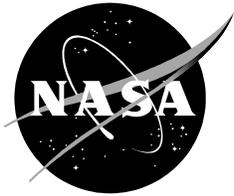


NASA Contractor Report CR-2006-214205



RSA/Legacy Wind Sensor Comparison. Part II: Eastern Range

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May 2006

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Executive Summary

The goal of this study was to evaluate the performance of ultrasonic wind sensors being used to replace mechanical wind sensors at the Eastern Range (ER). Launch Weather Officers, forecasters, and Range Safety analysts need to understand the performance of wind sensors at the ER and Western Range (WR) for weather warnings, watches, advisories, special ground processing operations, launch pad exposure forecasts, user Launch Commit Criteria (LCC) forecasts and evaluations, and toxic dispersion support. The current ER weather tower wind instruments are being changed from Legacy propeller-and-vane sensors to ultrasonic sensors through the Range Standardization and Automation (RSA) program. The Legacy sensors measure wind speed and direction mechanically. The ultrasonic RSA sensors have no moving parts. These differences in wind measuring techniques have been found to cause differences in the statistics of peak wind speed in previous studies. The 45th Weather Squadron (45 WS) and the 30th Weather Squadron (30 WS) requested the Applied Meteorology Unit (AMU) to compare data between RSA and Legacy sensors to determine if there are significant differences. This report addresses the comparison of Legacy and RSA wind speed and direction sensors on the ER.

An 18-day archive of 1-minute ER Legacy and RSA wind data was used by the AMU in this study. The period-of-record (POR) was 13 – 30 May 2005 from 5 towers: 0002, 0006, 0108, 0313 and 0403. The 5 towers were instrumented at numerous levels, ranging from 12 ft to 492 ft. The ER Legacy and RSA data archive covered 24 hours each day and included 1-minute average wind speed and direction and the peak wind speed/direction used to evaluate LCC during operations.

The Legacy data was provided by a propeller-and-vane system with the vane (direction) and propeller (speed) molded into one unit. The RSA wind data was obtained from an ultrasonic-type sensor that derives wind speed and direction information from the effect of wind on the transit time of ultrasonic pulses between three electro-acoustic transducer pairs, mounted in an equilateral triangle. The data archive for this study included one or two Legacy systems, depending on the tower, and one RSA sensor at each level. The Legacy and RSA systems were mounted at the same level. Data from a total of 19 RSA sensors, collocated with Legacy speed/direction systems were used.

The AMU created time series of wind speed and direction for each Legacy and RSA system on each tower at each level. The Legacy and RSA time series were then aligned, minute-by-minute. The AMU then used the Legacy wind direction information to obtain samples with the Legacy sensors on the upwind side of the tower. This procedure was followed to minimize effects of tower obstruction on the sensor inter-comparisons. A total of 357,626 1-minute comparisons of Legacy versus RSA wind information were obtained after the initial screening process. A secondary screening identified anomalous RSA peak wind speed readings on Tower 0108 and data from that tower were handled separately.

The overall comparison of 329,018 minutes of secondary screened data resulted in the following:

- Overall Average Wind Speed: Legacy 7.72 kts, RSA 8.27 kts, RSA – Legacy = + 0.55 kts
- Overall Peak Wind Speed: Legacy 9.51 kts, RSA 10.72 kts, RSA – Legacy = + 1.21 kts

The AMU also examined each Legacy/RSA pairing for consistency in wind speed and wind direction. Four of the 19 RSA sensors showed patterns of variability in differences from the Legacy sensors that were outside the norm of the other 15 RSA sensors. These 15 RSA sensors were used to define a composite average-Legacy/RSA comparison and the peak wind speed data from the same 15 RSA sensors were used to define a composite peak-Legacy/RSA wind speed comparison.

Comparisons of the 15 sensor composite were slightly different than the overall comparison cited above.

- Composite Average Speed: Legacy 8.09 kts, RSA 8.47 kts, RSA – Legacy = + 0.38 kts
- Composite Peak Speed: Legacy 9.79 kts, RSA 10.73 kts, RSA – Legacy = + 0.94 kts

From a technical point of view the small differences in average wind speeds reported by the Legacy and RSA sensors are statistically significant, due to the large sample size and small standard deviation of differences in 1-minute wind speed between the sensors, +/- 0.90 kts. From a practical point of view the differences in peak wind speeds are more important, indicating that the change to ultrasonic sensors can be expected to result in an increase in reported peak wind speeds. An increase in peak wind speeds would result in a decrease of launch availability, depending on the LCC threshold wind speed. For example, the probability of peak wind speeds at 20 kts or less using the Legacy data was 95.2%. For the same 20 kt threshold the RSA data showed a probability of 92.3%.

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1. Introduction

Launch Weather Officers, forecasters, and Range Safety analysts need to understand the performance of wind sensors at the Eastern (ER) and Western (WR) Ranges for weather warnings, watches, advisories, special ground processing operations, launch pad exposure forecasts, user Launch Commit Criteria (LCC) forecasts and evaluations, and toxic dispersion support. Through the Range Standardization and Automation (RSA) program, the current weather tower wind instruments are being switched from the Legacy propeller-and-vane (ER) and cup-and-vane (WR) sensors to ultrasonic sensors.

The Legacy sensors measure wind speed and direction mechanically, while the ultrasonic RSA sensors have no moving parts. Ultrasonic sensors, having no mechanical inertia, were originally developed to measure very light winds (Lewis and Dover 2004). The technology has evolved and now ultrasonic sensors provide reliable wind data over a broad range of wind speed. However, because ultrasonic sensors respond more quickly than mechanical sensors to the rapid fluctuations in speed that are characteristic of gusty wind conditions, comparisons of data from the two sensor types have shown differences in the statistics of peak wind speeds (Lewis and Dover 2004). The 45th Weather Squadron (45 WS) and the 30th Weather Squadron (30 WS) requested the Applied Meteorology Unit (AMU) to compare data from RSA and Legacy sensors to determine if there are significant differences between wind speed and direction information from the two systems. Short and Wheeler (2006) have documented a comparison of data from Legacy and RSA wind sensors on the WR. This report addresses the comparison of data from selected Legacy and RSA wind speed and direction sensors on the ER.

2. Data and Sensor Description

The 45 WS identified 5 ER towers to be used in the comparison of Legacy and RSA wind sensor data. Table 1 gives the Legacy tower numbers and sensor levels used in this study, with available data indicated by the letters “L” for Legacy and “RSA” for RSA. Data from 19 RSA sensors and 29 Legacy sensors were available. The Legacy and RSA wind sensors transmitted speed and direction readings every second to separate local processing systems. The local processing systems computed and recorded the following, based on the 1-second sensor readings.

- One-minute average wind speed/direction, and
- Peak wind speed/direction during the one-minute interval.

The one-minute average wind speed/direction and the peak wind speed/direction data were used in this study.

| Table 1. Tower identification numbers (IDs) and sensor levels for RSA and Legacy wind data from the 5 ER towers used in this study. Data from Legacy and RSA sensors were obtained at each level marked with the letters “L,” “L1,” “L2,” and “RSA,” where “L” denotes one Legacy sensor and “L1,” “L2,” denotes two Legacy sensors at the same level. | | | | | |
|--|----------------------------------|----------------------------------|----------------------------------|-----------------------------------|-----------------------------------|
| Level (ft) | Tower ID Legacy 0002 RSA 2 | Tower ID Legacy 0006 RSA 6 | Tower ID Legacy 0108 RSA 9 | Tower ID Legacy 0313 RSA 16 | Tower ID Legacy 0403 RSA 20 |
| 492 | - | - | - | L1, L2; RSA | - |
| 394 | - | - | - | L1, L2; RSA | - |
| 295 | - | - | - | L1, L2; RSA | - |
| 204 | L; RSA | L1, L2; RSA | - | L1, L2; RSA | - |
| 162 | - | - | - | L1, L2; RSA | - |
| 145 | L; RSA | - | - | - | - |
| 090 | L; RSA | - | - | - | - |
| 054 | L; RSA | L1, L2; RSA | L; RSA | L1, L2; RSA | L; RSA |
| 012 | L; RSA | L1, L2; RSA | L; RSA | L1, L2; RSA | L; RSA |

2.1. Legacy Wind Sensor

Figure 1 shows a schematic image of the Legacy propeller-and-vane type wind sensor used on the 5 ER towers listed in Table 1. The Legacy wind sensor system is comprised of a wind vane that aligns itself with the wind direction and a propeller that spins at a rate directly proportional to the wind speed. The wind speed and direction information is output every second and a local data processing system determines the one-minute average and peak conditions. The 5 ER Towers used in the present study were among the 33 used by Case and Bauman (2004) for a nine-year climatological study of Legacy wind data from the Kennedy Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS) tower network.

