. The antenna itself is a high frequency compression driver coupled to a four-foot diameter parabolic dish by means of a conical horn. The antenna is installed in an acoustic enclosure to reduce background noise.

Since there is generally good mixing in the lowest levels of the atmosphere, a surface wind measurement is included with the Doppler data. Depending upon the Doppler configuration, two-component or three-component, the anemometers will be configured in the same manner. The components are measured with axial propeller-type anemometers with one axis typically north and one typically west. The outputs from these anemometers are wired directly into the system so that the format of the data simply starts with the surface level and goes upward. Under most conditions, there will be relatively good agreement between the lowest level from the Doppler (typically 60 meters) and the surface winds.

All the electronics, including the microprocessor and software programs, the amplifier for the antennas, appropriate power supplies, and a TI 743 printer are contained in a bench-top cabinet inside the shelter. The TI 743 printer allows for a hard copy printout of the data. A Model 322A facsimile chart recorder is available to provide a display of mixing depth. For a permanent on-site recording of the data, a Kennedy Model 1600/360 tape recorder may be used in conjunction with the system.

**TI MODEL 743
TERMINAL**

**AV MODEL 322A
CHART RECORDER**

**AV MODEL 2000 SOUNDER
ELECTRONICS PACKAGE**

**KENNEDY 1600
INCREMENTAL MAGNETIC
TAPE RECORDER**

OPTIONS

Vertical Component

The first major addition to be considered is a third antenna to measure the vertical component of the wind. When this is included, the software will also provide the variation of this component. Since the average vertical wind is often very small, it is the short-term fluctuations that serve as the dispersing elements in the atmosphere.

Towers

To be consistent with World Meteorological Organization and U.S. EPA standards, the anemometers should be mounted at 10 meters above the site elevation. Typically, this is done with a ten-meter tower, which may be guyed, telescoping, self-supporting, or foldover.

Dish Heaters

In climates where snow and ice frequently occur, it is most helpful to have heated dishes for the antennas. Although this does not totally eliminate the effects of moisture, it maximizes the time during which useful data can be taken.

Trailer

Although the standard enclosures come with a steel-frame base for permanent mounting, trailer mounting for the two-component antennas may prove very useful. It not only serves as the base for the antennas and enclosures but is also a very easy way of transporting the system. This is especially useful when doing survey work. Provision is made for adjustment of the antennas and the outboard junction boxes are attached to the enclosure on the trailer.

Magnetic Tape Recording

This option provides for permanent recording of the data on 9-track, 800 bpi, 1/2" IBM computer-compatible magnetic tape. A printer is part of the standard system so that hard copy is available, but if no additional means of data recording is available, this recorder is almost a necessity.

Facsimile Recorder

This option provides a time plot of signal intensity versus height. The signal intensity represents the strength of the echo after initial processing by the comb-filter and computer -- i.e., it shows only "accepted" range gates. Thus, this recorder conveniently displays the overall height and quality of the data.

Real Time Spectra Display

By the simple addition of an oscilloscope, each spectrum can be displayed in real time. This feature is useful in setting up a particular installation and in verifying the proper operation of the instrument.

FIELD CONSIDERATIONS

One must consider the data requirements for which the Doppler is being used, as well as other factors which will affect the performance of the system. Four basic areas should be examined:

- o Site selection
- o Availability of commercial power
- o Instrument shelter
- o Site security

The selection of a suitable site is absolutely mandatory. First, the site should be representative of the area of interest. It should be open so there are no tall structures nearby which will give extraneous echoes thereby creating erroneous data. Secondly, the site should be as quiet as possible. As a general rule, the antennas should be placed on relatively high ground. This will help reduce the entry of noise into the enclosures. Noise from construction, traffic, and other sources should be at a minimum. A noise meter must be used and typical values under calm wind conditions should be less than 65dBA.

A good starting point for the selection of the site is a USGS topographical map of the area. Unlike the siting of surface meteorological instrumentation, the dimensions of the Doppler system give the user considerable leeway. When you keep in mind the fact that the Doppler is typically measuring winds up to 600 meters, AGL, it is more than acceptable to have the site within two kilometers of the particular point of interest. Typically this might be a mill, power plant, or other point source. It is also important to keep in mind that a typical averaging time of ten minutes to thirty minutes is utilized. Air over the site will generally travel a few kilometers during this averaging time, therefore, it is not at all impractical to consider a site up to approximately three kilometers away from the key point of interest.

It is strongly suggested that AeroVironment assist with the site selection. These services are provided on a time-and-materials basis.

Good commercial power is almost a necessity. Power should be 115 VAC, ± 15 volts, and a frequency of 60 Hz.

If a suitable existing building is not available, an instrument shelter should be built or purchased. This should be environmentally controlled to 20°C , $\pm 5^{\circ}$.

Security for the shelter and antennas is worthy of consideration. Fencing is suggested where appropriate.

Once the Model 2000 is in place, commissioning of the system is as simple as its design. It requires no setting up procedure other than turning on the power. All the initial operating parameters are preprogrammed and set automatically.

