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The use of a tethered kite balloon to probe the
lowest levels of the atmosphere

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THE USE OF A TETHERED KITE BALLOON TO PROBE THE LOWEST LEVELS OF THE ATMOSPHERE

C J Readings

1. Introduction

Although the last few years have seen an increasing amount of effort being devoted to the study of the earth's boundary layer, it is still fair to say that little information exists on regions outside the surface layer; the main problem, of course, being its inaccessibility. One method of overcoming this problem, which is receiving increasing attention, is to use a tethered kite balloon to support the instrumental packages. This article reviews this technique from the point of view of the user and starts by outlining the principles of balloon operations. It then proceeds to review the uses to which this system has already been put and to give examples of the sort of results that have been obtained. The final section reviews the potential of the system and includes a comparison with other alternatives (ie the use of aircraft and tall towers).

2. An outline of the principles behind balloon operations

It is possible to use this technique to carry out studies in a fairly wide range of atmospheric conditions - over both land and sea. However it is important to realise at the outset that balloons cannot be flown in all weather conditions, namely:-

- a) When the wind is too strong or too gusty (the limits vary from system to system).
- b) When there is a risk of a static discharge.
- or c) When there is a risk of icing.

There may also be further restrictions imposed by the local aviation authority. Thus the number of times in a year when it proves possible to operate a particular system will vary from place to place.

In any proposed application, one of the first decisions is the number of levels at which measurements have to be made simultaneously. If one level (with vertical scanning?) will suffice, the instrumental package can be quite heavy

since it can be suspended from the actual balloon. However, for simultaneous multi-level measurements, the individual packages have to be quite light as they have to be supported by the tethering cable; with the Cardington Mark 11 balloon for example: (see figure 1 and table 1) this imposes a weight limit of about 10 kg. From these considerations it should be possible to calculate the total payload and this figure, plus the proposed operating heights, should enable a potential user to decide whether a suitable balloon facility is available to him. Large balloons such as the Mark 11 (see table 1) will meet most requirements but they require specialised winches and very experienced crews. Thus for many purposes, a smaller balloon such as the Mark 15 (see table 1) becomes very attractive as its operation only needs a simple winch and relatively inexperienced personnel. The Mark 15 is about the largest balloon which meets this requirement.

At Cardington it is usual to tether the balloon to the winch (static or mobile) by a single metal cable. This allows the balloon to oscillate back and forth across the mean wind direction (see Readings and Thompson (1974)) and attempts have been made to reduce this by using three tethering cables. However this technique is not widely used as it leads to "snatching" as the balloon moves up and down which is usually far more serious than the oscillations. These will obviously vary from balloon to balloon but it is probably fair to say that the smaller the balloon, the higher the frequency of its lateral oscillations and the more prone it will be to vertical movements. Over the sea the motions of the ship will also have to be taken into account (see Thompson (1972)). Thus the importance of these oscillations will have to be separately considered in each instance. (eg Haugen et al (1974)). This appraisal must also include the possible effect of the inclination of the tethering cable to the vertical, (see Jones and Butler (1958)). A problem of a totally different order of magnitude arises if it is decided to save weight by using nylon instead of metal cable. This is prone to high frequency oscillations ($\sim 1\text{Hz}$ as opposed to the usual period \sim minutes) which can easily damage fragile equipment and can actually fracture the cable if an unsuitable method of attachment is used.

3. Examples of instrumental packages

It is perhaps appropriate to start this section by describing the Balthum Sonde (BALloon TEMPerature and HUMidity) which has been used since 1942 by the British Meteorological Office to provide profiles of pressure, temperature, humidity and wind speed up to an altitude of about 1 kg . This is done every six hours and is the only low-level sonde in regular use (see Painter 1970). It is quite heavy (~ 35 kg) so it has to be supported by an auxiliary cable attached to the balloon; though it is also fixed to the tethering cable to minimise any oscillations. The wind speed is measured with a cup contact anemometer, pressure by an aneroid capsule and wet/dry temperatures by two thermistors (see figure 2). The information from these sensors is relayed to the ground by radio.

