THE USE OF STATE-OF-THE-ART KITES FOR PROFILING THE LOWER ATMOSPHERE

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Abstract. This paper presents the capabilities and limitations of using state-of-the-art kites for atmospheric research. A brief historical review of the subject is first presented, followed by an outline of the current status of kite-borne measurement technology. The utility of the technique is then illustrated by presenting a series of recent measurements made using kite-borne technology. A summary of the advantages and limitations of kite-based measurements relative to other technologies is provided for reference.

Keywords: Kites, Atmospheric measurements, Turbulence, Profiling, Ozone

1. Introduction

Kites have been employed for thousands of years for both entertainment as well as for practical purposes. The use of kites specifically for atmospheric research dates back well over two hundred years. Atmospheric research using kites peaked sharply around the turn of the twentieth century, with near-daily observations being made at many observatories throughout the world. Information derived from these measurements comprised our first real systematic study of the free atmosphere and provided the earliest elements for subsequent data collection techniques using balloons, airplanes, and, ultimately, satellites.

With a few exceptions (Daniels, 1993; Hobbs, 1989; Smedman et al., 1991; McGowan and Sturman, 1996), atmospheric data collection using kites disappeared almost completely after the early 1930s. Much of the original hard-won technology has been all but forgotten by the current generation of researchers, although it pervades the early articles authored by well known atmospheric scientists of that period. A sampling of familiar names of atmospheric scientists involved in early kite-borne research programs includes A. Lawrence Rotch (founder and first director of the Blue Hill Observatory in Massachusetts), L. P. Tesserenc de Bort (founder of the Trappes Observatory near Paris and co-discoverer with R. Assman of the stratosphere), R. Assman (founder and first director of the Lindenberg Observatory near Berlin), W. L. Moore and M. W. Harrington (early chiefs of the U.S. Weather Bureau), Sir W. Napier Shaw (author of the well-known Manual of Meteorology),

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and W. H. Dines (an early president of the Royal Meteorological Society and one of the pioneers of kites-from-boats technology).

The purpose of this paper is to expand on the idea that kite-borne technology continues to have a well-defined niche in meteorological research. There are definite advantages provided by having an instrumented kite flying for extended periods a few kilometers above the earth's surface that cannot be provided by any other means. This statement can be made even stronger if one considers that the kite can be used as a 'sky hook' and the kite tether as a means of guiding a wind-driven, instrumented platform rapidly up and down the tether under radio control. Such a platform, or WindTRAM, provides a means of profiling a wide variety of atmospheric quantities simultaneously, rapidly, quasi-continuously, and at relatively low cost. Moreover, such systems gather data from ground level up to many kilometers, i.e., well into the free atmosphere. The totality of this region is difficult to access more-or-less continuously by any other technique. Tethered balloons have difficulty reaching altitudes above a kilometer or two and aircraft have obvious difficulties in covering the lowest heights. The only other possibility is to use a series of non-tethered balloonsondes that pass once through the region but are then typically unrecovered and the sensors lost. Quasi-continuous sampling using balloonsondes would, therefore, be exceedingly expensive.

2. A Brief History of Atmospheric Research Using Kites

Historically, the first kite-borne atmospheric measurements were reported in 1749 by Professor Alexander Wilson and his student Thomas Melville, both of the University of Edinburgh, Scotland. In a series of measurements, Wilson and Melville launched a string of paper kites on a single tether. Each kite carried a thermometer attached to the kite tail and enclosed in a bushy tassel of paper to insure a soft landing. The thermometers were released at their respective altitudes by smoldering fuses. If gathered quickly after their recovery, the thermometers yielded a rough estimate of the temperature profile up to heights 'where the highest kite was observed disappearing at times among the white summer clouds' (Wilson, 1826).

Wilson's kite experiments were followed in 1752, by the famous atmospheric electricity experiment of Ben Franklin near Philadelphia (Fisher, 1898). [According to Hart (1982), J. de Romas, a contemporary of Franklin in France, used the electric charge collected along a wire-wrapped kite string to electrocute dogs and pigeons]. Following Franklin's work, little more was reported for almost seventy years. Then, in 1822, near Igloolik in the Canadian Arctic, Captain Parry on his second Arctic expedition attached a thermometer to a paper kite to measure the lapse rate (Gold and Harwood, 1909). None was detected, at least up to the 400 foot height of the kite. However, in a similar measurement at the same location in 1836-7, Admiral Black raised a kite to 1200 feet from the deck of his frozen-in ship, HMS Terror, and detected an 8 degree Fahrenheit decrease (Jenkins, 1981).

Three years after Black's measurement, and in a much less rugged environment, J. P. Espy, a meteorologist and member of the Franklin Kite Club in Philadelphia, employed kites to verify his theoretical calculations of cloud base heights. He coincidentally detected strong updrafts under those same clouds, as well as further evidence of an electrically charged atmosphere (Espy, 1841). Espy's measurements were followed by the work of Cleveland Abbe, who in New Jersey in 1876, flew a kite to discover the depth of the sea breeze (Abbe, 1896). Subsequent to Abbe's work was that of E. Douglas Archibald in England in the mid-1880s. Archibald, who profiled the winds to over 1300 feet using a kite-borne self-recording anemometer (Archibald, 1884), is considered by many to be the first person to make systematic use of kites for atmospheric measurements. For these measurements, Archibald used a series of kites connected in tandem. His kites flew on a piano wire tether, following the suggestion of Sir William Thompson (Lord Kelvin).

Also about this same period, between 1885 and 1892, Alexander McAdie at Blue Hill (Massachusetts) and L. Weber at Breslau (Germany) used kite-borne electrometers to study atmospheric electric fields (McAdie, 1892, 1917; Gold and Harwood, 1909). These measurements built upon the earlier work of Franklin and de Romas.

Based upon these early successes, efforts to establish a global network of kite and balloon observatories began during the waning years of the nineteenth century.[*] These observatories systematically profiled winds, temperatures, humidity, and pressure in order to better understand the weather. In the United States beginning around 1898, the U.S. Agricultural Department's Weather Bureau (predecessor to the U.S. Weather Service) established seventeen sites east of the Rocky Mountains where kites were flown on a daily basis (weather permitting) until 1933 (Frankenfield, 1900). In addition to the Weather Bureau sites, A. Lawrence Rotch's privately funded Blue Hill Observatory near Boston played a major part in the development of meteorological kite technology (Rotch, 1898). It was from Blue Hill that W. A. Eddy in 1894 succeeded in launching the first recording thermograph (Fergusson, 1933). Eddy's success was followed a year later at the observatory by the launching of a recording meteorograph (temperature, pressure, and humidity). Numerous kite altitude records (with meteorographs) were established at Blue Hill over the next two decades. For example, the single kite altitude record of 12,507 feet (3,812 m), established at the observatory in 1898 stands today (Nature, 1899).[†]

Further outstanding contributions to scientific kite research were made around the turn of the century at a number of observatories in Europe, as well as from other

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[*] The use of non-tethered 'balloonsondes' to carry recording instruments well into the stratosphere began in 1893, but suffered from the fact that retrieval of the instruments was exceedingly difficult (Cave, 1914). Kites provided the vast majority of data in the first few kilometers of the atmosphere.

