NASA Contractor Report CR-1999-208556

Final Report on Evaluation of Wind Profiler Data

Prepared By:
Applied Meteorology Unit

Prepared for:
Kennedy Space Center
Under Contract NAS10-96018

NASA
National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1999

Attributes and Acknowledgments

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List of Acronyms

Term	Description
AMU	Applied Meteorology Unit
FC	False Cape
KSC	Kennedy Space Center
MI	Merritt Island
NASA	National Aeronautics and Space Administration
NE	Northeast
Q	Quality
QC	Quality Control
RMS	Root Mean Square
SLF	Shuttle Landing Facility
SNR	Signal to Noise Ratio
SOW	Statement of Work
SW	Southwest
WSMR	White Sands Missile Range

Executive Summary

This report presents the Applied Meteorology Unit's evaluation of a "Hypersodar" wind profiler located on KSC adjacent to tower 412. The sodar data used for this evaluation were collected during two different periods in March 1999 and November 1998. The sodar orientation and position were changed twice during the sampling periods considered in this study. In neither case was any attempt made to align the sodar qualitatively with true north.

The evaluation is performed by calculating sodar data availability as a function of height, and bias and Root Mean Square (RMS) differences of wind speed and direction between sodar and tower 313 observations at comparable heights. The bias and RMS differences are compared with those obtained by the vendor using 10-minute averaged sodar and tower data collected at White Sands Missile Range (WSMR). Finally, a spectral analysis of 1-second sodar data is performed to highlight the true temporal resolution of the data by differentiating between the noise and wind signals in the observations.

The following conclusions can be drawn from the evaluation described in this report:

- Based on vendor-supplied quality control (QC) checks, sodar data availability is generally near 100% below 100 m and is typically less than 50% above 200 m.

- For the second 5-minute sodar data set collected during 17 – 18 March 1998, solution A produces wind estimates that are inconsistent with those from solution B or tower 313 observations. The vendor-supplied QC checks did not flag these winds therefore some other form of QC is needed to identify erroneous data.

- Overall, the differences between tower 313 and sodar wind observations for the limited samples examined in this evaluation are due to misalignment of the sodar, variability in wind over the 3.5-km distance separating the two instruments, and instrument error. It is not possible to identify accurately the systematic errors due to alignment and spatial separation given the available data collected at KSC.

- Spectral response at all levels suggests that the sodar is able to resolve features down to the Nyquist frequency which is 0.5 Hz (2-second period) for the data sets examined in this evaluation.

The RMS differences in wind speed and wind direction from sodar wind solution B at KSC range from 0.65 m s^{-1} – 2.04 m s^{-1} and 4.5 – 32.3^{o}, respectively. Note that these RMS differences are not bias-corrected. The vendor claims that the accuracy of the wind measurements from the sodar is better than 0.5 m s^{-1} in speed and 10^{o} in direction. The results of the evaluation described here suggest that such accuracy may be attainable though the data available for this comparison made it impossible to confirm the vendor's claims. The sodar was not aligned with true north and was separated by a distance of 3.5 km from tower 313 used for comparisons in this study.

During the three data collection periods examined for this evaluation, the KSC sensor separation-adjusted wind speed and direction biases at certain times and levels are comparable to those from WSMR. However, at other times and levels, the adjusted speed biases at KSC exceed those at WSMR by more than 1.0 m s^{-1}. These statistics suggest that results at KSC are not entirely consistent with those from WSMR given the differences in spatial separation between the sodar and tower at each site.

1.0 Introduction

1.1 Purpose of this report

The purpose of this report is to describe the Applied Meteorology Unit's (AMU) evaluation of the experimental "Hypersodar" (hereafter referenced as sodar) wind sensor located on the Kennedy Space Center (KSC) adjacent to tower 412 near the Shuttle Landing Facility (SLF). The AMU was tasked to collect the best available data for comparison from the Eastern Range wind towers and 915-MHz profilers and perform an evaluation of the accuracy and reliability of the sodar. This effort originated from Technical Directive 4-1004 issued by Dr. Francis Merceret (Chief, AMU) and was conducted on a non-interference basis as an option-hours task.

