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Atmospheric Boundary Layer Sensors for Application in a Wake Vortex Advisory System

J. Allen Zak
ViGYAN, Inc., Hampton, Virginia

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List of Acronyms and Abbreviations

ACARS	Aircraft Communications Addressing and Reporting System
AMDAR	Aircraft Meteorological Data Relay
ARINC	Aeronautical Radio Inc.
ASC	Aviation System Capacity
AVOSS	Aircraft Vortex Spacing System
COTS	Commercial off-the-shelf
CW	Continuous Wave
DERA	(British) Defense Evaluation and Research Agency

DFW	Dallas-Fort Worth Airport
EDR	Eddy Dissipation Rate
ETL	Environmental Technology Laboratory
FAA	Federal Aviation Administration
FII	Frequency Domain Interferometer Imaging
FMCW	Frequency Modulated Continuous Wave
IMC	Instrument Meteorological Conditions
LaRC	Langley Research Center
LLWAS	Low Level Wind Shear Alert System
MAPR	Multiple Antenna Profiler Radar
MDCRS	Meteorological Data Collection and Reporting System
MIT	Massachusetts Institute of Technology
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NIMA	NCAR Improved Moments Algorithm
NOAA	National Oceanographic and Atmospheric Administration
RASS	Radio Acoustic Sounding System
RIM	Range Imaging
Rms	Root Mean Square
SADRASS	Spaced Antenna Drift Radio Acoustic Sounding System
SBIR	Small Business Innovative Research Program
TARS	Tethered Aerostat Radar System
TDWR	Terminal Doppler Weather Radar
TEP	Turbulent Eddy Processor
TKE	Turbulent Kinetic Energy
UHF	Ultra High Frequency part of electromagnetic spectrum
VAMS	Virtual Airspace Modeling and Simulation
VHF	Very High Frequency part of the electromagnetic spectrum
WakeVAS	Wake Vortex Advisory System

1.0 Introduction

Capacity at major world airports is constrained because of safety precautions for wake vortex avoidance. Rules are established for minimum aircraft separation based on aircraft weight classes during Instrument Meteorological Conditions (IMC). In the United States, these rules limit separation distance in the worst case to six nautical miles during landing in order to ensure that the trailing aircraft follows at a safe distance to avoid a potential wake vortex hazard. For departures, there are time and distance separation standards also based on aircraft follow-lead weight classes. Airports with closely spaced parallel runways and intersecting runways have constraints that can limit capacity by 50% during certain conditions (ref. 1).

The National Aeronautics and Space Administration (NASA) is addressing the problem of capacity at our major airports through its Aviation System Capacity (ASC) Program. The overall objective of ASC is to improve performance of the National Airspace System (NAS). Contributing to this overall effort, the NASA Ames Research Center, through its Virtual Airspace Modeling and Simulation (VAMS) Project, is developing advanced air transportation concepts, and high-fidelity model and simulation capabilities. NASA Langley Research Center (LaRC) is supporting VAMS in concept development for aircraft wake vortex hazard mitigation.

Operational specifications are needed for commercial off-the-shelf (COTS) sensors capable of measuring atmospheric parameters associated with wake behavior. These specifications will be used to define simulation models for the LaRC concept development efforts. In the near term, a survey of current COTS weather sensors will also support field data collection efforts for model development and operational concept investigations.

NASA LaRC has a successful history in aircraft wake-atmosphere interaction research and modeling as well as in dynamic Wake Vortex Advisory Systems (WakeVAS) development, testing and field demonstration. One project that terminated in 2000 was the Aircraft Vortex Spacing System (AVOSS) (ref. 2). The purpose of AVOSS was to integrate current and predicted weather conditions, real-time wake vortex transport and decay models, and wake vortex sensor data to demonstrate a dynamic wake vortex separation capability. Major field activities included high quality wake and atmospheric data collections from Memphis International Airport in 1994 and 1995, and at the Dallas-Fort Worth (DFW) Airport in 1997, and 2000. These, along with large eddy simulations, resulted in a major increase in our knowledge base of wake/atmosphere interactions. The conclusion of these and other similar studies was that it is possible to maintain safety at present levels by taking advantage of advanced knowledge of atmospheric conditions and reduce aircraft separations when atmospheric conditions warrant (ref. 3,4,5,6).

The field measurement programs in the past served to augment understanding of sensor performance in an operational environment and led to recommendations for optimal sensor combinations for a WakeVAS in the National Airspace System of the future (ref. 7). The technology used for these field studies was that available in the middle 90's. It included non-commercial pulsed and continuous wave lidars, as well as commercially available Doppler sodars, radar profilers and a Radio Acoustic Sounding System (RASS). Since then, there has been some progress in signal processing, hardware, commercial availability, and new technologies.

The purpose of this report is to document specifications of current technologies, update recommendations for technologies and sensor systems that may be used in any operational WakeVAS of the future, and to recommend testing of some of these improved capabilities as well as some promising new sensors that may reduce the limitations reported in the past.

This report will focus on ground-based and aircraft atmospheric profile measurements. Other options such as ground-based sensors to measure wake characteristics or on-board aircraft capabilities to detect and measure the wake hazard are not included**.** Based on previous results with AVOSS at DFW, it is assumed that an envelope of atmospheric conditions can be qualitatively determined from means and variances so as to provide a persistence probability forecast of at least 30 minutes duration.

2.0 Atmospheric Parameters Associated with Aircraft Wake Behavior

Wakes are generated by all aircraft in flight as a direct result of lift. Two counter-rotating, horizontal (parallel to the ground) vortex tubes form a short distance behind the aircraft. Their initial separation from each other is about three quarters of the aircraft's wingspan. The simplified picture is that these vortices descend at about one to two m/s and have an initial strength directly proportional to aircraft weight, and inversely proportional to air density, wingspan and airspeed. Wake vortex dimensions for typical transport aircraft are on the order of 10's of meters and lifetimes on the order of a minute or less, but they can last longer. Other behaviors such as horizontal and vertical meandering, vortex tube twisting, bursting, kinking of the vortex tube, and mutual annihilation have all been observed. Vortex interaction with the ground occurs starting at about the height equal to the initial separation. For a B-747, this is about 50.5 m. Here the descent rate slows or stops and may even reverse (vortex bounce) occasionally, and both vortices tend to push away from each other due to surface friction effects (ref. 8). Vortex linking with the ground has also been modeled and observed (ref. 9). An accumulation of knowledge about wake vortex characteristics and behavior can be found in an annotated bibliography consisting of abstracts of publications, which are maintained up-to-date and searchable by the John A. Volpe National Transportation Systems Center, at http://www.volpe.dot.gov/wv/wv-bib.html.

The atmosphere can transport the vortices in the horizontal dimension, change (stop or even reverse) the descent rate, and affect wake dissipation. In the "best case" for a following aircraft, wakes can be blown out of the flight path and they can dissipate quickly. In the worst case, they may linger, not descend (or even rise) and last longer. In the case of parallel runways the transport of the downwind vortex and its longevity (time to dissipation) are important. For lateral transport the cross-wind profile is of primary importance, but stratification (temperature profile-stability) and atmospheric turbulence also play a role. For descent rates atmospheric variables of turbulence and non-linear cross-wind shear have a primary effect while stratification is secondary. Turbulence has a primary effect for vortex dissipation, but stratification also plays a role (ref. 10). "Thermals" can be considered a form of turbulence in large time and space domains. Upward speeds in thermals can exceed several m/s even as low as 100 m above the ground and may affect vortex descent rates. For a more complete description of atmosphere-wake interaction, (see ref. 6, 11, 12, 13).

For a dynamic WakeVAS (and successor to AVOSS), it is assumed that vertical profiles of winds, temperature and turbulence are needed from near the surface to the top of the protected airspace envelope. This top altitude will depend on several factors including unique aircraft departure procedures at selected airports (ref. 11, 12, 14). In previous AVOSS demonstrations with landing aircraft at DFW and Memphis airports, a range of airspace protection was included for the volume from near the surface to about 600 m altitude corresponding to a protection region centered on the ILS localizer with a three- sigma buffer (ref. 14). For departure applications, data would need to be collected at specific airports to determine the mean flight paths on which to center the airspace region. Whether or not atmospheric measurements would be needed at more than one location at/near an airport would also depend on the location, since terrain can have a significant effect on meteorological variables in the lower boundary layer. Since most of the sensors sample a volume of air in an area, it is assumed that at least some of the spatial variability will be captured in the measurements from a single sensor system. It is not yet possible to provide precise requirements for the temporal and spatial resolution of atmospheric boundary layer properties or for the area of coverage because the learning process continues to evolve for details of a future WakeVAS as well as for wake-atmosphere interaction. Some relaxation in wind and turbulence profile measurement requirements may be possible. For example, there may be ways of using near-surface measurements of wind variability over sufficient periods to capture effects of afternoon eddy motion, which extends through the boundary layer. Also, wake sink is usually more effective than lateral motion in eliminating the threat at higher altitudes; so there may not be a need for crosswind variance at higher altitudes (ref. 10). Measurements of profiles of winds, temperature, and turbulence are discussed in more detail below.

