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A REVIEW OF EXISTING EDDY-CORRELATION SENSORS

by

C J Moore, D D McNeil and W J Shuttleworth

ABSTRACT

An extensive literature survey has been carried out to identify existing sensors of wind vector, temperature and humidity, and to evaluate their usefulness to a proposal to develop simple eddy-correlation apparatus capable of making a worthwhile measurement of evaporation. This report describes the results of a literature survey up to 1976 and makes recommendations on the priority to be assigned to the design and development of those sensors considered potentially useful to this proposal.

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1. INTRODUCTION

1.1 The Proposal

Probably the most fundamental problem in hydrology is the assessment of the 'water resources' presented by a particular catchment. To what extent this resource is 'available' depends on the ultimate destination of the water collected by the catchment (e.g. whether it appears as soil water or ground water), but the 'resource' itself is simply the net water input, ie, the difference between the water collected by the catchment as rainfall and that lost as evaporation. It is with the measurement, estimation and prediction of these two variables that a great deal of hydrology is concerned, the estimation and prediction usually depending on an earlier direct measurement. In this way the science depends utlimately on two measurements, those of rainfall and evaporation.

The rainfall measurement is in principle simple and fairly well understood; it is in the determination of evaporation loss that most of the problems arise. In principle evaporation can be measured directly using lysimeters to determine the weight loss, as water vapour, of representative samples of the catchment in drying periods: in practice the difficulties, expense and time scale involved in the implementation of this technique have restricted its use to only very limited research application.

The traditional solution has been to try and avoid measuring evaporation at all, by exploiting the principle of energy conservation and devising so-called 'combination equations', the most commonly used in this country being the Penman Equation. Such equations, which use measurements of meteorological variables, invariably rely on assumptions regarding the effect of surface cover (vegetation) on evaporation, although these assumptions are not always explicit. They are therefore semi-empirical and require calibration against direct measurement. In this respect the combination equation approach represents a self-defeating solution to the problem of evaporation <u>measurement</u>. In reality, it is a procedure for extrapolating one set of evaporation measurements to another area, in a way which allows for one of the important controls, namely meteorological dependence.

Over recent years a great deal of the Institute's effort has been concerned with experiments which attempt to measure evaporation by direct or indirect means. The problem provides the motivation not only for the direct measurements carried out in the Thetford project (see Report No. 3), but also for a large part of the work with the Wallingford Soil Moisture Probe (Report No. 19), and, in some not insignificant part, for the Institute's catchment experiment at Plynlimon in central Wales.

To eliminate many of the problems of present estimation methods, it is

passes the sensor in a direction away from the surface. Since the air in the atmospheric boundary layer near a natural surface is turbulent, there are, at any one position, alternate upward and downward instantaneous fluxes of energy; and the net energy flux is the sum of these instantaneous fluxes. At any instant, t, the instantaneous sensible heat flux, $H'(t)$, is given by:

$$H'(t) = \rho c_p T'(t)W'(t)$$

where $T'(t)$ is the instantaneous air temperature and $W'(t)$ is the instantaneous wind speed in a direction away from the surface, while ρ and c_p are the density and specific heat of dry air respectively. The instantaneous latent heat flux (evaporation) $\lambda E'(t)$ is given by:

$$\lambda E'(t) = \rho\lambda\, q'(t)\, W'(t)$$

where $q'(t)$ is the fractional concentration of water vapour in air and λ is the latent heat of vaporization of water. The outward latent heat flux (or evaporation) can either be determined directly as:

$$\lambda E = \int_o^t \lambda E(t).\, dt = \int_o^t \rho\lambda q'(t)W'(t).\, dt$$

or indirectly as:

$$\lambda E = R_N - H$$

ie $$\lambda E = \int_o^t R_N(t).\, dt - \int_o^t \rho c_p T'(t)W'(t).\, dt$$

where R_N is the net radiation input.

The determination is precise and not subject to theoretical limitation providing the measurements of wind speed and humidity (or temperature) are instantaneous. In practice this requirement is never entirely met: the consequence of this on the evaporation measurement depends on the frequency distribution of turbulent eddies transferring the energy, that is, on the proportion of energy flux transferred in the high frequency eddies. The evaporation measurement is, of course, also dependent on the precision of the sensors and their ability to respond to low amplitude inputs.

obvious that some technique of directly measuring the flux of water vapour as it leaves the surface is highly desirable. A 'direct' measurement in this context is one in which the necessary theoretical assumptions are few and easily justified; and which can if required give in real time (and *in situ*) an output proportional to the required measurement of evaporation rate. The only technique known at present which can do this (except perhaps that using weighing lysimeters) is the eddy correlation method.

A great deal of useful work has already been done on the measurement of energy fluxes by the eddy correlation technique, not only in this country, but particularly in the USA and to some extent Australia; but it has been limited by cumbersome electronics, inadequate sensors, and (to a lesser extent) a lack of understanding of atmospheric turbulence. Groups working in this field have tended to be interested in the study as a research topic, and to regard the technique as a tool for studying the turbulent structure of the atmosphere. As a result they have tended to develop expensive and very precise, 'state-of-the-art' instrumentation, unsuitable for other than research application.

Most of the instrumental development for previous work was done some time ago, but in the last few years there has been a revolution in the electronics field. The advent of cheap integrated circuits has opened up the possibility of easy-to-use (yet sophisticated), real-time electronic analysis. Although not as dramatic, there has also been some progress in the understanding of the sensors used in such instrumentation, and a much greater understanding of atmospheric turbulence.

The Institute is now attempting to design and build a simple piece of equipment which will work with minimum supervision, but which is capable of yielding a worthwhile measurement of evaporation for hydrological applications. The equipment will be based on the eddy-correlation principle and will exploit the recent breakthrough in digital electronics. Its development will draw very heavily on previous research work, firstly to define the minimum sensor specifications necessary for a worthwhile measurement, and secondly to identify sensors and measurement techniques with possible application in the instrumentation. It is this second aspect that is covered in this report.

1.2 An Eddy-Correlation Measurement of Evaporation

To a large extent the radiant energy incident on a natural surface leaves the surface in two ways; either as sensible heat, the transfer of warm air away from the surface, or as latent heat, the transfer of energy stored as the latent heat of vaporization of the water vapour present in the air. The evaporation to be measured is the energy lost as latent heat. It can either be done directly, or it can be deduced as the difference between the net radiation input, R_N, and the net sensible heat output.

The eddy-correlation technique can be used to measure energy fluxes (either sensible or latent) by integrating the rate at which energy

2. A REVIEW OF EXISTING WIND SENSORS

The range of wind sensors currently available is extensive but the operating principle behind a great many sensors is sufficiently similar to suggest a classification into the following groups:

Sensors with a Dynamical Response

(i) Cup Anemometers

(ii) Three-Dimensional Wind Vanes

(iii) Propeller Anemometers

Pressure (or Force) Sensors

(i) Three-Dimensional Thrust Anemometers

(ii) Pressure Sphere Anemometers

Thermal Sensors

(i) Heat Transport Anemometers

(ii) Heat Pulse Anemometers

(iii) Heat Loss Anemometers

Sonic Anemometers

Laser Anemometers

Each sensor will be reviewed individually and evaluated in terms of its potential usefulness to the proposal. The review concludes with a resume and a selection of those wind sensors considered worthy of further evaluation and development.

2.1 Sensors with a Dynamical Response

The traditional and well understood group of sensors whose response to the wind takes the form of mechanical (generally rotational) motion: the extent of this movement is related (usually linearly) to the measurement required and is conventionally detected by electrical pick-up. Such instrumentation is cheap, effective, reliable and, in its present advanced state of development, is capable of an adequate determination of mean parameters; its use in turbulent situations is restricted by

In the light of the above comments, it is clear that the use of an eddy-correlation technique for evaporation measurement is critically dependent on a determination of wind vector; but that, to some extent, a choice exists between the simultaneous measurement of humidity or temperature: although the measurement of both is optimum. For this reason, the survey included sensors for wind, humidity and temperature. It is also clear that response-time and physical size are important criteria. However, it is the philosophy of the proposal, outlined in the previous section, that such criteria should not assume overriding importance, but should be balanced by the requirement for simplicity and reliability.

1.3 The Survey

The survey was based on literature relevant to the eddy-correlation measurement of energy fluxes published before spring 1976. The range of available sources proved more extensive than had been anticipated; it involved some 1200 publications of which slightly more than half were concerned with sensors and measurement techniques. Although no survey of this type can claim to be complete, it is felt that the vast majority of the available information has been covered, and that this review represents a reasonable reflection of the 'state of the art' at this time.