DESIGN SPECIFICATIONS

Wind Speed Range (nominal)	0.25 m/s, component wind; 0.35 m/s, vector wind
Wind Speed Accuracy (nominal)	0.2 m/s in locations of high signal-to-noise ratio
Components	Two: horizontal orthogonal
Vertical Height Range	600-meter, AGL standard, operator-selectable: 60 to 1500m
Vertical Height Resolution (height interval)	30 meters
Minimum Height for Reliable Data (nominal)	60 meter AGL
Transmit Pulse Frequency	1500 Hz
Transmit Pulse Width	180 milliseconds
Transmit Pulse Interval	Dependent upon vertical height range; for 600-meter, a pulse is transmitted approximately every 5 seconds; antennas are alternated
Transmit Power Level	100 electrical watts at antenna
Averaging & Reporting Interval	15 min. standard; approximately 100 pulses per antenna for 600- meter vertical height range; operator-selectable: 2 minutes to 30 minutes
Output Format	Component output: u, v in m/s Vector output: U, θ in m/s and degrees Other formats operator selectable

RELIABILITY

Since there are very few moving parts to this system, the reliability is very high. The one exception is the propeller anemometers, which do require periodic maintenance. Under normal conditions, the system can be expected to operate for several years merely with proper maintenance of the printer, tape recorder, and antennas.

For further information, write or telephone:

**AEROVIRONMENT INC.
145 VISTA AVENUE
PASADENA, CALIFORNIA 91107
(213) 449-4392**

xonics

6849 Hayvenhurst Avenue, Van Nuys, California 91406, Telephone: (213) 787-7380 TWX 910-495-1725

January 25, 1980

Mr. William H. Hooke
R45/R45X7
USDC, NOAA Environmental Research Laboratory
Boulder, Colorado 80302

Dear Mr. Hooke:

I am writing in response to your letter of December 14, 1979, to Dr. Balser regarding your charge from the Department of Energy. I am enclosing a copy of our sales brochure and our current price list, copies of two published articles relative to our XONDAR, and a copy of a paper I presented before the Intercomparison of Low-Level Sounding Techniques last August. If you wish information relative to the XONDAR's performance at the intercomparison, John Gayner has all of the statistics.

The answers to the questions posed in Attachment 1 to your letter are as follows:

- 1) The XONDAR is a bistatic Doppler-Acoustic air-motion sensor system that transmits high energy pulses of sound vertically and detects the sound reflected back to three antennas by ever present microscale turbulent eddys and/or non-adiabatic density variations in the atmosphere.
- 2) The Doppler-shift spectrum in the sound scattered from a volume of air is directly proportional to a component of air motion in a volume delimited by the beam width and pulse length of the transmitted sound-burst. The trigometric resolution of three components of atmospheric motion (see accompanying brochure) results in the three orthogonal-component spectra of atmospheric motion within the sampled volume. These three spectra can be analyzed by the system's computer to extract the spectral mean and standard deviation of all three orthogonal components of the air motion within the pulse volume. In normal operation, several successive pulse spectra are summed to produce the temporal mean and standard deviations within each sampled volume.

The XONDAR's optional acoustic sounder capability produces a profile of the acoustic reflectivity of the atmosphere over the vertically-directed transceiving antenna. This reflectivity is proportional to stability of the atmosphere.

The XONDAR is an all-weather device when equipped with the optional snow-melting hardware. The maximum velocity quoted in the enclosed brochure (25 m/s) is relative to a motion component along a vector from the sampled volume to the receiving antenna. Horizontal velocity limits are nominally 30 to 40 m/s, depending upon the altitude of the sampled volume. The practical limitation, however, is a surface wind that generates noise through interaction with obstacles. This is a function of the operating environment.

- 3) The 4000 Hz Model 300 XONDAR has a nominal height range of 200m and a resolution of 12 or 25m (depending upon the sound pulse-length selected by the operator). The 2000 Hz Model 600 XONDAR has a height range of 500m and a resolution of 25 or 50m (depending upon the sound pulse-length selected by the operator).
- 4) The accuracy of the measured velocity component is 0.2 m/s. The wind speed accuracy is better than 1 m/s. Several comparisons against tower-mounted instruments have shown such agreement and correlations of .9 or better (.97 in comparison with your WPL tower instruments).
- 5) The space sampling rate is limited only by the range resolution specified in (3) above. The time sampling rate is limited by the maximum altitude of measurement, the speed of sound and the number of altitudes sampled. Three to five altitudes of observation of all three components of motion to 150 meters can be accomplished in two seconds. These observations can be integrated from 1 to 60 minutes or more at the decision of the operator.

* * *

- 1) The XONDAR is a commercially-available operational instrument.
- 2) The expertise required to install and operate a XONDAR can be learned in a few minutes with the instructions provided. The most complicated aspect of the installation is the placement of the two receiving antennas so that they form a horizontal right triangle with the transceiver at the right angle and determination of the compass direction of receiver No. 2. In routine operation,

Mr. William Hooke
January 25, 1980
Page three

the XONDAR operates for long periods unattended. The only attention required is the change of recording medium -- paper supply or magnetic tape.