2.1 Wind profiles

The mean crosswind can either cause one vortex to last longer near/along the runway and thereby cause a prolonged hazard, or both vortices can be blown harmlessly and quickly off the runway and away from approach/departure paths, depending on cross wind speed. Mean wind profiles on the order of 50 m vertical intervals and 30 minute averages were successfully used in past field demonstrations (ref. 7). Cross wind shear may affect the vortex descent rate. Numerical simulations have shown that vortices respond to non-linear vertical crosswind shears (ref. 15, 16). For example, when a cross wind shear of 3 m/s or greater was introduced over a 25m layer centered at 65m above the ground, the downstream vortex was deflected upward (ref. 15). Generation altitude was assumed to be 175 m. Cross wind shears of this detail (25 m height intervals and 10 minute output) were not measured reliably in the past, so confirmation of vortex behavior in wind shears was not possible, but such wake behavior was observed. Future wake behavior algorithms may require shear effects to be modeled, and will need measurements of the vertical wind profile in as much vertical detail as possible. The variance of crosswind shear over appropriate averaging intervals is also needed; a candidate interval could be from 10 minutes to an hour.

2.2 Temperature profiles

Temperature profiles were shown not to have a primary affect on wake behavior from a buoyancy standpoint, except during very strong inversions when vortices tended to dissipate rapidly; however, strong temperature inversions have a significant influence on mean wind, wind shears, and turbulence as well as on the performance of some of the remote sensor systems used to measure atmospheric properties. Winds can change in direction and speed rather abruptly near the altitude of the top of the nocturnal temperature inversion. Unstable atmospheres with strong surface heating can also enhance the development of low-level eddies as part of the normal convective process. These eddies can cause vertical currents (thermals), horizontal wind shifts and crosswind changes on a variety of time scales depending on their size. Therefore it may be important to know the vertical temperature structure at the airport for a WakeVAS. This would require vertical resolution near the ground in enough detail to determine the height of the inversion and its changes during the thermal gradient transitions in the morning and evening. Adequate measurement of variances generally require averaging periods of a least 30 minutes, and should be updated often (running averages) in rapidly changing conditions.

2.3 Turbulence profiles

The Turbulent Kinetic Energy (TKE) equations are the basis for understanding atmospheric turbulence. In their complete Navier Stokes form, they equate the eddy dissipation rate (EDR) to wind variances, covariances, and to a variety of terms related to atmospheric stability. In simplified steady state, first order closure form, they relate EDR to mechanical production of turbulence (vertical wind shear squared) and buoyancy or stability (vertical temperature gradient) (ref. 17). This simplification leads to ratios of the latter two terms called the Richardson Number, temperature gradient divided by wind shear squared and the square root of the temperature gradient term or Brundt-Vaisala Frequency. The eddy dissipation rate was used in the past and appears to be the turbulence parameter of choice (ref. 15). The variance of wind alone in the form of a parameter called TKE[1] can also provide a turbulence estimate. Tower-based measurements were used to produce EDR profiles. Atmospheric turbulence profiles in the form of the eddy dissipation rate are needed to help determine and predict such wake behaviors as reduced sink rate, increasing wake dissipation, and, in the case of larger scale turbulence outside of ground effect, promoting kinking of the vortex and instigating Crow instability. In numerical studies (ref. 18), turbulence was shown to be directly related to the vortex time to link. Turbulence in the upper boundary layer has also been associated with large vertical oscillations of the vortex pair (ref. 19). Turbulence acts together with stratification and cross winds to allow reduced aircraft spacing on the one hand, but also acts to reduce the sink rate and lateral drift rate near the ground on the other (ref. 12). Turbulence profiles and their variance are required in the region of monitored airspace for a particular WakeVAS configuration. The time and spatial resolution needed depend to some extent on the turbulence itself, with more frequent measurements required during rapidly changing conditions. It appears that 30-60 minute averages, updated every 10 minutes with 10 meter vertical resolution may be a starting point.

3.0 Existing Sensor Systems

Sensor system capabilities to measure vertical profiles of winds, temperature, and turbulence were determined from company literature, WEB sites, publications, and follow-up communications. In order to qualify as a candidate for measuring atmospheric boundary layer profiles in an operational environment, a sensor must operate unattended for long periods of time in “most[2]” weather conditions. Sensor technologies and pertinent characteristics of commercially available sensor systems are presented next.

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[1] TKE = $\frac{1}{2}(u'^2 + v'^2 + w'^2)$, where u, v, and w are the orthogonal wind components and primes are deviations from a mean over averaging periods of 30 minutes or greater.

[2] The term “most” is used to recognize that there are no remote (or aircraft) sensors that can operate in all weather conditions, nor is it a requirement for WakeVAS since default spacing would be appropriate in hazardous weather or heavy precipitation.

3.1 Wind profiles

Vertical wind profiles can be measured remotely (the standard radar tracked balloon measurements are not practical at airports) by lidar, radar, and sodar technologies. Aircraft can also measure winds during departure and landing phases of flight.

3.1.1 Lidars

Lidars or laser radars can be direct detection (molecular and particulate scattering), or just Coherent Doppler (particulate scattering); they can be pulsed for range gate analysis or continuous wave (CW) where the optics need to be focused on the range of interest. For Coherent Doppler lidars, the Doppler shift of the backscattered radiation from atmospheric particulates is converted to wind velocity along the measured azimuth. By scanning in the vertical plane, adjusting the focus range of the laser transmitter, and combining the atmospheric returns with a reference laser beam, vertical profiles of the horizontal wind can be obtained with a CW lidar. A 10.6-micron wavelength (CO_2) CW lidar developed by MIT Lincoln Laboratory (ref. 20) was used in the past to provide measurements of both wake characteristics and vertical wind profiles (when not measuring wakes); but vertical range was limited, it required a full-time operator, and was not commercially available.

For pulsed aerosol scattering lidars, the same principles apply, but ranging is accomplished by tracking pulses. A pulsed lidar developed by Coherent Technologies, Inc (CTI) under a NASA Phase II SBIR was also used in the past to measure both wake characteristics and atmospheric wind profiles (ref. 21). It too required a person to operate and was not commercially available.

Direct measuring Doppler lidars utilize backscattered signals from both Raleigh (molecular gas) and Mie (particulate) sources in the atmosphere. Small Doppler shifts in the change of transmission through a filter must be measured. Components include the laser, interferometer, transmitting and receiving telescopes and data processors (ref. 22).

Table-1 lists the companies from which lidars may currently be purchased along with pertinent performance specifications as provided by the manufacturers. Two commercial near-term sensors are also shown. Additional technical details are listed where available. Typically, CW lidars can produce high resolution wind measurements (on the order of one minute averages at 10 m vertical intervals), but range is limited to a few hundred meters. Pulsed Doppler lidars can achieve higher altitudes (up to 5000 m) with vertical resolution on the order of from 5 to 50 m. Five meter resolution can be achieved at lower heights through slant-path measurements or vertical scanning. There are several pulsed Doppler lidars available, one direct-measuring lidar, and one company offers a CW lidar. CLR-Photonics, a commercial products division of Coherent Technologies, Inc., offers a 2-micron (infrared) Doppler lidar called the Wind Tracer. It is an update of the scanning pulsed lidar used at DFW and JFK for wake and wind measurements, so it is capable of measuring both wind profiles and wake characteristics. It has also recently been used at the Hong Kong airport for low-level wind shear detection (ref. 23). The Michigan Aerospace Corporation GroundWinds Lidar is a direct detection lidar mostly used in the past for higher altitude wind measurements, but it has been configured to operate remotely. Wind accuracy is not as high as it takes a very large signal to noise ratio to measure small Doppler shifts in transmission changes through a filter. There are two systems operating to date. The cost shown is the cost to build a system. QinetiQ is a company recently formed from commercialization of the British Defense Evaluation and Research Agency (DERA). They offer a CW Doppler lidar with a limited range, but 10 m or better vertical resolution and at a cost of about $150,000. They also have transportable CW and pulsed CO_2 lidars, but they are not optimized for unattended operation. Qinetiq has a pulsed version of their 1.5 micrometer CW lidar under evaluation, and Yankee Environmental Systems is awaiting development by Virginia Polytechnical Institute of a small pulsed lidar.