The review is presented in three main parts, namely, WIND SENSORS, HUMIDITY SENSORS and TEMPERATURE SENSORS. Each part closes with a summary of the main conclusions, and the report as a whole finishes with an appraisal of the available sensors and recommendations on priorities for the initial stages of the development programme.

(ii) Three-Dimensional Wind Vanes

The bivane is a wind direction sensor which might be considered, in conjunction with a wind speed sensor (e.g. a propeller anemometer), as a means of determinging the local wind vector. Like other sensors with mechanical response, it is in advanced state of development and is well understood: which fact, together with its apparent simplicity and cheapness, makes consideration worthwhile. The equations of motion governing such a wind vane (MacCready and Jex, 1964) correspond to those of a 'second order' sensor, so that the degree of damping varies with frequency (wavelength). In use, the bivane is prone to experimental error (Wieringa, 1971), primarily caused by vane imbalance as a result of poor setting up, progressive soiling of the vane, precipitation impact and water retention in damp conditions.

Good commercial versions of the bivane are readily available (eg R M Young Co Ltd., Michigan, USA) with optimal design, which would be difficult to improve. They are also available with an (approximately) matched windspeed sensor (propeller anemometer), the 'distance constant' of the whole system being of order 5 m. A distance constant of this order is quite poor, even compared to other simpler systems (eg a vertical anemometer), which fact coupled with the systems susceptibility to operational difficulties make it an unlikely candidate for use as the primary wind vector direction sensor in this project.

(iii) Propeller Anemometers

In its modern form, the helicoid propeller anemometer, first described by Dines (1887), probably represents the best mechanical, linear wind speed transducer available. It is a 'primary' sensor (Gill, 1973) with a fairly low starting speed (~ 0.5 m s^{-1}) and a linear calibration over a wide range of wind speeds (from 1 up to at least 30 m s^{-1}): its steady state response is independent of changes in air density, humidity and pollution, and it has an ability to resolve the wind vector component parallel to its axis of rotation which is acceptable; and independent of wind speed (Gill, 1975), although Hicks (1972) previously found dependence on wind speed.

The best available modern design (R M Young Co. Ltd., Michigan, USA) has a 'distance constant' of order 1 m for gusts parallel to the axis of rotation: its response to 'off axis' wind vectors is slower and its effective distance constant for angles of attack near 90° is of order 4 m. The measured increase in distance constant with angle is slower than the cosine variation expected theoretically but has been measured reproducibly by different observers (Hicks, 1972; Gill, 1975).

Elegant theoretical descriptions of this type of sensor (Ackeson, 1970) predicting a fairly simple 'first order' response, have experimental confirmation in the wind tunnel (Ackeson, 1970; Gill, 1975; Hicks, 1972; Camp and Turner, 1970). Indeed, as well as being probably the best of the fact that the mechanical response is necessarily limited by the sensor's finite inertia.

The force on such a mechanical sensor is related to the amount of momentum dissipated on the sensor per unit time, and (to first order) is therefore proportional to the square of wind speed. As a result the time constant, T, of (say) a 'first order' sensor is inversely proportional to the wind speed, u, and it is more convenient (and usual) to express their response in terms of a 'distance constant', $l - uT$, which is less dependent on u. In fact it is a general result that sensors, whose response results solely from aerodynamic forces, have response characteristics determined by distance rather than time. In general terms, such characteristic distances are determined by the ratio of the (usually rotational) inertia, to the accelerating force; this force being related to the cross-sectional area of the sensor projected in the direction of the wind vector. In this way it might be expected that both the force and the inertia are related to the square of size of the sensor, and the response is independent of physical size. Such sensors have therefore been developed with an optimization between minimum physical size, and the requirement that frictional forces in the supports are small in comparison with the accelerating forces on the sensor-head.

(i) Cup Anemometers

Cup anemometers are probably the best known and most widely used wind sensors currently available; they give a measurement of the total wind speed in the (horizontal) plane of rotation. As such they do not in themselves represent a solution to the problem of wind vector determination required by this proposal, but they might be considered, in conjunction with a wind vane, as a means of determining the two horizontal components.

Theoretical studies (Ramachandran, 1965; 1969a; 1969b: Wyngaard *et al.*, 1971) have shown that the equations of motion of a cup anemometer, although approximating to a first order sensor, are non-linear to such an extent that the concept of a distance constant is of limited use. The effect of such non-linearity is to produce a systematic overestimation in the mean measurement of wind speed in the order of a few per cent in fluctuating conditions (dependent on the frequency content of the wind speed); which result has been confirmed experimentally (Kundo, *et al*, 1971; Hyson, 1972; Lindley, 1975). In the light of all of this work it is clear that the use of cup anemometers in the measurement of short-term fluctuations would be extremely difficult: however, it is possible that the best available design, consisting of six 'lipped' polystyrene cups (Lindley, 1975), might be considered, later in the program, as a standard (good to few per cent) against which to make a 'running calibration' of the wind vector sensor actually used in the proposal.

(b) The fact that the force is non-linear with wind speed ($F \alpha u^2$), which makes it hard to sense both low and high wind speeds on the same (linear) transducer.

(c) It is fairly easy to generate an expensive system unless care is taken to avoid doing so.

The thrust anemometer is an elegant and conceptually simple device, which has been the subject of a fair amount of useful study: its present limitations seem to be primarily technological. It probably represents a very real contender for use as the primary wind vector sensor in this proposal.

(ii) Pressure Sphere Anemometers

The pressure (or 'Yaw') sphere anemometer exploits the fact that the pressure distribution across the surface of a sphere suspended in a moving fluid reflects the magnitude and direction of fluid motion in the region of the sphere. In principle this pressure distribution is amenable to theoretical prediction (Lamb, 1932, Section 92), and the wind vector determinable from a few point measurements of pressure on (the front of) the sphere: in practice this theoretical distribution requires empirical re-normalization (Yap *et al*, 1974). However, given a wind tunnel calibration (or a running re-calibration), such sensors have been used quite successfully in the direct measurement of heat fluxes (Tanner and Thurtell, 1970; Yap *et al*, 1974), and are worthy of further consideration on this basis alone.

The point pressure measurements are made with pressure transducers which are connected to 'ports' in the front of a small sphere by manometer tubing. The sphere is held into the mean wind by a wind vane. The sensor has the advantage that, because it can be made quite small (a few cm), and because it has a fast response (of order 10 - 30 Hz), it can be used quite successfully near the ground (Yap *et al*, 1974). In its present form, however, these advantages must be set against the disadvantage that it is optimally used in turbulent situations where the instantaneous wind vector is never too far from horizontal ($\pm 25^{\circ}$: Wesely *et al*, 1972) and that it may be prone to quite large 'tilt' errors (Yap *et al*, 1974). Nevertheless the sensor has proven success in heat flux measurement and a great deal of potential for development: it must therefore merit further consideration in the context of this proposal.

the 'mechanical response' wind sensors, the propeller anemometer is perhaps also the best understood sensor in this group.

Apart from possible improvements in low-speed response of the propeller (by the use of very low friction bearings) it is hard to see how the commercially available sensor could be improved: however, a different arrangement of propellers might improve the commercial version of the three-dimensional sensor. In the medium term at least, most progress in the practical application of this, the best available mechanical sensor, is unlikely to come from an upgrading in design; rather it is more likely to come from the on-line application of corrections to allow for its (now well known) response (Horst, 1973; Drinkrow, 1972). The advent of micro-processors makes this suggestion worthy of further consideration.

2.2 Pressure (or Force) Sensors

(i) Three-Dimensional Thrust Anemometers

The operating principle behind thrust anemometers is conceptually simple: they rely on the result that the force on a body held stationary in a moving fluid is directly related to the square of the velocity of the fluid, with a 'constant' of proportionality, C_D, which does not alter a great deal over a wide range of wind speeds (Reynold's No.) - (Norwood *et al.*, 1966). Considerations of three-dimensional symmetry, necessary if all three components are to be measured, require that the sensing device should be spherical; it is found in practice (Ree and Lynch, 1963; Doe, 1967; Smith, 1970; Kirwan *et al*, 1974) that the presence of small depressions or holes in the surface of such a sphere enhances constancy of C_D by encouraging the shedding of small scale vortexes from its surface.

Since it is the 'force' on such a sphere which is used to sense the wind vector the measurement does not involve (significant) mechanical motion. As a result, such sensors can have rapid dynamical response, 10 - 100 Hz (eg Kirwan *et al*, 1974): in practice the response time is often determined externally by the introduction of mechanical damping to counteract the sensor's tendency to vibrate at its own natural frequency on the system used to support it. It is an open question whether such damping is necessary for the application described in this proposal - it is perhaps only necessary when studying the correlation between components of wind speed.

