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Surface Windshear Alert System, Part 2: Field Tests

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Field tests of the surface windshear alert system (SURFWAS) prototype described in a companion paper were conducted at the U.S. Air Force Academy Airfield. An array of seven remote stations on 6.1- and 9.2-m meteorological towers was erected alongside runway 16L (34R), covering a distance of about 2 n mile. Wind data were recorded for 11 days from Aug. 12–22, 1996, during which several windy episodes, associated mostly with thunderstorms and one cold front, passed through the airfield. Two of the episodes exhibited the patterns of dry and wet microbursts, respectively, which were consistent with the forecast at the U.S. Air Force Academy Weather Flight. The wind data measured with the SURFWAS and the airfield wind sensors agreed reasonably well. During the two episodes, the maximum windshears exceeded the alert threshold while the windshear patterns satisfied the alarm criteria, triggering the microburst alert alarm. The SURFWAS' capability of detecting microbursts near ground level to provide timely warning, via terminal display and direct broadcast, to air traffic controllers and pilots was successfully established. The success is attributed to the high runway-oriented resolution of the remote anemometer station array for wind measurements and the timely update of the wind information at the master station.

I. Introduction

AS described in a companion paper,[1] a SURFWAS prototype was successfully developed, fabricated, and tested. Subsequently, the prototype was set up at the U.S. Air Force Academy (USAFA) Airfield in Colorado Springs, Colorado, for three-week field tests from Aug. 5–23, 1996. The objectives were to demonstrate the capability and performance characteristics of the SURFWAS prototype operating in real time and in an established airport environment. One of the specific objectives was to determine whether microburst-type windshear patterns can be detected with a linear array of anemometers mounted on low-profile meteorological towers, an undertaking believed to be impossible.[2] During the field tests, important issues including portability/mobility, cost-effectiveness, reliability, timeliness, and ease/clarity of surface windshear detection and display were addressed. This paper presents the field tests and results of the prototype. A detailed documentation of the field tests was given elsewhere in a final technical report.[3]

II. Site Selection

As a part of the test plan, a site survey was conducted to select a suitable airport for deploying the surface windshear alert system (SURFWAS) prototype. Two sites were selected initially: Offutt Air Force Base and the USAFA Airfield. Requests were sent to the Commanders of both sites and approval from both sites were subsequently granted. Based on the terrain characteristics and historical weather patterns gathered from the two sites, the USAFA Airfield was selected as the primary site for conducting the field test. For the USAFA site, two time windows were given for the field tests, one in March and the other in August 1996. According to the meteorological personnel at the USAFA Airfield, microburst-type windshear only occurs in summer months. Because our interest was to test the capability of the SURFWAS for detecting microburst-type windshear, the decision was made to select the August window for the field tests.

The primary summertime weather activity at the USAFA site is thunderstorms. The upper winds are relatively light and do not produce mountain wave conditions. The diurnal winds, northwesterly–northerly at night and southeasterly–southerly during the day, are the same for all seasons. The afternoon diurnal is around 15 kn and, unlike those in the spring months, is usually not gusty. It may become gusty with maximum winds to the low- to mid-20s if assisted by flow from either the building or dissipation of thunderstorms. The daytime diurnal may also become gusty if a high-pressure system is located over the plains states. The night diurnal, like the winter diurnal, is usually less than 10 kn. Frontal winds rarely approach winter intensities. The average prevailing winds are northerly at 7–8 kn.

On a typical day in July and August, thunderstorms begin building along or just behind the mountains by late morning, drift across the USAFA Airfield by mid- to late afternoon, and are east of the station by early evening. The majority of the thunderstorm activity is caused by orographic lifting, convective heating, and differential heating over the mountains. Because the upper wind flow is primarily westerly during thunderstorm season, the necessary lift behind the mountains is always available. Two other important triggers, moisture and surface heating, are all that is needed to produce these storms. Wet or dry microbursts may accompany the thunderstorms during their passage, depending on the moisture content in the air mass.

Figure 1 is a topographic map of the area, where the USAFA Airfield is located; north is to the right of the figure. The scale of the map is 1 in. to 1500 ft (or 1 cm to 180 m). The topography of the airfield is relatively flat with few steep valleys. After an on-site review meeting took place at QUEST in June 1996, an array of up to nine remote anemometer stations (RSs) was planned to be installed along a line between runway 16L (34R) and taxiways A and B, with the two end RSs located about 1–2 n miles south of and 1 n mile north of the airfield, respectively. The spacing between RSs varied between 0.25 and 0.5 n mile. To satisfy the operational safety guideline of the airfield, 20-ft (6.1-m) towers were to be used for the RSs between 34R and taxiways A and B and some distances beyond the paved runway. (The tip of the anemometer is 7.3 m or 24 ft tall.) Thirty-ft (9.1-m) towers could be used, if needed, for the RSs toward the two ends of the array. The RSs were

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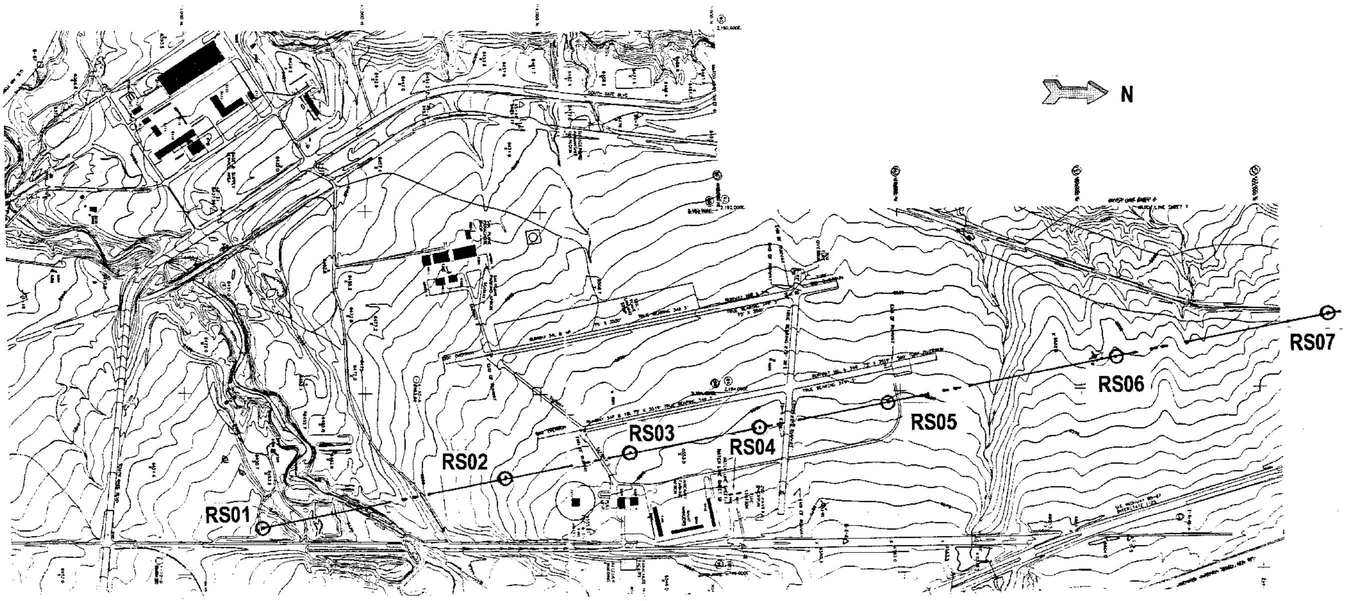