[†] The highest multiple-kite altitude record (9,740 m) was made at the Lindenberg Observatory (Germany) in 1919 using a train of eight kites (Yolen, 1968).

groups around the world. L. P. Tesserenc de Bort not only founded the Trappes Meteorological Observatory (kite and balloon studies) near Paris, but was exceedingly active in making balloon and kite-borne measurements in Hald (Denmark) and aboard ships in the North Sea. He and Lawrence Rotch (Blue Hill) also made similar measurements aboard Rotch's converted steam launch *Otaria* near the Azores and across the equator in the central Atlantic (de Bort and Rotch, 1909). These activities followed Rotch's initial trans-Atlantic voyage between Boston and England, during which he flew instrumented kites on five out of a possible eight days (Rotch, 1901a). Additional major contributions were made in Germany by Professors Hergesell and Assman at the Lindenberg Observatory near Berlin. Hergesell also pioneered the kite-from-boat technology on the Bodensee from a launch owned by Count von Zeppelin (Hergesell, 1901; Nature, 1904a) and in the Atlantic on the Prince of Monaco's private yacht *Princess Alice* (Prince of Monaco, 1908; de Bort and Rotch, 1909).

A further kite-from-boat development occurred in 1913, when Sir G. I. Taylor (Taylor, 1960) flew kites from the deck of the steamer 'Scotia' to study the generation of the intense fog banks off the coasts of Newfoundland and Nova Scotia in the northern Atlantic. This six-month effort used vertical temperature profiles obtained from the kite flights in conjunction with surface wind reports from other ships in the vicinity. The study established that the fog banks were produced by warm, moist air from nearby regions (e.g., the Gulf Stream) passing over the cold waters of the Banks.

A number of small observatories were also established throughout England just after the turn of the century. The outstanding work of W. H. Dines off the west coast of Scotland during 1898–1903 (Dines, 1903) provided strong impetus for the kites-from-boats technology and for studying the atmosphere over the ocean. Additional observatories in England (e.g., Aldershot, Brighton, Ditcham Park, Glossop, Oxshott, Petersfield, and Pyrton Hill) added appreciably to the store of atmospheric data from over the British Isles. Other observatories were established in subsequent years in Russia (Rotch, 1907), Egypt (Keeling, 1907), and India (Nature, 1906), while extended campaigns using kites and balloons were made to such far-flung places as East Africa (Berson, 1909), the Bahamas (Nature, 1904b), Java (Nature, 1910), and Antarctica (McAdie, 1917). In support of the global scale of these activities, the International Conference on Aeronautics held in Paris in 1896 established 'international days' – usually the first Thursday of every month – to coordinate kite and balloon flights in all countries (Fergusson, 1907).

The absolute level of activity in atmospheric research using kites during this early period is difficult to assess from a vantage point separated by almost a century. It is clear, however, that essentially all of the detailed global information on the first few km of the atmosphere before 1930 was derived from kite-borne instruments. Certainly tens of thousands of atmospheric kites were launched during the three to four decades centered on the turn of the century, and well over one hundred publishing scientists were actively involved in the technology during that period, with data being gathered from the Arctic to the Antarctic and on all other continents. Somewhere between one hundred and two hundred separate locations reported kite-borne measurements during these years.

The use of kites for atmospheric research declined rapidly in the early 1930s with the advent of inexpensive balloonsondes and aircraft. After about 1930, systematic measurements by kites were viewed as too labor intensive and expensive. M. W. Harrington, Chief of the U.S. Weather Bureau in 1893, estimated the cost of a single kite-borne profile to 15,000 feet ($\approx$ 4.5 km) to be \$16, roughly \$320 in today's dollars (Whitnah, 1965). Beginning in the early 1930s, kites were seen as impediments to the burgeoning aircraft activity, while balloonsondes promised a cheap and safer alternative for atmospheric measurements.

3. A History of Recent Kite Work at the University of Colorado (CIRES)

The Cooperative Institute for Research in the Environmental Sciences (CIRES) of the University of Colorado first became interested in the use of kites for atmospheric research in the late 1980s. Their early measurements incorporated a series of electrometers suspended at intervals along a kite tether to profile the fair weather global electric field over Christmas Island in the equatorial Pacific (Balsley, et al., 1992). While this campaign produced some useful electric field data, it demonstrated more importantly the potential of modern kite-borne platforms for other types of atmospheric measurements. It was apparent that state-of-the-art kites could fulfill a need to provide relatively continuous, in-situ, low-level (i.e., from the ground up to at least a few kilometers) measurements for extended periods. This need could otherwise be satisfied only by a combination of tethered balloons – which could cover the lowest kilometer or so – in concert with low flying aircraft. Aircraft, however, could not provide continuous in-situ data. Furthermore, it was clear that the use of tethered kites would enable measurements using expensive equipment that could not, for economic reasons, be sent up (and probably lost) on untethered balloonsondes. Although these advantages had been known for over a hundred years, they had been all but overlooked during the past few decades.

Subsequent kite-borne research at CIRES led to the profiling of a number of atmospheric properties at a number of locations around the world. During these campaigns, the CIRES group obtained excellent height resolution profiles of pressure, temperature, humidity, ozone and other trace gases (Balsley et al., 1994; Knapp et al., 1996). They also obtained preliminary high-time-resolution temperature fluctuation data to measure atmospheric turbulence properties (see Section 6.3). Data were obtained to heights extending well above the atmospheric boundary layer.

In addition to ground-based kite measurements, the CIRES group were also able to demonstrate the capability of kite-borne profiling from a large ocean-going vessel in the Pacific Ocean as well as from a small outboard boat in a tributary of the Amazon River. This capability, of course, had been developed almost a century earlier (Rotch, 1901b; Dines, 1903).

Possibly the most innovative concept made by the CIRES group centers on the idea of employing the kite as a ‘skyhook’, i.e., as a relatively stable, semi-fixed point high above the Earth’s surface (the Christmas Island kites achieved heights in excess of 11,000 feet ($\approx$ 3.3 km) and remained aloft for four days). With the kite at altitude, atmospheric measurements can be made from a WindTRAM that travels up and down the tether under radio control. The TRAM is basically a wing-like device that uses the wind as a power source for moving along the line. It carries with it the requisite telemetry for controlling TRAM speed and direction in addition to an instrumented payload. Repeated transits of the TRAM provide rapid, high-resolution profiles of the quantities being measured. A sketch of the CIRES WindTRAM, riding along the kite tether and carrying a typical payload, appears in Figure 1. A description of the TRAM capabilities is covered in Section 4.2.