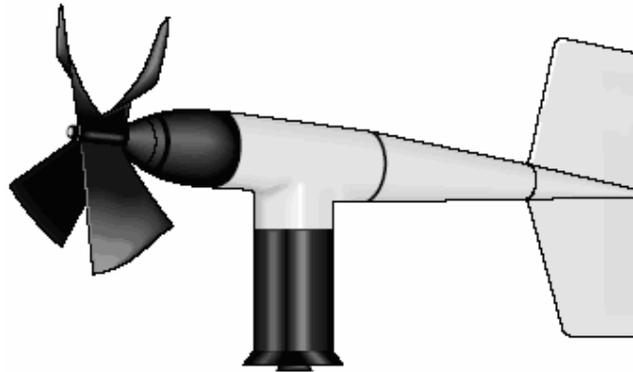


Figure 1. Schematic image of the propeller-and-vane type wind sensor used on the 5 ER towers listed in Table 1 (adapted from the R. M. Young Model 05305 Wind Monitor-AQ). See Computer Sciences Raytheon (2000) for details. Wind speed accuracy is ± 0.58 kts. The starting threshold wind speed is 0.64 kts.

The one-minute average wind speed data from the Legacy sensors were recorded at approximately 1-knot intervals (0.0, 1.0, 1.9, 2.9, 4.1, 5.1, 6.0, 7.0, 8.0, 8.9, ...etc.). This sequence of values appears to have been first recorded to the nearest 0.5 ms^{-1} , then converted to knots, then recorded to the nearest 0.1 kts. The peak wind speed was recorded to the nearest knot and the average and peak wind directions were recorded to the nearest degree.

2.2. RSA Wind Sensor

Figure 2 shows an image of the Vaisala WS425 Ultrasonic Wind Sensor and its three equally spaced ultrasonic transducers mounted in a horizontal plane (Vaisala 2004). The sensor measures the time it takes for ultrasonic pulses to travel from one transducer to the other, in both directions. The transit time increases on upwind paths and decreases on downwind paths, the difference being proportional to the wind speed component along the path. Within every second 32 raw wind-speed estimates are derived along each of the three paths. A proprietary algorithm is used to quality-control the raw data and produce a 1-second wind speed/direction reading. These 1-second data are used to produce a 1-minute average wind speed/direction reading and a peak wind speed/direction reading each minute.



Figure 2. Image of the ultrasonic type RSA wind sensor used on the 5 ER towers listed in Table 1 (adapted from the Vaisala Model WS425 Ultrasonic Wind Sensor). See Vaisala (2004) for details. Wind speed accuracy is ± 0.26 kts or 3% of wind speed, whichever is greater. The starting threshold is virtually zero.

The RSA average and peak wind speed data were recorded to the nearest 0.1 ms^{-1} (0.19 kts) and the average and peak wind direction data were recorded to the nearest degree. The RSA data was provided by Ms. Valek of Computer Sciences Raytheon.

3. Analysis Procedure

The analysis procedure was designed to compare Legacy and RSA sensor readings at the highest temporal resolution available and to avoid wind sheltering effects by the tower, when possible. This was accomplished by first matching times series minute-by-minute for all available sensors (Legacy, Legacy1 and Legacy2, when available, and RSA) at each level on each tower. For towers having data from 2 Legacy sensors the Legacy1 wind direction at each level on each tower was then used to separate the matched time series into two sectors. Each sector put the Legacy sensor on the upwind side of the tower for each of the two possible comparisons:

- Sector 1: Legacy1 versus RSA,
- Sector 2: Legacy2 versus RSA.

3.1. Extract Minute-by-Minute

Time series of wind speed and direction were obtained for each Legacy sensor on each tower at each level. Data from one RSA sensor at each level on each tower was available for this study. The Legacy and RSA wind sensor data were matched, minute-by-minute.

3.2. Wind Sector Filter

The wind direction filter was based on the instrument mounting scheme for each tower and was designed to avoid effects of wind flow around the tower, when possible. This was done by restricting data for each Legacy sensor on Towers 0006 and 0313 to wind flow from the up-wind side of tower. Figure 3 shows a schematic of the mounting scheme for the Legacy and RSA sensors used on Tower 0313. Note that the Legacy and RSA sensors were mounted on opposite corners of the tower, southwest (SW) and northeast (NE). RSA sensors were mounted just inboard of the Legacy sensors, although data from only one RSA sensor was available for this study. RSA information indicated that the RSA 16 sensors were mounted on the SW side of Tower 0313. This mounting scheme was used for each level on Tower 0313.

Figure 3 also defines 2 wind-direction sectors for Tower 0313. Data from Legacy1 SW was used for comparison to the RSA sensor when the Legacy1 SW sensor showed a wind direction between 135° to 315° , clockwise. Otherwise, data from the Legacy2 NE sensor was used for comparison to the RSA sensor.

The mounting scheme for Tower 0006 had Legacy and RSA sensors on the northwest (NW) and southeast (SE) sides of the tower. Wind direction sectors from 225° to 045° (NW; Legacy1), and 045° to 225° (SE; Legacy2) were used.