The experience of other workers with these devices suggests that it is not hard to obtain a good, durable system with a long-term consistent calibration against wind speed. The primary problems seem to be:

(a) The 'zero drift' in the sensors used to detect the force on the ball.

(f) It has a cosine response over a wide range of angles.

It has the following disadvantages.

(a) It has a finite starting speed and calibration is unknown for low wind speeds. (It may be possible to overcome this fault by redesign).

(b) Care must be taken to eliminate solar heating and air temperature gradient effects.

(c) The sensor might be affected by rain.

(e) It produces heat and thus disturbs the temperature field.

Taking account of all these factors, particularly its constructional simplicity, the HTA has at least possible use in the measurement of wind velocity components and merits some further consideration.

(ii) Heat Pulse Anemometers (HPA)

Basically, the HPA consists of a heater wire (which is pulsed to a high temperature by a current of μsec duration) and a temperature sensitive detector wire downstream. The pulsed wire produces a 'tracer' of heated air which then moves with the flowing air. The time taken for the tracer to move from the pulsed wire to the detector is measured and analysed to give (ideally) the wind speed (Bradbury and Moss, 1975; Tombach, 1973). This type of sensor has the following advantages.

(a) The sensor is simple and may be constructed in the laboratory, although the electronic analysis may be complex. There is, however, a commercial unit available manufactured by Precision Devices, Malvern, England.

(b) The HPA can measure very low speeds, but has an upper limit of about 15 m sec^{-1}.

(c) It has a cosine response to about 70° using the commercial design, and is directionally sensitive.

(d) It has a very high frequency response, related to a 'distance constant' that depends on the separation of the wires (in the order of 2 mm).

It has the following disadvantages.

(a) Careful design is necessary to obtain accurate values of the wind vector in the atmosphere.

2.3 Thermal Sensors

Sensors utilizing thermal effects may be generally divided into three sub-groups. The first comprises sensors whose sensitivity to wind speed depends on the flow (or advection) of heat in a moving fluid, the theoretical basis of which is the diffusion equation. The second sub-group comprises sensors that produce a heat pulse into the fluid stream and measure its time of movement; the third comprises sensors (typified by the hot-wire anemometer) whose sensitivity to wind speed depend on the forced convection of heat (by the moving fluid) away from a thermally sensitive source.

The time response of these sensors are generally limited only by the thermal inertia of the components used, and these can often be made as small as desired, although often at the expense of robustness and stability. In particular, forced convection sensors may have frequency responses up to the order of 1000 Hz or more. However, convection from such (necessarily small) sensors depends upon the Reynolds number and (thus) dimensions of the sensor element. They are very susceptible to contamination by the fluid, and severe drifts in sensitivity may occur.

Because of their small size, all these sensors disturb the wind field much less than (say) dynamical sensors. However they do produce heat and in this way can disturb the local temperature field: this may be a severe limitation if it is necessary to measure the temperature of the fluid close to the sensor. A further disadvantage of many of these sensors is the inability to resolve the wind vector into its components: they are strictly wind speed detectors. As such they would have to be used in conjunction with a wind-vane or other device that measures the wind direction.

(i) Heat Transport Anemometers (HTA)

The HTA consists of two wires (with large temperature coefficients) strung each side, and at right angles, to a heater wire (Taylor, 1958; Dyer, 1960). The sensitivity to wind speed of this sensor depends on detecting the temperature difference between the two wires resulting from the advection of heat in the direction of the wind. This sensor has the following advantages.

(a) It is simple and may be constructed in the laboratory.

(b) By suitable linearization techniques, it can give an output linear with wind speed.

(c) It has a time constant of about 0.1 sec (which may be made smaller by redesign).

(d) The sensor appears to have a stable sensitivity - in contrast to hot-wire anemometers.

(e) The sensor can indicate from which direction the wind vector is orientated.

There are clearly too many shortcomings of the HWA to consider any redesign for atmospheric work although, as a calibrated laboratory standard, it could be very useful for calibration of other sensors and for control of wind speeds in testing equipment, particularly in small enclosed windpipes. There are many commercial units available, eg Disa Electronik Flow Corporation.

Hot-film Anemometer (HFA)

The HFA has the same advantages as the hot-wire anemometer, while being at the same time somewhat more rugged. It is apparently also less sensitive to fluid contaminants, ie dust, because of the absence of any stagnation points on its surface (a stagnation point occurs on the downstream edge of the hot-wire anemometer). However, the HFA suffers from many of the same faults as the hot-wire anemometer, eg faults (a), (b), (c), (d), (f), (g). Possibly the major fault of the HFA is the lack of directionality or cosine response in all planes. Unless a HFA can be designed to give a cosine response in at least one plane, then it would clearly be unsuitable for atmospheric eddy correlation work.

Thermo-Anemometer

Thermo-anemometers consist of small temperature sensitive elements that dissipate heat by forced convection. They are similar to hot-wire and hot-film anemometers and may also be operated in constant voltage, constant current or constant temperature modes. They usually have a sensitive element consisting either of a thermistor (Martino and McNall, 1971), or a thermocouple (Miyake and Badgley, 1967; Kanemasu and Tanner, 1968).

Generally they have a poorer time constant than the hot-wire anemometer but they are probably more stable, less sensitive to contamination and more rugged. However they are basically wind speed detectors and cannot be used to determine wind vector components unless used in conjunction with a wind-direction sensor. In summary, their advantages are:

(a) They are small, robust, with a relatively high frequency response (depending on design).

(b) They can be used to measure very low wind speed.

They have the following disadvantages.

(a) They are not directionally sensitive.

(b) They produce heat and thus disturb the T-field.

(c) They have non-linear sensitivity to wind speed.

(d) They may be affected by rain.

(b) The sensor produces heat and may disturb the temperature field.

(c) The theory of operation and electronics is complex, although well understood.

A design of this type of sensor incorporating logic circuit digital electronics may prove to be very useful for measuring the atmospheric wind vector. There is no limit in principle to how small such a sensor may be made, and except for disadvantage (b) has no severe disability.

(iii) Heat Loss Anemometers

Several types of heat loss anemometers exist, the most relevant being:

Hot-wire Anemometer (HWA)

The most significant advantage of the HWA (and the hot-film anemometer) is its frequency response and spatial resolution. Because of the hot-wire's small mass and size, its time constant (not strictly a valid term for the HWA) can be a fraction of a millisecond and can thus be used to measure frequencies of up to 1000 Hz. The spatial resolution of the HWA, related to the wire's length, can be in the order of a few mm. These specifications, however, are far in excess of what will be required for eddy correlation measurements in the atmosphere. Unfortunately, the HWA has many disadvantages that make it impractical for atmospheric work (cf. Bradshaw, 1971). These may be summarized as follows:

(a) It is small and fragile.

(b) It may be affected by rain.

(c) It is sensitive to temperature as well as wind speed fluctuations, although this problem is usually reduced by operating the HWA at temperatures well above the ambient temperature (this accentuates fault (d)).

(d) It introduces heat into the flow, making measurements of air temperature in its neighbourhood difficult.

(e) The HWA is non-directional in the plane normal to the wire axis, and does not have a good cosine response in the plane through the axis, as a result of short wire lengths and disturbance to the flow by the wire supports.

(f) The HWA does not have a sensitivity that is linear with u, but has a power-law relationship (about $u^{0.48}$).

(g) Calibration depends on the physical size of the HWA, and on the heat flow from wire to air. Calibration drift, perhaps its most significant fault, can occur due to changing ambient temperature, or contamination of the probe by dirt collecting on the wire.

(h) The anemometer has a very wide range of wind speeds, from about 0.01 m sec^{-1} to 30-40 m sec^{-1}.

However use of the sonic anemometer is not without a number of problems, (common to all current models): these are -

(a) The anemometer requires fairly complex electronics.

(b) To an accuracy of about 1%, it has an upper wind speed limit of about 35 m sec^{-1}.

(c) The calibration does depend to a small extent on temperature and humidity, and can thus vary during a day.

(d) The temperature output also depends to a small extent on humidity.

(e) Because of a finite path length, a loss of frequency response to atmospheric turbulence occurs due to line averaging. Attenuation occurs for eddies of length scales less than $2\pi d$, where d = path length (Kaimal *et al*, 1971).

(f) Errors result from path separation, and depend on temperature fluctuation, array geometry, etc. Geometry is chosen to minimize these complicated effects (Kaimal *et al*, 1971).

(g) At certain wind directions, the wake of the transducers produces errors. These can be neglected if the mean wind is approximately normal to the anemometer path.

In general, these problems are not severe and can, with consideration and careful design, be made insignificant. There are however, a number of technical problems associated with each kind of anemometer and a large amount of effort has been used in eliminating the more significant problems.