Costs for existing longer-range lidars range from $700,000 to $1,200,000. Costs are rough orders of magnitude since quotes would have to be obtained for specific applications and configurations. They do not include maintenance or training. Prices have not dropped as expected because there has been a very limited market. The future of lidar wind and turbulence measurement still looks very bright as more requirements evolve for a wide variety of applications. Several companies have predicted cost to reduce by a factor of 4 or 5 for demands of 100 units or more.

In the wavelength range of lidars used for wind measurements, atmospheric attenuation in the form of scattering and absorption is similar to that for visible light, except for rain where IR attenuation is greater. Therefore, operational use of lidar wind profilers would be restricted and vertical altitude reduced in fog, clouds, rain, and other types of precipitation.

3.1.2 Radar profilers

Profiler technology has been around for more than 30 years, and there are profiler networks in routine operation by the National Oceanographic and Atmospheric Administration (NOAA), the US Air Force, NASA, and other agencies. The NOAA 404 MHz profiler network was optimized to provide high altitude coverage over time periods of from 30 minutes to an hour. NASA Kennedy Space Center operates a network of five 915 MHz profilers and one 50 MHz profiler for range support. Another network of 11 sites along the southern US border is being built by NOAA Environmental Technology Laboratory (ETL) and installed for the US Air Force Tethered Aerostat Radar System (TARS) project (ref. 24). This new 449-MHz radar wind profiler is designed to provide 15 min average winds (updated every 5 minutes) from 0.15 to 4.0 km above the ground with 0.12 km vertical resolution and run continuously with little operator intervention. They will become part of the national network. Additional radar profiler networks operate in California, Texas, and Alaska. There are networks across Europe as well (ref. 25).

Radar wind profilers typically operate at frequencies from 50 to 1300 MHz. They detect minute fluctuations in atmospheric density, which are caused by the turbulent mixing of volumes of air with slightly different temperature and moisture content. One vertical beam with up to four tilted radial beams is used to transmit pulses of energy that are scattered from these index of refraction variations in the atmosphere. Processing of the returned Doppler signals along tilted radials lead to horizontal and vertical wind solutions (ref. 26).

Operational characteristics of commercially available radar wind profilers are shown in Table-2. Five companies are listed as having an existing capability. There were only a few companies available prior to 1995. Scintec AG, and Atmospheric Research Pty, LTD have indicated that their UHF radar wind profilers will soon be available. These are also included in Table-2. When the user may select parameter settings to change performance characteristics of averaging period, output rate, and vertical resolution, such ranges are listed. There are tradeoffs in operational use. Even though averaging periods as short as one minute may be available, accuracy and performance will suffer for averaging periods less than 10 to 15 minutes. Shorter averaging periods and higher vertical resolution means that fewer along-beam samples are available (lower signal/noise) for processing and calculating winds. Peak altitudes may not be achieved and some range bins even in the lowest altitudes may be missing. In general, higher frequency radar profilers provide greater vertical resolution at the expense of range or peak altitude. Vaisala (formerly Radian Corporation) has over 100 systems fielded followed by Tomco, Degreane, and Applied Technologies. The number of units sold for ATRAD is unknown. Several companies offer a short-pulse mode for greater resolution, but at reduced peak altitudes, and a longer pulse mode for maximum altitude coverage at reduced vertical resolution. For a 60 m pulse length, typical altitude coverage is 1000 – 2000 m. Notice that the highest vertical resolution available is 50-75 m with the lowest range gate being about 70-75 m. Most can operate in multi-pulse mode to optimize resolution in the lower levels and maximize the peak altitude reached. Since these profilers are typically designed for measurements to 3000 – 5000 m, a WakeVAS application could take maximum advantage of the highest resolution modes. For example, vertical wind profiles could be produced every 5 to 10 minutes based on 10 to 15 minute running averages at vertical intervals of 50-100 m. Accuracies in wind measurements are provided by the manufactures and may not include adverse impacts of the environment. Antennas can be phased arrays, flat panel arrays, collinear dipoles, or multiple dish/parabolic reflectors as indicated. For 50 mHz systems, antennas are typically vertical poles connected by wires over a large area, but these systems are intended for high altitude coverage at reduced vertical resolution. Costs range from $220,000 to $320,000 for UHF wind profilers, and were estimated from information collected for a sensor system optimized for atmospheric wind measurement capabilities below two kilometers. Typically, it includes special processing, maximum power, power supplies, and optimum antenna configurations where available. Not all sensor manufacturers provided cost information. Costs are rough orders of magnitude since quotes would have to be obtained for specific applications and configurations. International exchange rates as of September 2002 were used to convert currencies to US dollars. Shipping is usually included, but technical support, training, graphic display software, installation, spare parts, and maintenance were not included. Trailers or mounting platforms are available from most companies, but these costs were not included. All systems can be operated remotely. Most can be combined with a Radio Acoustic Sounding System to measure vertical temperature profiles as well as winds (see Section 3.2.1).

Major limitations of the profilers are moderate or greater precipitation (particularly for UHF profilers), aircraft and birds in the radar beams, and side lobe interference. Strong temperature inversions and very dry atmospheres can adversely affect performance as well. There is some built-in quality control in the spectral processing of tilted radials for all systems. Therefore, manifestations of adverse effects are typically missing data rather than incorrect solutions. Measured signal characteristics are usually included in the output so that additional automated quality control can be applied and is highly recommended.

There are new signal processing techniques making their way into operational sensor systems. One technique is to use wavelet domain thresholding to obtain filtered reconstructions for automated clutter suppression (ref. 27). Another is called range imaging (RIM) or frequency domain interferometric imaging (FII) (ref. 28). RIM is a pulse compression technique using multiple frequencies to improve range resolution of Doppler radars which are limited by their minimum pulse length. The National Center for Atmospheric Research (NCAR) Improved Moments Algorithm (NIMA) is a technique using mathematical analysis, fuzzy logic synthesis, and image processing to mimic a human expert’s ability to pick out the correct wind signals from a large noise source (ref. 29). NIMA was developed for wind shear warning applications in Alaska using radar wind profilers. Another technique developed at the NOAA ETL is called CASPER (ref. 30) where optimum techniques such as longer time series are used for removing the contamination of along-beam Doppler spectra, and thus allow better wind solutions. These new processing techniques are likely to add some increment of cost to the sensor systems as they are implemented. Multiple peak processing is currently available in the Degreane radar wind profiler, and Vaisala, working with NOAA ETL, has implemented running averages in the TARS systems.

Another popular technique for achieving higher temporal resolution is that of spaced antennas. Antennas are physically separated to allow measurements of the drift of atmospheric refractive index patterns across the antennas (ref. 31). Wind solutions are possible every few minutes compared to 10-15 minutes with the traditional tilted-radials approach. A sensor system using this technique is about to be offered by METEK called SADRASS for Spaced Antenna Drift Radio Acoustic Sounding System (ref. 32). Performance specifications are included in Table 2. It combines RASS technology with radar profiler spaced antenna technology to produce one-minute wind profiles at 10 m vertical increments to about 250 m altitude. Vertical wind variance with a resolution of 10 seconds is also possible for an estimate of the vertical turbulence profile. Average temperature profiles will be available every 15 minutes at 10 m vertical intervals.