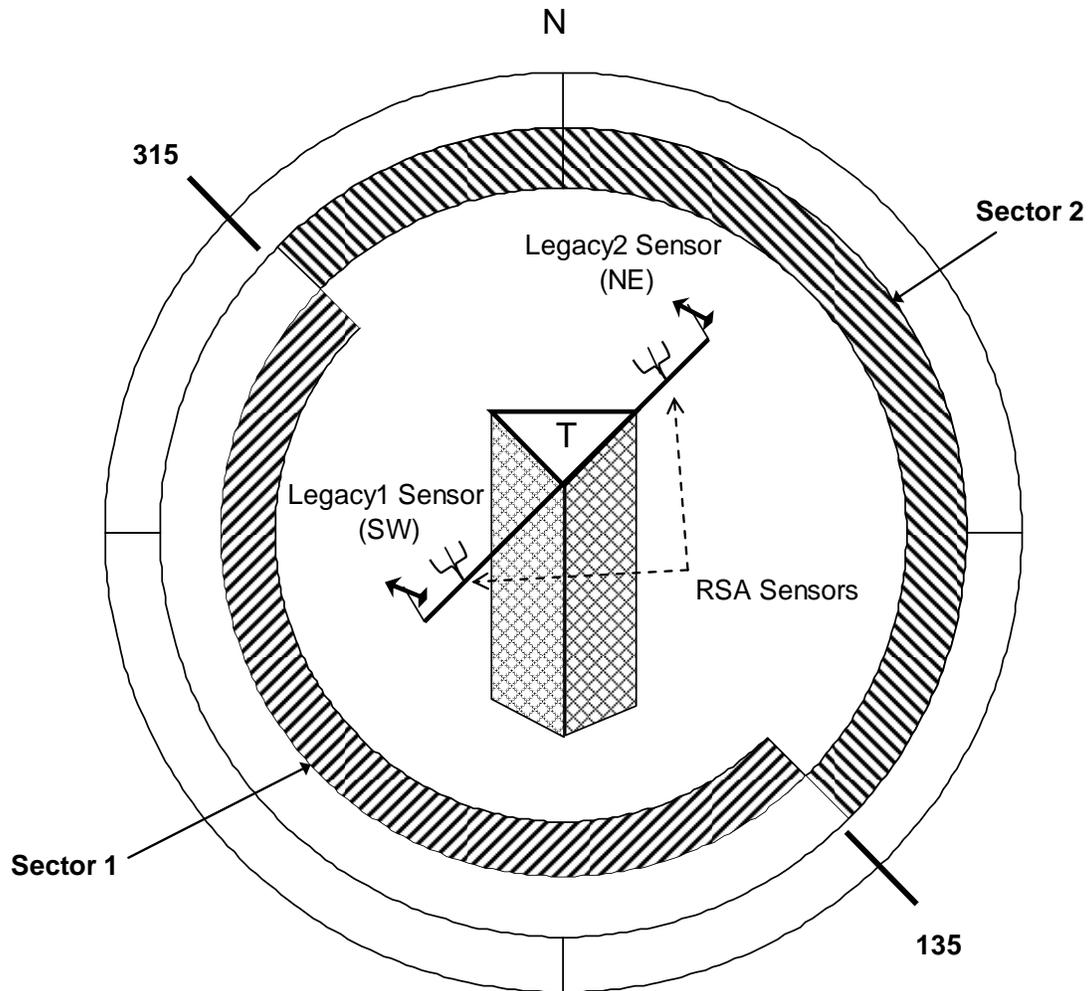


Figure 3. Schematic of Legacy and RSA instrument configurations and wind-direction sectors used for wind speed comparisons on Tower 0313. Sector 1, spanning the SW from 135° to 315°, was used for comparing the Legacy1 and the SW RSA sensor. Sector 2, spanning the NE from 315° to 135°, was used for comparing the Legacy2 and the SW RSA sensor. Wind direction from the Legacy1 sensor was used as the reference.

Table 2 shows tower ID numbers and wind direction sectors used to constrain the Legacy wind sensor data to the up-wind side of the tower.

Table 2. Legacy and RSA Tower IDs, number of levels with data, number of Legacy and RSA sensors at each level used in the comparison, and wind sectors used in sensor comparisons for 5 towers on the ER. See Figure 3 for a schematic depiction of the sectors on Legacy Tower 0313.

| Legacy Tower ID | RSA Tower ID | Levels with data | Sensors | Sector 1 | Sector 2 |
|-----------------|--------------|------------------|-------------|-------------|-------------|
| 0403 | 20 | 2 | L, RSA | 0° → 360° | N/A |
| 0313 | 16 | 7 | L1, L2, RSA | 135° → 315° | 315° → 135° |
| 0108 | 9 | 2 | L, RSA | 0° → 360° | N/A |
| 0006 | 6 | 3 | L1, L2, RSA | 225° → 045° | 045° → 225° |
| 0002 | 2 | 5 | L, RSA | 0° → 360° | N/A |

Table 3 lists the sample size, in minutes, for each sector, and sensor pair, after filtering by wind direction. Total sample size excludes Legacy Tower 0108. See Section 4.2.4 for a detailed discussion of the RSA sensor data from Legacy Tower 0108. The Cross-Reference Number (CRN) will be used to simplify further discussions.

| Table 3. Sample size, in minutes, after the time series for each sensor pair was filtered by the wind direction sectors listed in Table 2. The Cross-Reference Number (CRN) will be used as a cross-reference to the RSA sensors. *Total sample size excludes CRNs 10 and 11 on Tower 0108 (sample sizes in parentheses). See Section 4.2.4 for a detailed discussion of the RSA sensor data from Tower 0108. | | | | |
|---|-----------------|------------|--------------------------------|--------------------------------|
| Cross-Reference Number | Legacy Tower ID | Level (ft) | Sector 1 Legacy1 versus RSA | Sector 2 Legacy2 versus RSA |
| 1 | 0403 | 054 | 18451 | N/A |
| 2 | 0403 | 012 | 14771 | N/A |
| 3 | 0313 | 492 | 12245 | 7351 |
| 4 | 0313 | 394 | 11905 | 7684 |
| 5 | 0313 | 295 | 12709 | 7097 |
| 6 | 0313 | 204 | 12802 | 5220 |
| 7 | 0313 | 162 | 19824 | 19806 |
| 8 | 0313 | 054 | 12828 | 6927 |
| 9 | 0313 | 012 | 11962 | 7860 |
| 10 | 0108 | 054 | (12985) | N/A |
| 11 | 0108 | 012 | (15623) | N/A |
| 12 | 0006 | 204 | 5173 | 13460 |
| 13 | 0006 | 054 | 5056 | 13498 |
| 14 | 0006 | 012 | 5091 | 12300 |
| 15 | 0002 | 204 | 19088 | N/A |
| 16 | 0002 | 145 | 19295 | N/A |
| 17 | 0002 | 90 | 19280 | N/A |
| 18 | 0002 | 054 | 19414 | N/A |
| 19 | 0002 | 012 | 7921 | N/A |
| | Total | All Levels | *227815 | 101203 |

Figure 4a shows how the total sample size from sectors 1 and 2 was distributed across Legacy average wind speeds. The average sample size has a plateau-like appearance from 5-to- 9 kts and falls to zero at 38 kts. The plateau results from a super-position of peaks from individual sensors. The distribution is right-skewed with a mean value of 7.44 kts, slightly to the right of the center of the plateau.

Figure 4b shows how the total sample size from sectors 1 and 2 was distributed across Legacy peak wind speeds. The peak sample size has a single peak at 10 kts and a long tail of small sample sizes, with only one sample exceeding 45 kts. The distribution is right skewed, but has a mean value of 9.32 kts, slightly lower than the mode, due to large samples of low peak wind speeds.

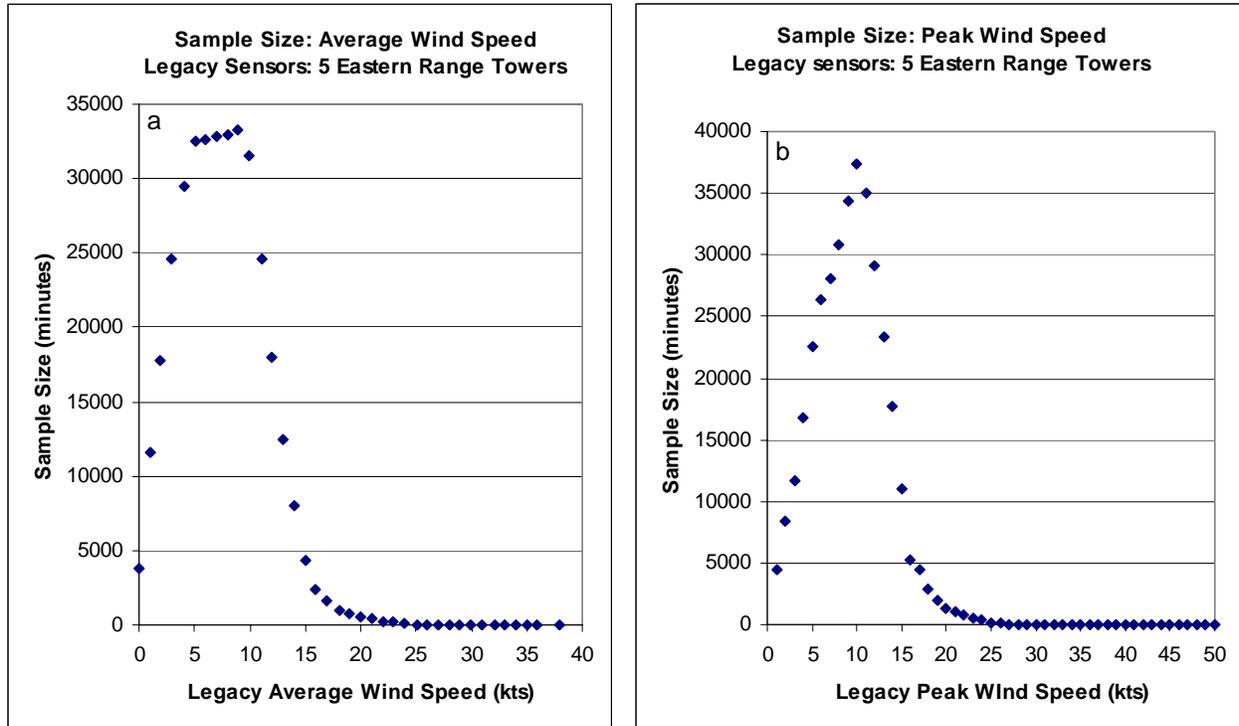


Figure 4. (a) Sample size for average and (b) peak wind speed data from 29 Legacy sensors on 5 ER towers. The POR is 13 May – 30 May 2005. Total sample size is 357,626.