1.2 Non-Disclosure Compliance

The proprietary nature of the technology used to collect the sodar data required that the AMU take measures to ensure non-disclosure of the data. The non-disclosure provision of this task was fulfilled by purchasing a Commercial Off-The-Shelf software program called Folder Guard. This program restricts access to and hides protected folders under Windows 98/95 from any user not supplying the proper password. Disks containing the sodar data were copied to a directory protected by Folder Guard and the original disks were returned to NASA. In addition, only selected personnel were permitted to examine the sensor data, subsequent analyses, and final report. The primary technical work on the task was performed by Mr. Robert Palmblad and supervised by Dr. John Manobianco. For the purpose of data analysis, interpretation of results, and document review, Mr. Palmblad and Dr. Manobianco consulted with other experts on instrumentation and profiler evaluation. These personnel included Dr. Merceret, Dr. Gregory Taylor, Ms. Winifred Lambert, and Ms. Robin Schumann. Upon completion of the task, all task-related data were copied to a disk and submitted with the final report. All other media containing task-related data were purged.

1.3 Data

NASA supplied the following sodar data in textual format.

- Disk A contains a 2-minute-averaged sodar data file from 16 March 1999 and two 5-minute-averaged data files from 17 March 1999. One 5-minute data file covers the period from 1715:00 – 2055:00 UTC 17 March 1999 and the other 5-minute sodar file covers the period from 2140:00 UTC 17 March – 0420:00 18 March 1999.

- Disk B contains 1-second data from 1832:07 – 1902:49 UTC 16 March 1999 computed by Method B.

- Disk C contains 1-second data from 1904:56 – 1937:40 UTC 16 March 1999 computed by Method C.

- The final disk contains 1-, 5-, and 10-minute data from 28 October 1998 – 2 November 1998.

During the data collection periods, the sensor was located adjacent to tower 412 near the SLF. At this location, the sensor was approximately 4.5 km from the Merritt Island 915-MHz profiler, 7.8 km from the False Cape 915-MHz profiler, and 3.5 km from tower 313 (Fig. 1). Although the sensor was closest to tower 412, this tower only measures wind speed and direction at 3.7 and 16.5 m. Therefore, sensor data were obtained from tower 313 that provides wind speed and direction measurements up to 150 m. The AMU received all available 5-minute and 1-minute data from towers 412 and 313 for the period of interest from Computer Sciences Raytheon.

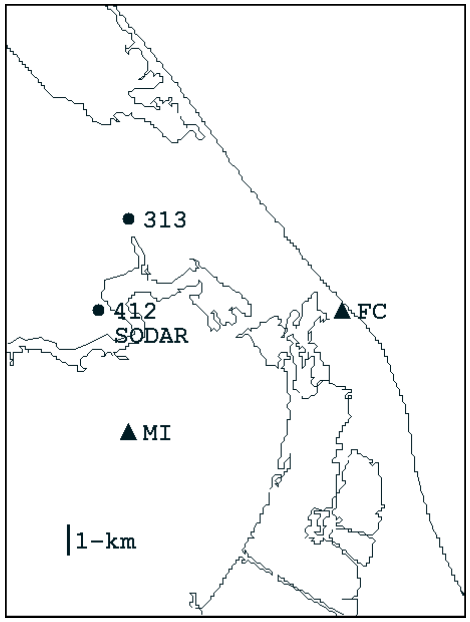


Figure 1. Map showing locations of the sodar (SODAR), towers, 412 and 313, and False Cape (FC) and Merritt Island (MI) 915-MHz profilers.

The sensor was closest to the Merritt Island (MI) 915-MHz profiler. However, data were available from the MI profiler for only 3 of the 8 days that sensor data were collected (see Table 1). For this reason, data were obtained from the False Cape (FC) profiler for the entire 8-day period (Table 1). The FC profiler is located adjacent to the Atlantic Ocean while the MI profiler is located inland by roughly 8.2 km.

Table 1. Data availability for the periods of interest ('X' indicates data are available from the particular instrument on the given date).