3) The XONDAR operating requirements are:

- (a) 115 VAC $\pm 10\%$ @ 50-60 Hz
15 Amps to the transceiving antenna
15 Amps to the processor and printer
- (b) All data processing hardware and software are included with each unit, and there are several available options such as magnetic-tape recording, telephone modems, etc.

4) The XONDAR sells for about \$60,000 depending upon the data recording device or other options selected.

I hope the enclosed material and the answers above fulfill your need for information. If you have any further questions or would like to discuss some aspect of XONDAR, please feel free to call me any time.

Very truly yours,

XONICS, INC.

Robert L. Peace, Jr.
Principal Meteorologist

RLP:ps

Enclosures

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XONDAAR

REMOTE AIR
MOTION SENSOR

A-47

4/ 2/80	11:20			20-MIN. AVE.		
ALT	VX	VY	VZ	SDX	SDY	SDZ
M	M/S	M/S	M/S	M/S	M/S	M/S
50	2.9	2.3	-0.1	1.9	2.2	0.5
100	4.9	2.5	-0.3	1.6	2.1	0.4
150	4.5	3.1	-0.2	1.5	2.3	0.5
200	4.8	3.2	-0.2	1.3	2.1	0.7
250	5.2	3.5	-0.1	1.0	2.1	0.8
300	5.2	2.6	-0.1	1.1	1.8	1.0
350	6.0	2.7	-0.0	0.9	1.6	1.1
400	6.1	2.8	-0.0	1.1	1.7	1.1
450	6.0	2.7	-0.1	1.3	1.7	1.2
500	6.3	2.5	-0.2	1.4	1.8	1.2

4/ 3/80	10:40			20-MIN. AVE.		
ALT	DIR	SPEED	VERT.	SDCW	SDDW	SDVER
M	DEG	M/S	M/S	M/S	M/S	M/S
50	130	1.5	-0.1	0.8	0.3	0.1
100	122	1.4	-0.1	0.8	0.3	0.2
150	118	1.1	0.0	0.8	0.3	0.2
200	124	1.0	0.2	0.9	0.2	0.3
250	89	1.0	0.0	1.3	0.6	0.4
300	28	1.3	-0.3	1.0	0.3	0.2
350	25	1.9	-0.4	0.7	0.4	0.2
400	19	3.1	-0.2	0.4	0.3	0.1
450	15	3.8	-0.1	0.4	0.3	0.2
500	13	4.3	-0.1	0.3	0.1	0.2

4/ 2/80	11:40			20-MIN. AVE.		
ALT	VX	VY	VZ	SDX	SDY	SDZ
M	M/S	M/X	M/X	M/S	M/S	M/S
50	2.8	2.5	-0.2	1.8	2.0	0.4
100	3.3	3.0	-0.4	1.5	2.1	0.4
150	3.7	3.3	-0.3	1.0	2.3	0.6
200	4.2	3.4	-0.2	1.5	2.0	0.8
250	4.8	3.7	-0.2	0.9	1.7	0.9
300	4.9	3.5	-0.4	0.9	1.6	1.1
350	5.5	3.4	-0.2	1.0	1.3	1.2
400	5.5	3.4	-0.2	0.9	1.1	1.2
450	5.4	3.4	-0.1	0.9	1.3	1.2
500	5.2	3.5	-0.1	1.1	1.3	1.3

4/ 3/80	11:00			20-MIN. AVE.		
ALT	DIR	SPEED	VERT.	SDCW	SDDW	SDVER
M	DEG	M/S	M/S	M/S	M/S	M/S
50	70	1.7	0.0	1.4	0.7	0.2
100	50	2.8	-0.2	1.8	0.9	0.2
150	44	3.3	-0.1	1.9	1.1	0.4
200	42	3.6	-0.2	1.7	0.8	0.7
250	42	3.8	0.1	1.5	0.8	0.9
300	40	3.8	-0.2	1.3	0.8	0.9
350	40	3.6	-0.1	1.2	1.0	1.0
400	37	4.1	-0.2	1.4	1.2	0.8
450	31	4.3	-0.3	1.3	1.1	0.7
500	20	4.6	-0.3	1.4	1.1	0.7

The XONDAR Remote Acoustic Air-Motion Sensor

XONICS TECHNOLOGY, INC.