(i) Continuous Wave Sonic Anemometer

The continuous wave sonic anemometer was amongst the first successful sonic anemometers developed and depends on detecting the phase difference between continuous sound wave transmitted in opposite directions. This system was considered to be more stable and less noisy than the then current pulse type of anemometer (Kaimal and Businger, 1963). Mitsuta *et al*, (1967) have since indicated that this continuous wave type of anemometer suffered from problems including those due to reflected soundwaves and external noises, and difficulties with the stability of the phase detector, which in particular produced drift in the zero-wind point.

(ii) Pulsed Sonic Anemometer

This type of anemometer uses pulse techniques to determine the difference in transit time for two pulses travelling in opposite directions along a fixed path. However, decreasing power of the received signal led, in the earlier models, to substantial difficulties in detecting accurately the leading edge of the pulses (Mitsuta, 1966; Kaimal *et al*, 1971). At this time, continuous wave techniques were more dependable in measuring

These anemometers do not appear to be suitable for general atmospheric measurements but may be useful as a laboratory instrument: they would have to be constructed in the laboratory.

2.4 Sonic Anemometers

The principle behind the sonic anemometer is that the wave-front of a sound wave travels at a velocity that is the vector sum of $\underline{c}$ and $\underline{u}$, where $\underline{c}$ is the vector in the direction of the transmitted sound ray with a magnitude of the speed of sound in still air, and $\underline{u}$ is the wind vector. The difference in time taken for a wavefront to travel from point A to point B and time taken to travel from B to A is therefore a measure of the component of $\underline{u}$ in the direction of AB. It is the method of measuring this time difference that constitutes the principle difference between current sonic anemometers.

In theory, and to a large extent in practice, the sonic anemometer has many important advantages over most other wind sensors.

(a) Wind sensing is over a path length that does not contain any object that could disturb the wind field. (This is not entirely true for some wind directions - the transducers and supports can produce wake effects; but this is not a real problem.)

(b) Because sensing is taken over a path length, the anemometer should not be affected by rain or contaminants in the air.

(c) It is possible to have a wide frequency response. It can respond to changes in bulk wind speed of up to 200 Hz. For atmospheric turbulence the situation is not so simple (this is discussed below.)

(d) As the frequency response does not depend on the thermal or dynamic inertia of its material parts, it need not be fragile or easily damaged. However, wake effects require that the transducers should be small.

(e) In theory, the calibration of the sensor is absolute, requiring a measurement of a distance, time and temperature. Thus (ideally) it would not require calibration or recalibration.

(f) As a result of the physics involved, the sonic anemometer has a precise cosine response, except for a small range of wind directions where wake effects from the transducers is important. The anemometer also indicates the direction of the wind component.

(g) As the speed of sound is temperature dependent, the anemometer can also be used to determine temperature.

2.6 A Summary of Existing Wind Sensors

Sensors with a Dynamical Response

(i) Cup Anemometers are of no use as primary wind sensors, but might have a place in the final hardware to provide a 'running calibration' of the wind vector sensor actually used.

(ii) Three-Dimensional Wind Vanes are fraught with practical difficulties, and even when used carefully are inferior to simpler devices.

(iii) Propeller Anemometers are popular devices in this application and are probably worthy of further consideration. Existing design is close to optimal (except at low wind speeds); improved performance is most likely to come as a result of 'real-time' corrections for well understood short-comings in its response.

Pressure (or Force) Sensors

(i) Three-Dimensional Thrust Anemometers represent a very real contender for use as the primary wind sensor in the proposal and certainly merit further development.

(ii) Pressure Sphere Anemometers have proven success in heat flux measurement and merit further consideration on this basis alone; they are however more complex than Thrust Anemometers.

Thermal Sensors

(i) Heat Transport Anemometers have possible application in the proposal but would require a good deal of development work first.

(ii) Heat Pulse Anemometers have possible application, but would also require development and would require quite complex electronics and on-line calculations.

(iii) Heat Loss Anemometers (particularly the Hot Wire Anemometer) are not suitable as primary sensors; but, as a calibrated laboratory standard, would be extremely useful to the proposal for calibrating and testing other sensors in wind tunnel conditions.

Sonic Anemometers are undoubtedly the best available sensors and would certainly be capable of providing the required wind vector measurement. An attempt should be made to make this successful research tool into a routine field instrument.

Laser Anemometers have specialized application in fields outside this proposal.

transit time by phase comparison. Nevertheless, the pulse-type is inherently less sensitive to thermal drift in the transducers and less drift in the zero-wind point. This aspect combined with more recent improvements in detecting the leading edge of the pulses (Mitsuta, 1966; Mitsuta *et al*, 1967) has led to the pulse-type anemometer being the more popular of the two types.

From the theoretical basis, the sonic anemometer appears to be the most suitable instrument for measuring the atmospheric wind components, and it must be considered to be the primary choice of sensor. Many of its technical problems have been greatly reduced in the expensive commercial models that are available (Kaijo Denki Co., Ltd., EG & G Environmental Equipment). However, it seems feasible that a new design specifically for eddy correlation instrumentation, using modern electronics could be considered - with a view to simplification of operation (elimination of drifts) and great reduction in cost. The sonic anemometer has been a successful research tool, and because of the advantages it has over most other anemometers, an attempt should be made to make it a routine field instrument.

2.5 Laser Anemometers

The laser anemometer is a comparatively recent development in anemometers using highly advanced technology. It operates in the following way. A small region of optical fringes is produced at the intersection of two coherent light beams (from two laser sources). Minute particles carried along by the wind pass through these fringes of spacing d, with a velocity u. The light reflected by these particles is then modulated with a frequency u/d. The reflected light is detected with a photomultiplier tube. As many particles in some random manner pass through the fringes, analysis of the output is complex, requiring photo correlation, spectrum analysis, zero-crossing or frequency tracking methods (Abbiss *et al*, 1974). Besides all the main advantages offered by the sonic anemometer, the laser anemometer can measure the wind component in a very small region of space at a distance from the actual instrumentation. This is a very considerable advantage in many situations, but it is not considered necessary for eddy correlation work.

There are three severe disadvantages that make it unsuitable for the current work.

(a) It is very expensive, as it requires good optical, detector and electronic systems.

(b) A commercial unit would have to be used, but these are all laboratory bench-type instruments and are not designed for hostile environment operation.

(c) It is not directional although it should have an ideal cosine response. Further instrumentation and electronic analysis is required to overcome this limitation (Denham *et al*, 1975).

order to maintain data quality, and are subject to error when the aspiration is insufficient: forced aspiration is not possible in eddy correlation applications since this would destroy the turbulent structure of the atmosphere which is a fundamental part of the measurement. Wet and dry bulb psychrometers are therefore not favoured for a fast response, almost maintenance-free, eddy-correlation apparatus.

3.2 Dew Point Hygrometers

A dew point hygrometer makes use of the fact that the vapour pressure of water in the air can be recorded by cooling a polished surface until a thin condensate of the water vapour is formed and then readjusting the temperature so that the deposit is in equilibrium with the water vapour: the vapour pressure of water in the air can be determined from this dew point temperature. This type of instrument generates an absolute measure for the humidity, although its response to changes in humidity depends on the speed with which the mirror surface can be changed, and the rate of flow of air over it. In commercial instruments this is of the order of $2^{o}C$/sec, which includes the feedback control (making it a second-order system). However, carefully designed mirrors based on the same resistive heating have been made with a first order time constant of 1.3 seconds (Jury, Bosanquet and Kim, 1967), which is equivalent to an average full scale response speed for the whole instrument of $14.5^{o}C$/sec. The literature suggests that radiant or inductive heating would increase the response speed further (Barrett and Harndon, 1951; Soumi, 1948), but that the added complexity has not been worth the effort, considering that the instrument is not normally required to monitor large step changes quickly or follow high-frequency humidity fluctuations.

In assessing the instrument's potential use in connection with eddy correlation work the following comments are relevant:

(a) The normal intake does not interfere with wind temperature or humidity fields.

(b) It is not affected by rain and any heavy accumulation of dirt is easily removed.

(c) It has a slow frequency response with a 3 db cut-off of the order of 1 Hz.

(d) Spatial resolution would be very good as the normal intake is very small; however a time lag must occur between this and the mirror.

(e) It does not affect the air that it is sampling.

(f) It will operate below and above freezing point.

(g) The response becomes slower the lower the dew-point.

(h) It gives an absolute value for humidity.

3. A REVIEW OF EXISTING HUMIDITY SENSORS

A measurement of evaporation based on the eddy-correlation technique necessitates the use of a fast response humidity sensor, so that fluctuations in air movement away from and towards the evaporating surface can be correlated with coincident fluctuations in the water content of the air. A great deal of effort has been directed to obtaining such a fast response humidity sensor over the last two decades. Attempts have been made to adopt traditional methods and to create new methods but in general the level of success is not high. This research has, however, been successful in identifying potentially unproductive fields and isolating those techniques where potential is still available.