4. Results

The results of the sensor comparison are presented in this section in three different ways:

- Overall composite results,
- Sensor-by-sensor comparisons, and
- Composite results from the most consistent sensors.

The sensor-by-sensor comparisons were done for each Legacy/RSA pair.

4.1. Overall Composite Results: Average and Peak Wind Speeds

Data used for the overall composite results were obtained by first matching time series from all sensor pairs, minute-by-minute, and then excluding Legacy data from wind directions affected by the towers, as described in Section 3. A total of 329,018 one-minute comparisons of Legacy versus RSA wind information were obtained after the screening process. Total sample size excludes CRNs 10 and 11 on Tower 0108. See Section 4.2.4 for a detailed discussion of the RSA sensor data from Tower 0108.

The overall comparison of all the screened data resulted in the following:

- Overall Average Wind Speed: Legacy 7.72 kts, RSA 8.27 kts, RSA - Legacy = +0.55 kts
- Overall Peak Wind Speed: Legacy 9.51 kts, RSA 10.72 kts, RSA - Legacy = +1.21 kts

Average wind speeds with sample sizes larger than 30 minutes during the POR ranged from 0 to 25 knots. Peak wind speeds with sample sizes larger than 30 minutes during the POR ranged from 1 to 28 knots

In order to depict the difference between RSA and Legacy sensors over the full range of observed wind speeds, the AMU computed the overall results for 17 of the 19 RSA sensors, excluding Legacy Tower 0108, conditioned on the Legacy average and Legacy peak wind speeds. That is, for all Legacy one-minute average wind speeds of 1 knot at all levels on all towers, the corresponding RSA one-minute average wind speed was computed from data at all

levels on all towers. This procedure was followed for all Legacy average wind speeds, knot-by-knot, up to 25 knots. The results are plotted in Figure 5a. Above 25 knots the sample size for Legacy average wind speeds fell below 30 one-minute-averages and the comparison results became noisy. Also, for all Legacy peak wind speeds of 1 knot, the corresponding average of all RSA peak speeds was computed. This procedure was followed for all Legacy peak wind speeds, knot-by-knot, up to 28 kts. The results are plotted in Figure 5b. At wind speeds above 28 knots the sample size for Legacy peak wind speeds fell below 30 and the comparison became noisy.

Figure 5a shows RSA average wind speeds just above the 1:1 line with an offset of 0.64 kts when the Legacy speed is zero. This low wind speed performance is remarkably consistent with the starting thresholds for the two instruments: Legacy, 0.64 kts, RSA, essentially zero. Figure 5a also shows a weak inflection point near 15 kts. Figure 5b shows the RSA peak wind speeds are also above the 1:1 line with a weak inflection point near 17 kts. The inflections points are located in the region where the sample sizes for average and peak winds are falling rapidly, and the dispersion among individual sensors is increasing, as will be shown in the following section.

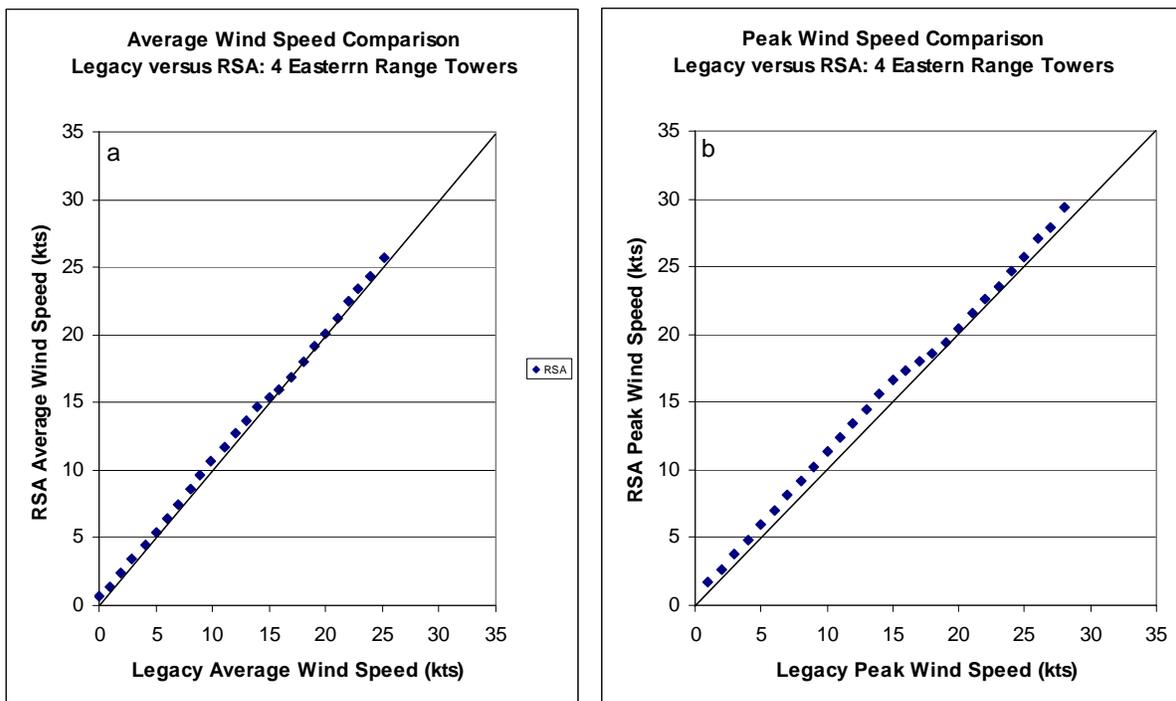


Figure 5. (a) Average and (b) Peak wind speed comparisons for 17 sensor pairs on 4 ER towers. The POR is 13 May – 30 May 2005. Total sample size is 328,916. Each data point plotted had at least 30 one-minute samples.

4.2. Sensor-by-Sensor Comparisons

The Legacy/RSA comparisons shown in Figure 5a and Figure 5b reveal the composite behavior of 17 of the 19 RSA wind sensors with respect to 27 Legacy wind sensors for the one-minute average and peak wind speed data. A more detailed sensor-by-sensor comparison was also made to assess the consistency and reliability of the RSA sensors.

4.2.1. Conditional Averages

Figure 6 shows conditional averages of each of the 19 RSA sensors with respect to their collocated Legacy sensor. These were computed in the same manner as the curve shown in Figure 5a, with wind direction sectors as defined in Table 2. The majority of comparisons are tightly clustered just above the 1:1 line up to a speed of about 15 kts. Above 15 kts the sample sizes for the individual sensors become smaller and the comparison become noisy. However, the data from 4 sensors are plotted with red, green and blue connecting lines to highlight variable deviations, even in the well sampled zone, above and below the 1:1 line. These 4 sensors were labeled as outliers in this initial comparison.