Fig. 1 Topographic map in the vicinity of the USAFA Airfield and the locations of the RSs.

to be installed about 400-ft (120-m) away from the center of runway 16L.

III. Field Preparation

On Aug. 5, the first day at the USAFA Airfield, the author and a field technician met with USAFA personnel from Academy Base Operations, Academy Ground, i.e., air traffic control (ATC), and Weather Flight to go over some of the details of the test plan, preapproved by the USAFA Airfield management. Personnel from Base Operations gave a debriefing concerning airfield safety operations and radio communication procedures with the airfield control groups including Academy Ground, Base Operations, and Sky Train. A radio was assigned to the author for communicating with the groups. The civil engineers of the USAFA Airfield also checked and approved the locations of the RSs as planned. In the afternoon, the designated contact person from Weather Flight, who served as a liaison between QUEST and the USAFA during all phases of the field test, went out with the author and technician to the airfield to stake out the locations of the RSs using two portable global positioning systems (GPSs) on loan by the USAFA for the tests. The liaison demonstrated the procedure of radio communication calls with the airfield controlling groups and safe movements in and out of the airfield. The liaison also gave an orientation on the airfield vicinity, prepared test equipment, and assisted in erecting the first RS.

During the site survey the discovery was made that the maximum number of RSs able to be deployed in the airfield was seven because it was impractical to put RSs beyond 1 n mile south and 1.2 n miles north of the ATC tower because of security concerns and interference by tall trees. In some cases, the terrain features prevented the alignment of the RSs on a straight line parallel to runway 34R (16L), which has a true bearing of 349°5′. The exact coordinates of the RS locations are accurate to within the resolution of the portable GPS (~ ±40 m tracking at least four satellites). Figure 1 illustrates the actual RS locations, which differs slightly from the planned locations approved by the USAFA Airfield management.

The equipment arrived on the morning of Aug. 6. Three of the tower sections were damaged badly during shipping. However, there were enough spare units for installing the seven RSs as planned. The equipment was unloaded in a storage and staging area in one of the buildings (no. 9204) provided by the USAFA. Subsequently, the master station (MS) was installed at the ATC tower. The antennas were installed on the roof of the ATC tower and cables were routed into the tower. At completion, both hardware and the software were tested successfully.

Table 1 Calibration parameters for correction of wind directions

RS no.	Compass bearings, deg	System calibration, deg
01	359.22	−187.26
02	358.75	−172.11
03	7.39	−171.09
04	359.32	−189.88
05	8.03	−181.58
06	6.63	−174.67
07	356.51	−183.80

The next morning the sensors and controllers of the RSs were set up for a secondary calibration outside the staging area. The procedure of the secondary calibration was the same as that of the primary calibration conducted at QUEST's headquarters except that the former does not align the compass bearing to a known bearing.[1] The secondary calibration served to check the primary calibration and to detect potential damages of electronics during shipping. The secondary calibration also facilitated rechecking of the alignment of the anemometers and correction for misalignment when needed during deployment, e.g., after a severe wind storm. With the azimuth of each anemometer (at the 180-deg orientation) fixed to the plane of the compass circuit board and with the compass pointing to about 10 deg, data were polled by executing the program **wshr9600.trm** using the full query format.[1,3] For the calibration, an auxiliary master modem (MM) connected to the serial port of a laptop computer (NEC VERSA M/100 with a 80486 CPU at 100 MHz) was used. A dummy load replaced the omnidirectional antenna. For each set of the compass, data were polled 20–30 times. The average bearing of the compass was then calculated from the polled data. Table 1 lists the calibration parameters for the correction of the wind direction. Subsequent comparison of the primary and secondary calibration results confirmed that they were consistent with each other.

Installation of the seven RSs began at the airfield on the afternoon of Aug. 7 and was completed by Aug. 10. On average, it took two people about two and a half hours to set up an RS in the field. The installation of the RSs was suspended during two afternoons while thunderstorms with heavy rain and strong lightning developed, resulting in unexpected delays

Table 2 Coordinates and physical parameters of RSs

RS no.	Longitude	Latitude	Distance, n miles (km)	Sensor height, m (ft)
01	38°57.57′	104°48.76′	−0.96 (−1.74)	10.3 (34)
02a	38°57.96′	104°48.88′	−0.54 (−0.99)	9.1 (24)
02b	38°57.97′	104°48.86′	−0.54 (−0.98)	9.1 (24)
03a	38°58.25′	104°48.94′	−0.25 (−0.45)	9.1 (24)
03b	38°58.22′	104°48.95′	−0.28 (−0.51)	9.1 (24)
04	38°58.49′	104°48.97′	0	9.1 (24)
05a	38°58.70′	104°49.01′	0.22 (0.39)	9.1 (24)
05b	38°58.72′	104°49.03′	0.23 (0.43)	9.1 (24)
06a	38°59.26′	104°49.13′	0.79 (1.44)	9.1 (24)
06b	38°59.23′	104°49.12′	0.76 (1.39)	9.1 (24)
07	38°59.66′	104°49.18′	1.20 (2.18)	10.3 (34)

in completing the set up of the SURFWAS prototype. The actual coordinates of the RSs were measured with the two GPSs on loan from the USAFA. Table 2 lists the actual coordinates of and the distances from the reference station (RS04 in front of and slightly to the north of the ATC tower), as measured with the portable GPSs. Repeated measurements conducted at different times are labeled as "a" and "b" following the RS number. The mean bearing of the best-fitted line through the RS array is 351.1 deg, about 2-deg deviation from the runway bearing.