A certain preselection is apparent in the review below which does not attempt to cover all the possible methods of measuring humidity but rather to restrict itself to those methods where at least some possibility of obtaining a fast response exists. Such methods can be conveniently grouped as follows:

Wet- and Dry-Bulb Psychrometers

Dew-Point Hygrometers

Solid State Devices; comprising

(i) 'Surface' sensing devices
(ii) 'Interstitial' sensing devices

Radiation Absorption Devices

3.1 Wet- and Dry-Bulb Psychrometers

Wet- and Dry-Bulb Psychrometers consist of a pair of temperature sensing elements, one having a film of water maintained around its surface which is allowed to evaporate into the air stream. The dry bulb monitors air temperature, while the combination monitors humidity - providing the air flow over the sensors is sufficient to maintain the correct wet bulb temperature depression. Obviously the smallest sensors give the fastest response; the alternatives are thermocouples, thermistors and resistance elements with time constants no shorter than 0.1 seconds for the wet bulb and possibly faster for the dry bulb. In eddy correlation work these time constants must be equal, which necessarily means matching to the slowest (Taylor, 1965). The response time of the psychrometer decreases typically by a factor of three if the wind speed is increased by an order of magnitude, and the wet bulb time constant decreases by a further factor of three when the temperature increases from 0-30°C (Sano and Mitsuta, 1968); there is therefore a temperature dependent difference in response time between the two sensors.

Wet and dry bulb psychrometers have been at the centre of meteorological investigations for a long time and have proved extremely useful. They do, however, require a reasonable standard of continuous maintenance in desorption of water from their surface. They have a similar time response to carbon elements but have lower hysteresis, a lower temperature coefficient and are more reproducible and less prone to damage as a result of exposure to high humidity (Johnson and Duggan, 1965).

(d) Aluminium Oxide Elements determine humidity by measuring the impedance (resistive and capacitive) of an aluminium oxide surface which extends between two electrodes, this impedance being dependent on relative humidity (e.g. Stoner, 1963; Chleck and Brousaides, 1965). The element has a time-response which is usually significantly greater than 1 sec (Jason 1965; Hilsenrath, 1974), although response times of order 0.12 to 0.4 sec have been observed for very small elements (Lai and Hidy, 1968). These devices are already in an advanced state of development; there is little hope of increasing their performance to make them suitable for this proposal.

(e) Polyelectrolyte Elements. These elements are based on the properties of a surface-layer of ion-exchange resin. Materials of this type have bound counter-ions which become mobile as water concentration is increased. Measured time constants vary between 2 and 60 seconds (Musa and Schnable, 1965) although a time constant of 0.22 seconds was achieved by Beck (1967) when an element was artificially aspirated at high wind speed (16 m s^{-1}). The sensors exhibit large scale changes in calibration as a result of ageing, changing by factors of 2 to 10 over a few months. These devices are likely to be of little use in this proposal.

(f) Piezoelectric Sorption Devices work by coating the surface of a piezoelectric crystal with a hydroscopic film (King, 1965; Gjessing *et al.*, 1968). The absorption or desorption of water from this film changes the effective mass of the crystal and thereby its resonant frequency; the change in frequency is then calibrated against atmospheric humidity. The calibration of such devices is temperature and pressure dependent; the device is subject to contamination by airborne particles and obviously must be protected from rain. Accurate measurements of its response time are not available, but 'experience indicates a response time $\lesssim$ 0.1 sec'(Hicks and Goodman, 1971). Although superior to some similar devices, it is hard to see much scope for the development of this principle into unsupervised application in rigorous conditions.

(ii) 'Interstitial' Sensing Devices

At present one such device is available; it is a solid-state semiconductor device called 'the Brady Array'. The device differs from other 'surface' sensing devices in that it does not require the agglomeration of water or moisture prior to measurement: in the Brady Array individual molecules drift freely into the structure and generate a change in resistivity by distorting molecular bands and releasing energy to the free electrons. The manufacturers claim response times in the order of 0.15 to 0.25 seconds

Therefore, it is unlikely that such instruments will be included in this project because they are too slow and expensive.

3.3 Solid State Devices

The demand for simple, cheap, solid-state humidity sensors with a fast-response is so large, and the likely commercial return so great, that a great deal of research effort has been concentrated into the development of such sensors. The range of options available to the material scientist is extensive: research of this intensity necessarily generates a great many solutions, all of which are successful to a greater or lesser degree. Practically all the devices described in the literature are capable (after calibration) of producing a measurement of humidity with sufficient accuracy, and all are sufficiently small for use in the project. On the other hand, several are prone to serious calibration ageing, and so far none have a sufficiently good time response for use in this application.

Classification of these sensors is difficult; the only attempt at classification made here is to distinguish between 'surface' sensing devices, which were the first to be produced, and more recent 'interstitial' sensing devices.

(i) 'Surface' Sensing Devices

Devices in this class detect changes in humidity by virtue of the effect such changes have on the physical properties of a thin layer of active material. They include

(a) Lithium Chloride Elements. An early humidity sensor first described by Dunmore (1938), which exploits the humidity dependence of the resistance of a thin layer of lithium chloride. It has been much used in radiosonde work but is now largely superseded in performance by carbon elements (Matthews, 1965) which have a somewhat faster response.

(b) Carbon Humidity Elements possess a surface layer of humidity sensitive material which contains carbon granules set in a cellulose-based matrix material. The matrix exchanges water with the air according to the relative humidity and in so doing changes the distribution of the electrically conducting carbon granules; changes in the electrical conductivity of the sensor film occur which are related to humidity (Stine, 1965).

These devices are small, cheap and readily available, but they have a temperature dependent calibration (Morrissey and Brousaides, 1970) and a time response in the region 1-60 seconds, depending on temperature (Marchgraber and Grote, 1965), which precludes their use in this proposal.

(c) Ceramic Elements, elements of cerium oxide-titania which change electrical resistance in response to absorption and

(b) Because of this sensing path, the instrument is not sensitive to air contamination, rain, or other blown particles.

(c) It has a good electronic frequency response, at least 10 Hz and possibly much higher, but has an overall frequency response which is limited by line averaging along the path length. (This factor has been discussed in connection with the sonic anemometer).

(d) Spatial resolution (and line averaging) will depend on the path length: with careful design this could be made adequately small.

(e) The method does not effect the air that it is sampling (in contrast to some other humidity sensors that can introduce further moisture, etc).

(f) Since no change in state is involved, this method will operate below as well as above freezing point.

(g) The absorption function results in an increase in the sensitivity of the sensor as the humidity decreases: most other humidity sensors become less sensitive or more difficult to operate.

(h) For the system described by Hyson and Hicks (1975), the calibration is independent of the electronics, being related only to the absorption coefficient; as such it is a well-known function of temperature, humidity etc. It is known that for some wavelengths, significant corrections (associated with ambient conditions) must be made to the calibration, but there are others where such corrections are insignificant.

In conclusion, if technical problems can be overcome (and they largely have) then the radiation absorption method has very clear advantages over all other presently available humidity sensors (particularly with respect to its potential frequency response). Further, as it has been demonstrated by currently available sensors that such an instrument need not be very expensive or unduly complex, it therefore must be considered as the primary humidity sensor for this project.

3.5 A Summary of Existing Humidity Sensors

Wet- and Dry-Bulb Psychrometers have already proved unsuccessful in this application; they probably do not merit further consideration.

Dew Point Hygrometers provide an excellent absolute measurement of humidity but their time-response prohibits use in this proposal.

Solid State Devices exist in many forms but as yet none are sufficiently fast for use in this application, although there may be some scope in with low hysteresis and high accuracy; however Thorpe (1973) has tested such devices against a fast response Lymon Alpha humidity sensor as part of a micrometeorological study and deduces an effective time constant of the order 0.8 sec. He concludes that the device 'is only marginally fast enough in response for use in turbulence measurements'. In the light of such a result, it is doubtful if further studies of this sensor are worthwhile in connection with this proposal, albeit that this device is perhaps the best available solid state humidity sensor.

3.4 Radiation Absorption Devices

These devices exploit the fact that water vapour, in common with other gases, exhibits bands of spectral absorption over a wide range of spectral frequencies, including the ultra-violet, near infra-red and far infra-red regions. Monochromatic radiation of wavelength corresponding to one such absorption band passing through humid air will lose energy to an extent depending on the amount of water vapour, the path length of the beam in the air, the absorption coefficient at the given wavelength, and, to a lesser degree, on the temperature and pressure of the air. Detecting the amount of absorbed energy using a suitable sensor is therefore a measure of the humidity.