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The XONDAR Remote Acoustic Air-Motion Sensor

1. INTRODUCTION

Many of the activities of modern society must deal with problems that involve the thermal structure and motion of the lower few hundred meters of the atmosphere. Air quality management, aerosol transport, wind-energy development, airport operations, weather modification, urban and industrial planning, industrial and commercial design (especially electrical generation and refining) and many other disciplines either depend upon, or could benefit from, a knowledge of these atmospheric conditions. Until recently, determination of air motion (wind, convection, wave motion, turbulence, etc.) and thermal structure above the standard 10-meter anemometer height has been inhibited by the substantial cost and siting problems associated with large towers or the severe limitations of measurements using tethered or free-flying balloons. In the past few years, the situation has been changed dramatically by the introduction of instruments that are installed on the ground and remotely observe thermal structure and measure air motion through the lower few hundred meters of the atmosphere. They require only bursts of sound to pass through the layer of atmosphere to be studied. These instruments exploit the phenomenon of scattering of sound waves by the large number of small, ever-present, turbulence-induced irregularities in the distribution of temperature and wind. Such instruments are referred to as Acoustic Sounders, Acoustic Radars, Sodars or just Sounders when they simply observe the intensity of the acoustic return. They are known as Doppler-Acoustic Wind and Vertical Motion Sensors, Doppler-Acoustic Radars, or Acoustic Anemometers when they measure atmospheric motion.

Experimental acoustic sounders were first developed during and immediately after World War II, but a practical system was not introduced to the meteorological and engineering communities until the late 1960's. These instruments consist basically of a high-energy sound transmitter that directs short pulses of sound vertically, a sensitive receiver and a recorder (such as a facsimile machine) for a time-versus-height record of acoustic reflectivity. In most acoustic sounders, the sound is both transmitted and received through the same antenna or "horn" in a monostatic configuration. The theory for the scattering of sound in turbulent air shows that only temperature variations are effective in producing the 180 degree back-scatter detectable with such a configuration. A few sounders use separate transmitting and receiving antennas in a bistatic configuration. Both temperature and wind variations contribute to the echo returned in systems with a bistatic configuration.

For the past several years, Acoustic Sounders have been widely utilized to ascertain lower atmospheric characteristics. These include the presence, height, thickness and relative intensity of thermally stable layers, the presence and characteristics of wave motion on (and the time and character of formation and break-up of) such layers. They also indicate the height

of the top of fog or low clouds, the character of sea-breeze fronts, heated plumes from smoke stacks and jet aircraft exhaust, the mixing height and several other phenomena.

As early as 1968, XTI personnel began the development of a coherent, bistatic acoustic sensor to observe winds in the lower few hundred meters of the atmosphere. Through years of engineering and testing, the XONDAR concept evolved into a sophisticated, efficient, remote air-motion sensor, field proven in the United States as well as in other countries. This system, its principles of operation, attributes and physical description are outlined in the following two sections. Section four describes a number of standard options that make the basic XONDAR more versatile and adaptable to specialized applications. The last section describes computer software support that is available to facilitate special data formatting and real-time calculation of many different wind and vertical motion-related variables of interest in air pollution, and environmental definition studies.

2. PRINCIPLE OF XONDAR OPERATION

The XONDAR transceiver transmits a short pulse of high-intensity sound vertically. A small fraction of this sound is scattered back toward the surface by each volume of air through which it passes. (This is shown schematically in Figure 1.) At the point of scattering, the frequency of the

FIGURE 1 Observing geometry of the XONDAR

sound is altered by an amount proportional to the velocity component of the scattering air in the direction of the bisector of the angle between the incident and the scattering directions. (Figure 1.) The frequency-altered sound is detected by the transceiver and two receiving antennas at displaced locations, amplified and transmitted to the processor over interconnecting cables.

At the processor, the signals from all three antennas are sequentially digitized and supplied to the computer. In the computer, the received digital data are processed by a Fast-Fourier-Transform algorithm to analyze the frequency content of the signal returning to each receiver from each sampled altitude.

The frequency spectra are summed for a number of transmitter pulses (typically 24) to enhance the scattered acoustic signal relative to interfering noise. Once this summation is complete, the means and standard deviations of all velocity components at all observing levels are calculated and any desired coordinate transformations are made. The data are then printed and/or stored on magnetic tape.

In the calculation of horizontal components of motion (wind), the measured vertical velocity is trigonometrically combined with the slant components as diagrammed in Figure 1. This prevents serious error in calculations of horizontal velocity from the strongly inclined vector velocity when vertical velocity is appreciable.

3. THE BASIC XONDAR ACOUSTIC ANEMOMETER

A basic XONDAR wind-profile measuring system consists of five subsystems—the sound producing and sensing hardware, the computer, the printer, the program input and storage device, and the command keyboard. Two models of the XONDAR are offered—the Model 300 and the Model 600. These differ primarily in hardware attributes. The Model 300 provides finer height, time and velocity resolution. The Model 600 system offers a greater altitude range. The characteristics and attributes of both models are given on the inside back cover.

3.1 The Sensor Subsystem

The sensor subsystem for both models of XONDAR is composed of one transceiving and two receiving antennas with their supporting electronics as diagrammed in Figure 2. Each of the three antenna assemblies (shown

FIGURE 2 Block diagram of the XONDAR sensor subsystem

on the inside front cover) consists of an aluminum parabolic reflector mounted in the bottom of a fiberglass housing lined with foam rubber and lead. This effectively prevents sound from escaping the transceiver housing or entering any of the housing except through their openings. At the focal point of the transceiving antenna is an acoustic transducer that both emits high-power pulses of sound in a narrow circular beam and detects sound returning from the atmosphere.