Test runs conducted at the MS setup in the ATC tower indicated that all seven RSs functioned properly except that the compass at RS02 did not reset. This unit was subsequently replaced with a spare unit. Full queries using **wshr9600.trm** were conducted for polling the data collected by the microprocessors inside the controllers on all seven RSs; the results were used to calculate the actual bearings of the electronic compasses. The compass bearings were input into the sub virtual instrument (VI), **wd_correction.vi**, for deriving the wind directions with reference to the magnetic north from the data collected at the individual RSs. After a severe wind storm, the bearings of the compasses should be rechecked again to detect potential shifts in the compass bearing, as a result of possible twisting of the tower.

The airfield is equipped with two wind sensors or wind-measuring sets installed near the two ends of runway 16L and are about 100 ft west of the RS array. They are installed about 2 m above the ground on two poles. They served to provide as a reference and a check to the SURFWAS measurements. The sensor elements consist of two orthogonal thick-film platinum pairs, X and Y, representing the East–West and North–South pairs, respectively. The elements are maintained at a temperature approximately 100°C above ambient. As the wind blows across the elements, heat is removed and more power is required to maintain the elevated temperature. The power required to maintain a constant temperature is measured by the sensor electronics, and the wind velocity is calculated from these measurements. By using two pairs of elements at right angles to each other, the wind speed and direction are calculated. Two-min running average wind speed, direction, and gust conditions derived from one of the sensors are displayed at two indicators at the ATC tower and at Weather Flight. The results are also printed on hardcopies at Weather Flight as the archived record. The wind speed accuracy is ± 1 kn (0–50 kn), $\pm 5\%$ (50–75 kn), $\pm 10\%$ (75–99 kn), and $\pm 15\%$ (99–150 kn) and the wind direction accuracy is ± 3 deg. For a detailed description of the sensors and their operations, refer to the technical manual (Air Force TO 31M1-2FMQ13-1). The north-end sensor AS1 (for 16L configuration) is between RS04 and RS05 but closer to RS04, whereas the south end AS2 (for 34R configuration) is between RS03 and RS04 but closer to RS03.

IV. Field Tests and Results

The SURFWAS prototype was fully functional on the morning of Aug. 11. Test runs were conducted to ensure that both hardware and software performed as designed. Data were collected from Aug. 12–20. On Aug. 21, removal of the RSs from the airfield began. RS03 and RS04 were left running for another 24 h before they were removed from the airfield the next day.

Visual comparison of the wind conditions measured with the airfield sensors (2-min running average) and the SURFWAS sensors (30-s running average) shows good correlation most of the time. Differences are a result of variance in the sensor locations, heights, and in the running averages.

Each morning, the archived wind data measured with the airfield wind sensors at Weather Flight were first reviewed and examined. From the record, the periods with high wind speed and gust were marked as the reference for reviewing and analyzing the SURFWAS archived data. The meteorologists on duty were consulted about the 24-h weather forecast, which was used as the basis for preparing the test agenda for the day. In the morning hours, the airfield is usually calm with little wind activity. Data collection was halted for a few hours until a strong wind picked up again later in the day. During these hours, work was performed to backup data files, to modify or refine the software if needed, or to review and analyze the archived wind data.

During the field tests, some of the features recommended by the ATC controllers during the debriefing and subsequent interactions were implemented. For example, a soft switch was added to override the audible signal after the alert messages (windshear or microburst) had been brought to the attention of and acknowledged by the ATC controllers. Pressing the same switch again would reactivate the beeper. In addition, a **main_replay.vi** was modified from the **main.vi** to play back the archived wind data. The VI recalls the archived data and treats them as if they were acquired in real time so that the measured wind field can be reviewed closely. Such a recreate-the-scene capability is an important tool for optimizing the performance of the SURFWAS. For example, the threshold values that define the five different windshear states can be refined based on historic events of strong to severe windshear occurrences. The capability can also be used to detect malfunction of wind sensors or evaluate potential topographical/structural interference of wind sensors.

A. Sample Wind Profiles

The personal computer at the MS was left running to acquire data overnight at a sampling rate of 0.5 Hz from Aug. 12–22 for a total of 11 days. During one of the weekends, from Aug. 16–18, wind data were recorded consecutively for about 92 h. During these days, there were several windy episodes passing through the USAFA Airfield. Most of the episodes were associated with thunderstorms that brought about weak to strong windshear, which with few exceptions exceeded the alert status. The airfield was usually closed temporarily during passage of a severe thunderstorm and then reopened later after its passage.

Two of the episodes recorded on Aug. 13 and 14 exhibited the characteristics of dry and wet microbursts, respectively, with the runway-oriented windshear exceeding the alert threshold. The patterns of the wind speeds and directions and those of the windshear, however, differ considerably. Profiles of the wind speeds and directions measured during the two episodes and the corresponding windshear are presented in the following subsection. The wind data are analyzed and examined to demonstrate the performance of the SURFWAS prototype and to serve as a database for near-ground-level windshear detection.

1. Wind Speeds and Directions

After the airfield was closed on Aug. 13 between 18:00 and 19:30, the Weather Flight archive record of airfield sensor AS2 showed the passage of an active but relatively dry episode, with maximum wind speeds (2-min running average) up to 24 kn and gusts up to 34 kn. On Aug. 14 between 22:00 and 23:00, the record showed a wet episode (thunderstorm) with a maximum wind speed up to 25 kn and gusts up to 46 kn. The thunderstorm produced 1.12 in. (2.84 cm) of rain with a wide spread of hail (0.6–1.2 cm) over Colorado Springs.