The particular wavelengths used depends to some extent on the application. Measurement of water vapour in the stratosphere uses the far infra-red region (20-40 micron), while measurements nearer the ground generally use the near infra-red; and, in particular, bands centred on 1.12, 1.38, 1.87, 2.6, 2.7, 6.0, and 6.3 microns. The only other band used to any extent is one centred on 0.1215 micron, the Lyman-alpha band in the ultra-violet. The basic instrumental requirements for a unit employing any of these wavelengths are a source of light, a light chopper, optical filter and suitable detector. Many units have required a second reference beam of radiation at a wavelength not absorbed by water vapour (eg Foskett *et al*; 1953) in order to measure absolute humidity, not just the fluctuations. Requirements of stability and optical complexity have made such units expensive and difficult to use.

For measuring humidity fluctuations, instrument requirements are less severe, and a new technique has been developed (Hyson and Hicks, 1975) where the signal from the detector (of a single beam) is divided by the mean component, thus eliminating any drift in the signal due to variation in lamp strength, dust in the atmosphere, drift in electronics (except the divider) and so on. Associated with recent developments in electronics and solid state sensors, this technique indicates an optimistic future for the radiation absorption method. Now that many of the technical problems associated with the method are being solved, its real advantages over other humidity detection techniques in this application are becoming evident, as listed below.

(a) The sensing path does not contain any solid components, so that there is no disturbance to the local wind, temperature or humidity fields.

4. A REVIEW OF EXISTING TEMPERATURE SENSORS

Given an adequate determination of the local wind vector, the eddy-correlation technique can be used to measure the sensible-heat flux leaving a surface (ie, the energy used to warm the air above the surface), by correlating air motion away from and towards the surface with coincident and simultaneous short-term fluctuations in air temperature. A determination of the energy lost in this form, together with a measurement of the radiant energy input, is tantamount to a measurement of evaporation: the difference between the two is the energy used in converting liquid water into water vapour.

In order to use the eddy-correlation technique, the temperature measurement has to be made with a sensor that is ideally able to respond to the smallest eddies contributing to the flux: a sensor with good frequency response and spatial resolution is therefore necessary. In themselves these two requirements are fairly easy to satisfy; however, in the context of this proposal, it is also necessary that the sensor should be capable of use in a hostile environment with minimum supervision. Sensor selection is a compromise between such criteria. Before reviewing existing temperature sensors relevant to this proposal, it is therefore convenient to establish first the basic requirements of a good sensor in this context. These requirements might be summarized thus: the sensor should

(a) be small and have a good spatial resolution

(b) have a small thermal inertia and high frequency response

(c) preferably have an output linear with temperature

(d) have *negligible self-heating, and not* act as a thermo-anemometer

(e) not disturb the wind field

(f) not disturb the temperature field

(g) have a stable calibration

(h) not be affected by rain, wind speed and air contaminants

(i) not be affected by radiation heating or temperature gradients in the air: this requirement is sometimes equivalent to (a)

(j) preferably be capable of removing the low frequency trend in temperature by itself, leaving only the fluctuating part: this is not strictly essential but may be useful in meeting requirement (c).

(k) not be easily damaged, or at least be easily replaced.

There are in general a great many ways in which temperature can be measured but several have no relevance to this proposal. Those devices which are relevant can be classified in the following groups:

the new interstitial devices. Development in this field should be carefully monitored throughout the project in case a worthwhile sensor is produced.

Radiation Absorption Devices are likely to be the most useful to the proposal of all existing sensors.

where T = temperature, R = resistance at temperature T, R_o = resistance at 0 ^{o}C, and a, b ... are constants. Since the response of such sensors as a function of temperature is quadratic (or cubic), they are very often used with linearizing circuitry, to produce a voltage output that is linear with temperature. A great deal of effort has been spent in developing such circuits (eg. Diamond, 1970) and they are readily available. The problem can be reduced by operating over small temperature ranges.

By choosing a wire of sufficiently small diameter and length, it is possible to produce a temperature sensor with a frequency response flat to frequencies as high as 1000 Hz, with a spatial resolution of about one mm (LaRue *et al.*, 1975): the circuitry required by such a sensor is however quite sophisticated - such exacting standards are not necessary in this proposal, but the fact that they have been achieved suggests that frequency response need not be a limiting factor. A broader perspective on the merits of resistance elements is obtained by evaluating them against the requirements set out in the introduction. In this respect this type of sensor can be made

(a) small (short) to give good spatial resolution

(b) with a small thermal inertia for high frequency response by reducing wire diameter (this does however make it more fragile)

(c) with an output voltage linear with temperature, either by linearizing circuitry or by operating over a small temperature range

(d) to have insignificant self-heating, although at the expense of sensitivity and simplicity of circuitry

(e) physically small so as not to disturb the airflow

(f) to dissipate negligible power, and then not disturb the temperature field

(g) to have a very stable calibration

(h) so as to be unaffected by wind speedor air contaminants: rain is a more difficult factor to deal with (see below)

(i) so as to be unaffected by radiation heating, and temperature gradients by making the sensor small (this again makes it more fragile)

(j) to be able to have low frequency trends removed, either electronically or perhaps in conjunction with a lagged matched sensor

(k) easily replaced: it must remain somewhat fragile in order to satisfy other requirements.

The sensor does possess disadvantages however, namely

(α) To satisfy a number of criteria (above) the wire of the sensor must have a very small diameter. This makes the sensor fragile

Sensors with Temperature-Dependent Resistance; comprising

(i) Resistance Elements

(ii) Thermistors

(iii) Semiconductor Elements (diodes, transistors)

Thermocouples

Acoustic Thermometers

The last of these methods, acoustic thermometry - the determination of temperature from the speed of sound, has particular advantages in eddy-correlation work, which is possibly its only major field of application.

4.1 Sensors with Temperature-Dependent Resistance

In general the electrical conductivity of any solid is dictated by the availability, or otherwise, of mobile carriers of electrical charge; such carriers can be actual ('electrons') or conceptual ('holes'). The mobility of available carriers is, like all microscopic phenomenon, controlled by quantum mechanics: in perhaps oversimplified terms, the ability of a 'carrier' to move in response to applied voltage depends on the availability of unoccupied 'energy levels' which involve motion through the solid. The extent to which such energy states remain unpopulated depends on absolute temperature; in this way the availability of mobile carriers, and therefore electrical conductivity, are necessarily temperature dependent. In many applications the unavoidable temperature dependence of conductivity/resistance is not desirable, however sensors in this group exploit such dependence to provide a second order measurement of temperature. 'Solid state' devices, such as thermistors, diodes etc., can be manufactured with much higher temperature coefficients than metals, but to set against this, the reproducibility of the response from one example of the device to the next is less.

(i) Resistance Elements

This type of sensor involves wires of metal that have a good temperature coefficient, eg. platinum, iridium, copper, tungsten, nickel, etc. In general their temperature response may be written as

$$R = R_o \ (1 + aT + bT^2 + \ldots)$$

(a) can be small, with excellent spatial resolution

(b) can have a small thermal inertia and acceptably high frequency response.

(c) can be made to generate an output which is sufficiently linear with temperature over a defined temperature range

(d) necessarily have self heating, but in application have much less than resistance elements

(e) are physically small so they do not disturb the airflow

(f) have a negligible effect on the temperature field

(g) can have a reasonably stable calibration, if care is taken to ensure this

(h) are not affected by wind speed and can be protected against air contaminants and rain, with some loss of frequency response

(i) are small enough not to be affected by radiation heating or temperature gradients

(j) would require electronic removal of low frequency trends

(k) are fragile but easy and cheap to replace (a system could contain redundant thermistors)

Thermistors are probably the most commonly used temperature sensors in eddy correlation work and, having proven success, will almost certainly be the initial choice in this proposal.

(iii) Semiconductor Elements

The use of readily available semiconductor elements, such as diodes and transistors as temperature sensors is most constructively viewed as an alternative to the use of thermistors. In a great many respects such devices fulfil the necessary requirements in much the same way as thermistors (Section 1(ii)): for the purposes of the present study it is necessary only to compare their merits relative to thermistors.

The most commonly used device is the junction diode, whose use depends on the temperature dependent variation of the reverse saturation current (Sargeant, 1965). The favoured type in this application are silicone diodes with high conductivity, low leakage and glass encapsulation, which have not been gold doped or chemically treated to increase speed and recovery time, (Hinshaw and Fritschen, 1970). Their advantages over thermistors are a higher temperature coefficient and lower power dissipation ie, self heating, (Dimick and Trezek, 1963): they are also more easily linearized and are possibly more reproducible from one example to the next (Sargeant, 1965). Their primary disadvantage is that they are not manufactured for this application, the most serious consequence of this being that they are physically large and do not, as standard items, provide a satisfactory time constant for use in this proposal. It is this single fact, which is also true for transistor-based temperature sensors, that restricts their use in this proposal and liable to break in a very hostile environment. It is, however, possibly more robust than equivalent thermistor wires.