The next instrument considered is the Cardington turbulence probe - earlier forms of which were described by Jones and Butler (1958) and Readings and Butler (1972). The present instrument basically consists of an arm with a vane at one end and the various sensors at the other (see figure 3). It is free to rotate about the tethering cable so the vane is able to keep these sensors facing into wind. The latest version is designed to measure the instantaneous values of all three wind components as well as temperature and incorporates:-

- a) an 120-slot photo-electric cup anemometer - total wind speed;
- b) a $25\ \mu$ platinum wire wound non-inductively - temperature;
- c) two "double V" hot wire heads (Jones (1961)) - the inclinations of the wind to the horizontal and the angle between the vane and the wind in the horizontal plane;
- and d) a magnetic flux gate - absolute orientation of the vane, with respect to the earth's magnetic field.

Any errors that might arise from the tilting of the cable are minimised by mounting the two hot-wire heads and the magnetic flux gate on the vertical arm which is attached to the horizontal arm by a universal joint. Oscillations are minimised by two oil-dashpots. A further joint/dashpot near the tethering cable

keeps the cup anemometer horizontal. The vane contains circuit boards and temperature range switches - the batteries being contained in a battery box which is usually mounted just below the probe. Nowadays the signals are relayed to the ground by radio but originally cable was used. This is cheaper and more accurate but introduces severe handling problems as well as imposing a weight penalty and restricting the number of levels to two. A probe based on this design has recently been constructed by the Norwegian Defence Establishment and Thompson (1972) has used a similar probe over the sea. The latter version also includes a platinum wire covered in wet cotton to measure wet-bulb depressions.

In general almost any type of instrument could be operated from a tethered balloon and to date the list includes:-

cup anemometers, quartz hygrometers, hot wires, refractometers, thermistors, aneroid barometers platinum resistance elements, magnetic sensors, radiometers as well as hygrometers.

Examples of some of the applications may be found in Yokoyama (1960), Stilke et al (1967), Hall and Gardiner (1968), Munday (1970) and Gjessing et al (1968).

For any particular application the influence of the balloon and its motions will have to be assessed. Thus for example a team from the University of Oxford who were studying radiation, found it advisable to mount their package about 1 km below the actual balloon to prevent it obscuring the zenith. The Cardington turbulence probe has been designed to eliminate the effects of tilting and twisting of the cable, but not the lateral/vertical oscillations. As it proved impossible to estimate the effect of these, a set of experiments were carried out in Florida in which tower-based and balloon-based measurements were compared (see Haugen et al (1974)). These revealed that only the lateral wind components were affected; the longitudinal and vertical values comparing very well (see figure 4).

4. Examples of the results

As the bulk of the data described here was obtained using the Cardington balloon facility, it is relevant to point out that until recently this was the

only one available to scientists which used large kite balloons. The American Air Force now has a similar facility and this was used in both Florida (see Haugen et al (1974)) and Minnesota (Readings et al (1974)). Smaller balloons have of course been used generally for some time but few results have been obtained with them.

For many years the facility at Cardington has been used by the Meteorological Research Unit Cardington to study wind and temperature fluctuations throughout the earth's boundary layer. This work has enabled mean profiles of the rates of dissipation of turbulent velocity fluctuations and of temperature fluctuations to be published (see Rayment (1973) and Caughey and Rayment (1974)). Recently this has been extended to cover such topics as the dependence of the turbulent fluctuations on the local state of the atmosphere and the existence of a free-convection limit (see Caughey and Readings (1974a) and (1974b)). Similar observations have been reported by Yokoyama (1969). Measurements have also been made at Cardington by the Appleton Laboratory (Slough) and the Norwegian Defence Establishment using refractometers and a quartz crystal hygrometer. These have revealed some very interesting features including very thin layers of enhanced refractivity (see Warhaft (1973) and Gjessing et al (1973)). However all these investigations have relied on a series of sequential single level measurements and for many purposes simultaneous observations at several levels are essential. The first of these was carried out at Malvern (Worcs) in 1972 (unpublished). A more comprehensive study was carried out in Minnesota in 1973. This took the form of a full study of the diurnal development of the earth's boundary layer and included low-level measurements by the AFCRL turbulence probe as well as measurements at five levels by Cardington turbulence probes (see Readings et al (1974)). A further series of experiments are planned for this year in Southern England. These will involve multi-level and multi-site observations of the structure of the earth's boundary layer using Cardington turbulence probes at two sites plus an aircraft, a glider, the high-power 10 cm radar facility at Defford (see Watkins (1971)) and five special radiosonde stations.