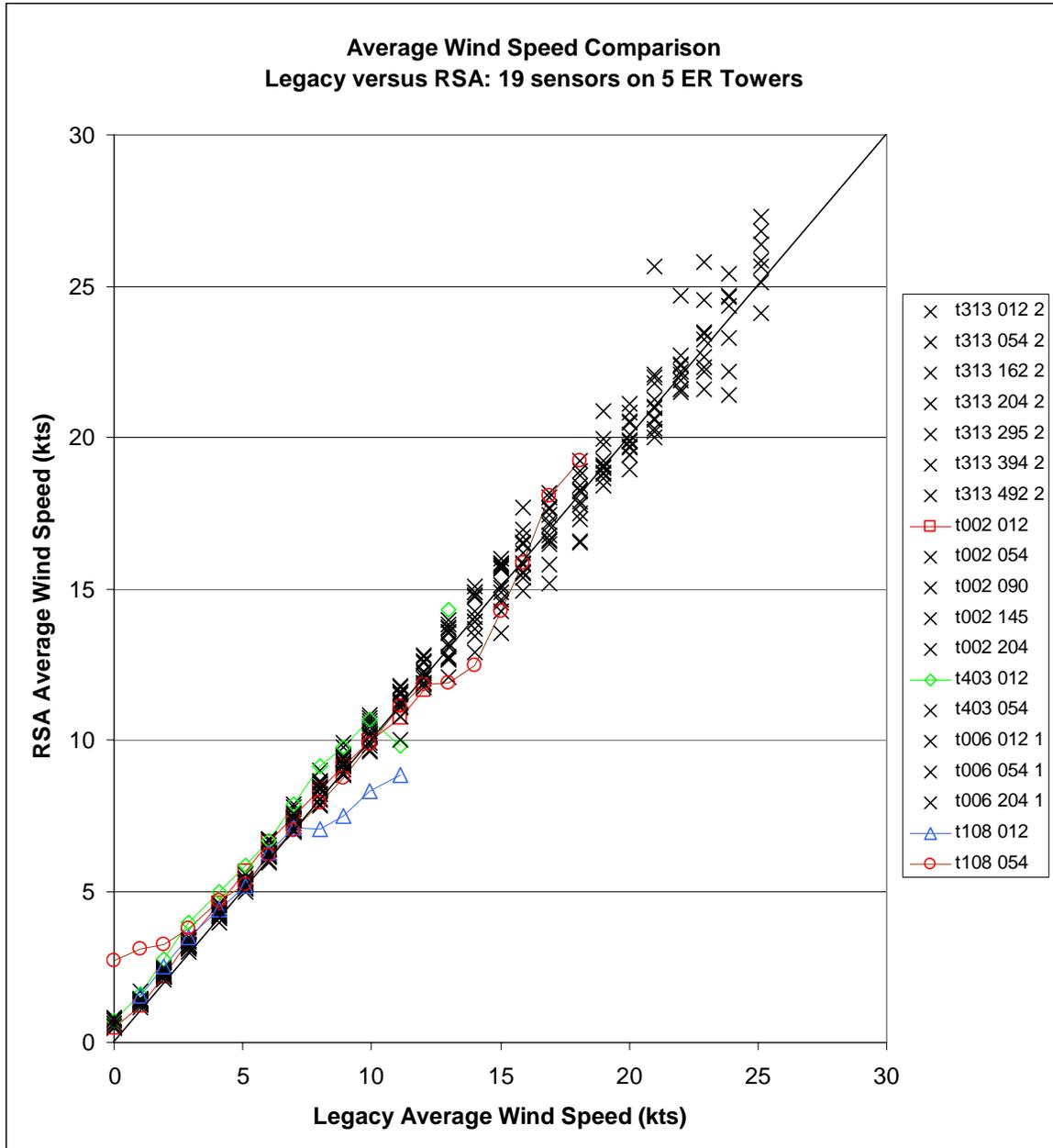


Figure 6. Average wind speed comparisons for each of the 19 Legacy/RSA sensors pairs on 5 ER towers. POR is 13 May – 30 May 2005. The legend indicates Legacy Tower ID, level (in ft) and Legacy sensor number, when applicable. Four outliers are marked by solid lines. Above ~15 kts the number of samples becomes small (< 30) for each sensor and the comparisons become noisy. The 1:1 solid diagonal line extends from the point 0,0 to the point 30,30, and represents the no-difference line.

4.2.2. Difference of Average Wind Speeds

For each of the 19 RSA wind sensors on the 5 towers, the matched time series in Sectors 1 and 2 were used to compare overall average wind speeds between RSA-Legacy pairs. Table 4 lists the results. Bias was defined as the average of the RSA – Legacy difference in average wind speed. The standard deviation of the RSA – Legacy difference in average wind speed was also calculated and listed in Table 4.

| Table 4. Bias and standard deviation, in knots, of average wind speed for sensor-to-sensor comparisons. Entries in bold type were chosen for the composite best comparison. | | | | |
|--|--------------|------------|---------------------------|---------------------------|
| Cross-Reference Number | Legacy Tower | Level (ft) | Sector 1 RSA - Legacy1 | Sector 2 RSA – Legacy2 |
| 1 | 0403 | 054 | +0.16 +/- 0.92 | N/A |
| 2 | 0403 | 012 | +0.83 +/- 0.69 | N/A |
| 3 | 0313 | 492 | +0.77 +/- 1.62 | +0.54 +/- 0.73 |
| 4 | 0313 | 394 | +1.12 +/- 2.06 | +0.46 +/- 0.70 |
| 5 | 0313 | 295 | +0.78 +/- 1.50 | +0.08 +/- 0.67 |
| 6 | 0313 | 204 | +0.91 +/- 1.78 | +0.48 +/- 0.66 |
| 7 | 0313 | 162 | +0.96 +/- 1.55 | +0.80 +/- 1.01 |
| 8 | 0313 | 054 | +0.60 +/- 1.40 | +0.29 +/- 0.69 |
| 9 | 0313 | 012 | +0.29 +/- 0.79 | +0.24 +/- 0.63 |
| 10 | 0108 | 054 | +0.31 +/- 1.86 | N/A |
| 11 | 0108 | 012 | +0.47 +/- 0.84 | N/A |
| 12 | 0006 | 204 | -0.15 +/- 0.69 | +0.89 +/- 0.76 |
| 13 | 0006 | 054 | -0.05 +/- 0.72 | +0.43 +/- 0.78 |
| 14 | 0006 | 012 | +0.27 +/- 0.78 | +0.57 +/- 0.85 |
| 15 | 0002 | 204 | +0.80 +/- 0.93 | N/A |
| 16 | 0002 | 145 | +0.36 +/- 1.16 | N/A |
| 17 | 0002 | 090 | +0.41 +/- 0.95 | N/A |
| 18 | 0002 | 054 | +0.26 +/- 0.91 | N/A |
| 19 | 0002 | 012 | +0.98 +/- 3.35 | N/A |

From a technical point of view the small differences in average wind speeds reported by the Legacy and RSA sensors and listed in Table 4 are statistically significant, due to the large sample size and small standard deviation of differences in 1-minute wind speed between the sensors, +/- 0.90 kts. Under ideal conditions, with identical exposure the average wind speeds reported by the two instruments would be expected to be statistically indistinguishable. The small difference in average wind speed noted in this study, averaging < 0.5 kts for the most consistent sensor pairs, is not considered to be operationally significant.

Under ideal conditions of identical exposure and high numerical precision in reported values, the standard deviation of differences in wind speed would be expected to be approximately +/- 0.64 kts, obtained by Pythagorean addition of the accuracies of the two sensors: +/- 0.58 kts (Legacy) and +/- 0.26 kts (RSA). Table 4 shows standard deviations somewhat larger than the theoretical value, likely attributable to sensor separation, small scale turbulence, and numerical truncation of reported values. The average observed standard deviation of +/- 0.90 kts is reasonable.

Table 4 shows that for Legacy Tower 0313 the smallest bias and standard deviation were from Sector 2 (RSA – Legacy 2). Sector 2 utilizes the NE Legacy sensor, even though the corresponding RSA designation, Tower 16, would indicate the SW RSA sensor. On the other hand, for Legacy Tower 0006 the bias and standard deviation statistics are low for both Sector 1 and Sector 2, with Sector 1 being slightly better. This result is consistent with the understanding that the RSA Tower 6 sensor and the Legacy1 Sensor are on the NW side of the tower.

4.2.3. Difference of Average Wind Direction

For each matched time series the average and standard deviation of direction differences were calculated. This procedure was followed for both sectors, when applicable, for each of 19 sensor levels on the 5 towers. The comparisons of wind direction differences are listed in Table 5.