The two outlying receiver antennas are equipped with transducers and feed-horns that detect sound from a narrow horizontal, but fan-shaped vertical, angular region centered on the transmitter beam.

In operation, the three XONDAR antennas are normally located in the right-triangle configuration diagram in Figure 3, with an antenna separation of approximately 80% of the maximum altitude to be observed. Thus,

FIGURE 3 XONDAR antenna configuration

for the nominal 200m maximum observing altitude of the Model 300, antenna spacing should be about 150m. For the nominal 500m maximum altitude of the Model 600, antenna spacing should be 350 to 400m. The configuration shown in Figure 3 and these antenna separation specifications are standard, but the computer program that performs data reduction is sufficiently versatile to allow considerable variation in antenna spacing, orientation and relative height where site considerations dictate. XTI personnel can advise a user of the quantitative consequences of any particular non-standard configuration so site-imposed constraints can be minimized.

The principal difference between the Model 300 and the Model 600 XONDAR's lies in the operating frequencies of the two systems. The Model 300 system operates at a frequency of 4 kHz to achieve the advantages listed earlier. However, atmospheric attenuation at this frequency is approximately twice as great (in dB) as that at the 2 kHz frequency used by the Model 600. Figure 4 shows the dependence of attenuation on atmospheric temperature and humidity at both frequencies. It is seen that the best performance is expected when the equipment is operated in a warm and humid or cold and dry environment. In addition, detectability is proportional to the duration of the sound pulse emitted and height resolution is inversely proportional to it. When atmospheric conditions are favorable (or higher-altitude data are not desired), an optional shorter pulse (see Table on inside back cover) can be used for finer height resolution. When data are needed above 200m or under very cold and humid or warm and dry conditions, the 2-kHz Model 600 system is advised.

The electrical power requirements of both XONDAR systems are 100-120V, 50-60 cycles at 15A supplied at the computer location and 15A supplied to the transceiver antenna. The low-voltage power requirements of the receiving antennas are provided through the interconnecting cables supplied with the system. These cables also carry all intelligence to the computer.

FIGURE 4 Atmospheric attenuation as a fraction of temperature and humidity at 2 and 4 kHz

3.2 The Computer Subsystem

The heart and brains of the XONDAR system is an LSI-4 mini-computer with 64,000 words of memory, a real-time calendar-clock, a precision lapse-time clock and a small non-volatile memory sufficient to read-in and restart the program after a power failure. Figure 5 shows the basic functions performed by the computer.

FIGURE 5 Computer function

The upper cabinet in Figure 6 contains the computer and data-interface hardware. Because it controls all functions of the system, the computer and the XTI-provided program offers considerable flexibility in system configuration, operational mode and data format. The standard selectable system configuration elements are relative antenna altitude, spacing and orientation. Selectable operational modes are pulse duration (which determines velocity and height resolution), pulse repetition frequency (which determines maximum unambiguous observable height as well as the number of samples per summation period), summation time (which must balance the frequency of observations against the statistical significance of the data), duration of observation versus no observation (if intermittent operation is desirable), and height levels to be sampled (up to 10). The data output consists of mean wind and standard deviation in either vector component form (V_x , V_y , V_z , σ_x , σ_y , σ_z) or polar coordinate form (θ , S , V_z , σ_θ , σ_S , σ_z). Additional types of output are discussed in Section 4 and 5.

FIGURE 6 The processor, keyboard and mini-floppy disk drives

3.3 The Program-Storage Subsystem

The computer program to control the XONDAR's operations and the default values of the system configuration, operational mode and data format are provided on two mini-floppy disks. These disks are automatically read into the computer through the system's dual mini-floppy disk drive (located in the lower cabinet in Figure 6) when the system is activated or when changes in the program or default parameters are desired. Once read in, the computer program automatically begins operation of the XONDAR. If power is interrupted during operation, the computer automatically rereads the program and automatically begins operation whenever power again resumes. The real-time calendar-clock continues to operate for long periods on its own storage battery. Thus, the system resumes operation without loss of date or time reference.

The residence of both the controlling program and a default value of all operational parameters on a pair of floppy disks makes it possible for XTI to rapidly and economically provide the user with different default values whenever his basic XONDAR use changes. Should it be desirable to add optional hardware or data-analysis capabilities (such as outlined in Sections 4 and 5), the computer program necessary to accomplish the changes will also be provided by XTI on system-compatible mini-floppy disks.

3.4 The Printer

The system printer (Figure 7) is a stand-alone 40-column printer connected to the computer through a simple cable. This arrangement makes it possible to locate the printer wherever most convenient within several feet of the computer. The unit prints data, heading information, command prompts and echos keyboard entries on a 3¼" wide roll of standard paper. The printer is equipped with a take-up reel that rewinds the paper a few inches beyond the print roller. Sufficient paper is exposed to allow examination of the most recent set of air-motion data without removing the take-up reel from the printer.