One of the most exciting developments in recent years has been the combinations of remote and in-situ techniques. A very early example of this was the 1971 Malvern Experiment, when detailed observations of the structure of an inversion were made by a Cardington turbulence probe at the same time as the atmosphere was scanned by the high-power 10 cm radar at Defford (Worcs). This study revealed the complex structure of a subsidence inversion and has enabled an entrainment mechanism to be hypothesized (see figure 5 and Rayment & Readings(1974)). Observations have also been made over the sea and the reader is referred to Thompson(1972) and Stilke et al (1967) for details.

5. Closing remarks

In this review the potential of the tethered balloon facility, has been considered, with emphasis on the difficulties and drawbacks, and it seems appropriate to end by listing its main advantages :-

1. it is fairly cheap to operate;
2. it is quite mobile;
3. it can be used over both land and sea;
4. the cable does not disturb the air flow;
5. a full coverage of the boundary layer is possible (both time and height)
6. measurements can be made very close together;
7. the atmosphere can be scanned vertically - at several levels simultaneously if necessary.
8. almost any instrument can be accommodated.

Thus it will usually be preferred to a tall tower unless a rather wide range of weather conditions at one site over a limited height needs to be monitored. When aircraft are considered, the decision is not so clear-cut as both systems have their strengths and weaknesses - the main points being that aircraft provide for spatial variations and spatial averaging and can be operated over a wider range of weather conditions. However they are much more expensive to operate, they do not permit as wide a frequency coverage or as accurate a measurement of wind structure, and they do not provide vertical profiles as conveniently. The eight points above also need to be considered.

6. Acknowledgements

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* Figures 1-3 are photographs and are not included in this TDN. They will however be part of a full report which will appear in the *Journal of Atmospheric Technology*, NCAR, at the end of 1974.

TABLE 1

DETAILS OF TWO STANDARD BRITISH KITE BALLOONS

Type Details	Mark 11	Mark 15
Volume	1300 m ³	140 m ³
Weight of balloon	430 kg	90 kg
Weight of tethering cable	200 g/m	45 g/m
Static Lift - Surface	1000 kg	80 kg
300 m	950 kg	60 kg
600 m	900 kg	40 kg
900 m	800 kg	20 kg