The principal difficulty encountered in most campaigns involves obtaining permission from the FAA (or its foreign equivalent for non-U.S. flights) to fly over a few hundred meters above the ground. Kites and tethered balloons flying somewhat above this height are a legitimate concern for small aircraft flying in the area. For higher heights, the problem extends to regularly scheduled commercial aircraft. The problem of flying kites at heights normally allocated to aircraft traffic is typically obviated by obtaining a NOTAM (NOTice to AirMen) that temporarily prohibits aircraft from flying in the area. Alternatively, it turns out to be possible to obtain permission to fly in restricted areas in which aircraft are permanently prohibited from flying. Such areas typically exist around military facilities. Thus, while the sites for kite-borne atmospheric measurements should be chosen with care, it is reasonable to expect clearance, at least for specific periods.

4. Description of the CIRES Kite and Wind TRAM Systems

4.1. KITE SYSTEMS

The kites used in virtually all of the CIRES studies are moderate-aspect ratio, ram-air-filled parafoils designed for stability, portability, and reasonable-payload capability at high elevation angles. They are typically constructed of Kevlar-strengthened Mylar with Kevlar or Spectra bridles. Kite surface areas range from the smallest kite at 5 m^2 to large kites that have areas on the order of 15–20 m^2. A picture of a typical parafoil being launched appears in Figure 2. The kite shown in this figure was specially designed for CIRES by Bill Tyrrell and Associates of Doylestown, Pa.

The CIRES kites use Kevlar tethers, with the tether strength chosen according to the size of the kite and the existing wind conditions. Typical breaking strengths lie in the range 100–400 kg. Typical tether diameters range from 1 mm to 3 mm.

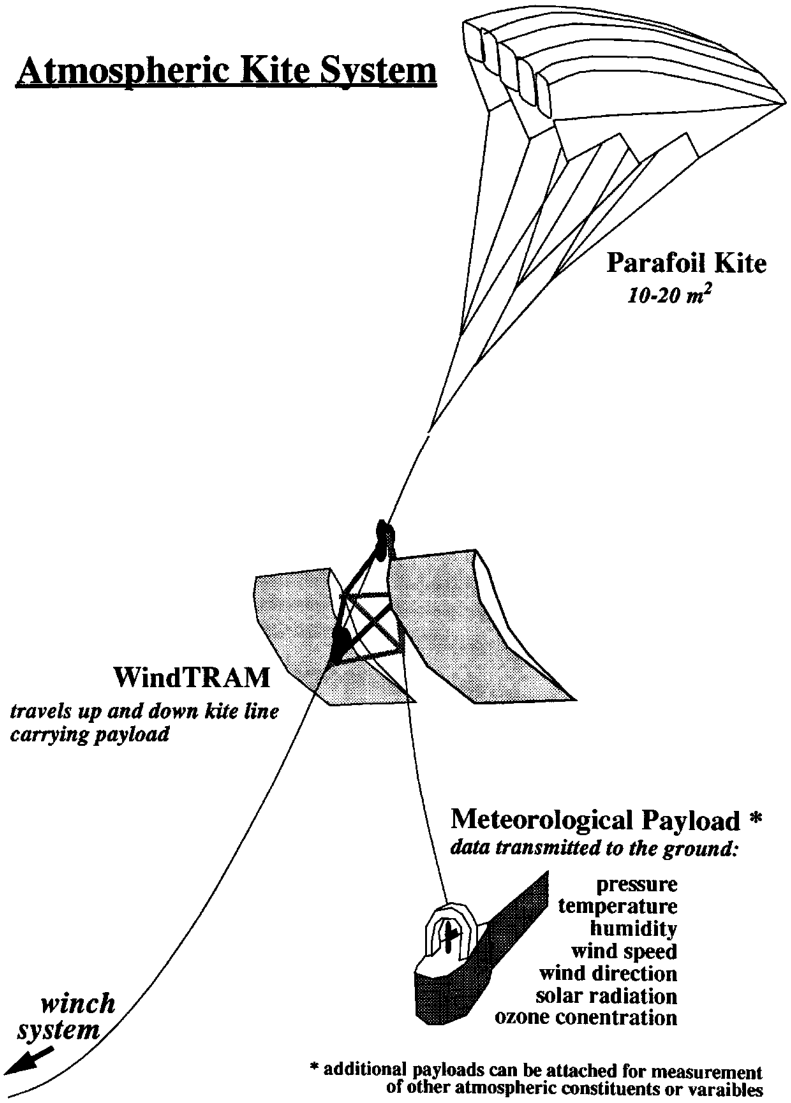

Figure 1. Artist's sketch of the CIRES atmospheric kite system including the parafoil kite, the WindTRAM, and a typical meteorological payload.

Proper tether selection is very important, since the weight of the tether can be much larger than the payload weight. Also, tether drag is proportional to the line diameter. Since the tether length is 1.5–2 times the height of the kite, both the tether weight and the drag are critical factors in achieving maximum kite heights.

In terms of wind speed, reasonable conditions for kite launches and for sustained flying require that the wind speed at kite height lies between roughly 6–18 m s^{-1}. This lower limit clearly will increase for sustained flights at altitudes

Figure 2. Photograph of a typical kite launch, showing a 15 square meter parafoil.

well above the boundary layer where the air density decreases significantly. For launches and sustained flights within the boundary layer, however, these are reasonable values for current kite designs. Future developments will certainly increase the maximum wind speeds under which kites will fly stably.

For the kite sizes and line tensions outlined above, it is imperative to make use of some sort of winching system to raise and lower the kites under a wide variety of wind conditions. Typical requirements include the ability to allow the kite to be let out rapidly at low line tension and to bring it in reasonably rapidly under heavy wind conditions, i.e., at high line tension. It is also desirable to be able to hold the kite on a fixed tether length for extended periods.

With regard to the design of a usable winching system, it is important to point out the inadvisability of winding the tether directly onto a take-up reel. Winding the tether directly onto a take-up reel under very high tensions abrades the Kevlar, shortens its lifetime, and can result in line breaks when the line is wound under tension across the underlying tether. Also, each additional wrap on the take-up reel can increase the inward force on the reel. Thousands of turns of tether on a take-up reel at high tension can collapse the reel unless it is carefully designed. This problem was effectively demonstrated in 1899, when a $10,000 heavy steel winch purchased for winding in a piano wire kite tether was crushed beyond recognition when it was first put into operation (Rotch, 1898).

In view of the above problem, the CIRES winch system incorporates a capstan to reduce the line tension prior to spooling the tether onto a take-up reel. A few turns around a capstan greatly reduces the line tension and thereby allows the line to be spooled easily onto a take-up reel. The CIRES group uses both electrically-driven capstans and capstans driven by gas or diesel engines. In a typical operation at a remote field site, they use the rear wheel of a vehicle that has been replaced by a capstan, after blocking up the rear axle. In this operation, the vehicles engine supplies the necessary power, while the transmission enables the line to be reeled out or in rapidly, if necessary. In addition, the line length can be fixed indefinitely by either the vehicles brake or park system. Moreover, as the tether comes off the capstan it can be wound around the take-up reel at low tension. The take-up reel can then be driven by a small (3/4-1 HP) gasoline engine or by a comparable electric motor using the vehicle battery as a power source. Such a system is shown in Figure 3.