FIGURE 7 The air-motion printer

3.5 The Keyboard

All operational communication with the XONDAR system is accomplished through a standard computer-type keyboard, mounted on the door-shelf of the lower processor cabinet (Figure 6). A list of the standard commands and a brief description of their functions is given in Table I.

TABLE I
BASIC OPERATOR COMMANDS

BEgin = hh:mm:ss	Commands the system to begin operation at hh:mm:ss. If only BE is entered, the system begins immediately.
STop	Commands the system to stop immediately.
CYcle = AV, ON, OFF	Commands the system to operate for ON minutes, then pause for OFF minutes. While operating, the system will collect data for AV minutes for each data output.
LIst	Commands the system to list the current values of the system parameters below.
TEmpérature = NN	The average air temperature (°C) for calculation of the speed of sound.
ALtitudes = MIN, MAX, SEP	Defines the height above the transmitter (m) of the first and last range gate and gate separation.
PL = (0 or 1)	The transmitter pulse-length desired.
INtegration = ss	The number of seconds for spectra accumulation.
PRi = ss.s	The pulse-repetition interval in seconds.
GEometry = N	Output coordinates—equipment orientation, compass cartesian coordinates, or polar coordinates.
BAse = B1, B2	Distance (m) between the transceiver and the two receivers.
HEight = H1, H2	The altitude difference (m) between the transceiver and the two receivers.
ROtation = DDD	Defines the angle (degrees) between true north and the direction from the transceivers to receiver #2.
DAte = mm/dd/yy	Resets system calender when desired.
TIme = hh:mm:ss	Resets clock when desired.

4. XONDAR SYSTEM OPTIONS

The basic XONDAR system described in the previous section can be augmented with additional components to enhance its usefulness for particular applications. The standard optional components described in this section represent only the most generally useful additions. XTI personnel can evaluate the feasibility and cost of particular optional attributes or capabilities in response to specific inquiries.

4.1 Sounder Output Printer

The principal option offered is one that displays a time-height profile of the intensity of acoustic signal returned from the atmosphere—sounder data. XTI accomplishes this with a computer-controlled printer in place of the conventional facsimile recorder.

The sounder system utilizes the flexibility, analysis power and decision-making capabilities of the XONDAR digital computer to process the returning signal. This allows the sounder data to be corrected for loss due to range, to be largely compensated for attenuation and to minimize the effects of extraneous noise. It also can provide the user with a variety of time-scales for data output.

The sounder system can be operated in the conventional monostatic manner (using the intensity of signal received by the transceiver antenna) or bistatically through one of the two receiving antennas. The choice of antenna, or antennas, utilized can be easily changed by the user in a few minutes.

The XONDAR sounder output device is a custom-modified, 132-character/line, dot-matrix computer printer (Figure 8) that uses standard tractor-feed, Z-fold paper. The printer's set of characters or shades-of-grey is controlled by pre-programmed prompts, and includes the letters and numbers required to label the output.

FIGURE 8 The sounder printer

Since the dot combinations for the various levels of received sonic intensity are controlled by replaceable prompts and the computer program, great versatility of sounder output is possible. The standard prompts offered by XTI allow 10 discrete shades-of-grey and one set of number symbols (as shown in Figure 9).

FIGURE 9 Sample sounder output

The number of received reflectivity profiles (and the corresponding time interval) represented by each line of printer output can be varied if desired. This further increases the versatility of the optional sounder output.

4.2 Ice and Snow-Melting Hardware

If use of the XONDAR is contemplated under freezing rain or snow conditions, the optional ice and snow-melting hardware should be ordered with the system. This hardware consists of electrical heating cables fastened to the underside of the aluminum parabolic reflector, an individual thermostat, special insulation of the antenna base and the necessary power cables.

4.3 Magnetic Digital Recording

XTI offers a broad spectrum of hardware and software support for the user who wishes to record data on magnetic tape for later analysis or combination with information from other sources. This support ranges from simply interfacing the user's recorder to the computer to customized recording and on-line or off-line analysis and parameter calculation (see Section 5).

4.4 Ten-Meter Anemometer

Many applications require a knowledge of air-motion characteristics at the international standard height of 10 meters above the surface. The XONDAR is capable of observing wind averaged through a depth equal to the length of its sound burst—to 25m for the Model 300 and to 50m for the Model 600—if reflection from objects and external noise are minimal. Generally however, the average wind close to the surface is not sufficiently similar

to that at a specific level to satisfy most requirements for 10m wind. To fill this need, XTI offers an optional anemometer on a 10-meter tower. Data from the anemometer is supplied directly to the computer. There it is incorporated with XONDAR air-motion data to complete the profile down to this significant level.

4.5 Telephone or Radio Modem Option

Should it be desirable to control the XONDAR system and monitor its output at a considerable distance from the observing site, XTI can provide the necessary modems to interface the computer and its peripherals with either a telephone line or FM radios.