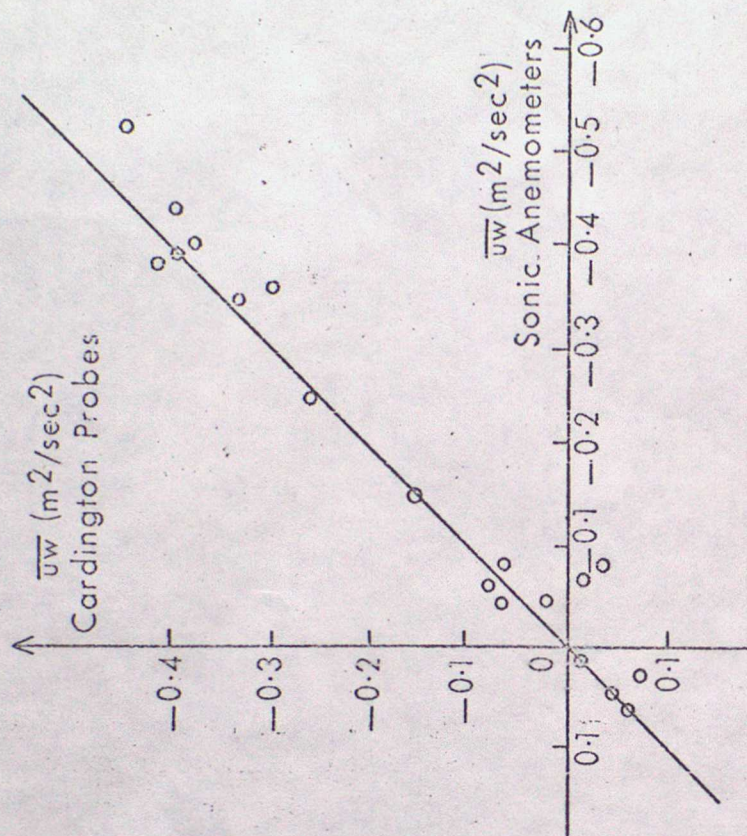
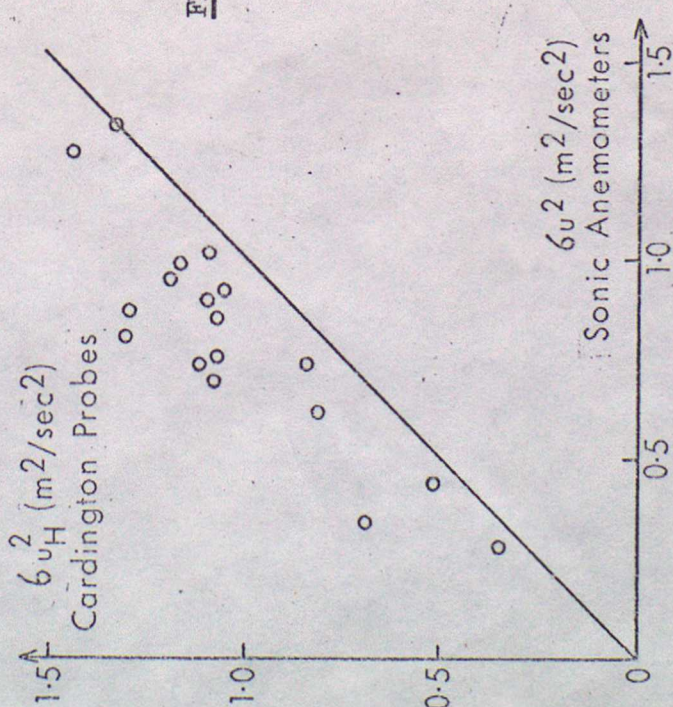
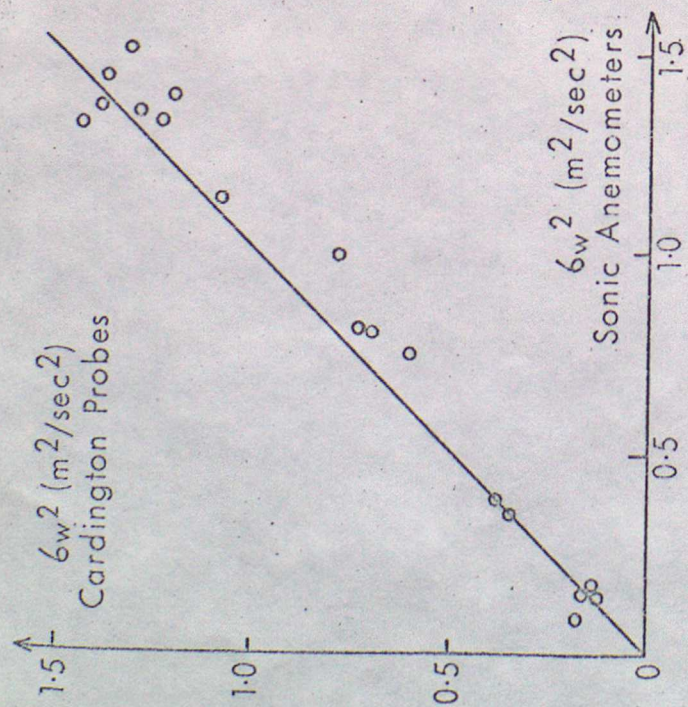


FIGURE 4

The 1971 Comparison of the Cardington Probes and the Sonic Anemometer with the Sonic Anemometers mounted on a tower and the Cardington Probes on the flying cable of a kite balloon.