3.1.3 Sodars

Sodar principles of operation are much like those of radar or even pulsed lidar except that acoustic pulses are used instead of radar or optical frequencies. Briefly, pulsed audio signals are directed along tilted radial channels and the returned signal is reflected by thermal turbulence or temperature discontinuities in the atmosphere. The reflected signal is processed according to its observed Doppler shift into horizontal winds for each range gate depending on internal parameter settings. This class of remote sensors has proven to be useful for a variety of low-level atmospheric boundary layer measurements and have been used for boundary layer wind measurements in the air pollution arena for about 30 years. Manufacturers and pertinent operational characteristics are shown in Table-3. There are at least eight companies who supply sodars for wind profile measurements and several more are on the horizon. There were only about four companies in 1998 (ref. 33). Sodars were all phased array antenna systems unless noted. There are several sodars offered by the same companies. One is usually a higher power, larger antenna system for achieving maximum altitudes (1000-1500 m); the other a low power, lower cost, portable version (minisodar) for measuring high resolutions below about 250 m. Notice that all the time and spatial resolutions are higher than those for radar wind profilers. Typical values for the long-range sodars are on the order of 10 minutes time and 30 m vertical resolution. For minisodars resolutions for time and space (vertical) resolutions are about one minute and 10 meters. Very high vertical resolutions (10-15 m) may not be achievable as advertised because they are often based on signal depths from the pulse length alone. Processing involves spectral averages which leads to sampling depths larger then the theoretical signal depth. The trade-off in higher resolution, as with radar wind profilers, is in maximum altitude achieved. The maximum altitude listed is not achievable all of the time even with reasonable settings of averaging times and vertical resolutions. An altitude achievable about 70 percent of the time is on the order of a half to one third of the maximum listed; and it is highly dependent on ambient noise, location, and atmospheric conditions. The higher frequencies used in minisodars allow a smaller antenna and shorter pulses for maximum resolution, but there are significantly lower maximum altitudes achieved. Accuracies in wind measurements are provided by the manufacturers and may not include adverse impacts of the environment. Rough costs for highest range sodars are from $50,000 to $109,000. For minisodars the range is from $35,000 to $50,000. These costs included all capabilities offered to produce maximum resolution and performance. They included heaters, antenna shields, special processing, and power supplies. Graphic display software, if optional, was not included. Shipping is usually included, but technical support, training, installation, spare parts, and maintenance were not included. Trailers or mounting platforms are available from most companies, but these costs were not included. All systems can be operated remotely. Most can be combined with RASS to measure vertical temperature profiles as well as winds.

AQ-Systems (formerly Sensitron), METEK, Scintec and Remtech use multi-frequencies to increase S/N ratios and possibly improve performance. AQ-Systems also employs multi-mode cycles with different pulse lengths and pulse repetition frequencies. AeroVironment processes individual pulses for frequency, amplitude and noise information. Noise processing is available from all manufacturers and most have real-time noise subtraction techniques. It is important to understand the effects of such techniques, however, if they influence future measurements of the sensor after the noise disappears. Atmospheric Research and Technology LLC and Tele-IP have systems in test and evaluation. Performance specifications are also shown in Table 3 for these two systems under development.

Altitude ranges for all sodars are limited during strong temperature inversions that reduce thermal turbulence. Other limitations are heavy precipitation, ambient noise, and cold, dry atmospheres. Winds greater than 10 m/s not only create noise near the sensor, but they also can move the signal away from the receiver. The physical siting of the sensor is important as obstructions can produce unwanted reflections. As with radar profilers there is some built in quality control in the signal processing of all sensors, but additional quality control is highly recommended.

3.1.4 Aircraft

Modern aircraft are capable of measuring wind, temperature, and turbulence profiles when on stable, straight paths during landing and departure. There are about 130,000 meteorological reports from aircraft per day (ref. 34). These automated reports are called ACARS[3] data from US carriers. The more generic term is AMDAR (Aircraft Meteorological Data Relay) reports. ACARS data are sometimes called MDCRS (Meteorological Data Collection and Reporting System), but this refers more to the database of aircraft reports residing at ARINC. Winds are measured from the air speed via a pitot static probe and ground speed from inertial navigation systems. Total air temperature is usually measured by an immersion thermometer probe. Turbulence in the form of eddy dissipation rate is obtained from algorithms developed by NCAR (ref. 35). There are presently only about 75 aircraft equipped for EDR measurements, and EDR data are not yet useful from departing and landing aircraft. Accuracies of winds and temperatures have been reported to be equivalent to those from standard radiosonde soundings (ref. 36).

Pertinent operational performance characteristics of aircraft measurements are shown in Table 4. About 70 % of ACARS data is available for use within 20 minutes after the measurements are made in the existing ARINC communications system. Special arrangements must be made for aircraft data acquisition and use. The reporting frequency (and therefore vertical resolution) is not yet standardized in this country. While the maximum vertical resolution on a stabilized three-degree glide slope is about 20 m, assuming a 5 sec average of 15 measurements, more typical altitude resolution reported is on the order of 40-300 m. Package carriers produce the highest resolution measurements in this country. ARINC 620 is a US effort to standardize the reporting frequency for departure, enroute and landing phases of flight, but compliance is optional. There is an activity underway by NASA and the FAA to increase data coverage below 6 km around smaller airports (ref. 37).

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[3] ACARS stands for Aircraft Communication Addressing and Reporting System

3.1.5 Other

The Next generation weather RADar system (NEXRAD) established by NOAA, DOD, and FAA is a Doppler radar capable of measuring clear-air winds as well as precipitation. Operational characteristics and other specifications are shown in Table 2. There are 146 NEXRADs protecting all major US cities in the Continental US. They are usually located in rural areas so as to minimize ground clutter. Therefore, if the distance from the radar were 50 km, the lowest altitude reported would be about 800 m. Also, minimum vertical resolution is on the order of 350 m close to the radar, but more like 1000 m at a distance of 50 km.

Terminal Doppler Weather Radars (TDWR) are typically closer to airports and are designed specifically for detecting low-level wind shear. There are 48 operational systems located at/near all high volume airports where convective wind shears can occur. West coast airports are typically not included. Update rates for TDWRs from Table 2 are five minutes (for wind vector solutions), and vertical resolution is 50 m or less, so these data will be useful for WakeVAS when processed to produce vertical wind profiles. A major limitation is operation in cold, dry air. Availability can be less than 50% in the winter (ref. 7).

The FAA Low Level Wind Shear Alert System (LLWAS) consists of surface networks of up to 12 anemometers (mostly sonic anemometers) mounted on poles at 110 airports. Algorithms compute wind shears for display to air traffic controllers. The Vaisala sonics used for the FAA LLWAS Relocation and Sustenance program are based on the Vaisala Model 425AH. It uses an averaging process with data samples taken at one-second intervals and processed over six seconds. This is not fast enough for direct turbulence calculations from cross-correlations, and individual wind components are not output; but these sensors could provide a good measure of surface wind variability as well as average winds. Some unused poles may exist at a few airports as a result of the LLWAS Relocation and Sustenance program, which replaced many of the older poles. These could be used in place of new towers for mounting meteorological instruments provided that their locations are not close to buildings or other obstructions.

3.2 Temperature profiles

Temperature profiles can be measured remotely using Radio Acoustic Sounding Systems or radiometers. Temperatures can be measured by aircraft as well (see para 3.1.4 above). Remote sensors for temperature profile capabilities are listed in Table 5.

3.2.1 Radio Acoustic Sounding Systems (RASS)

RASS can be used with either sodars or radar profilers. A Doppler radar is used to track the propagation speed of the acoustic pulses from the vertical beam. Enhanced scattering occurs when the acoustic signals match half the radar wavelength (Bragg scattering). A range of acoustic frequencies is used and Doppler shift of the Bragg scattering leads to speed of sound as a function of height. That speed is directly related to the atmospheric virtual temperature, the temperature of dry air if its pressure and density were the same as the moist air. Correction for vertical air motion is usually applied. In the case of sodar wind profilers with RASS, a Doppler radar must be provided. An acoustic source is added to the radar wind profiler. One can see from Table 5 that costs vary from $35,000 to $70,000. In general, both the time and vertical resolution was higher for the RASS option with the sodar because of the shorter pulse length of the supplied radar matched to the rather short acoustic pulses. Limitations exist for the RASS in the form of ground interference with the radar profiler-RASS combination. Precipitation, strong temperature inversions, and dry-cold atmospheres are also limitations.

Cost for a Vaisala combined RASS-radar profiler is about $255,000, whereas price for a combined METEK sodar-RASS is about $100,000. Sodar-RASS combinations are not as widely used as radar profiler-RASS, so additional testing may be needed with the former. However, in the NASA experience with RASS used in conjunction with the radar wind profiler combination at DFW, there was much missing and incorrect temperature data, particularly for the lowest two range gates (ref. 7).