	915-MHz Profilers		KSC /CCAS Towers*	
Date	Merritt Island	False Cape	412	313
10/28/98	X	X	X	X
10/29/98	X	X	X	X
10/30/98	X	X	X	X
10/31/98		X	X	X
11/1/98		X	X	X
11/2/98		X	X	X
3/16/99		X	X	X
3/17/99		X	X	X

*Includes both 5-minute and 1-minute data

The sodar was initially co-located with tower 412, but its orientation and position were changed during both the 1998 and 1999 sampling periods. For all orientation adjustments, the sodar was not aligned with true north. Consequently, the bias in wind direction computed between the sodar and 915-MHz profiler or tower data contains a systematic component that is constant with height and reflects changes in sodar orientation. Without quantitative information regarding the orientation of the sodar relative to true north, it is not possible to isolate and remove the systematic (alignment) bias from total instrument bias. For the purpose of this evaluation, the bias and RMS difference statistics do not account for changes in sodar location.

1.4 Data Quality Control

Quality control (QC) of the sodar data was accomplished based on the signal-to-noise (SNR) ratio and quality (Q) flags provided by the vendor. As specified by NASA in the Statement of Work (SOW), sodar data were not used when the SNR < 2 dB and Q < 0.6 for the u, v, or w wind components. The sodar data files from 28 October 1998 – 2 November 1998 already contained values of 999999 that were assumed to designate points failing the SNR and Q checks as identified by the vendor. The 915-MHz profiler data from the Merritt Island and False Cape sites were quality controlled using algorithms discussed in Lambert and Taylor (1998). Additional QC of the sodar, tower, and 915-MHz profiler observations, including identification and removal of unrealistic values, was accomplished by visual inspection.

1.5 Evaluation Protocol

The SOW required the calculation of bias and root mean square (RMS) difference as a function of height for sodar wind speed and direction as well as sodar data availability as a function of height. The bias and RMS differences in wind speed and direction were computed separately using scalar averaging as discussed by Merceret (1995). Given the spatial separation between the sodar and reference instrumentation as well as the potential error in the reference observations, this report presents bias and RMS differences and makes several inferences from those statistics to evaluate the performance of the sodar. The differences between sodar and tower or 915-MHz profiler observations at a given level are defined as $\Phi' = \Phi_s - \Phi_o$. Here, the subscripts *s* and *o* denote sodar and tower or 915-MHz profiler quantities, respectively. The bias is computed using N pairs of observations for each data set at a given vertical level as:

$$\overline{\Phi'} = \frac{1}{N}\sum_{i=1}^{N} \Phi'_i \qquad (1),$$

and the RMS difference is computed as:

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N} (\Phi'_i)^2\right]^{1/2} \qquad (2).$$

Note that the RMS difference includes bias and no attempt is made in this evaluation to compute and display bias-corrected RMS differences.

For the tower comparisons, the available discrete heights are compared to the closest available gates of the sodar. For the 915-MHz profiler comparisons, the sodar data are averaged temporally and spatially to match the gate spacing and time intervals of the profiler data. The averaging procedure is applied before computing the bias and RMS differences. The bias and RMS differences are not computed if the SNR < 2 dB and Q < 0.6 or the missing value flag of 999999 is present in the sodar data files. The data availability as a function of height is computed as a ratio of sodar observations passing the QC checks to the total number of observations possible for each data collection period.

Sodar data are excluded from the spectral analysis when the SNR < 2 dB and Q < 0.6 for the u, v, or w wind components. In order to perform Fourier transforms for the spectral analysis, it is necessary to interpolate for missing data or data removed by the QC checks. The interpolation in time is performed using a cubic spline. Spectral response is calculated by first removing the mean from the interpolated sodar data. The wind speed data are then divided into roughly five-minute periods, Fourier transformed, and averaged to produce the spectral density which is plotted against frequency. Each graph also contains a –5/3 reference line to indicate the inertial sub-range of the turbulence spectrum. Where the spectra depart from the –5/3 reference line within the inertial sub-range, the frequency response of the sodar is indistinguishable from noise so that frequency provides an estimate of temporal resolution for the instrument.

2.0 Results

Comparisons between the sodar and the tower and 915-MHz profiler data are organized by data set. The proposed level of effort for the evaluation did not include time required to address unexpected issues with sodar data formats. For example, the time convention was local rather than UTC, there were eight separate reporting periods, and there were three different file formats. These issues complicated the collection, processing, and QC of sodar data. Consequently, the AMU underestimated the amount of time required to complete this task. Due to these time constraints, the AMU completed only the following tasks.

- Computation of bias and RMS differences for the two sets of 5-minute sodar data from 17 – 18 March 1999.
- Computation of bias and RMS differences for 5-minute sodar data from 2 – 3 November 1998.
- Spectral analysis of the 1-second Method B and Method C sodar data from 16 March 1999.