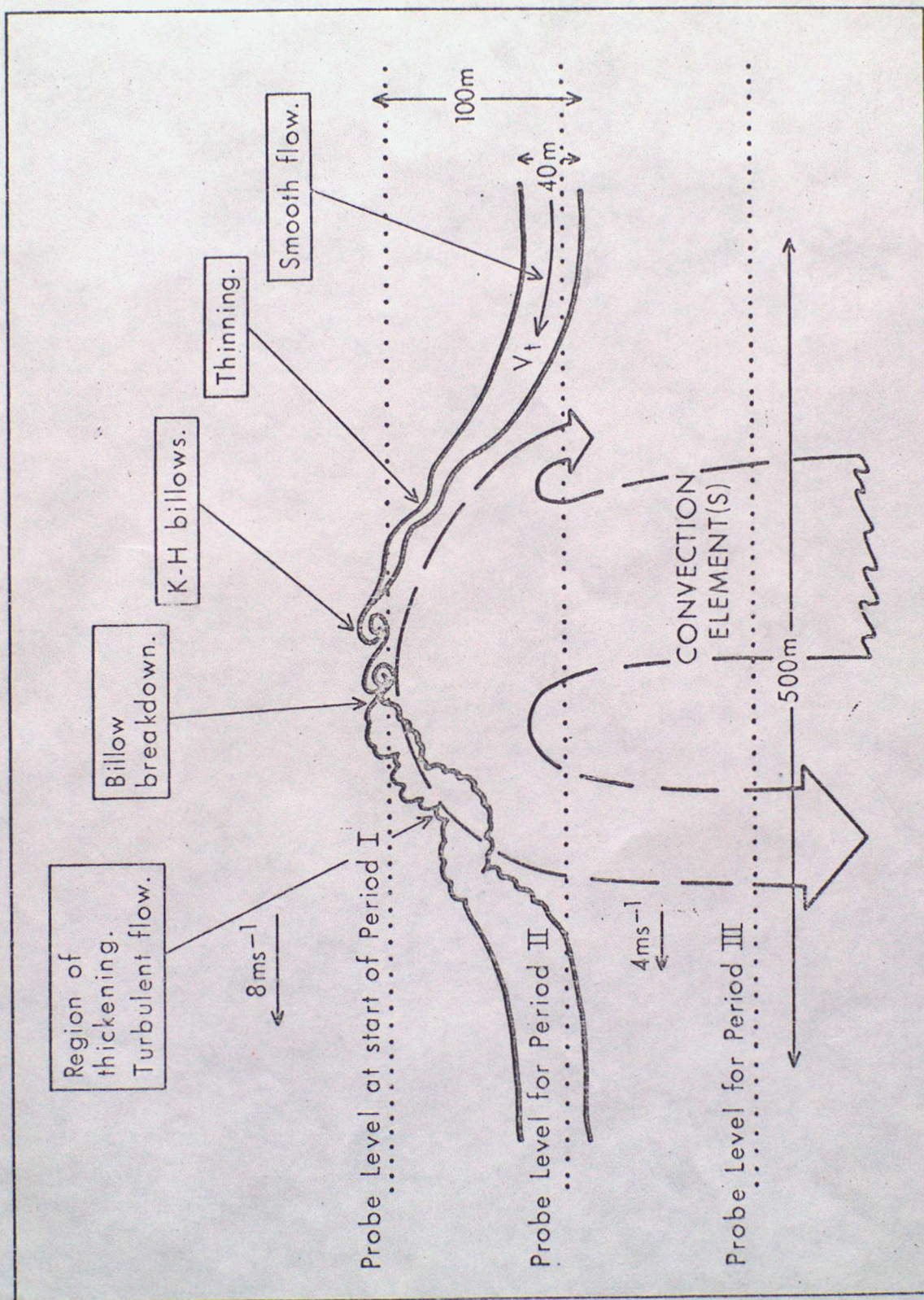


FIGURE 5