Table 5. Bias and standard deviation, in degrees, of average wind direction for sensor-to-sensor comparisons. Entries in **bold type** were chosen for the composite best comparison.

| Cross-Reference Number | Legacy Tower | Level (ft) | Sector 1 RSA - Legacy1 | Sector 2 RSA – Legacy2 |
|------------------------|--------------|------------|---------------------------|---------------------------|
| 1 | 0403 | 054 | -04.3 +/- 07.0 | N/A |
| 2 | 0403 | 012 | +49.9 +/- 07.6 | N/A |
| 3 | 0313 | 492 | -05.3 +/- 05.4 | +05.4 +/- 04.9 |
| 4 | 0313 | 394 | -05.9 +/- 06.9 | -02.8 +/- 06.0 |
| 5 | 0313 | 295 | -06.8 +/- 04.4 | +09.1 +/- 05.7 |
| 6 | 0313 | 204 | -05.9 +/- 04.8 | -10.1 +/- 04.1 |
| 7 | 0313 | 162 | -01.5 +/- 08.0 | -03.0 +/- 04.8 |
| 8 | 0313 | 054 | -01.6 +/- 05.9 | +00.0 +/- 07.3 |
| 9 | 0313 | 012 | -04.6 +/- 06.6 | -00.2 +/- 09.6 |
| 10 | 0108 | 054 | -03.6 +/- 26.8 | N/A |
| 11 | 0108 | 012 | +04.2 +/- 11.1 | N/A |
| 12 | 0006 | 204 | -01.4 +/- 04.1 | +0.6 +/- 04.6 |
| 13 | 0006 | 054 | -03.6 +/- 06.2 | +04.7 +/- 04.9 |
| 14 | 0006 | 012 | -02.6 +/- 11.4 | +04.4 +/- 09.1 |
| 15 | 0002 | 204 | -01.9 +/- 03.7 | N/A |
| 16 | 0002 | 145 | +06.6 +/- 04.3 | N/A |
| 17 | 0002 | 090 | 03.6 +/- 04.3 | N/A |
| 18 | 0002 | 054 | +03.4 +/- 04.7 | N/A |
| 19 | 0002 | 012 | +01.1 +/- 11.8 | N/A |

The largest bias in wind direction shown in Table 5 is + 49.9° for CRN 2, at the 012 ft level on Legacy Tower 0403. This large bias value suggests a misaligned sensor. The largest standard deviation in wind direction shown in Table 5 is 26.8° for CRN 10, at the 054 ft level on Legacy Tower 0108. Both RSA sensors on Legacy Tower 0108 were classified as outliers on the basis of patterns in the average wind speed comparisons shown in Figure 6. The following section describes anomalous peak wind speeds from the RSA sensor at the 054 ft level on Legacy Tower 0108.

4.2.4. Anomalous Peak Wind Speeds from RSA Sensors on Tower 0108

This section describes an extreme example of anomalous peak wind speeds affecting ~ 4 % of the data from the RSA sensor at the 54 ft level on Tower 0108. Table 5 shows that the average wind direction data from this sensor (CRN 10) showed the largest overall variability from collocated Legacy sensor data; a standard deviation of 26.8°. Further examination of data from this sensor showed anomalous peak wind speeds, documented below.

Figure 7 shows the diurnal cycle of peak wind speeds from the RSA sensor at the 54 ft level on Tower 0108. The RSA sensor data stream included 4 quality flags with each one-minute report. All data points plotted in Figure 7 had all 4 quality flags set at zero, indicating “nominal.” However, there is a clear separation between the cluster of reasonable looking values < 40 kts and a higher cluster > 100 kts. The higher cluster is considered anomalous, because the highest peak wind speed observed by the collocated Legacy wind speed sensor during the POR was 27 kts. Note the absence of anomalous data from Universal Coordinated Time (UTC) hours 15 through 20

One unresolved puzzle concerning the anomalous wind speeds is that the measurement range for the ultrasonic anemometer is given as 65 m/s (125 kts; Vaisala 2004), yet values as high as 150 kts were archived.

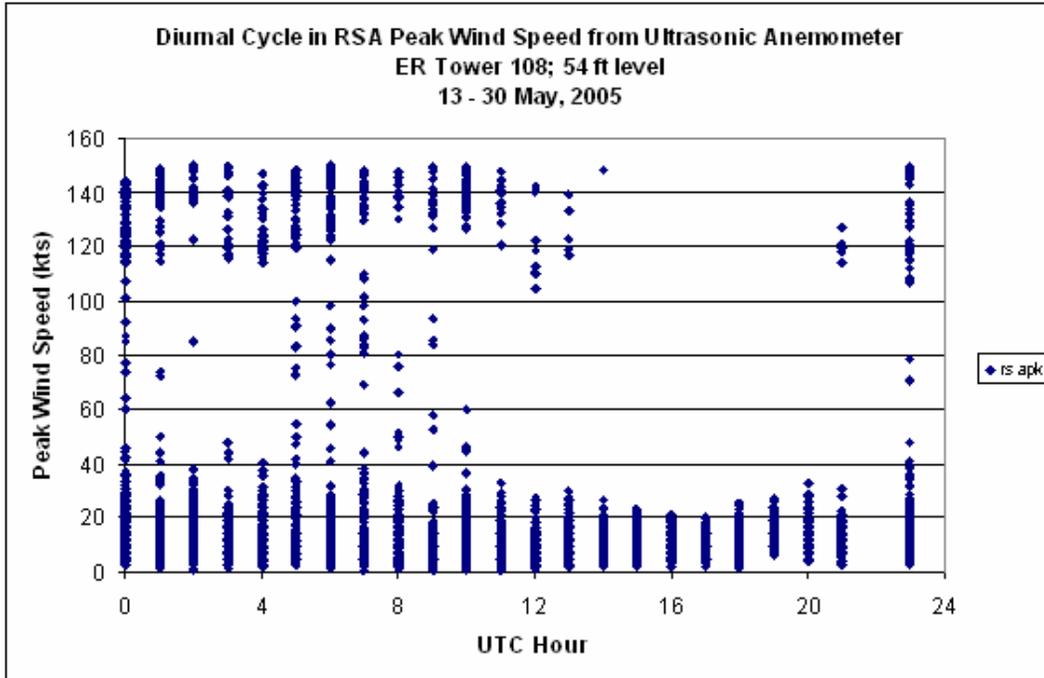


Figure 7. UTC hour versus Peak Wind Speed (kts) from the RSA wind sensor at the 54 ft level on Tower 0108.

Figure 8 shows the directional dependence of peak wind speed from the RSA sensor at the 54 ft level on Tower 0108. The anomalous peak wind speeds are clustered at 5 directions; 30°, 150°, 210°, 270° and 330°.

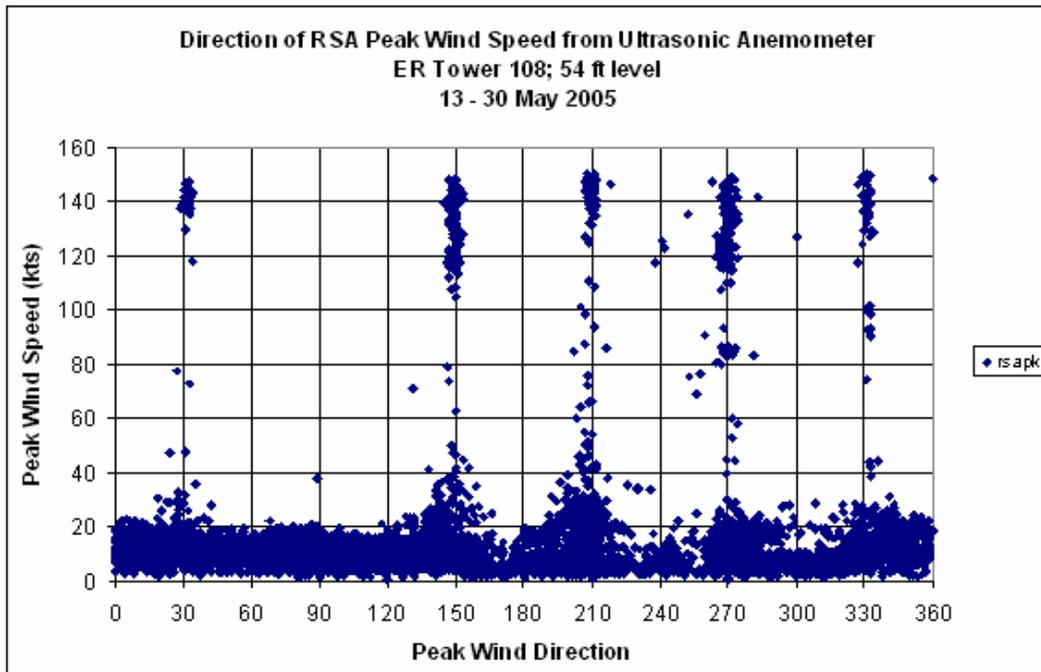


Figure 8. Peak Wind Direction versus Peak Wind Speed from the RSA wind sensor at the 054 ft level on Tower 0108.