Although the sodar was located adjacent to tower 412, comparisons between tower 412 and the sodar were not useful because the lowest sodar gate is above the highest sensor on tower 412. Additionally, comparisons between the sodar and False Cape 915-MHz profiler using sodar data collected on 17 March 1999 resulted in bias and RMS differences which were generally much larger than those computed from sodar and tower 313 data. This result was not surprising because the sodar and False Cape 915-MHz profiler were separated by a distance of about 7.8 km (Fig. 1). Furthermore, only the lower 915-MHz profiler and upper sodar gates were used to compute the bias and RMS differences. The sodar data at these levels were least reliable and often flagged by QC checks. Given these limitations and results from preliminary comparisons, additional calculations of bias and RMS differences were not performed using either the False Cape or Merritt Island 915-MHz profiler observations.

2.1 Five-minute sodar data: 1715:00 - 2055:00 UTC 17 March 1999

2.1.1 Average Speed and Direction

The general wind flow for the period from 1715:00 – 2055:00 UTC 17 March 1999 is characterized in the average wind speed and direction versus height shown in Fig. 1. The average wind speed and direction for tower 313 are calculated using all wind samples from both the northeast (NE) and southwest (SW) sensors for the entire time period at heights of 50, 62, 90, 120, and 150 m. Average wind speed and direction for the sodar are calculated using all wind samples passing the SNR and Q checks from two wind solutions (A and B) for the entire time period at heights of 50, 65, 95, 125, and 155 m. The time series of wind speed and direction between 1715:00 – 2055:00 UTC 17 March 1999 at each level for the sodar and tower 313 are shown in the Appendix (Figs. A1 – A5).

The average wind speeds during the period 1715:00 – 2055:00 UTC 17 March 1999 range from 4 – 5 m s^{-1} as shown in Fig. 1. The differences between the sodar and tower 313 average wind speeds are less than about 0.5 m s^{-1}. However, the differences in average wind direction between the two sensors are greater than 15^{o} at all levels and show less variation than the speed differences with height. The misalignment of the sodar would produce a systematic wind direction bias that is constant with height. Since the differences in average wind direction are not constant with height, the spatial separation between the sodar and tower 313 and instrument errors are likely causing the differences shown in Fig. 2.

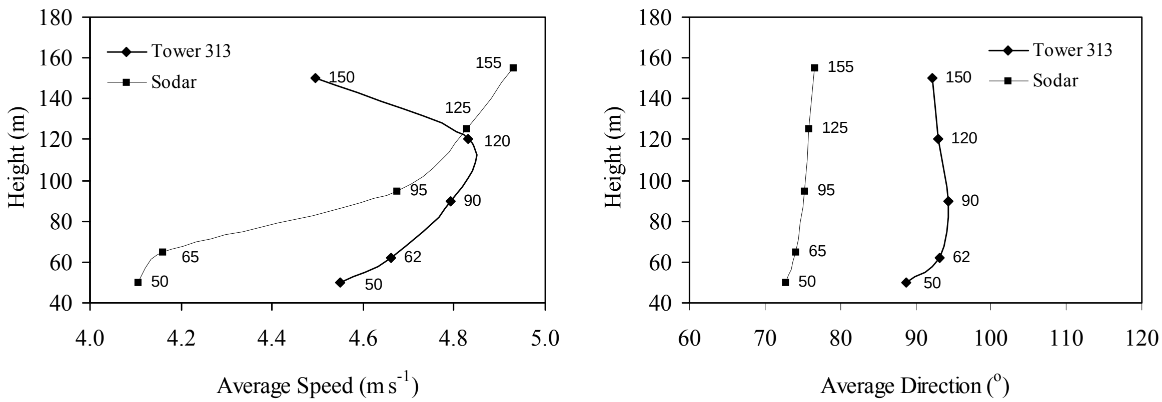


Figure 2. Average wind speed (m s^{-1}) and direction (degrees) versus height for the period 1715:00 – 2055:00 UTC 17 March 1999 from sodar and tower 313 observations. The heights for tower 313 sensors and sodar gates are shown adjacent to the lines in each panel.