4.2. THE WINDTRAM

A picture of a 3/4-sized prototype WindTRAM appears in Figure 4. Wing length (fore to aft) of this prototype system is 0.6 meters, and the transverse wing width is 0.9 meters. The wing width can be extended to 1.5 m by adding an additional panel to either side. Total actual wing area (note that there is no wing in the center frame area) is 0.54 m^2 (or 0.9 m^2 extended). Note, in particular, the inverted airfoil on the TRAM wings that provides downward lift when the TRAM is in the down mode. Wing position is controlled using conventional RC (radio-control) systems coupled to a relatively powerful servo. Additional features on this prototype model include a tachometer (to measure TRAM speed along the line), an anemometer (to measure relative air speed), a tilt sensor (to measure the tether angle), a po-

Figure 3. Photograph showing one possible winching technique. In this case, the kite tether is brought down through a pulley to a capstan mounted on the rear axle of a vehicle. The line is then wound onto a take-up reel under light tension. The power necessary to reel in the kite is provided by the vehicle.

Table I
Prototype WindTRAM characteristics

Characteristic	Non-extended	Extended
Wing length (m)	0.6	0.6
Wing width (m)	0.9	1.5
Wing area (m^2)	0.54	0.9
Line speed (m s^{-1})	3–9	3–9
Vertical speed (m s^{-1})	2–6	2–6
Payload weight (kg)	3	5

tentiometer (to measure the angle of the TRAM wing relative to the tether), and a pressure sensor (to measure altitude). Typical operating characteristics of this prototype WindTRAM are presented in Table I. Note that the values shown are listed for this prototype, assuming nominal wind conditions, i.e., at least 5 m s^{-1} at the surface and increasing with height. TRAM speeds and payload capabilities are strongly dependent on local wind conditions.

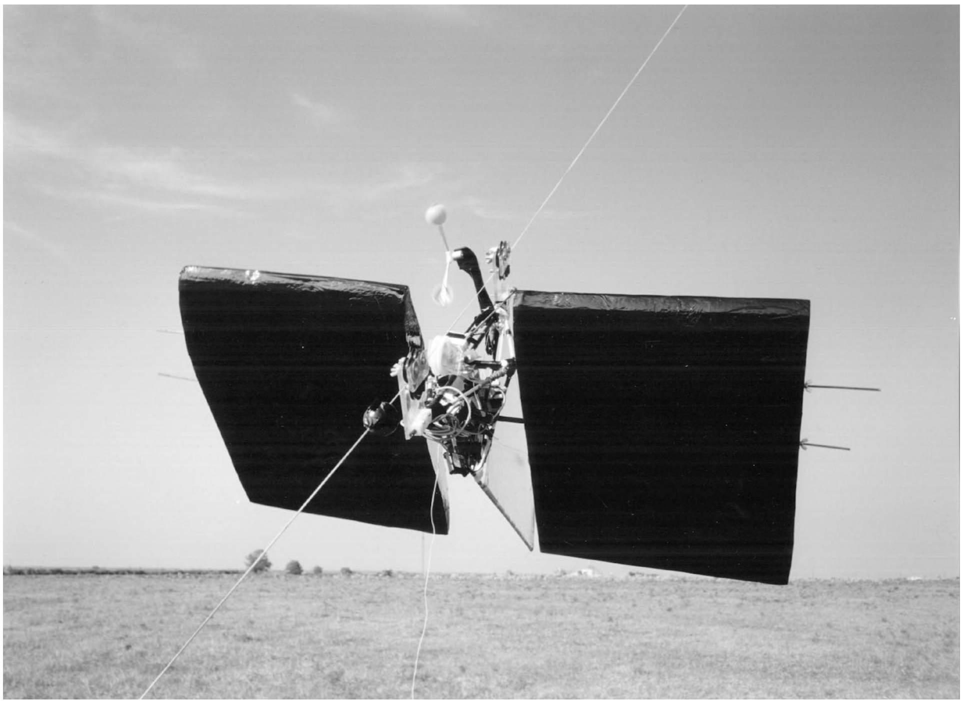

Figure 4. Photograph of the prototype WindTRAM connected to the kite tether. This shows the smaller version of the TRAM, with only one set of wing panels.

4.3. PAYLOAD OVERVIEW

There are a number of important points to be discussed in outlining the capabilities of a kite system to carry a payload. It is important to stress that *a typical payload can consist of any type of instrumentation that meets the criteria described below.* A payload – including the requisite power source – must satisfy specific weight requirements. Basically, current payload weights under nominal wind conditions range from 5–10 kg for a tether-mounted payload, and 2–5 kg for a payload carried by the WindTRAM* Moreover, the physical size of a payload must be reasonably small and/or aerodynamically shaped for minimal drag, and must not present an appreciable cross-section to the incident wind. Finally, the payload package must operate within the temperature, pressure, and humidity limits imposed by the environment.

Payload data collection can be accomplished by payload-to-ground telemetry, provided that such a capability is included in the instrumented payload. Alternatively, data can be stored digitally on the payload for subsequent downloading after the payload has landed. The choice between these two possibilities involves the

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* These are not fundamental, but rather current limitations. Man-lifting kites at the turn of the century carried payloads in excess of 100 kg to altitudes of at least 1,200 m (Hart, 1982).

quantity of data being collected along with the possible need to control the payload position based on the on-line observations.

Note that payloads can be carried aloft either on the WindTRAM or on the kite tether itself. It is also feasible to connect a series of lightweight payloads along the tether to make simultaneous measurements at a variety of heights. WindTRAM measurements are useful for making relatively continuous, high resolution profiles. Since the TRAM is typically brought down to ground level every profile, it is also useful when the payload power requirements are such that the payload batteries need to be replenished often. Single payloads attached to the tether, on the other hand, are useful for long-term continuous measurements at a single (reasonably constant) altitude, particularly if the payload power requirements are minimal. Multiple payloads attached to the tether can be best used for simultaneous data taking at a number of different altitudes, particularly if the individual payloads are lightweight and have low power requirements.

In all of the above instances, it is desirable to keep the kite aloft as much as possible. Kite launches and retrievals are typically the most problematical of all of the associated activities. On land, low-level turbulence is typically a problem, while launch and recovery complications arise onboard boats and ships.

4.4. POSSIBLE POWER SOURCES FOR WINDTRAMS AND PAYLOADS

The most obvious power sources for both the WindTRAM and the payload(s) are batteries. Since most of the payload instruments require low voltages (e.g., 5–18 VDC), it is only necessary to use batteries that are capable of maintaining the voltage and current capabilities under relatively cold conditions (i.e., -20 °C). Both Lithium and NiCad batteries satisfy this requirement. Lithium batteries supply more energy per mass but are not rechargeable. NiCad batteries, on the other hand, are rechargeable, but are heavier than comparable lithium units. Upcoming battery technology (e.g., rechargeable lithium-ion cells) will provide improved capabilities. Thus, both economics and weight requirements are important considerations in choosing the proper battery.