3.2.2 Radiometers

Passive radiometry has been used for 40 years to measure temperature profiles from satellites using weighting functions for a variety of absorbing gases of assumed concentration. For ground-based measurements with the microwave radiometer profiler (MAPR), there are seven frequencies used in the oxygen absorption band between 51 and 59 gHz. Temperature profiles are derived from measured brightness temperatures with neural network retrieval algorithms (ref. 38). The neural network is trained with ten years or more of radiosounde temperature profiles from which brightness temperature are calculated using a microwave radiative transfer model. Calibration is accomplished with a liquid nitrogen-cooled blackbody target. The performance characteristics of the TP-2500 Radiometrics temperature profiling radiometer are listed in Table 5. The high temporal resolution (three minutes) is somewhat offset by a reduced vertical resolution (100 m, but depends on look angle). There are performance data available from Radiometrics, Inc. in the form of comparisons to radiosondes. More testing and experience is needed with performance during strong temperature inversions. The price for a stand-alone commercial unit is $120,000. A major limitation is operation in precipitation.

3.3 Turbulence profiles

Turbulence profiles are the most difficult to measure and there are presently no off-the-shelf systems specifically available to measure turbulence profiles in the form of eddy dissipation rate remotely from the ground, but there are some promising developments for the short term (see section 4.0). Arriving and departing aircraft can also measure turbulence, but only a few are capable of such measurements at the present time (para 3.1.4). Lidars are capable of measuring turbulence from the statistics of the wind field when the outer scale of turbulence is greater than the spatial dimension of the lidar pulse (ref. 39). Additional research and testing may be necessary to develop the optimum scan strategies and signal processing for lidars to measure EDR. Universities and research laboratories have assembled capabilities for a variety of research measurement campaigns. Some of these are discussed under future capabilities. Radar profilers can measure wind statistics along the tilted radials and vertical antenna beams, but beam widths are too wide and pulse lengths too long for valid variance measurements in resolutions needed. Pulsed sodars used in the past were not good candidates for turbulence measurements, although acoustic techniques have been used for measuring structure characteristics of the lower boundary layer related to turbulence from the raw reflected signal strengths presented in graphic form. A recent effort used all three channels of a Doppler sodar to derive the thermal and velocity structure constants along with an outer scale of turbulence in the boundary layer (ref. 40). A narrow-beam (3-5deg) bistatic sodar was used to investigate spectral broadening and compare it with the scattering volume cross-sections, but more work is needed (ref. 41). It is possible that sodar-measured structure constants (C_t^2), (C_v^2) and radar structure constants (C_n^2) may be more useful in the future. An experiment to use a 915 mHz radar wind profiler to measure turbulence properties was described in 1998 by Gossard et. al. (ref. 42). It required significant effort in processing and analysis by a trained expert. Profiles of atmospheric quantities other than mean winds, such as eddy dissipation rates, might be available for operational use in the future if and when the special manual analyses could be replicated by computer algorithms in real-time, and when radars more specifically designed for turbulence measurements might be available.

4.0 Future Capabilities

New processing techniques already discussed and spaced antenna techniques are expected to become available in the next year or two. New commercial lidars, profilers and sodars soon to be available with higher resolutions have also been discussed. In the near term (2002-2005), wind profiles will be available from radar wind profilers and sodars tailored more specifically for higher-resolution lower boundary layer measurements. The right combinations of new processing software, frequency diversity, antenna technology, and power will produce both height coverage to a few km and resolutions of 30 m and 5–10 minutes. ETL and NCAR are both working on high-resolution UHF profilers. ETL, using phased-array radar profilers, is anticipating small-scale, high-density networks for local scale monitoring and prediction for airport applications. Some of the new technologies are listed in Table 6. The NCAR Multiple Antenna Profiler Radar (ref. 43) will achieve time resolutions on the order of 30 sec and height resolutions of 50 m or better up to at least 2 km altitude. Within a year Vaisala expects to have new digital IF architectures to include wavelet processing, multiple peak algorithms and running consensus. And within three years, range imaging is expected to allow a five to ten fold increase in resolution. METEK’s SADRASS is another application of spaced antenna techniques now in test and evaluation. The Atmospheric Research and Technology’s VT-1X (Table 3) is a near-term sodar with a combination of higher power and frequencies to measure wind details in the lower boundary layer. Aircraft measurements will be increasingly useful in the near term for all parameters needed by a WakeVAS.

Some processing developments in both radar and lidar technologies will allow turbulence profiling to become increasingly available. Progress has been made in using large antenna arrays such as the Turbulent Eddy Processor (TEP) of the University of Massachusetts (ref. 44), and more practically, for potential operations at airports, an S-Band FMCW Profiler. It has a narrow (3 deg) beam, and so spectral width is less corrupted by finite beam width and more indicative of rms radial velocity, which can be related to the EDR. Cost to build such a system was estimated by the University of Massachusetts to be $100,000 for parts. Total costs including labor, profit, etc. could still be under $500,000. The University of Iowa has a multi-beam lidar under development for high resolution wind and turbulence measurements (see table 6). NCAR and ETL jointly developed a 2 micrometer coherent Doppler lidar for use on aircraft and space platforms (ref. 45). There are many other lidar systems used in the research community. In the next few years there will be radar profilers and unique sodars that will be capable of measuring horizontal winds in increasing detail. Signal processing techniques and spaced antennas will be implemented within a few years and enhance the capabilities of radars and RASS. Pulsed lidars using fiber-optic technology will be increasingly available.

The Integrated Terminal Weather System (ITWS) will be available for all major terminals in the US within the next two years. ITWS has the capability to assimilate TDWR , LLWAS, aircraft, automatic weather stations, NEXRAD and model data to produce a variety of wind, temperature, and hazardous weather information products. However, the capabilities provided in the past with research prototypes, such as 50 m vertical resolution every 30 minutes for winds, the use of observations instead of mixed model and observation output, the variance calculation based on multiple inputs, and the ingest of data from sodars, radar profilers, and lidars are not planned capabilities for operational systems. Temperature information is ingested from ACARS, surface observations and models, but is not output. Winds are output at about 250 m vertical intervals from some of the sensor sources. Gust front and wind shift estimates will be available with all the operational systems and would be very useful to a WakeVAS.

Cost for all sensors have been increasing at a rate of about five percent per year. Increasing demands and competition are likely to be offset somewhat by implementation of new capabilities. Lidar costs may not rise, however, as new pulsed fiber-based lidars enter the commercial market in the near and mid terms (2005-2010). Temperature measurements will improve as new processing techniques are implemented. Vertical motion measurements in the lower 200 m of the atmosphere will become more accurate and thereby allow RASS temperatures to be measured more accurately. Radiometers may also offer an alternative if costs come down and testing confirms performance. Sonic anemometers are becoming less sensitive to precipitation through more careful design and orientation of orthogonal components. As requirements continue to evolve in areas such as air quality, wind shear, toxic spills, and development of high-resolution numerical models, more sensors capable of measuring details of the wind, temperature and turbulence profiles will become available.

In the mid term, new sensor technologies will emerge and cost sharing among many customers will keep costs at reasonable levels for networks near airports. A few local scale numerical models will begin assimilating high-resolution wind, temperature and turbulence profiles from networks and aircraft. Lidars will become increasingly popular despite limitations in clouds and precipitation.

As we approach the far term (2010-2015), there will be more sophisticated technologies, and combinations with more extensive cooperative sensor networks, autonomous aircraft capabilities and integrated systems within the NAS. Uplinks (of critical information) from ground sensor systems to aircraft will be the norm. High-resolution numerical models will be capable of 30-minute to 3-hour forecasts of atmospheric wind and temperature profiles through combinations of observations, statistical methods, and numerical prediction.

5.0 Summary and Conclusions

While there are a number of technologies available for profiling the lower atmospheric boundary layer, none are all-weather systems capable of high time and altitude resolutions. Aircraft measurements offer great promise if standards are established (and followed) in reporting frequency/altitude resolution near the ground, and if quality control and accessibility is provided in real-time. There are three technologies for measuring wind profiles remotely: lidars, radar profilers, and sodars. Temperature can be measured with RASS either using a sodar and adding radar or using a radar profiler and adding a sound source. There is at least one stand-alone RASS system as well. There is also a new radiometer profiler that offers some promise, but the vertical resolution is somewhat limited, and more testing is needed. For turbulence measurements lidars come the closest to being able to achieve the high response-narrow beam measurements of velocity fluctuations along the beam, but not much experience has been accumulated in operational settings and there has not been much ground-truth data available in order to measure performance. There is some promising development on the horizon in various lidar and narrow-multiple beam, spaced antenna radar technologies.