2.1.2 Sodar Data Availability

For the period 1715:00 – 2055:00 UTC 17 March 1999, there are two wind solutions (A and B) at 21 discrete heights and 45 discrete 5-minute time samples. Using the SNR and Q criteria, the sodar data availability is near 100% up to ~140 m and then decreases to less than 50% above 230 meters (Fig. 3).

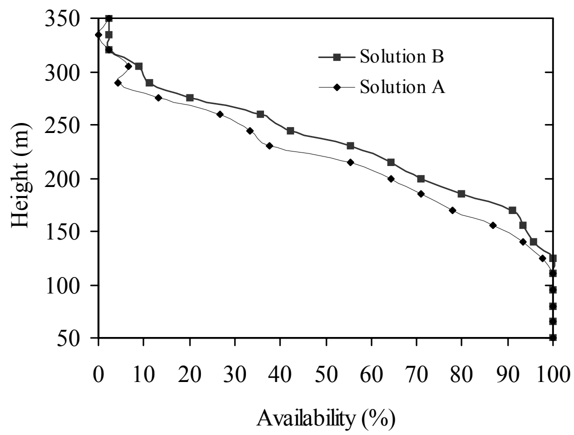


Figure 3. Sodar data availability (%) versus height (m) for sodar data collected from 1715:00 to 2055:00 UTC 17 March 1999.

2.1.3 Wind Speed Bias and RMS Differences

The bias and RMS differences are calculated from equations (1) and (2), respectively using the number of valid samples (N). The number of samples varies by height and sodar wind solution with a maximum of 45 corresponding to all available 5-minute times between 1715:00 – 2055:00 UTC, inclusive. For heights at 50, 65, 95, 125, and 155 m, sodar wind solution A has 45, 45, 44, 38, and 29 valid data samples, respectively while sodar wind solution B has 45, 45, 45, 43, and 39 valid data samples, respectively.

The magnitude of the wind speed bias for this period is less than 1 m s^{-1} at all levels and tends to be negative at and below 95 m and positive above 95 m (Fig. 4). It is interesting to note that the two sodar wind solutions exhibit a bias that is on the order of 0.1 – 0.3 m s^{-1} (Fig. 4). The RMS differences are also generally less than 1 m s^{-1} except at a few levels as shown in Fig. 4. The small differences illustrated here indicate that the sodar and tower 313 measurements are consistent given that the instruments are separated by a distance of ~3.5 km.

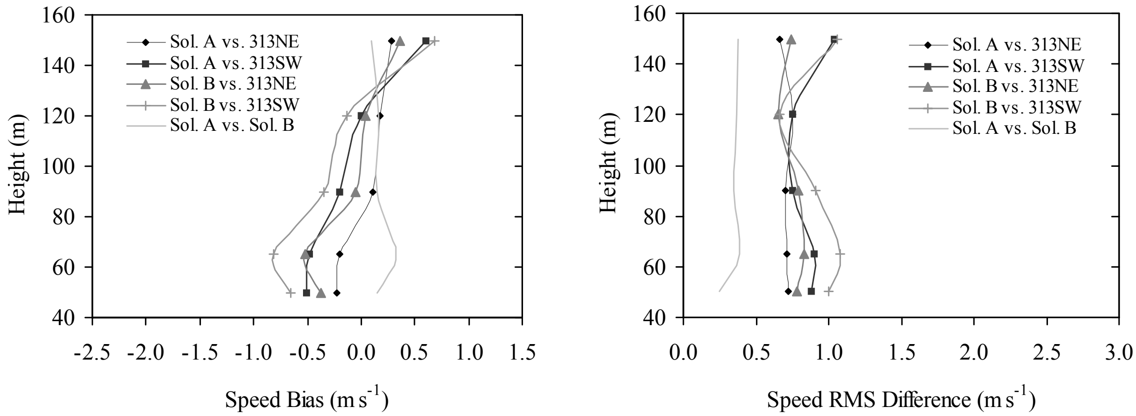


Figure 4. Wind speed bias (m s^{-1}) and RMS differences (m s^{-1}) versus height (m) for sodar data collected from 1715:00 to 2055:00 UTC 17 March 1999. Comparisons are shown for both sodar wind solution A (Sol. A) and solution B (Sol. B).