Alternative energy sources include both lightweight wind-powered generators carried on the WindTRAM (or the payload), as well as solar cells. Wind-powered generators weighing roughly one kg can supply a few watts of power on a continuous basis (A test system has been supplied by Windstream Power Systems, Inc. of Burlington, Vermont). They are typically quite useful, since a reasonably strong wind is all but certain if the kite is in the air. Moreover, since the wind blows night and day, only minimal power storage is necessary. Solar cells, on the other hand, are lighter weight, but require considerable storage since they supply power only under daylight conditions. Also, solar panels need to be oriented relative to the sun's position. (Thin, lightweight panels are available, for example, from Jade Mountain, Inc., Boulder, Colorado.)

A third alternative energy source is the Earth's global electric field. Vertical electric field magnitudes at typical kite heights are of the order of tens of volts/meter. Unfortunately, the source impedance of this supply is quite high and extraction of reasonable amounts of power requires large collection areas. Although the global electric field is predictable under clear weather conditions, the presence of local convective activity produces greatly enhanced, and typically reversed electric fields. Little work has been done to date to develop the Earth's electric field as a power source for kite-borne studies, although early attempts to extract power from the electric charges carried down a kite wire succeeded in driving a very small electric motor (Eddy, 1900).

5. Kites from Boats

As pointed out in the historical review in Section 2, the idea of flying kites from boats for meteorological purposes dates back to the turn of the century. There are a number of advantages that accrue by flying a kite from a moving boat. First of all, the boat's motion significantly modifies the wind seen by the kite. In fact, as pointed out by both Rotch (1902) and Dines (1903), given a boat speed of at least 12 knots, it is possible to fly kites in virtually all weather conditions excepting violent storms. Secondly, surface wind conditions are typically less turbulent over large bodies of water, a fact that facilitates kite launches and retrievals. A third advantage of using boats is that, since the wind velocity seen by a kite is controlled by the boats speed, kite tether adjustments can be easily made under optimum wind conditions. An example of launching a kite from a small boat appears in Figure 5. This picture was taken during a CIRES campaign on the Marañón River in Peru's Upper Amazon Basin in 1996. Note the 5 m wide launching platform near the aft end of the locally-made outboard motor boat. In this case the boat's speed was carefully controlled during launch in order to trim out the kite by adjusting the bridle lines. With the 1–2 m s^{-1} current and the 65 HP motor, it was possible to fly both up and down river with minimal difficulty. In fact, with the kite flying at an altitude of about 100 m, it was possible to make 360 degree turns with care.

6. Examples of Data Gathered Using the Kite and Wind TRAM Systems

6.1. OVERVIEW

As discussed earlier, both the kite and the WindTRAM should be considered merely as platforms for making atmospheric observations. The type of observation is limited only by power and weight limitations. A number of different types of observations can be made simultaneously, provided that the total payload meets the weight limitations. Continuous data can be gathered at one or more heights. Alternatively,

Figure 5. Kite launch from a small outboard boat on the Maranon River in Peru’s Upper Amazon Basin. In this case, the relative wind velocity is controlled by the boat’s speed and the river current.

rapid high-resolution profiles can be achieved from ground level up to the kite height. The type of observation depends primarily on the needs of the experimenter. Some typical examples of the kind of data obtained by the CIRES group are shown below.

6.2. PROFILES

An example of raw profiles of potential temperature, humidity, and ozone mixing ratio obtained during a CIRES campaign to Cape Sable Island, Nova Scotia in 1993 are shown in Figure 6. These specific profiles, which extend to about 1.5 km, correspond to the ascent of instruments suspended directly from the kite tether, with both the kite and the payload being slowly raised (and lowered) together. Note, for example, that the ozone profile exhibits a pronounced peak at about 300 meters, with values in the range 110 ppbv. Note also that the ozone concentrations aloft correlate poorly with the ground level values. Wind directions aloft are shown on the right-hand side of the figure, and were obtained from a nearby wind profiler that was operated during this campaign. This type of data clearly illustrates the need to obtain data not just at ground level when studying transport of trace gases.

An example of using rapid, quasi-continuous profiles to produce height-time contours of temperature appears in Figure 7. These data were obtained during a field trip to the Atmospheric Radiation Measurements (ARM) site near Lamont, Oklahoma, in 1996. The profiles were gathered using the WindTRAM shown in Figure 4 (but with the extended wing sections). The TRAM was flown rapidly up and down the tether for roughly 1.5 hours. The contours shown in this figure were formed from nine separate profiles made during this period. Note the gradual warming of the near surface region and the slow apparent rise (≈ 5 cm s^{-1}) of the cool region as the morning progresses. Note also that the 800 m height limit in this instance resulted from a 1000 meter maximum-altitude set by the FAA in their NOTAM for these measurements.

Profiles of humidity and temperature in Figure 6 were obtained using conventional Vaisala rawindsonde packages. Ozone measurements shown in Figure 6 were made using a conventional electrochemical ozonesonde manufactured by the Science Pump Corporation of Camden, New Jersey. In all cases, profile data were telemetered down to a ground station periodically using conventional techniques.

6.3. IN-SITU SAMPLING

The ability of kite-borne or TRAM-borne instruments to continuously obtain data at one altitude for extended periods is important for studying the dynamic properties of the atmosphere. Such a capability is also important for studying the morphology of chemical species in and above the boundary layer, as well as for measurements of cloud properties. It is also feasible to consider using multiple sensors suspended below the kite or WindTRAM to measure the three-dimensional properties of dynamic processes such as atmospheric turbulence.