There is no single sensor technology effective in all weather conditions when a WakeVAS may be needed (cold-dry, mod precip, clouds, fog, winds > 10 m/s, etc.). Some sensor systems are complementary such as the TDWRs that operate effectively in rain and clouds, lidars not as sensitive to inversions as sodars and RASS, and sodars less sensitive to rain than radar profilers. Therefore, it is prudent to use more than one sensor technology. A radar wind profiler optimized to low-altitude, high-resolution capabilities together with a pulsed or CW lidar (when available) and TDWRs would make a good combination if the lidar could also be used for turbulence profiles and wake measurements.

5.1 Wind profiles

All remote sensor technologies are capable of measuring wind profiles in great detail (few minutes time and 10 m vertical) in the lower 300 m of the atmosphere. Most can measure the atmosphere to a kilometer or higher in coarser resolutions of about 50 m over averaging periods of 10-15 minutes. Lidars have the potential to measure wind details using slant paths and vertical or volume scans for achieving higher altitudes in the absence of clouds/precipitation. Scanning strategies available with the CTI lidar can offer a combined high-resolution mode below about 500 m and coarser resolution to two km or higher; but optimum strategies would be needed and more testing accomplished for combined turbulence/wind/wake measurements; and acquisition costs are high. The highest resolution radar profilers are capable of 50-60 m vertical resolution up to at least 2 km altitude every 10 –15 minutes. These are LAP 3000 (Vaisala) and PCL-1300 from Degreane. With RASS combinations, the costs are on the order of $250,000 and $400,000 respectively. A single sodar cannot offer both high resolution and altitude coverage to a km, although minisodars are attractive for detailed winds below 200-300 m for a reasonable cost. The COTs sodars with the highest resolutions combined with greatest altitude coverage with RASS capability in order of increasing cost are METEK PCS 2000-64, AQ-System AQHR-90 (in 2003), and Remtech PA-2. The new mid-range sodars, PCS 2000-24 by METEK, and AQMR-90 by AQ-Systems, offer good capabilities at attractive prices as well. Combined Sodar-RASS costs range between $92,000 and $110,000 for the mid-range and long-range sodars respectively. Noise at airports and temperature inversion effects still reduce their effectiveness, but new processing, antenna technologies, and sensor combinations will provide better capabilities for the future at reasonable costs.

5.2 Temperature profiles

RASS additions to either sodars or radar profilers and stand-alone units can provide valid temperature measurements from about 150 m for radar profiler options and from 20-50 m to about 500 m in the case of RASS with sodars. The METEK RASS-sodar has the best reported vertical resolution (20 m) and can achieve altitudes of 1.0-1.5 km. Costs are comparable to other systems. The radiometer may not have the ground clutter difficulties of RASS-radar profiler measurements below 200 m, but more operational experience is needed to see how much valid detail near the nocturnal temperature inversion is available, and costs are high.

5.3 Turbulence profiles

Although no turbulence profile sensors are listed as a separate entry, lidars are capable of such measurements as are any radars with beam widths under about three degrees. Available COTS Radar wind profilers do not have such narrow beam widths. The only lidar available with altitude coverage is the CTI Wind Tracer at over a million dollars. In the absence of an operational turbulence-profiling sensor, it may be possible to use a combination of vertical profile sensor winds, LLWAS sonic anemometers, and a few near-ground direct turbulence measures from sonic anemometer/thermometers available from a number of manufacturers to infer reasonable eddy dissipation rate profiles. It is also possible to use models that tie together all available observations to produce assumed vertical profiles. Aircraft turbulence measurements should be more routinely available in calibrated, quality-controlled form within the next three years. The future is bright for ground-based sensors capable of measuring turbulence profiles. Research sensors in the form of radars and lidars will make their way into commercial production as new requirements emerge.

6.0 Recommendations

There are a number of reasons for testing some of the COTS and very near-term sensors. First of all, many performance claims of manufacturers are based on near perfect conditions that are seldom experienced in operational environments. Secondly, there are some unique new capabilities available with little or no impartial validation data. Third, new software has been implemented by a number of manufacturers, and there may have been some changes in performance from previous versions. Finally, the myriad combinations of parameter selections need to be optimized for WakeVAS applications through some trials in different environments with ground truth of known accuracies. The following is a list of those sensors for which testing is recommended: (a) METEK sodar-RASS combination for the PCS 2000-64 and 24; (b) AQ-Systems AQMR and AQHR sodars; (c) all three available lidars for turbulence profiling capabilities as well as for scanning strategies and vertical resolutions available; (d) The new Applied Technologies RWP-406 UHF wind profiler, Scintec’s new AP-100 profiler, and the new METEK SADRASS; (e) the new Radiometric’s TP 2500 radiometer. Although SADRASS will have a limited altitude capability, it can be combined with the low-cost VHF Tomco radar profiler to provide a reasonable cost multisensor wind and temperature capability. Some of the above are being tested by other government agencies so it may not be necessary for an independent test if some coordination can be maintained. Also, several of the manufacturers indicated that they would be willing to make special accommodations in exchange for test results. NASA LaRC tested a Remtech PA-2 sodar which performed well in an early software configuration at the NASA Wallops Island test range; Remtech claims that the problems noted at DFW in the past have been corrected with latest software releases; since we know the performance of this sensor, its data could offer some corroboration for other sensors used in a test. Recommendations that follow are continuing efforts or longer-term activities, which could benefit a WakeVAS capability in the future.

Prior to performing a sensor down select based on user requirements, attempt to use all sensors and technologies available at airports where WakeVAS is contemplated to facilitate a comprehensive cross validation. Take advantage of TDWRs, LLWAS, NEXRADs, automated weather stations, aircraft data and any sodars or profilers in the vicinity. Add a radar wind profiler at a minimum, if none exists. Augment ITWS capabilities to ingest and merge sensor profiles into a single profile of wind, temperature, and turbulence and to provide multi-level quality control for the individual sensor inputs as well as the merged solution (time and space continuity) and to develop a measure of variability and confidence; use ITWS to develop a measure of surface wind variability from LLWAS high resolution sonic anemometer output. Use ITWS to provide a valid wind solution even if no sensors operate at a given time; develop conditional climatology (persistence probability)[4] for all major airports for temperature and wind profiles; have a fall-back position for turbulence profiles (use a surface direct measurement) as well. Continue efforts to modify ITWS operational specifications to include the ingest of temperature, radar profiler, sodar, lidar, RASS/Radiometer data as well as aircraft, LLWAS, TDWR and NEXRAD winds and climatology, and to produce the best-merged profiles of winds, temperature, and turbulence as was accomplished at DFW in the past. Include some quality control, quality assessment and variability measures (as from all sensors measuring the same parameter and from LLWAS and other surface based measurements available). Use ITWS to provide significant weather change alerts (wind shifts, thunderstorms). If ITWS is not available, develop sensor merging capabilities and multi-level quality control capabilities for each raw sensor output stream.

Continue to support efforts to acquire standardized, quality controlled, high-resolution aircraft (ACARS) data at US major airports. ACARS data have continued to improve in quality and quantity. The first aircraft to land or depart does not have a wake vortex problem.

Encourage continued development of sensor technology, which could be more tailored to WakeVAS anticipated needs of higher resolution in the lower boundary layer. Also encourage numerical model development focused on the details of airport terminal areas. Such models should be able to ingest profiling sensor data for initialization, validation and performance adjustments to current observations. Continue to work with other countries with similar WakeVAS applications and monitor the effectiveness of some of the weather categories and surface-based systems under development. Finally, many government agencies (NOAA, EPA, FAA, industry (air quality)) could benefit from additional airport weather profiling sensors. It may be possible to share in some of the costs for future operational networks.

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[4] Persistence probability answers the following question based on many years of observations: given the latest valid measured value, what is the most likely wind vector and temperature for this time, location, and altitude at a given location?