2.1.4 Wind Direction Bias and RMS Differences

There is a negative bias in wind direction between the sodar and tower 313 that ranges from –9^{o} to almost -25^{o} (Fig. 5). However, this bias is consistent with the differences between the average wind direction shown in Fig. 2. As with wind speed, sodar wind solutions A and B show a bias between 5 – 8^{o} (Fig. 5). Although the direction bias is not constant with height, the RMS differences in direction are nearly the same magnitude as the bias (Fig. 5). This result suggests that the systematic error represents a large fraction of the total error.

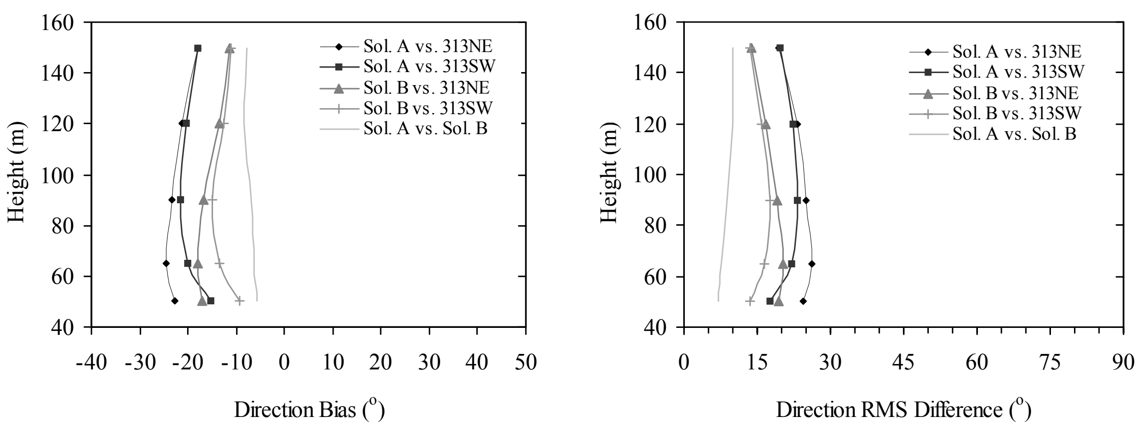


Figure 5. Wind direction bias (degrees) and RMS differences (degrees) versus height (m) for sodar data collected from 1715:00 to 2055:00 UTC 17 March 1999. Comparisons are shown for both sodar wind solution A (Sol. A) and solution B (Sol. B).

2.2 Five-minute data: 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999

2.2.1 Average Speed and Direction

Average wind speed and direction from the sodar and tower 313 versus height are shown in Fig. 6 to characterize the general wind environment for the period from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999. The average wind speed and direction for the sodar and tower 313 are calculated as described in Section 2.1.1. The time series of wind speed and direction between 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 at each level for the sodar and tower 313 are shown in the Appendix (Figs. A6 – A10).

The average wind speeds from tower 313 during this period range from 4.6 – 5.6 m s^{-1} (Fig. 6). The average wind speeds from the sodar are lower than those from tower 313 by 0.7 – 1.8 m s^{-1}. The differences in average wind direction between the two sensors are nearly constant with height on the order of 25^o at and below 95 m. This result is consistent with the fact that the sodar was not aligned with north. In fact, the average wind direction at 16.5 m on tower 412 during this time period is about 120^o. The average wind directions at tower 412 adjacent to the sodar are very similar to those at tower 313. Therefore, most of the differences between the sodar and tower 313 average wind directions below 95 m for this period are likely due to misalignment of the sodar.

Above 95 m, the average sodar wind directions exceed 130^o while those at tower 313 are less than 130^o (Fig. 6). However, an examination of the time series in Figs. A9 – A10 indicates that wind solution A is producing estimates of wind speed and direction which are not consistent with those from wind solution B or tower 313. Since the averages are computed using both wind solutions and these data are not flagged by the SNR and Q checks, the average wind directions include these values. The inclusion of potentially erroneous sodar data from wind solution A causes the average wind direction profile to veer significantly with height above 95 m (Fig. 6).

For comparison, the average wind speed and direction from only sodar wind solution B are shown as dotted lines in Fig. 6. The average sodar wind speeds at and above 95 m are slightly stronger when the erroneous wind solution A is excluded from the calculations. In addition, the average sodar wind directions excluding solution A veer less dramatically with height.