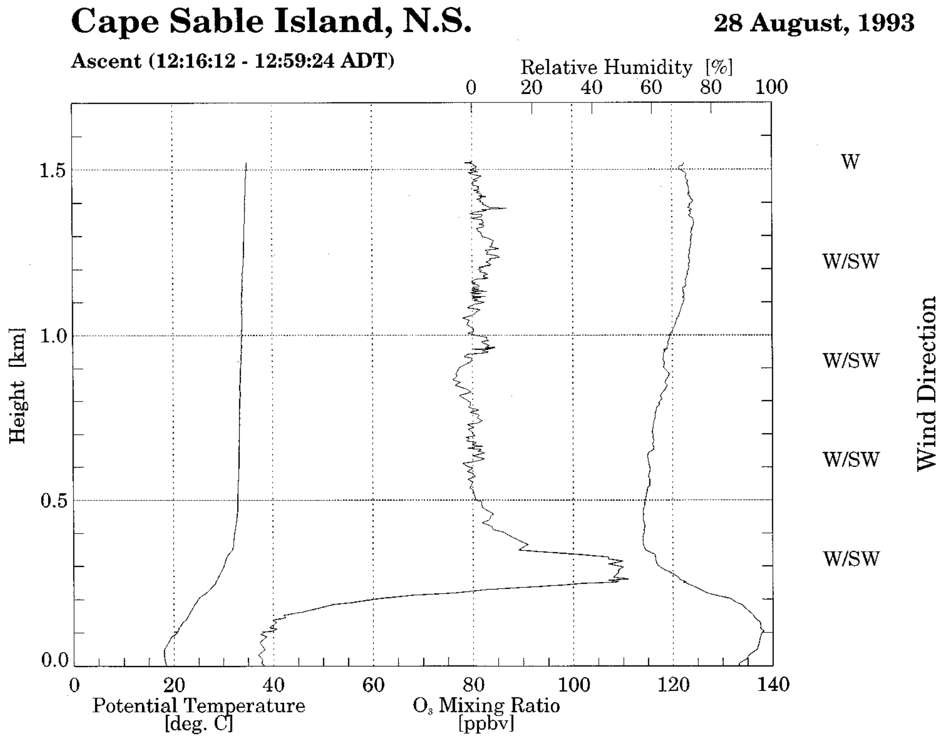

Figure 6. Vertical profiles of ozone, temperature, and relative humidity obtained during the Cape Sable Island Campaign (NARE) in August 1993. Wind direction at various heights appears on the right of the figure.

Examples of the importance of in-situ sampling are shown in Figures 8–10. High-speed measurement of turbulent temperature fluctuations were produced using an inexpensive type E thermo-couple probe with 0.001 in diameter wire and recorded with a 12 bit digitizer on a small onboard storage device. A calibration curve for the thermocouple probe was provided by the manufacturer. Temperature samples were obtained every 2.5 milliseconds for a period of approximately two minutes at an altitude of 300 m. A continuous 16-second sample of the temperature fluctuation time series appears in the two panels of Figure 8. Values of the temperature structure constant, C_T^2, obtained from a spectral analysis of the fluctuations during that selected period, appear in the upper left-hand corner of each panel. A power spectrum of the entire 128 seconds of the data set was produced by averaging the periodograms from 16 consecutive 8-second sections of data. The results are shown in Figure 9 (circles) along with a best-fit theoretical turbulence spectrum modeled as a Kolmogorov power law $Kf^{-5/3}$ multiplied by the frequency response of the probe $(1 + f^2/f_0^2)^{-1}$ (Press, 1986). (The windowing effects of the finite data length can be included in the spectral model to produce more accurate

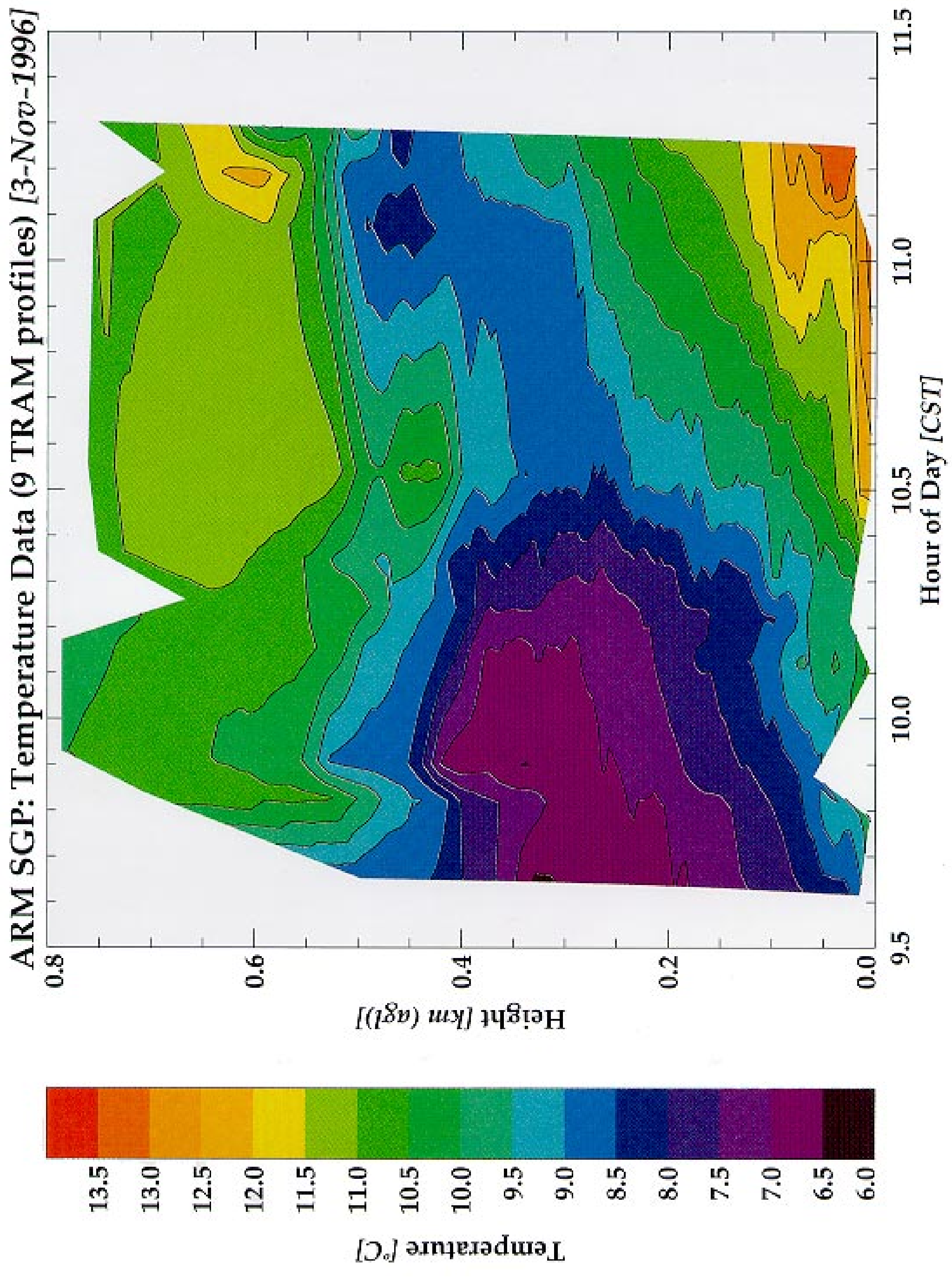

Figure 7. Preliminary temperature vs. height contours obtained from a WindTRAM using a low-precision sensor.