(β) It is again required that the length of the sensor be kept to a minimum but this reduces the resistance of the sensor to a few ohms. To maintain negligible self heating the sensitivity must be reduced. This may require more elaborate circuitry and design of leads etc.

(γ) For a small thermal inertia, the sensor should consist of an open wire, but if the wire is covered by water, the sensor would be useless. It is therefore anticipated that a study on suitable insulation to overcome this problem may be necessary.

In conclusion, this type of sensor has been used in the past for eddy correlation work (eg. McIlroy, 1961) with considerable success. With improvements in electronic techniques, improvements in the actual sensor may be possible to give an even better performance. A study of insulation, and care in design of the sensor circuitry, could produce an excellent eddy correlation temperature sensor.

(ii) Thermistors

Thermistors are solid state devices whose resistance, R, is given to a good approximation by the expression

$$R = R' \exp\left[B\left(\frac{1}{T} - \frac{1}{T'}\right)\right]$$

where R' is the resistance at the absolute temperature T', T is the instantaneous thermistor temperature, and B is a positive constant (Becker, Green and Pearson; 1946). Improvements on this expression, which is merely derived from consideration of the free energy of an electron gas, have been suggested; one of the most successful has been to include a further free parameter θ by replacing T by $(T+\theta)$ (Bosson, Gutman, Simmons; 1950). They have a very high temperature coefficient of resistance: a percentage change in resistance of order 5% per $^{\circ}$C is quite possible.

Thermistors are conventionally used in Wheatstone bridge circuits which yield a linearized output over a limited temperature range (eg. Pitts and Priestley, 1962). Their frequency response depends on size; small thermistors are readily available with time constants of order 0.1 sec. (Pottie, 1967). In practice, the actual time constant depends to some extent on the conditions in which the thermistor is used; there can be some dependence on local air velocity.

Viewed against the requirements outlined in the introduction, thermistors

(j) Low frequency trends in the temperature may be eliminated by lagging the cold junction of the thermocouple

(k) Small thermocouples, necessary for a short time-constant, are fragile, although they are probably as robust as comparable thermistors. Replacements can however be constructed in the laboratory without too much effort. For example Gelb *et al* (1964) describe the construction of a thermocouple with a time constant of about 1 msec, while Kovács and Mesler (1964) describe the construction of surface thermocouples with time-constants as low as about 0.1 msec.

Except for two significant disadvantages, namely very low sensitivity and the need for a reference junction, thermocouples appear to satisfy most of the criteria for a suitable temperature sensor, possibly as well as thermistors and resistance elements. They cannot be dismissed as possible temperature sensors for use in this proposal.

4.3 Sonic Thermometers

The sonic thermometer depends on the fact that the speed of sound C in air is temperature dependent, viz.,

$$C = 20 \left[T(1 + 0.3\ e/p)\right]^{\frac{1}{2}} \ \mathrm{m\ s^{-1}}$$

where T = absolute temperature, $^{\circ}$K

e = vapour pressure and p = air pressure, mb

Unfortunately, as can be seen from the above equation, C also depends to a lesser extent on vapour pressure, and corrections have to be made because of this factor; this may be less important when investigating fluctuations only. Wind speed fluctuations can also affect measurements of T, although only in certain circumstances (Kaimal & Businger, 1963).

These two factors and the complexity of instrumentation required are the main disadvantages of the sonic thermometer, besides some of those specified for the sonic anemometer - the main one of these being line averaging of the fluctuations as a result of the finite path length. In contrast, this sensor has the following advantages:

(a) Does not disturb the wind or temperature field

(b) Is not affected by rain, or contaminants in the air

(c) Can have a wide frequency response and spatial resolution, depending on the size of the path length

(d) As frequency response does not depend on thermal inertia, the transducers etc. can be made quite rugged, so that the sensor is not fragile.

However, because of the simplicity and reliability of other temperature at the present. If at some time in the future, commercial products become available with a shorter thermal time-constant, they would, on the basis of the advantages described above, be given further consideration.

4.2 Thermocouples

Thermocouples consist of strands of dissimilar metals joined to give a 'hot'junction and a 'cold' junction; this produces a thermoelectric e.m.f. that is a function of the temperature difference between these two junctions. To determine the temperature of the hot junction, a knowledge of the temperature of the cold junction is necessary, and in many applications this can be a severe disadvantage. When measuring temperature fluctuations however, a suitably lagged cold junction may possibly be used beneficially to give the mean temperature; such an arrangement would have the useful side effect of limiting the output voltage range over a very wide range of mean operating temperatures. A further advantage of thermocouples may be the elimination of self-heating effects, because electrical currents through the sensors can be kept small.

Evaluating these devices against the requirements listed in the Introduction:

(a) Thermocouple junctions are very small giving excellent spatial resolution

(b) They can be made sufficiently small to give a high frequency response, with time constants often in the order of 1-100 msec (Sirs, 1961; Balko and Berger, 1968; Gelb *et al*, 1964)

(c) The output voltage is not linear with temperature but can be easily linearized (Barancok *et al*, 1972; Conrad, 1968)

(d) Thermocouples have negligible self-heating

(e) They can be made small, so they do not effect the local wind field

(f) Since they produce little joule heating, they do not effect the local temperature field

(g) Their calibration is stable, but a single thermojunction has a very small sensitivity. These are often joined in series to produce a thermopile with greater sensitivity

(h) They may be affected by rain, although with suitable insulation this problem may be reduced. Balko and Berger (1968) discuss a number of insulations that do not increase the time constant to prohibitive values

(i) Thermocouples may be affected by radiation heating but probably to no greater extent than resistance elements or thermistors. These effects can be minimized (Daniels, 1968)

5. CONCLUSIONS

5.1 Discussion

The primary purpose of this review must be to establish (or otherwise) the feasibility of a direct measurement of evaporation using the eddy-correlation technique. Fundamental to such a measurement is an adequate determination of wind vector; this is necessary for the measurement of any flux using eddy-correlation. At the same time, it is also necessary that techniques exist which are capable of measuring either the humidity or the temperature on a sufficiently small time scale because as demonstrated in section 1.2, a determination of either latent or sensible heat flux is tantamount to a measurement of evaporation. This, the primary objective of the review, is possibly the most easily satisfied. There is little doubt that existing sonic anemometer/thermometer systems can make the necessary measurement; therefore, a measurement of evaporation using eddy correlation techniques is certainly possible. However, it must be said immediately that the cost, complexity and level of supervision required by currently available commercial sonic-anemometers, are such that they do not in themselves satisfy the objective of the proposal, i.e. to create simple instrumentation capable of making an adequate measurement of evaporation for hydrological applications. If sonic anemometry is to be used it must be cheap, rugged and capable of use in the field with minimum supervision. This might be possible, and the first recommendation is that an attempt should be made to do this.

Bearing in mind that such simplification might not be successful, consideration should be given to alternative sensing techniques, and the development and testing of at least some other types of wind vector sensors must proceed in parallel with such work. Of the wind sensors reviewed, Cup Anemometers, Wind Vanes, Heat-loss Anemometers (Hot Wire Anemometers) and Laser Anemometers have been rejected as unsuitable for use in instrumentation to give the primary determination of wind vector (although a cup anemometer might prove useful as a 'running calibration' of the system used). Heat Transport Anemometers and Heat-Pulse Anemometers are not rejected outright by this review - heat pulse techniques in particular might be applicable - but it must be recognized that their use would involve a fair amount of development work and some risk. It is recommended that, as there are limited financial and manpower resources available, further development of such sensors be postponed unless and until simpler devices, which require less development, prove inadequate.

The remaining sensors, i.e. Propeller Anemometers, Thrust Anemometers and Pressure Sphere Anemometers have all been used in eddy-correlation with some degree of success, the propeller anemometer being the most popular; but in its basic form, perhaps least successful of the three. It is felt that there is some scope for mechanical improvement in the three-dimensional propeller anemometer, partly by possible rearrangement and miniaturization of the propellers, and partly by improving low wind sensors, the complex sonic-thermometer could not be considered as suitable per se: it would only be considered if a sonic anemometer were used to measure the wind vector. In this case, little new instrumentation would be required and the system would possess an additional advantage in that both the wind vector and the temperature are measured over the same path length.

4.4 A Summary of Existing Temperature Sensors

Sensors with Temperature Dependent Resistance

(i) Resistance Elements could be useful to the proposal, but have comparatively low sensitivity and might be prone to self-heating.