5. PARAMETER CALCULATION AND DATA ANALYSIS SUPPORT

The use of a Fast Fourier Transform and advanced analysis techniques allows XTI to offer both mean motion and the standard deviation of motion as basic output data. Further, these data can be formatted in either Cartesian or polar coordinates. When this information is combined with the optional 10m data and the height distributions of stability shown by the sounder, the elements are available for calculation or estimation of most atmospheric characteristics that impact on human endeavor and environment. Virtually everything that can be learned from a meteorologically-instrumented tower can be extracted from acoustic air-motion and sounder data. Much of it can be determined automatically in real time or near real time.

XTI stands ready to provide a variety of services to support an individual user's needs. These services range from special computer programs to allow the XONDAR computer to perform real time calculation of specific parameters of interest to the user, to statistical analysis of observed or derived parameters for climatological purposes, to complete planning, observation, data reduction, analysis and reporting services to meet EPA, NRA, DOE or other requirements related to air-motion and atmospheric stability.

The most generally useful motion parameters or atmospheric characteristics are those related to turbulence and aerosol diffusion. XTI can provide the computer programs to determine such parameters as relative aerosol concentration (x/Q) as a function of distance from the source, the exchange coefficient for momentum or concentration of fine aerosols, the friction velocity, the exponent of the power law wind profile relationship, turbulence scale length, the Pasquill stability class, the Sutton coefficients, mean mixing height, and other parameters. XTI also has in-house capability for determining various site-specific parameters from XONDAR system data. A few examples of such information are the local surface roughness as a function of fetch and stability, the characteristics of local mountain and valley and/or land and sea breezes and the correlation of low-level winds aloft at a particular site with conventional data from nearby weather stations with climatologically significant lengths of records.

For more information relative to your specific data or analysis needs, contact Xonics Technology, Inc.

XONICS DOPPLER-ACOUSTIC REMOTE (XONDAR) WIND SENSOR TECHNICAL SPECIFICATIONS

	Model 300	Model 600
Antenna diameter (inside)	3 ft (0.9 m)	4 ft (1.2 m)
Peak power to transducer (electrical)	250 watts	250 watts
Peak output power (acoustic)	40 watts	80 watts
Transmitted frequency	4000 Hz	2000 Hz
Pulse duration (computer controlled)	80/40 msec	160/80 msec
Altitude resolution	25/12 m	50/25 m
Velocity accuracy (one component)	.2/.4 m/s	.2/.4 m/s
Maximum velocity (one component)	±25 m/s	±25 m/s
Pulse repetition interval (nominal)	2.5 sec	5 sec
Nominal maximum altitude for velocity	200 m	500 m
Maximum altitude for sounder	400 m	800 m
Number of altitudes sampled	10	10
Averaging time (nominal)	2 min	2 min
Power requirements	115V ±10% @ 30 amps, 50-60 Hz	

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80303

30 November 1979

TO: W.H.Hooke, NOAA/WPL / Atmospheric Studies Program Area
FROM: R.B.Fritz, NOAA/WPL / Optical Sensor Development Program Area
SUBJECT: Optical Crosswind Sensors (Contribution to DoE Wind Energy Survey)

The Optical Sensor Development Program Area of NOAA/WPL has developed a series of remote sensing devices that measure wind across an optical path. This provides a path-averaged reading across the line-of-sight between a light source and the receiver. The principle on which this operates is that the scintillation of a distant light is caused by refractive index variations in the clear air and these eddies are blown along by the prevailing wind. Although the eddies are constantly forming and dissipating, there is enough persistence for two detectors very close together to sense coherence in the scintillation patterns and a simple correlation computer relates this to the component of wind across the path and in the plane of the source and the two detectors. This measures the path-averaged wind relatively uniformly weighted along the path except at the ends, where like a camera there is a minimum focus distance.

Sensors have been built by NOAA/WPL that use a laser light source, an incandescent light, background natural light, and a modulated .94 μm LED source. A commercial version of the laser system is being built by Campbell Scientific Co. of Logan, Utah. These sensors are described and pictured in the references appended to this summary.

These devices have been used with paths parallel to the ground, over valleys, etc., and may not be suitable for measuring the vertical profile of wind. They can substitute for a series of conventional anemometers over an extended area and have the advantage of using no moving parts. They do require line-of-sight visibility and cannot operate during heavy rain, snow, or fog. The minimum range at which they have been used is 100 meters; the maximum range is limited only by visibility, or for the laser system by saturation (see paper by Ochs, Clifford, and Wang). Various wind speed ranges have been used, up to ± 40 meters per second in the Boulder high wind environment, and the system has no minimum speed inertia problem, being able to measure down to zero wind. Precision of measurement is generally limited by the recording device. Due to space averaging, sampling rates less than once per second are not realistic and these sensors are designed to have a 1 to 100 second (selectable) output time constant.