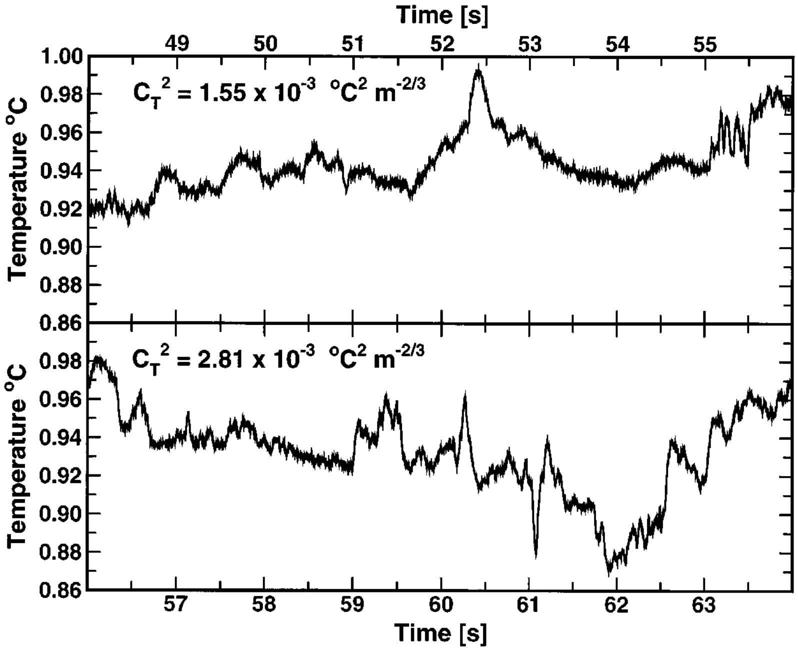

Figure 8. Temperature fluctuation time series from an height of 300 m. The mean temperature of 21 °C was removed by a high-pass analog filter. The temperature structure constant C_T^2 for the data is obtained from spectral analysis of the data.

estimates.) The frequency response of the probe is $\approx$ 10 Hz. and the spectrum with the correction for the probe response is shown in the bottom panel of Figure 9. Note the close correspondence between the actual data points and the theoretical curve. The level of the spectrum K (estimated for frequencies less than 16 Hz.) and the average flow velocity of 5 m s^{-1} produce an estimate for the average C_T^2 which is shown in the bottom panel of Figure 9. Applying the same spectral analysis to consecutive 4-second sections of data produce the high temporal resolution estimates of C_T^2 shown in Figure 10. The 1-σ error bars are produced from the mean-square error of the fit assuming that these short sections of data are locally stationary with statistically independent spectral estimates. These large random variations in C_T^2 have been called ‘global intermittency’ (Mahrt, 1989) and are typical of boundary-layer turbulence (Frehlich, 1992). Similar results have been obtained for velocity statistics using the energy dissipation rate as a measure of the level of turbulent velocity fluctuations (Frehlich, 1992).

The statistical description of the intermittency is essential for correct interpretations of basic turbulence quantities and for estimating the statistical accuracy of measurements. For example, if one assumes that the spectral estimates are statistically independent, then the mean-square-error of the very good fit to the average spectrum in Figure 9 results in an estimation error for the estimate for C_T^2 of approximately 3% (Press, 1986), which is inconsistent with the large variability of

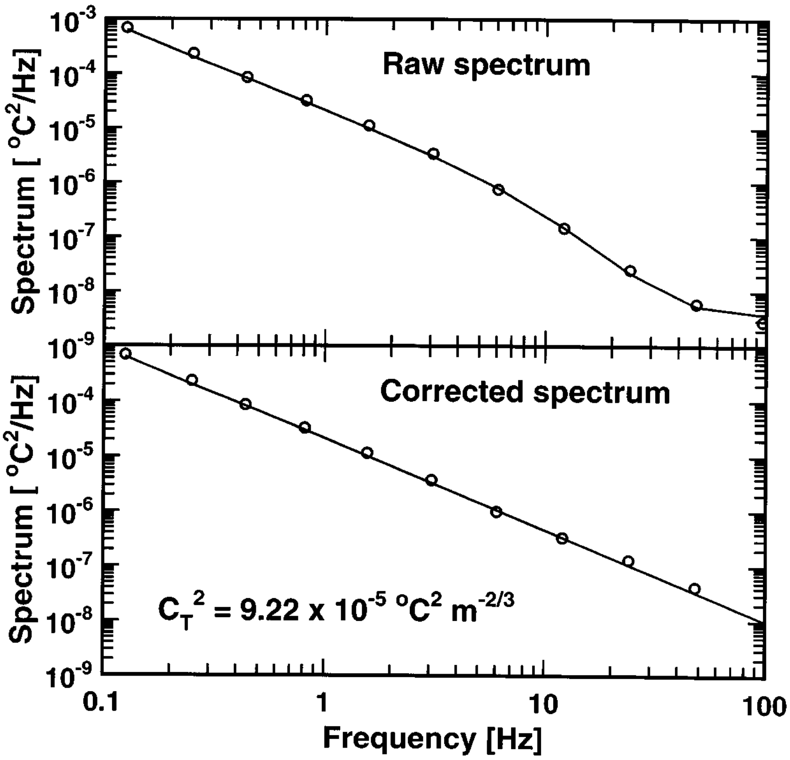

Figure 9. Average temperature spectrum for 128 s of data, the best-fit theoretical model (—), and the spectra with corrections for the probe instrument response.

C_T^2 displayed in Figure 10. The spectral estimates in Figure 10 are not statistically independent. However, the spectral estimates from the 4-second sections of data used in Figure 10 may be approximately statistically independent because these shorter sections of data may be locally stationary.

7. Advantages and Disadvantages of Data Gathering Using Kite and Wind TRAM Technology

7.1. GENERAL COMMENTS

It seems appropriate to summarize the advantages and disadvantages of the kite and WindTRAM technology in order to compare kite-borne sampling and other extant techniques. This summary appears in the following two sections (7.2 and 7.3). The following section (7.4) provides a comparison of the kite-borne technology relative to other current atmospheric sampling techniques.