Table 1: Lidar Wind Profiers

Sensor Type	Sensor System	Manufacturer	Parameter Output	Averaging Period	Freq./Output Rate	Horizontal Resolution	Vertical Resolution	Altitude Range
Pulsed Doppler IR RADAR-LIDAR	Wind Tracer	CLR-Photonics (CTI)	wind speed, direction, turbulence	0.5 - 5 min	25 Hz/30 sec-5 min	50 - 100 m	5 m with slant path	0 - 5 km
Pulsed DopplerLIDAR	Ground Winds	Michigan Aerospace Corp.	wind speed, direction, turbulence	1 sec	1 sec		250 m	250 m - 5 km
CW Doppler Lidar	Made to Order	Qinetiq	wind speed, direction, turbulence	1- min	10-100Hz		10 m (range dependent)	20 - 200 m
Pulsed DopplerLIDAR	***Under Development***	*Qinetiq*	*wind speed, direction, turbulence*	*1-min*	*10-100Hz*		*10 m*	*20-300 m*
MOPA Fiber LADAR Pulsed DopplerLIDAR	*Model TDL-6200* ***Under Development***	*Yankee Environmental Systems, Inc.*	*wind speed, direction, turbulence*	*1-min*				

Table 1 (continued)

Manufacturer	**Major Limitation**	**Availability**	**Claimed Accuracy**	**Cost**	**Wave Length**	**PRF**	**Pulse Length**	**Technique**	**MTBF**	**Output Power**
CLR-Photonics (CTI)	dense fog/ mod rain/clouds	Now	0.1-0.5 m/s	$1,200,000	2.022 microns	500 Hz	400 ns	aerosol scattering	8 mos	1 Watt
Michigan Aerospace Corp.	dense fog/ mod rain/ clouds	Now	1.0 m/s	$700,000	0.35 microns	10 Hz	8 ns	molecular and aerosol scattering		12 Watts
Qinetiq	dense fog/ mod rain	Now	5 cm/s	$150,000	1.5 microns		333 ns	aerosol scatter		1 Watt
Qinetiq	*dense fog/ mod rain*	*1 year*			*1.5 microns*			*aerosol scattering*		
Yankee Environmental Systems, Inc.	*dense fog/ mod rain/ clouds*	*2 Years*			*1.5 microns*			*aerosol scattering*		*1 Watt*

Table 2: Radar Wind Profilers

Sensor Technology	**Frequency (mHz) Power**	**Sensor Name**	**Manufacturer**	**Parameter Output**	**Averaging Period**	**Freq./Output Rate**	**Minimum Vertical Resolution**	**Altitude Range**	**Accuracy**	**Cost**	**Temp. Option**	**Tilted Radials**	**Beam Width (deg)**	**Pulse Length (µs)**	**PRF (µs)**	**Number of Beams**	**Antenna Type**
UHF Wind Profiler Doppler Radar	915 500 W	LAP-3000	Vaisala (Sweden US Office)	Horiz. Speed/direction Vertical speed	10-60 min	10-60 min	60 m (short pulse) 97 m (long pulse)	75 m - 2000 m 145-4881m	1.0 m/s 10 deg.	$220,000[5]	RASS	15.5 deg	10	0.4-2.8	25	5	Electrically steerable, micropatch-phased array
VHF Wind Profiler Doppler Radar	46.5 1200 W	BL-Tropo Radar	Tomco Electronics Pty Ltd Austrailia	Horiz. Speed/direction	1 min	1 min	75 m	250 m – 5 km+		$150,000			15	0.25 , 1.5	16		Dipole, 3 groups of 9
UHF Wind Profiler Doppler Radar	915 or 1290 3500 W	PCL-1300	Degreane Horizon (France) US Republic Gp	Horiz. Speed/direction Vertical speed σw	2 – 60 min	2 – 60 min	50 m	70 m – 5 km	<1.0 m/s 10 deg.	$325,000[6]	RASS or Radiometer	17 deg	8	0.5, 1.0, 2.5	25 – 100	5	8 co-linear dipoles
UHF Wind Profiler Doppler Radar	915 1000 W	RWP-406 Mini Radar Wind Profiler	Applied Technologies Inc. (ATI)	Horiz. Speed/direction Vertical speed Cn^2	1 – 60 min	5 – 60 min	75 m	100 m – 3 km	1.0 m/s 5 deg.	$239,700	RASS	15 deg	8.4	0.5 – 2.0	16 – 32	5	Flat panel array
UHF Wind Profiler Doppler Radar	1250-1300 500 W	UHF-BLR	Atmospheric Radar Systems Pty Ltd (ATRAD) (Austrailia)	Horiz. Speed/direction			75 m	300 m – 3 km							40		3 Parabolics

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[5] Includes extended antenna aperture, mounting frame, weatherization

[6] For the 915 mHz; includes 915 mHz conversion

Table 2 (continued)

Sensor Technology	**Frequency (mHz) Power**	**Sensor Name**	**Manufacturer**	**Parameter Output**	**Averaging Period**	**Freq./Output Rate**	**Minimum Vertical Resolution**	**Altitude Range**	**Accuracy**	**Cost**	**Temp. Option**	**Tilted Radials**	**Beam Width (deg)**	**Pulse Length (µs)**	**PRF (µs)**	**Number of Beams**	**Antenna Type**
VHF Wind Profiler Doppler Radar	30 – 60 2500 W	BLTR	Atmospheric Radar Systems Pty Ltd (ATRAD) (Austrailia)	Horiz. Speed/direction											40		27 Yagis in 3 rows of 9
FAA Wind Shear Radar	*5650* *250 KW*	*TDWR*	*Raytheon*	*Horiz Speed/direction*	*1 min*	*1 min*	*125 m*	*50 m – 5 km+*		*N/A*	*N/A*	*Scanning*	*0.55*	*1.0*	*3.2*		*Large parabolic*
National Doppler Weather Radar	*3000* *750 KW*	*NEXRAD WSR-88D*	*Unisys*	*Horiz Speed/direction*	*10 min*	*10 min*	*250 m*	*1 km - 21 km*		*N/A*	*N/A*	*Scanning*	*0.95*	*1.6, 4.5, 5.0*	*1.6*		*Large parabolic*
UHF Doppler Wind Profiler [7]	915 1200 W	AP-100	Scintec AG (Germany)	Horiz. Speed/direction Vertical speed	1 - 60 min	1 – 60 min	37.5 m	50 m – 3 km	0.5 m/s 5 deg.		No						
UHF Doppler Wind Profiler [3]	1270	ARPL EM Sounder	Atmospheric Research Pty Ltd (ARPL) (Austrailia)	Horiz. Speed/direction Vertical speed	10 min	10 min	75 m	75 m – 1500 m	0.5 m/s 5 deg.						40		
SAD Profiler-RASS [3]		SADRASS	METEK (Germany)	Horiz. Speed/direction Vertical speed σw, Tv	1 min wind 15 min Tv	10sec /15 min	10-20 m	20 m – 250 m		$150,000	Included						

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[7] Under Development; available within 1 year

Table 3: Sodar Wind Profilers

Sensor Technology	Frequency Power	Sensor Name	Manufacturer	Parameter Output	Averaging Period	Freq./ Output Rate	Maximum Vertical Resolution	Altitude[8] Range	Accuracy	Cost	Temp. Option	Tilted Radials	Pulse Length (ms)	Puse Interval	Antenna
Doppler Sodar	1000-3000 Hz 1000 W	PCS 2000-24	METEK Messtechnik GmbH (Germany)	Horiz. Winds Vert. wind σu, σv, σw	10 min	5 – 30 min	5 m	15 m-1 km	0.4 m/s 5 deg	$48,000[9]	RASS	14-25 deg	50 - 300		Phased Array
Doppler Sodar	1000-3000 Hz 1000 W	PCS 2000-64			10 min	5 – 30 min	5 m	15m-1.5 km	0.4 m/s 5 deg	$52,000[10]	RASS	14-25 deg	15 - 300		Phased Array
Doppler Sodar	825 – 1375Hz 35 W	XFAS	Scintec GmbH (Germany)	Horiz. Winds Vert. wind σu, σv, σw	1 – 60 min	1 - 60 min	20m	20 m-2 km	0.2 m/s 2-3 deg	$88,500	RASS				Phased Array
Doppler Sodar	1650-2750 Hz 7.5 W	MFAS			1 – 60 min	1 – 60 min	10 m	20 m-1km		$56,000	No				Phased Array
Doppler Sodar	2250 Hz 10 W	PA-2	Remtech, Inc (France, US Office and Rep.)	Horiz. Winds Vert. wind σu, σv, σw	2 – 60 min	2 – 60 min	10 m	25m–1.5 km	0.2 m/s 3 deg	$69,000	RASS			6 sec	Phased Array
Doppler Sodar	4000 Hz 1 W	PAO			1 – 60 min	2 – 60 min	7.5 m	10-600 m		$38,000	No				Phased Array
Doppler Sodar	1525-2225 Hz	ARPL Sodar	Atmospheric Research Pty Ltd (Austrailia)	Horiz. Winds Vert. wind, σw	10 min	10 min		50-900 m	0.2 m/s 2-3 deg	$109,000	RASS	18 deg	50 - 100	2 sec	Phased Array
Doppler Sodar	4500-5000 Hz	ARPL minisodar		Horiz. Winds Vert. wind, σw	1 min	1 min		5-290 m	0.2 m/s 2-3 deg		No	18 deg	100 - 150	4 sec	Phased Array