In addition to the preceding two episodes, the wind fields produced by several other energetic episodes on Aug. 17, 19, and 22 were examined. For example, in the early afternoon on Aug. 19 between 14:30 and 15:00, an active thunderstorm passed through the airfield with intensive lightning and heavy rainfall mixed occassionally with hail. The thunderstorm brought about a maximum wind speed of 22 kn and gust up to 37 kn but produced very little windshear at the airfield. These episodes were produced at the strongest windshear status.

Figure 2 illustrates the time series of wind speeds (Fig. 2a) and directions (Fig. 2b) measured at RS03 (solid curve) and RS04 (dashed curve) between 18:00 and 19:30, Aug. 13. Note that the wind direction ranges from −180 to 180 deg instead of 0 to 360 deg to avert the appearance of a discontinuity as the wind direction crosses back and forth over the magnetic north or 360 deg. The corresponding wind speed and direction measured at the airfield sensor AS2 are also plotted in the Fig. 2 as circles. To account for the difference in the running averages between the SURFWAS and airfield sensor data, the latter was shifted −45 s in the figure. As a whole, the wind patterns measured at the three locations were reasonably correlated, particularly for the large-scale features. The wind data measured at the airfield sensor AS2 agreed better with those measured at RS03 than at RS04, as AS2 was much closer to RS03 than to RS04. As a result of the difference in the running averages used for the airfield and the SURFWAS sensors, the maximum wind speeds measured with the former were generally lower than those measured with the latter, particularly for short events, although the frequency response of the former is faster than the latter.

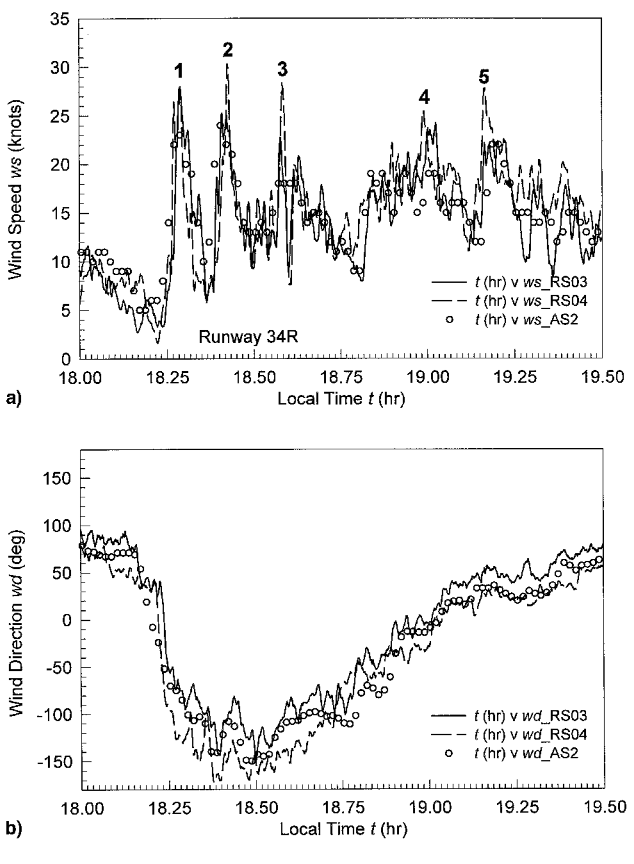

Fig. 2 Time series of a) wind speed and b) direction recorded on Aug. 13.

Figure 2 indicates that before 18:15 and the arrival of the episode, the wind condition in the airfield was relatively calm with wind speeds measured at the two RSs and AS2 below about 12 kn. The wind directions were northeasterly. The wind speeds fluctuated with large amplitude at the arrival and passage of several events associated with the episode. The average wind speeds during the entire episode increased from below 10 kn (18:00 to 18:15) to about 18 kn (18:15 to 19:30) with a significant increase in gusts. The wind directions shifted from northeasterly to southwesterly during the passage of the first three events, as the wind speeds strengthened with the arrival of the episode. The wind directions shifted gradually back to the original directions after passage of the third event.

During the one-and-a-half-hour period, the wind data measured with the SURFWAS sensors showed five events (labeled 1–5 in Fig. 2) with wind speeds exceeding 20 kn while those measured with the airfield sensor registered only three such events (1, 2, and 5). The first three events lasted about 5 min. The maximum wind speeds measured at RS03 and AS2 were 28 and 24 kn, respectively. In other words, the wind data measured with the SURFWAS sensors showed many more sharp peaks and valleys than those measured with the airfield sensor, indicating a more active wind field. Therefore, optimum running averages must be chosen in preprocessing the wind data for proper characterization of the wind field and for detecting windshear along the runway(s).

Figure 3 illustrates the wind speeds and directions recorded during passage of the thunderstorm between 22:00 and 23:00 local time on Aug. 14, 1996. The wind pattern differed considerably from the essentially dry episode the previous day in that the storm carried a relatively large, energetic, and moist air mass; this is evident from the relatively large amount of rainfall in such a short period (2.84 cm in about 0.5 h). The episode consisted of a relatively long event that lasted about 15 min, in contrast with the relatively short but energetic events during passage of the episode the day before. Before the arrival of the storm (22:00–22:15), the wind condition at the airfield was breezy with average wind speeds between 9 and 11 kn. The wind speeds increased with the arrival of the storm and then decreased gradually as the storm passed by. The wind was very gusty (up to 46 kn measured at the AS2) during passage of the storm. The wind calmed down considerably after passage of the storm (22:30–23:00); the average wind speeds reduced to about 5 kn with very little gust. During the episode, two of the peak wind speeds recorded at AS2 were slightly higher than those measured at RS03. The wind directions shifted from northeasterly to northerly at and after the arrival of the storm. The wind directions shifted back to northeasterly and finally to northwesterly during and after passage of the storm, respectively.