Several examples of these sensors are in routine operation by WPL. The sensor must be calibrated for the range at which it will be used, and a stable mounting with protection from weather must be provided. Installation and operation is not complicated. Battery operation of the LED light source and of the receivers is possible, but availability of 110 v AC power is preferable since batteries have to be recharged periodically, typically every week. Operation of a data logger or other recorder may also require 110 v AC. Installation, including optical alignment of the light and receiver can be carried out in a couple of hours and will require communication between people at each end of the path. If the path is long, travel time between ends becomes a consideration. If the modulated LED system is used, a means of finding the IR beam, e.g. a hand held detector scope, is needed.

The cost to build one of the LED systems, including light source and receiver, but not shelters or recorders, would be on the order of \$5000. Cost of operation would depend on time spent to service the equipment, the data recording and analysis systems, and cost of providing power, either battery or AC.

R.B.F.

Model CA-9

SPACE AVERAGING

ANEMOMETER

By

Campbell Scientific

CS

DESCRIPTION

When small scale temperature fluctuations, produced by atmospheric turbulence, are swept across a laser beam path by the wind, a drifting scintillation pattern is produced. The CA-9 Space Averaging Anemometer measures the drift velocity of the scintillation pattern and computes from it the component of the wind velocity which is perpendicular to the beam. Weighting of the signal is relatively uniform over the beam path so the reading is a measure of space averaged wind. The path length over which the measurement is made can be varied from 300 meters to 10 kilometers.

In addition, the CA-9 also measures the strength of the turbulent temperature fluctuations (standard deviation of the log-amplitude fluctuations) over the beam path.

This method of wind measurement has several advantages over conventional anemometers. Among them are:

1. A true space average is obtained rather than the average of several point measurements.
2. Measurements can be made in otherwise inaccessible locations.
3. There are no moving parts so the unit is reliable and remains accurate at very low wind speeds (no threshold as in conventional anemometers).

The anemometer will not provide accurate wind measurements when scintillation saturates. This will occur on long paths that are close to the ground when there is a high level of surface heating during a hot day. Precipitation will also interfere with accuracy. Circuitry is provided in the CA-9 to indicate conditions that will invalidate the measurement.

FEATURES

- Optics, electronics, and batteries all included in a single small package
- One year continuous operation on a single set of batteries
- Durable taut band panel meter
- Crystal controlled calibration unit
- Recorder outputs for all measurements
- Valid indicating output
- 1 nanometer bandwidth optical filter

APPLICATIONS

- Monitoring pollution drift
- Runway cross-wind measurements at airports
- Short term wind predictions for forest and brush fires
- Determination of low level convergence of thunderstorms.
- Researching mountain valley circulation systems.
- Cross-wind indication along golf course fairways and artillery ranges
- Continuous measurement of wind across inaccessible regions such as canyons, lakes, valleys or rugged terrain.
- Prediction of drift of radio-active materials from potential nuclear disaster sites
- Collection of wind data for use in structural design.
- Feasibility studies on wind energy conversion.

Laser with rifle scope mounted on a pan and tilt head.

SPECIFICATIONS

Path length: 300 meters to 10 kilometers with a 4 milli-watt helium neon laser.

Full scale range: 5, 10, and 20 meters per second.

Meter switch function: off, wind velocity, correlation, log-amplitude standard deviation, light intensity, battery check.

Time constant selection: 1, 10, and 100 second time constants on velocity, correlation and log-amplitude standard deviation measurements both on the meter and the recorder outputs.

Recorder outputs: wind velocity: ± 1 volt for $\pm$ full scale. $+1$ volt corresponds to full scale wind velocity from left to right across the path. correlation: ± 1 volt for ± 1 full scale. log amplitude standard deviation: 0 to 1 for $\bar{Ox} = 0$ to 1. valid indicator: $+2$ volts — valid -2 volts — invalid log-amplitude: ± 1 volt for $\pm$ full scale

Maximum output current: 20 microamperes

Operating Temperature range: 0° to 70°C

Power supply: 3 mercury batteries (Eveready E12N or equivalent) current drain without meter operation is 300 microamperes.

Calibration stability: velocity: $\pm 2\%$ of full scale. Correlation: $\pm 2\%$ of full scale. log-amplitude standard deviation: $\pm 2\%$ of full scale after correction proportional to the kelvin temperature.

OPTICS

Objective lens: 50 mm dia., 198 mm focal length

Aperture at focal point: 4 mm dia.

Filter: 1 nanometer at 632.8 nanometers

Sensors: United Detector Technology Pin Spot 2 D

MECHANICAL

Weight: 6.75 lbs.

Dimensions: 7" x 12" x 4"

Finish: Brushed, clear anodized aluminum

Mount: Standard $\frac{1}{4}$ " x 20 camera mounting screw

CAMPBELL SCIENTIFIC

P. O. Box 551 • Logan, Utah • 84321 • (801) 753-2342

APPENDIX B

REMOTE-SENSING BIBLIOGRAPHY

The following pages provide a bibliography to remote sensing literature, arranged according to technique (optical, acoustic, radio, or hybrid).

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