The 60° separation between the anomalous peak wind speed clusters shown in Figure 8 appears to be related to the geometric layout of the sensor as follows:

Figure 9 shows a schematic horizontal cross-section of the triad of ultrasonic transducers that comprise the ultrasonic wind sensor. The instrument configuration is that of an equilateral triangle, resulting in 3 equal baselines, ~15 cm long, with a transducer on each end.

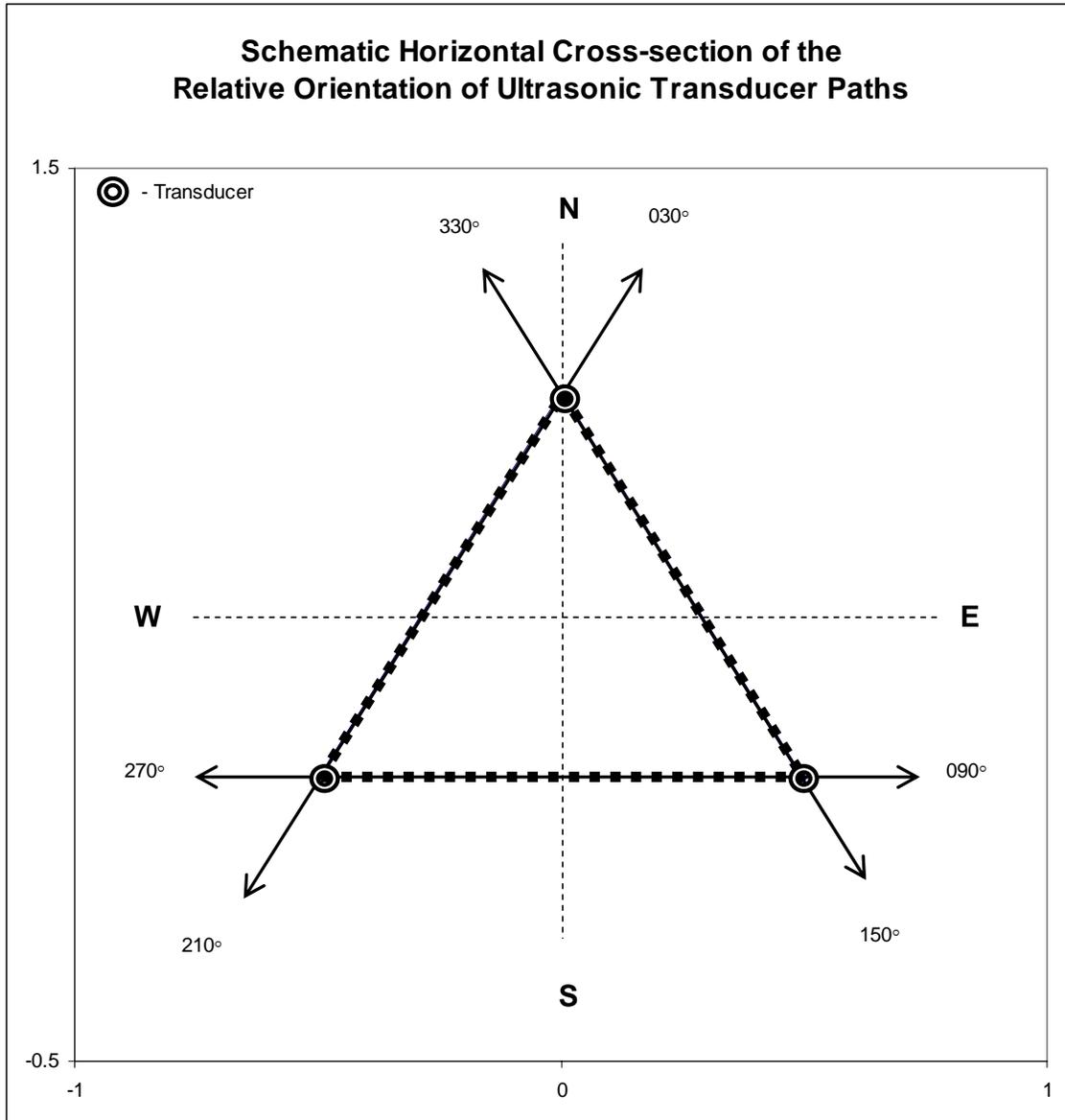


Figure 9. Schematic horizontal cross-section of the relative orientation of ultrasonic transducer paths.

Note that the transducer paths shown in Figure 9 are aligned at 60° intervals from each other. The occurrence of anomalously high peak wind speeds at 60° intervals strongly suggests they are related to the geometry of the instrument.

One hypothesis for the occurrence of anomalous wind speeds at 60° intervals is the effect of one transducer being blocked. This would leave only one transducer pair with the capability of inferring a wind speed/direction along their connecting path. This hypothesis could be tested in a controlled environment. Candidates for such blockage in the field would be birds, bats, or insects. It is also possible that the occurrence of anomalously high peak wind speeds is an indicator for a certain mode of instrument failure, influenced by the diurnal cycle of temperature and humidity, since the span of daytime hours from 14-to-20 UTC were free of the anomalies.

4.3. Best Composite Results: Average and Peak Wind Speeds

The 15 RSA sensors that showed the most consistent performance, with respect to the Legacy sensors, can be inferred from Table 4 and Table 5 by including all RSA sensors with speed/directional differences in bold type. These 15 RSA sensors were used to produce composite comparisons, following the procedure described in Section 4.1. The results for average wind speed are shown in Figure 10a and the results for peak wind speed are shown in Figure 10b.

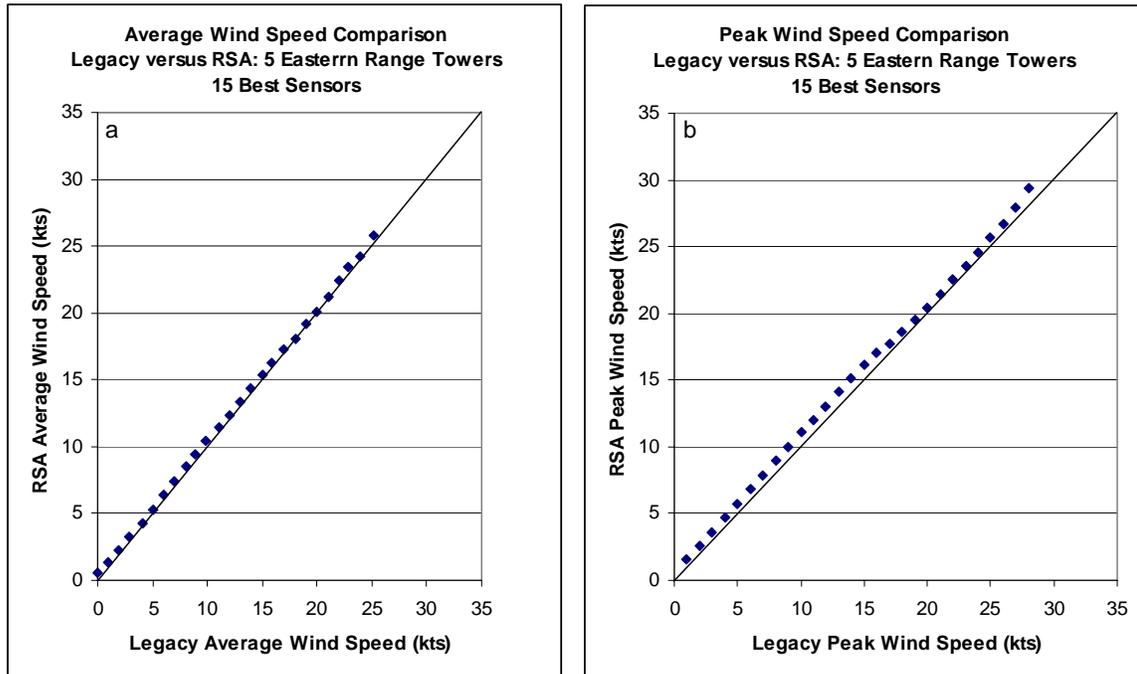


Figure 10. (a) Average and (b) Peak wind speed comparisons for the best 15 RSA sensors on 5 ER towers. POR is 13 May – 30 May 2005. Total sample size is 171,726. Each data point plotted had at least 30 one-minute samples.