2. Windshear Profiles

By definition, the windshear is the difference between the projected wind speed components (along the runway bearing) measured at two neighboring RSs, divided by the distance between the two RSs. For the runs recorded on Aug. 13 and 14, the threshold settings for the windshear states were 0.006 s^{-1} (weak windshear), 0.012 s^{-1} (strong windshear), and 0.02 s^{-1}

(windshear and microburst alert). For a windshear of 0.02 s^{-1}, a T3 aircraft cruising at 70 kn would experience a gain or loss shear of 14 kn over a 10-s interval. The threshold of 0.02 s^{-1}, when converted into the F-factor format at near-ground levels [Eqs. (1–4) in Ref. 1], agrees reasonably well to the recommended F-factor of 0.13 for airborne detectors.[4,5]

From the data presented in Figs. 2 and 3 and the distances between the RSs (Table 2), the windshear between the RSs was calculated. The results are plotted in Figs. 4 and 5, respectively. During the episode shown in Fig. 4, there were two events between 18:15 and 18:45, where the windshear alert threshold of 0.02 s^{-1} was exceeded, with a third event just below the threshold. All three events were loss shear that occurred between RS03 and RS04; the maximum value exceeded 0.026 s^{-1}. Replaying this section of the archived wind data through the SURFWAS triggered the windshear alert message displayed on the monitor several times together with the emergence of the strong windshear and weak windshear messages. Just prior to the arrival of the episode, between 18:00 and 18:15, the wind field was relatively calm and the no windshear message was displayed on the monitor. After 18:45, the wind field was still very active with wind speeds around 20 kn. There were several events with the strong windshear status between 18:45 and 19:30, mixed with both gain and loss shear. The time series of the windshear associated with the thunderstorm passing through the airfield on Aug. 14 are shown in Fig. 5. Over the 15-min episode, the windshear exceeded the alert threshold only once.

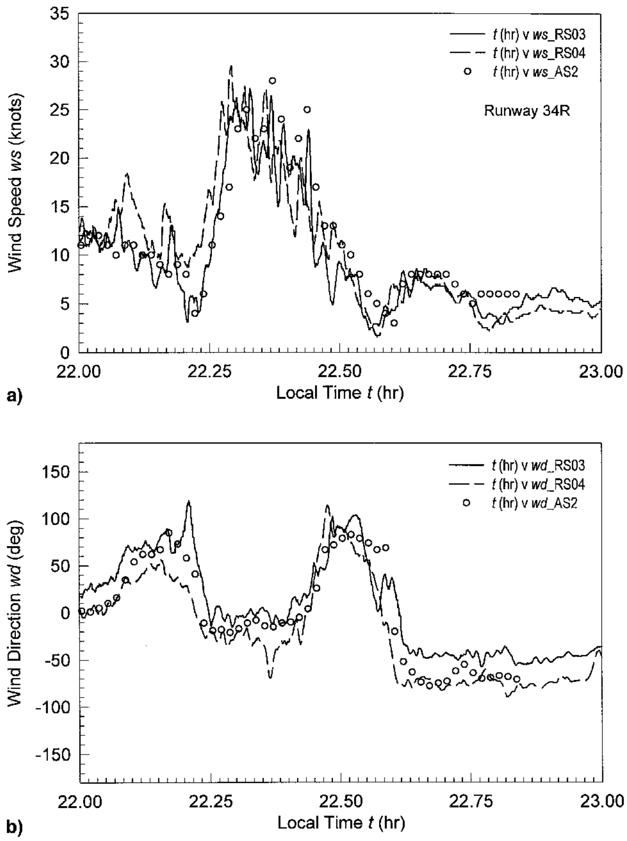

Fig. 3 Time series of a) wind speed and b) direction recorded on Aug. 14.

From the windshear data shown in Figs. 4 and 5, the windshear profiles at several selected times along the RS array were derived and illustrated in Figs. 6 and 7. The abscissa and ordinates are the midpoints and the windshear between RSs, respectively. Attempts were made to characterize the windshear profiles at times with various windshear states, particularly those exceeding the windshear alert threshold.

There are six windshear profiles plotted in Fig. 6 showing events between 18:00 and 19:30 on Aug. 13. The times at which the profiles were derived were given in the legends. At 18:12, prior to the arrival of the storm, the windshear profile (circles) was flat with the maximum value below the threshold of the weak windshear status. The next two windshear profiles (squares and triangles) were selected during passage of the first event shown in Fig. 2, with a maximum wind speed measured at RS03 up to 28 kn. The fourth profile (inverted triangles) was selected from the second event and the last two profiles (diamonds and hexagons) were selected from the third event. Note that all of the windshear profiles shown in Fig. 6, with the exception of the first one (before the arrival of the episode), registered the maximum loss shear between RS03 and RS04. These five profiles each exhibited the characteristics of a typical (dry) microburst although the display showed windshear alert. Several replays of the archived data showed that the output from the analysis module reported MBAlert when the alert

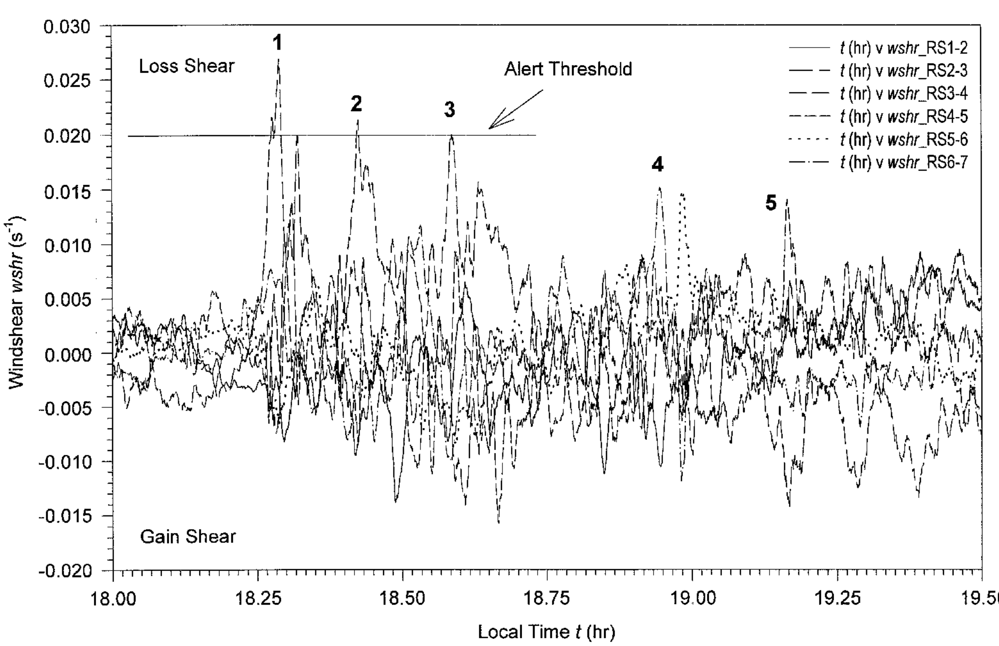

Fig. 4 Time series of windshear derived from data recorded on Aug. 13.