(ii) Thermistors are probably the best available sensors of this type, but would probably require individual calibration.

(iii) Semiconductor Devices have certain advantages over thermistors but, at the present time, lack the necessary short thermal time-constants.

Thermocouples could be used in the proposal: their disadvantages are low sensitivity and the need for a reference junction.

Sonic Thermometers are too complex and expensive for use in the proposal merely as temperature sensors: they would be the optimum sensor if sonic anemometers were used to determine the wind vector.

All the sensors in groups 1 and 2 are necessarily fragile, and all need some development for use in rain. It might be necessary to incorporate several spare sensors into the apparatus, with automatic switching in the presence of sensor failure. Initial attention should probably be concentrated on the use of thermistors.

(v) A humidity sensor should be developed and tested which is based on radiation absorbtion and uses the Hyson-Hicks automatic recalibration technique.

(vi) Monitoring of the literature on solid state humidity sensors should continue: purchase and testing of a 'Brady Array' humidity sensor is probably still necessary.

(vii) Tests should be carried out on commercially available bead Thermistors to establish their suitability as temperature sensors and should begin as soon as possible. Preliminary development of Resistance Elements, the most likely alternative, is worthwhile in parallel with such work.

speed calibration by reducing friction in the bearings. However, the most significant improvement in response would probably come from the application of real-time corrections to take account of well understood defects in its response. It is recommended that an attempt be made to do this using a dedicated micro-processor operating (initially) on a commercial version of the anemometer. Appendix 1 provides a preliminary description of how this might be done. If the correction procedure proves successful, mechanical upgrading would then be worthwhile.

The Thrust Anemometer and the Pressure Sphere Anemometer both show promise as primary wind vector sensors in this proposal, but the Thrust Anemometer may be simpler, cheaper and more suitable for use in wet conditions. It is recommended that a determined effort should be made to design and build a Thrust Anemometer for use as the wind vector sensor in this proposal, if possible incorporating into the design the ability to provide regular automatic recalibration of the system under micro-processor control. Development of a Pressure Sphere Anemometer might be assigned a lower priority, it being regarded as the best of the three techniques held in reserve at this stage.

The conclusion drawn on the basis of the review of humidity sensors is that at this time the only technique available with any real possibility of success is that using radiation absorbtion. It is therefore recommended that the development of such a sensor be undertaken, exploiting the method described by Hyson and Hicks (1975). At the same time it is recommended that the literature should continue to be monitored in case some new and relevant solid state device is developed.

The review of existing temperature sensors is encouraging in that it reveals that Resistance Elements, Thermistors, Thermocouples and, in certain circumstances, Sonic Thermometers could all be useful to the project. Since the use of thermistors requires least development it is recommended that tests are carried out on these devices to establish their suitability before development of the alternatives is undertaken.

5.2 Summary of the Recommendations

(i) An attempt should be made to convert the Sonic Anemometer/thermometer from a successful research tool into routine field instrument.

(ii) An attempt should be made to up-grade the three-dimensional Propeller Anemometer by the application of real-time corrections to allow for defects in its response. If tests prove this correction procedure successful, mechanical improvements should be undertaken.

(iii) A three-dimensional Thrust Anemometer should be designed, built and tested.

(iv) The Pressure Sphere Anemometer, Heat Pulse Anemometer and Heat Transport Anemometer should be held in reserve as wind sensors with possible application in this proposal; development programmes to be initiated later if required.

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APPENDIX I: THE USE OF A 'DEDICATED' MICROPROCESSOR TO MAKE ON-LINE CORRECTIONS FOR SHORT-COMINGS IN THE RESPONSE OF A THREE-DIMENSIONAL PROPELLER ANEMOMETER

Purpose. To create an effective wind sensor for use in eddy correlation measurements by merging a three-dimensional propeller anemometer of existing (or improved) design, with a dedicated microprocessor system capable of making on-line corrections for defects in:

(a) cosine-response

(b) time-response

Such corrections must be capable of implementation at sensor interrogation rates of order 20 Hz (or greater), and must result in a significant improvement in the sensor's performance; that is

(i) reduce remnant errors in cosine response to 2-3%

(ii) reduce the 'effective distance constant' of the sensor to $\lesssim$ 0.5 m.

Assumptions

1. The proposal assumes that propeller anemometer sensor assemblies can be obtained whose response (both static and dynamic) is sufficiently reproducible for standard correction formulae to have meaning from one sensor to the next (within the required specification).

2. It is assumed that the response of the propeller anemometer; (expressed here as a voltage V) to a time dependent wind speed u(t), incident at an angle θ to the axis of rotation, obeys the equation:

$$L\,\frac{dV}{dt} = u^2 - \left(\frac{V}{C}\right)^2 \qquad \text{(A1)}$$

where C is the D.C. calibration against wind speed; and the 'constant', L, has a 'known' dependence on θ: this equation being a variant of equation 11b (Acheson, 1970), with a first order solution;

$$u = \left[\frac{V}{C}^{\;2} - L\,\frac{\Delta V}{\Delta t}\right]^{\frac{1}{2}} \qquad \text{(A2)}$$

the second term of which (in essence) is the required on-line correction for defects in time-response. The value of L will be defined as a (numberical) function of θ (from equation (14); Acheson, 1970) after wind-tunnel experiments. (Note if such experiments do not validate this assumption, an alternative correction equation may be required.)

Breakdown of the Problem

Consider a 3-D propeller anemometer system with X, Y and Z propellers rotating at angular velocities ω_x, ω_y and ω_z, which give rise to voltage outputs V_x, V_y and V_z respectively. The true wind vector has components (u, v, w) along the three axes; that is, it has true 'direction cosines' (l, m, n), where

$$l = {}^{u}/_{U}$$

$$m = {}^{v}/_{U} \qquad \text{(A3)}$$

$$n = {}^{w}/_{U}$$

with $$U = (u^2 + v^2 + w^2)^{\frac{1}{2}} \qquad \text{(A4)}$$

Defects in 'cosine response' give rise to a variation in the effective calibration constant for each anemometer which is a function of θ, the angle between the wind vector and the axis of rotation of the propeller. It is assumed that this (numerical) function, F, can be expressed (alternatively) in terms of the cosine of this angle, so that the effective calibration constants for the X, Y and Z propellers are:

$$C'_x = C_x/_{F(l)}$$

$$C'_y = C_y/_{F(m)} \qquad \text{(A5)}$$

$$C'_z = C_z/_{F(n)}$$

At the same time, it is assumed that the dynamical response of each sensor is determined by an equation similar to equation (1) and that the variation in the effective value of the constant (as a function of angle) can be expressed as a (numerical) function, L, of the relevant direction cosine. It is therefore possible to obtain a value for the three components of wind speed (which is correct to first order) in terms of V_x, V_y and V_z, the present voltage output, and ΔV_x, ΔV_y and ΔV_z, the change in that output since the last measurement at a time Δt earlier. These components are given by the equations:

$$u = \left\{ \left[\left(\frac{V_x}{C_x}\right) \quad F \quad (l) \right]^2 \quad - \quad \left(\frac{\Delta V_x}{\Delta t}\right) \quad L(L) \right\}^{\frac{1}{2}}$$

$$v = \left\{ \left[\left(\frac{V_y}{C_y}\right) F(m) \right]^2 - \left(\frac{\Delta V_y}{\Delta t}\right) L(m) \right\}^{\frac{1}{2}} \qquad \text{(A6)}$$

$$w = \left\{ \left[\left(\frac{V_z}{C_z}\right) F(n) \right]^2 - \left(\frac{\Delta V_z}{\Delta t}\right) L(n) \right\}^{\frac{1}{2}}$$

Since the true values of (l, m, n) are not known, it is necessary to iterate towards these values of u, v, w at each instant; the computation (which is initiated at each sensor interrogation) taking the form:

(a) Obtain new values of V_x, V_y, V_z

(b) Output results of the last on-line correction

(c) Compute:

$$\left({}^{\Delta V_x}/_{\Delta t}\right), \quad \left({}^{\Delta V_y}/_{\Delta t}\right), \quad \left({}^{\Delta V_z}/_{\Delta t}\right)$$

from current and previous values.

(d) Compute:

$$\left({}^{V_x}/_{C_x}\right), \quad \left({}^{V_y}/_{C_y}\right), \quad \left({}^{V_z}/_{C_z}\right)$$

(e) Take existing direction cosines (l, m, n).

(f) Obtain F(l), F(m), F(n) and L(l), L(m), L(n); from 'look up' tables

(g) Compute (u, v, w) from equations (A6)

(h) Compute new values of (l, m, n) from equations (A3) and (A4).

(i) Start iteration again at (e) until it is time for a new set of measurements; in which case start again at (a).