Figure 10a shows the best 15 RSA average wind speeds just above the 1:1 line. Figure 10b shows the best 15 RSA peak wind speeds are also above the 1:1 line with a weak inflection point near 17 kts.

Comparisons of the 15 sensor composite were slightly different than the overall comparison cited in Section 4.1.

- Composite Average Speed: Legacy 08.09 kts, RSA 08.47 kts, RSA – Legacy = + 0.38 kts
- Composite Peak Speed: Legacy 09.79 kts, RSA 10.73 kts, RSA – Legacy = + 0.94 kts

The differences in peak wind speeds reported by the Legacy and RSA sensors are statistically significant, due to the large sample size and relatively small standard deviation of differences in peak wind speed between the sensors, +/- 1.10 kts. The differences in peak wind speeds are also consistent with previous studies and are physically reasonable, given the nature of the sensors. The difference in peak wind speed noted in this study, averaging 0.94 kts for the most consistent sensor pairs, indicates that the change from mechanical to ultrasonic wind sensors has the potential to increase reported peak wind speeds, which could result in a small decrease in launch availability, depending on the LCC threshold.

Consider a hypothetical LCC threshold of 20 kts. Based on the sample of wind conditions used in this study, the probability of peak wind speeds at 20 kts or less using the Legacy data was 95.2%. For the same 20 kt threshold the RSA data showed a probability of 92.3%. That represents a 3% decrease in launch availability for the hypothetical threshold.

5. Conclusions

The RSA program is changing wind-measurement instrumentation on wind towers from the current Legacy mechanical systems to an RSA ultrasonic system with no moving parts. Launch Weather Officers, forecasters and Range Safety analysts need to understand the performance of the new RSA sensors and possible impacts on weather warnings, watches, advisories, special ground processing operations, launch pad exposure forecasts, user LCC forecasts and evaluations, and toxic dispersion support. This AMU report addresses the comparison of selected Legacy and RSA wind speed and direction sensors on the ER.

Data from 29 Legacy and 19 RSA wind sensors on 5 ER towers was obtained and analyzed by the AMU to characterize differences in average wind speed, peak wind speed and wind direction. The Legacy system on the ER uses a vane to measure wind direction and a spinning propeller to measure wind speed. The RSA system relies on the effect of wind on the transit time of ultrasonic pulse between closely-spaced transducers in a triangular array.

A total of 357,626 one-minute data samples, from the 18-day interval 13 May to 30 May 2005, were compared. Sensor heights ranged from 12 to 492 ft. Data were obtained from 1 RSA and 1 or 2 Legacy sensors at each level, depending on the tower. For towers with 2 Legacy sensors, an initial screening process was used to select Legacy sensor data from the upwind side of those towers for use in the comparisons.

A secondary screening identified anomalous RSA peak wind speed readings at Tower 0108 and data from 2 RSA sensors on that tower were analyzed separately.

The comparison of 329,018 minutes of secondary screened data from 17 RSA sensors resulted in the following:

- Overall Average Wind Speed: Legacy 7.72 kts, RSA 8.27 kts, RSA – Legacy = + 0.55 kts
- Overall Peak Wind Speed: Legacy 9.51 kts, RSA 10.72 kts, RSA – Legacy = + 1.21 kts

The AMU used the Legacy wind data as a “reference” and identified 15 RSA sensors with the closest agreement, based on differences in speed and direction. The 15 RSA sensors were used to define a composite average-Legacy/RSA comparison and the peak wind speed data from the same 15 RSA sensors were used to define a composite peak-Legacy/RSA wind speed comparison.

Comparisons of the 15 sensor composite were slightly different than the overall comparison cited above.

- Composite Average Speed: Legacy 08.09 kts, RSA 08.47 kts, RSA – Legacy = + 0.38 kts
- Composite Peak Speed: Legacy 09.79 kts, RSA 10.73 kts, RSA – Legacy = + 0.94 kts

The positive bias in the composite RSA average wind speed was roughly constant over the range 0-to-25 kts. The positive bias in the composite RSA peak wind speed ranged from 0.44 kts to 1.14 kts over the range 1-to-28 kts.

From a technical point of view the small differences in average wind speeds reported by the Legacy and RSA sensors are statistically significant, due to the large sample size and small standard deviation of differences in 1-minute wind speed between the sensors, +/- 0.90 kts. From a practical point of view the differences in peak wind speeds are more important, indicating that the change to ultrasonic sensors can be expected to result in a small increase in reported peak wind speeds. An increase in peak wind speeds would result in a decrease of launch availability, depending on the LCC threshold wind speed. For example, the probability of peak wind speeds at 20 kts or less using the Legacy data was 95.2%. For the same 20 kt threshold the RSA data showed a probability of 92.3%

5.1. Comments on RSA/Legacy wind sensor comparison from Western Range Data

Short and Wheeler (2006) documented a similar comparison of RSA and Legacy wind sensor data from 5 towers on the WR. Overall, the WR and ER comparisons are consistent. The average RSA wind speed was about 0.35 kts higher than the average Legacy wind speed. The peak RSA wind speed averaged about 1 kt higher than the peak Legacy wind speed with a tendency for an increasing difference with increasing wind speed.

One significant difference between the ER and WR studies was the presence of anomalously high peak wind speeds from one ER RSA sensor. The anomalous peak wind directions were clustered at 60° intervals and the anomalous peaks were absent in the afternoon, suggesting either interference from wildlife (birds, bats, insects) or the signature of a failure mode of the instrument influenced by the diurnal cycle in temperature and humidity.

Because the WR data were restricted to the afternoon hours, it may be prudent to examine some night-time or early morning data to determine if similar anomalous behavior is detected.

References

- Case, J. L., and W. H. Bauman, III, 2004: Tower Mesonet Climatology and Interactive Display Tool. NASA Contractor Report CR-2004-211526, Kennedy Space Center, FL, 88 pp. [Available from ENSCO, Inc., 1980 N. Atlantic Ave., Suite 230, Cocoa Beach, FL, 32931.]
- Computer Sciences Raytheon (CSR), 2000: *45th Space Wing Eastern Range Instrumentation Handbook*, Computer Sciences Raytheon, Inc., 758 pp.
- Lewis, R., and J. M. Dover, 2004: Field and Operational Tests of a Sonic Anemometer for the Automated Observing System. AMS Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface. Seattle, WA, 12-16 January 2004. Paper 7.1, 6 pp.
- Short, D.A., and M. W. Wheeler, 2006. RSA/Legacy Wind Sensor Comparison: Part I: Western Range. NASA Contractor Report CR-2006-214200, Kennedy Space Center, FL, 23 pp. [Available from ENSCO, Inc., 1980 N. Atlantic Ave., Suite 230, Cocoa Beach, FL, 32931.]
- Vaisala, 2004: Ultrasonic Wind Sensors WS425 User's Guide. Vaisala Oyj, Helsinki, Finland, 95 pp.

List of Acronyms

| | |
|-------|--------------------------------------|
| 30 WS | 30th Weather Squadron |
| 45 WS | 45th Weather Squadron |
| AMU | Applied Meteorology Unit |
| CCAFS | Cape Canaveral Air Force Station |
| CSR | Computer Sciences Raytheon |
| CRN | Cross-Reference Number |
| ER | Eastern Range |
| ID | Identification Number |
| KSC | Kennedy Space Center |
| LCC | Launch Commit Criteria |
| NE | Northeast |
| NW | Northwest |
| POR | Period of Record |
| RSA | Range Standardization and Automation |
| SE | Southeast |
| SW | Southwest |
| UTC | Universal Coordinated Time |
| WR | Western Range |

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