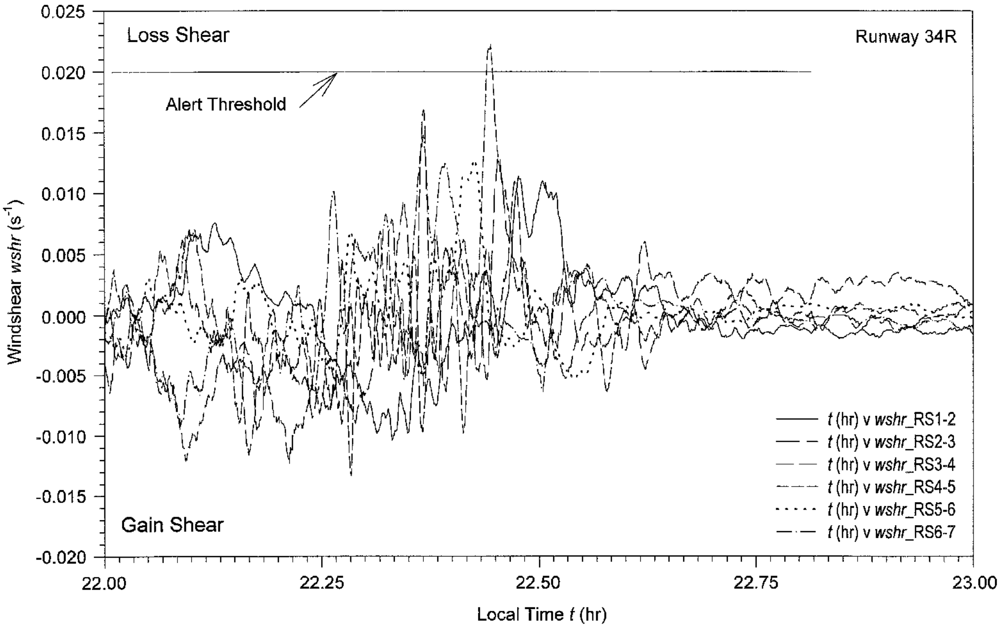

Fig. 5 Time series of windshear derived from data recorded on Aug. 14.

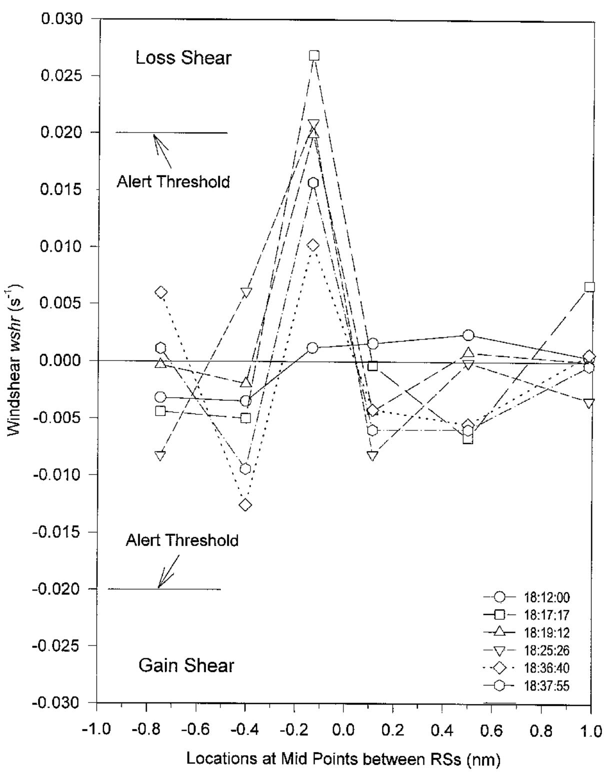

Fig. 6 Windshear profiles derived from the Aug. 13 episode.

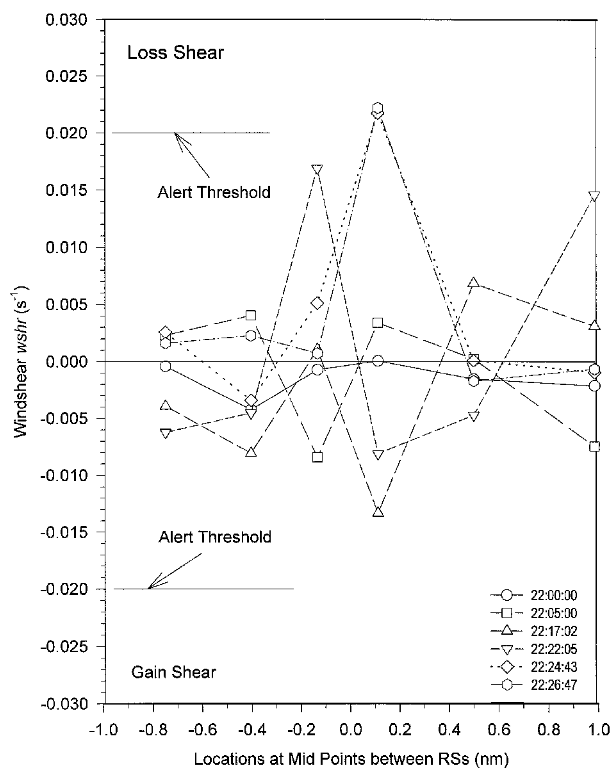

Fig. 7 Windshear profiles derived from the Aug. 14 episode.

threshold was exceeded during those events. The corresponding display would have been microburst alert rather than windshear alert. It turned out that there was a logical error in the display subprogram of text-based software program (sub VI) that caused the incorrect display of the windshear alert message. After the software error was corrected, the inconsistency disappeared and the correct messages were properly displayed.