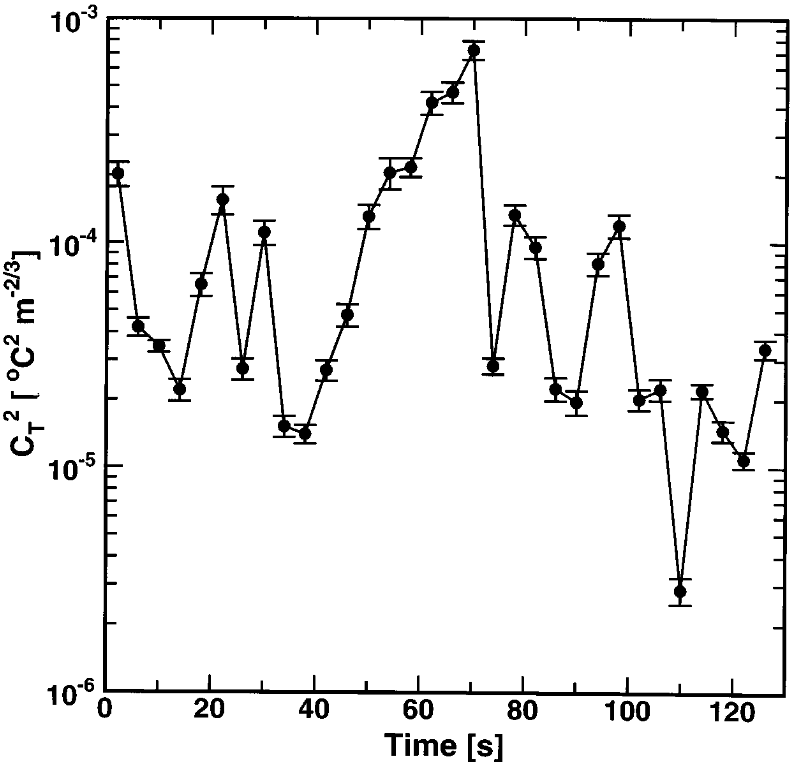

Figure 10. The intermittency of C_T^2 using 4 sec of data for each estimate. The 1-σ error bars calculated from the mean-square-error of the best-fit model spectrum are also shown.

7.2. ADVANTAGES

Modern kites are relatively simple, lightweight, portable, structures that operate in winds ranging from roughly five to about 20 m s^{-1}. Moderate-sized parafoils with areas up to about 20 m^2 are capable of carrying reasonable payloads (i.e., 2–10 kg) to heights up to at least a few km. Under benign conditions, they can remain aloft for days. Kites can be flown from either land-based locations or from boats, with boat flights being somewhat preferable (excepting the more confined working conditions), since the boat velocity controls the effective wind seen by the kite. In either case, payloads can be either suspended directly from the kite tether or carried up and down the tether by a WindTRAM. Data collection using kites is relatively inexpensive, since the instrument packages are not lost. The primary restriction to the type (or types) of data lies in the weight limitations of the payload. Data can be telemetered or archived for later downloading. Data gathered by the kite-borne technology can provide high height and time resolution profiles from the ground up to at least a few km on a relatively continuous basis under reasonable conditions. Alternatively the payload can remain for extended periods at a given altitude. The data provide relatively continuous information in an Eulerian framework. Spatial sampling is achievable, if desired, by flying a series of kites in a spatial grid. Sampling is clean, in that the payload is suspended well below the kite to minimize contamination and undesired blocking effects that can occur in other types of atmospheric sampling.

7.3. DISADVANTAGES

There are also a number of disadvantages to using kites for atmospheric sampling. Kites require winds of at least 5–7 m s^{-1} at kite level to remain aloft. Kites are not all-weather systems, and cannot fly during periods of high convective activity or in strong storm conditions. Control of the precise altitude has yet to be accomplished. The most pressing problem, however, is the need to fly in either NOTAMed areas, or in areas that are permanently restricted to all aircraft.

7.4. A COMPARISON OF TECHNIQUES

In order to better evaluate the advantages and disadvantages of kites for atmospheric research, Table II lists a series of pertinent aspects of kite-borne techniques discussed above. Similar aspects for a number of other techniques have been included for comparison. Comparisons are made with tethered balloons, conventional non-tethered balloons, aircraft and meteorological towers. Non-standard balloonsondes, which are relatively special-purpose devices with a wide range of capabilities are not included. Also not included are the next-generation unmanned aircraft that are planned to fly in the middle stratosphere.

Note that the kite/WindTRAM capabilities include only those that have been shown to be currently feasible. Clearly kites have flown well above the listed capability many years ago. Furthermore, the maximum payload carried by a kite has already exceeded the stated value in Table II. While it may turn out that kite systems can fly much higher and carry heavier payloads, the purpose of this comparison is to concentrate on existing capabilities rather than to speculate on future possibilities.

8. Conclusions

This paper reviews the use of kites for atmospheric research. The review began by outlining the use of kites for obtaining temperature, pressure, humidity, and wind data in the free atmosphere from the 1750s to well into the present century. During this period kites provided a unique and valuable means of lofting primitive instruments to altitudes well in excess of three kilometers. While gas-filled balloons occasionally carried men and/or instruments to greater altitudes for such studies, kites clearly were the primary vehicles for gathering the day-by-day information necessary to build a reasonable data base of the first few km of the atmosphere.

Table II

A short intercomparison of atmospheric sampling techniques

ITEM	KITES	Tethered balloons	Standard balloon-sondes	Aircraft	Towers
Maximum altitude coverage*	>5 km	$\leq$ 1-2 km	>30 km	≤ 18 km	$\leq$ 300 m
Very low-level sampling	yes	yes	yes	no	yes
Constant-height sampling	yes	yes	no	yes	yes
Eulerian measurements	yes	yes	no	no	yes
Lagrangian measurements	no	no	questionable	difficult	no
Max payload weight	$\approx$10 kg	$\approx$100 kg	$\leq$ 3 kg	$\approx$500 kg	large
FAA clearance needed	yes	yes	no	no	no
Height resolution	$\leq$ 1-10 m	$\leq$ 1-10 m	50 m	<10 m	$<$ 1 m
System costs	\$10-20k	\$10-200k	\$10k	\$50 k-\$6M	\$1-800k
Cost/profile	very low	$\approx$low	low-high	$\geq$avg.	low
Wind requirements	$>$5-7 $(\mathrm{m\ s^{-1}})$	$\leq$ 12 $(\mathrm{m\ s^{-1}})$	$\leq$ 10 $(\mathrm{m\ s^{-1}})$ (launch)	minimal	none
All weather?	no	no	yes	typically	yes
Portable	yes	yes	yes	yes	no
Payload recovery	yes	yes	very difficult	yes	yes
Telemetry	yes	yes	yes	yes	yes
Payload vertical velocity	0- 5 $(\mathrm{m\ s^{-1}})$	0-5 $(\mathrm{m\ s^{-1}})$	$\approx$4-6 $(\mathrm{m\ s^{-1}})$	0- 5 $(\mathrm{m\ s^{-1}})$	0- 5 $(\mathrm{m\ s^{-1}})$
Vertical profiling	yes	yes	yes	expensive**	possible

* The highest altitude (9,740 m) achieved by a train of kites occurred in 1919 at Lindenbérg, Germany (Yolen, 1968).

** Measurements of the spatial turbulent statistics in the vertical direction are difficult with airplanes.

This review of early work was followed by reviewing some of the current kite studies by the University of Colorado that extend well into the free atmosphere, and that again provide a unique tool for a wide range of studies. It seems clear to us that state-of-the-art kites in the present day offer a relatively inexpensive means of obtaining quasi-continuous measurements of many of the critical quantities necessary to expand our understanding of meteorological and chemical processes, as well as atmospheric dynamics.

Perhaps the best summary statement of the potential of the kite technology for atmospheric science is to point out that *it is currently impossible to obtain continuous, high-resolution measurements of any atmospheric quantity for extended periods (i.e., for many hours) at a single location at altitudes greater than about two km by any other means.*

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