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[8] For 70% availability, reduce max altitude by 60%

[9] Includes multi-freq option

Table 3 (continued)

Sensor Technology	Frequency (Hz) Power	Sensor Name	Manufacturer	Parameter Output	Averaging Period	Freg./ Output Rate	Maximum Vertical Resolution	Altitude[10] Range	Accuracy	Cost	Temp. Option	Tilted Radials	Pulse Length (ms)	Puse Interval	Antenna
Doppler Sodar	4604 1.5 W	ART VT-1	Atmospheric Research and Technology, LLC (Hawaii)	Horiz. Winds Vert. wind, σw	2 - 60 min	2 – 60 min	10 - 40 m	15 – 300 m	0.2 m/s 2 deg	$41,000	No				Phased Array
Doppler Sodar	2704 15 W	ART VT-1X[11]		Horiz. Winds Vert. wind, σw	2 – 60 min	2 – 60 min	20 – 40 m	20 – 600 m	0.2 m/s 2 deg	$51,000	No				Phased Array
Doppler Sodar	1800-2200 82 W	AQHR-90	AQ System (Sweeden)	Horiz. Winds Vert. wind, σw, σθ	2-60 min	2-60 min	25 m	20 m -1.5 km	0.2 m/s 2 deg	$47,500	Avbl in 2003	20 deg	30 - 600	1-9 sec	Phased Array
Doppler Sodar	2000-2400 44 W	AQMR-90		Horiz.Winds Vert. wind, σw, σθ	2-60 min	2-60 min	25 m	20 m – 1 km	0.2 m/s 2 deg	$28,000		20 deg	30 - 300	1-6 sec	Phased Array
Doppler Sodar	1400-2500	Model 2000	AeroVironment, Inc	Horiz. Winds σu, σv, σw	1-60 min	1-60 min	20 m	50 – 750 m	0.5 m/s 3 deg	$50,000	No	20 deg	50 - 300	2-5 sec	Parabolic reflector
Doppler Sodar	4500	Model 4000 (mini)		Horiz. Winds σu, σv, σw	0.5-60 min	0.5-60 min	5 m	15 – 200 m	0.2 m/s 2 deg	$35,000	No	18 deg	20 - 80	1-2 sec	Phased Array
Doppler Sodar	2100 1100 W	KPA 1000	Kaijo Corp (Japan)	Horiz. Winds Vert. wind σu, σv, σw	1-30 min	1-30 min	20 m	30-700 m	0.3 m/s 3 deg			20 deg	10 - 350	3-10 sec	
Doppler Sodar[12]	600 – 5000 40 W	PC1000	Tele-IP (Austrailia)	Horiz Winds and Turbulence	0.5-5 min	0.5-5 min	0.3-4 m	5 – 2000 m	10% 2 deg		Yes		1 s	2 min	Parabolic reflector

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[10] For 70% availability, reduce max altitude by 60%
[11] Under development
[12] Pulse compression technique; under development

Table 4: Aircraft Reports

Sensor Technology	**Manufacturer**	**Parameter Output**	**Averaging Period**	**Output Rate**	**Vertical Resolution**[13]	**Horozontal Resolution**[14]	**Accuracy**
ACARS (see text)- Aircraft Reports on approach and departure	All Major Airlines	Wind speed and direction Temperature, Turbulence	1- 30 sec	1-3 Samples per Second	20 - 110 m typical 40 – 300 m in US	70 – 210 m	~1-2 m/s ~0.4 – 1.5 C

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[13] On a 3 degree glide slope; best case 5 sec average, 3 samples per second; worst case 30 sec average, 1 sample per second

[14] at 70 m/s aircraft speed, 1- 3 samples per second

Table 5: Temperature Sensors

Sensor Technology	Frequency (Hz) Power	Sensor Name	Manufacturer	Parameter Output	Averaging Period	Freq./Output Rate	Minimum Vertical Resolution	Altitude Range	Accuracy	Cost
RASS/w sodar	480 80 W	PCS2000-64 RASS option	METEK GMbH (Germany)	Virtual Temperature	1-30 min	1-30 min	20 m	15 m - 1.5 km	0.3 C	$52,000
	1290 20 W	PCS2000-24 RASS option		Virtual Temperature	1-30 min	1-30 min	20 m	15 m -1.0 km	0.3 C	$44,000
RASS/w sodar	1270-1295 20 W	XFAS RASS	SCINTEC GmbH (Germany)	Virtual Temperature	1-60 min	1-60 min	20 m	40 - 500 m	0.2 C	$48,300
RASS/w sodar	2250 20 W	PA-2 RASS	REMTECH (France)	Virtual Temperature	2-10 min	2-10 min	20 m	50 - 400 m	0.3-1.3 C	$47,300
RASS Stand-Alone	2000-3000 15 W	ARPL RASS	Atmospheric Research Pty Ltd (Austrailia)	Virtual Temperature	10-15 min	10-15 min	35 m	50 - 700 m	0.5 C	
RASS/w profler	2000-3000 800 W	LAP 3000 RASS	VAISALA (Sweden)	Virtual Temperature	3-60 min	30 min	100 m	100 m -1.5 km	1.0 C	$35,000
RASS/w profiler	2100 400W	PCL 1300 RASS	DEGREANE (France)	Virtual Temperature	5 min	15 min	50 m	100 m -1.2 km	0.5 C	$70,000
RASS/w profiler	2000-3000 75 W	Mini Profiler RASS	APPLIED TECHNOLOGIES INC.	Virtual Temperature	5-60 min	5-60 min	75 m	100 - 500 m	1.0 C	$41,000
Passive Microwave Radiometer Profiler	51-59 gHz 7 channels	TP-2500	RADIOMETRICS CORP.	Average Temperature	1-5 min	3min	< 100 m depends on look angle	5 m - 2 + km	0.4-1.2 C	$120,000

Table 6: New Technology

Sensor Technology	**Sensor Name**	**Manufacturer**	**Parameter Output**	**Averaging Period**	**Freq./Output Rate**	**Minimum Vertical Resolution**	**Altitude Range**	**Availalability**[15]
Spaced Antenna Radar Profiler UHF	Multple Antenna Profiler (MAPR)	NCAR[16]	Winds, Turbulence	30 sec	30 s – 5 min	50 m	50 – 2 + km	2-5 yrs
FMCW Doppler Radar Profiler S-Band	FMCW Radar	Univ of Mass.	Turbulence	5 sec	5 sec	2.5 m	200 m - 2 + km	2-5 yrs
Volume Imaging UHF Doppler Radar-Spaced Antenas	Turbulent Eddy Processor (TEP)	Univ of Mass.	Turbulence	5 sec	5 sec	30 m	200 m – 1.5 km	2-5 yrs
Multi-Beam Lidar	Multi-Beam Lidar	Univ of Iowa	Winds	2 sec	2.5 sec	1.5 m	1.5 m – 3 km	2-5 yrs

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[15] If the market place would support it

[16] National Center for Atmospheric Research

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13. ABSTRACT *(Maximum 200 words)*

Remote sensing of the atmospheric boundary layer has advanced in recent years with the development of commercial off-the-shelf (COTS) radar, sodar, and lidar wind profiling technology. Radio acoustic sounding systems for vertical temperature profiles of high temporal scales (when compared to routine balloon soundings-(radiosondes) have also become increasing available as COTS capabilities. Aircraft observations during landing and departures are another source of available boundary layer data. This report provides an updated assessment of available sensors, their performance specifications and rough order of magnitude costs for a potential future aircraft Wake Vortex Avoidance System (WakeVAS). Future capabilities are also discussed. Vertical profiles of wind, temperature, and turbulence are anticipated to be needed at airports in any dynamic wake avoidance system. Temporal and spatial resolution are dependent on the selection of approach and departure corridors to be protected. Recommendations are made for potential configurations of near-term sensor technologies and for testing some of the sensor systems in order to validate performance in field environments with adequate ground-truth.

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