When the Aug. 13 archived data were replayed, the microburst alert message was displayed three times for the first three events (Figs. 2 and 3): between 18:16:28 and 18:17:38 for a duration of 70 s, between 18:25:24 and 18:25:38 for 14 s, and between 18:35:02 and 18:35:14 for 12 s (Fig. 5 in Ref. 1 corresponds to the display at 18:17:20). The duration of the alert messages was proportional to the width of the windshear profiles at the threshold level. Note that a secondary peak (Fig. 4) that occurred during the first event was just below the alert threshold and did not trigger the display of the alert message. As an aircraft approached 34R and moved into the air mass designated as a microburst (see Fig. 1 in Ref. 1), it experienced an increase in the headwind (a weak gain shear) in the horizontally spreading (outer) region. The aircraft then encountered a decrease in the headwind followed by an increase in the tailwind (strong loss shear) as it entered and passed through the downdraft region. Finally, the aircraft experienced a decrease in the tailwind (gain shear) as it exited the air mass. The most hazardous region was where the aircraft exiting the downdraft; both the downdraft and the loss shear would cause the aircraft to lose altitude, potentially leading to a crash if the pilot did not react promptly.

The spatial distribution of the individual events can be estimated from the time series of the wind speed and direction based on the space–time relationship. For example, the differences in the arrival times of the three events are measured from Fig. 2 to be about 7 and 10 min, respectively. Let's assume that the events are advected by the mean wind speeds measured to be about 10 kn. The spatial separations between the first three events are, therefore, estimated to be approximately 1.2 and 1.7 nm, respectively.

The windshear profiles for the Aug. 14 episode shown in Fig. 7 differed from those in Fig. 6. First, in Fig. 7, there were only two profiles where the maximum loss shear exceeded the alert threshold. Second, there were profiles with higher gain shear than loss shear. Third, the locations at which the maximum windshear occurred were distributed over the length of the RS array, with one between RS03 and RS04 and the other between RS04 and RS05. Fourth, only three out of the six profiles exhibited the pattern of a microburst; two out of the three had peak values that exceeded the alert threshold. Replay of the archived data showed that only one event triggered the display of the microburst alert message, between 18:26:28 and 18:26:50 for 22 s.

Comparison of the wind fields for the two episodes previously discussed indicates that the windshear conditions are much more hazardous for the Aug. 13 dry episode than for the Aug. 14 thunderstorm. The Aug. 13 episode contained several small-scale, short-duration but energetic events that moved through the airfield, while the Aug. 14 episode contained a relatively large-scale, long-duration, and wet air mass. The maximum wind speeds between the two episodes were about the same at 24 to 25 kn (AS2 sensor) or about 30 kn (RS03). Because of the difference in the duration, the air masses passing through RS03 and RS04 were more energetic as a whole for the Aug. 14 thunderstorm than for the Aug. 13 dry episode. Also, the peak gusts measured at the AS2 sensor for the two episodes were 46 and 34 kn, respectively. The small-scale air masses corresponding to the individual events 1 through 3 of the August 13th episode were so localized that they formed large spatial gradients of the wind component along the RS array, leading to large windshear. In particular, the difference in the time at which the first event arrived at RS03 and RS04 is responsible for the large spatial gradient and, therefore, the largest loss shear measured during the field tests.

B. VHF Broadcast

At the USAFA Airfield ATC tower, the windshear alert broadcast subsystem was tested a number of times. One of the tests was to determine the range of the vhf broadcast. Several T3 aircraft pilots were asked to tune their radio to the broadcast frequency at 126.975 MHz during routine flights. In those tests, the transmitter broadcast only the runway identification "3 4 right" at an update rate of 0.25 Hz. The feedback from the pilots indicated that they were able to hear the synthesized voice "3 4 right loud and clear" at distances of at least 7–10 miles (6–9 n miles) out, more than enough to satisfy the range requirement.

Other tests demonstrated the broadcast format and content to the controllers and pilots. The merits of the broadcast windshear information were discussed. To avoid too much repetition, one format option was to broadcast only the runway identification when the windshear status is either no windshear or weak windshear. For the full broadcast format, the recommended order of the broadcast content was to reverse the original format[1]:

"*strong windshear (windshear alert*, or *microburst alert)*, 1 6 left (3 4 right)"

The reversal would be more effective in getting the attention of the pilots whenever the windshear reached the strong or alert status.

Other recommendations included reporting the maximum windshear, e.g., 10-kn loss/gain shear, and the location where the maximum windshear is detected, e.g., 1 n mile north/south of a common reference position. Inclusion of the preceding quantitative information would be very helpful to the pilots. Although the information is already available from the SURFWAS measurements, such inclusion would increase the length of the windshear message and thus compromise the update rate of the broadcasting.

Furthermore, there is a compatibility issue to be resolved between the windshear measured with the SURFWAS and that experienced or reported by the pilots. For example, the pilot would report to the tower when his aircraft encounters a strong windshear: "10 knots loss (gain) shear at 30 feet." This represents essentially an instantaneous loss (gain) shear. On the other hand, the windshear measured by the SURFWAS represents a spatial gradient of the wind-speed component parallel to the runway; the dimension of the windshear illustrated in Figs. 6 and 7 is meters per second per meter or s^{-1}. For example, the alert threshold of 0.02 s^{-1} set for the field test corresponds to a 14-kn loss (gain) shear in a 10-s interval for the aircraft cruising at 70 kn. Therefore common rule must be established to merge these two sets of information so that the pilots can relate the windshear encountered by the aircraft to the broadcast information derived from the SURFWAS measurements.

V. Summary and Recommendations

A three-week field test was conducted to demonstrate the performance of the SURFWAS prototype at the U.S. Air Force Academy Airfield during the thunderstorm season in August 1996. The wind data measured with the SURFWAS agreed consistently with the airfield sensors. During that period, several windy episodes passed the airfield. Two of the episodes produced microburst type windshear with high intensity that exceeded the alert threshold. Based on the findings derived from the field test, recommendations for improving the performance characteristics of the SURFWAS are discussed next.

To demonstrate the performance characteristics of the SURFWAS prototype in an airport environment, a three-week field test was conducted at the U.S. Air Force Academy Airfield from Aug. 5–23, 1996. Seven RSs were set up parallel to and about 120 m east of runway 34R (16L). The separations between RSs were approximately 0.25–0.5 n mile. The RS array spanned a total distance of 2.2 n miles from one end to the other. The MS was set up at the airfield control tower with the vhf (126.975 MHz) and uhf (413.1 MHz) antennas mounted on the roof. All seven sets of RSs worked well throughout the entire test period from Aug. 12–22.

During the field test, several recommendations from air-traffic controllers, meteorologists, and pilots regarding the display and broadcast formats of windshear message were incorporated into the SURFWAS:

1) Installed a soft switch for overriding the beeper after the alert message has been acknowledged.

2) Reversed the order of the windshear message to bring the windshear status to the attention of the pilots first.

3) Considered including the maximum loss shear and its relative location in the message broadcast to aircraft; this was a compromise that would inevitably reduce the update rate and so was not included.

4) Modified the **main.vi** to replay data selected from the archived data files to recreate the scene. This important feature allows for fine tuning of the array configuration and the selection of various site-specific parameters, such as the thresholds for the five windshear states, in the configuration files.

During the 11-day period, several windy episodes, most of them associated with thunderstorms and one of them with a cold front, passed through the airfield. The wind fields associated with these episodes were examined and the archived data were replayed through the SURFWAS prototype. Two of the episodes with windshear that exceeded the alert threshold were studied in great detail.

On Aug. 13, a dry microburst with a maximum wind speed of 24 kn and gusts up to 34 kn (measured by the airfield AS2 sensor) passed through the airfield. The episode consisted of several short events (5-min duration) with windshear that exceeded the alert threshold (0.02 s^{-1}). The windshear profiles of these events were typical of a dry microburst with large loss shear; the maximum windshear occurred consistently between RS03 and RS04. The peak values of three of the events exceeded the alert threshold and triggered the microburst alert message displayed on the monitor and broadcast via the vhf radio channel. The maximum windshear was 0.027 s^{-1} and the corresponding duration for the display of the alert message was 70 s. On Aug. 14, a thunderstorm with a maximum wind speed of 25 kn and gusts up to 46 kn passed through the airfield together with a rainfall of 2.84 cm in less than half an hour. Three events brought about windshear profiles typical of a wet microburst. The locations at which the peak windshear was measured were distributed. The peak values of windshear induced by the thunderstorm are, however, lower than those associated with the dry episode that occurred the night before. Although there were two events with peak windshear values that exceeded the alert threshold, only one of them triggered the display of the microburst alert message, between 18:26:28 and 18:26:50 for 22 s. The locations of the maximum windshear were distributed along the airfield. The considerable differences observed in the wind and windshear patterns of the two microbursts have demonstrated the inadequacy of the symmetric microburst model that has been used by LLWAS to aid in deriving the runway-oriented windshear.

The preceding results demonstrated that a linear, low-profile array of anemometers, as low as 7.3 m above ground, is capable of detecting the windshear pattern associated with microbursts, dry or wet. One reason is the high resolution of the linear array that facilitates the characterization of the windshear pattern unique to microbursts. In conclusion, the surface-based, one-dimensional SURFWAS, with adequate spatial resolution and timely display and broadcast of the windshear message, is capable of detecting microburst phenomenon in time to warn approaching (or departing) aircraft, which was previously believed to be impossible.[2]

The software and hardware of the SURFWAS prototype have been subject to extensive testing through various stages from the initial development to the final field test. Several features should be considered for incorporation into the SURFWAS to improve its overall performance:

1) Mount dual wind sensors on each RS. The redundancy is expected to improve the reliability of the SURFWAS and provide a means to diagnose imminent sensor failure.

2) Consider similar provisions for detecting other imminent hardware and/or software failure at any RS, which should be taken off-line until the problem is corrected. Taking a problematic RS off-line would improve the accuracy of the windshear derived from the wind data and reduce the false-alarm rate.

3) Evaluate options for supporting multiple displays. Currently, the Windows-based SURFWAS prototype supports only one display at the MS. For some applications, multiple displays at various locations are desirable and sometimes necessary.

4) Optimize the **MAIN** for user friendliness and cost-effectiveness and take advantage of LabVIEW's parallel computing and multitasking capabilities being incorporated in its future versions.

5) Modify the RS hardware to allow software updates of RS software via the radio link.

6) Improve the battery charge algorithm in the RS.

7) Establish a common rule to relate the SURFWAS-measured windshear in s^{-1} to the pilot-reported windshear that represents an instantaneous loss or gain shear.

The record showed that it took a two-man crew about 2 to $2\frac{1}{2}$ h to erect an RS and about one half of that time to take it down. There is room for improving the portability and mobility of the SURFWAS by miniaturizing the wind sensor and controller and downsizing the sizes of the tower elements. To speed up the erection of the RS, all fasteners should be replaced with the snap-on-and-lock type instead of nuts and bolts, which must be hand tightened.

Future work would require upgrading the SURFWAS and at least six months of deployment to assess its long-term performance and reliability, a necessary step toward developing a field instrument. In particular, the deployment must demonstrate that the false-alarm rate of the SURFWAS is acceptably low. Preferably, the SURFWAS will be deployed alongside low-level windshear alert system and/or other remote sensors through the use of the F-factor to compare and enhance the performance of one another and to achieve subsequent integration of these systems.

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References

[1]Liu, H.-T., Golborne, C., Bun, Y., and Bartel, M., "Surface Windshear Alert System Part 1: Prototype Development," *Journal of Aircraft*, Vol. 35, No. 2, 1998, pp. 422–428.

[2]Fujita, T. T., *The Downburst, Microburst and Macroburst*, Univ. of Chicago Press, Chicago, IL, 1985.

[3]Liu, H.-T., Golborne, C., Bun, Y., and Bartel, M., "Prototype Development of a Surface Windshear Alert System for Aeronautic Missions," QUEST TR 721, Kent, WA, Oct. 1996.

[4]Shen, J., Parks, E. K., and Bach, R. E., "Comprehensive Analysis of Two Downburst-Related Aircraft Accidents," *Journal of Aircraft*, Vol. 33, No. 5, 1996, pp. 924–930.

[5]Frederick, G., "Forward-Looking Windshear Radar," *World Aerospace Technology International '95*, edited by M. Williams, Sterling Publications Ltd., London, 1995, pp. 108–110.