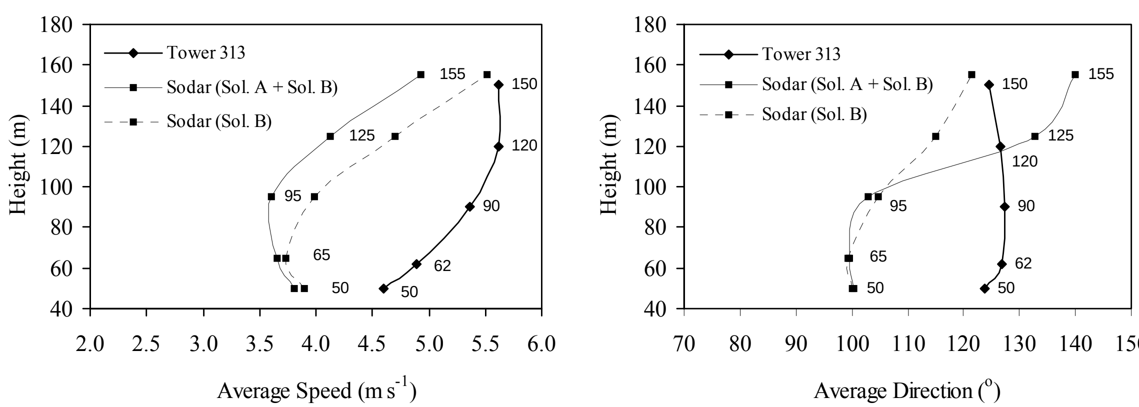


Figure 6. Average wind speed (m s^{-1}) and direction (degrees) versus height for the period 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 from sodar and tower 313 observations. The heights for tower 313 sensors and sodar gates are shown adjacent to the lines in each panel.

2.2.2 Sodar Data Availability

For the period 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999, there are two sets of sodar data for wind solution A and B at 21 discrete heights and 81 discrete 5-minute time samples. Using the vendor-provided SNR and Q criteria, the sodar data availability is near 100% through ~140 m and then decreases rapidly to less than 50% above 230 meters (Fig. 7).

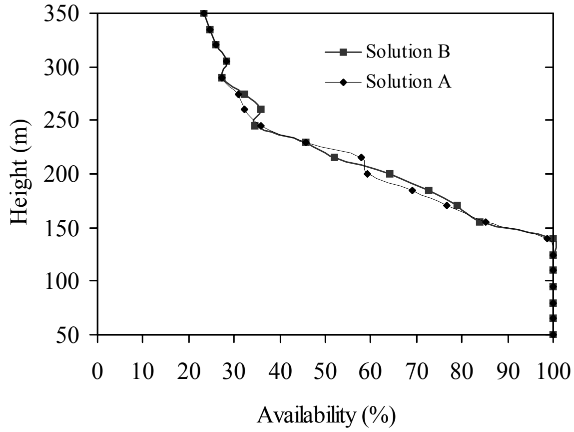


Figure 7. Sodar data availability (%) versus height (m) for sodar data collected from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999.

2.2.3 Wind Speed Bias and RMS Differences

The number of samples for the bias and RMS differences varies by height and wind solution with a maximum of 81 corresponding to all available 5-minute times between 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999, inclusive. For heights at 50, 65, 95, 125, and 155 m, sodar wind solution A had 81, 80, 78, 68, and 54 valid data samples, respectively while sodar wind solution B had 81, 81, 78, 63, and 51 valid data samples, respectively.

The wind speed biases in sodar wind solution B for this period are between –0.6 and –1.5 m s^{-1} and the RMS differences range from 0.9 to nearly 2 m s^{-1} (Fig. 8). The magnitude of the bias and RMS differences are greater than those computed from 1715:00 – 2055:00 UTC 17 March. These discrepancies may be related to possible variations in the wind field over the ~3.5-km distance that separates the two sensors.

In contrast, the wind speed bias and RMS differences in wind solution A are nearly double those in solution B above 65 m (Fig. 8). These results are clearly related to the differences in the wind solutions mentioned at the beginning of Section 2.2.1 and shown in Figs. A8 – A10. Although the questionable data points in wind solution A are not flagged by the SNR and Q checks, the solution A wind speed is not consistent with the solution B and tower 313 observations. This problem strongly suggests that some other form of quality control is needed to identify potentially erroneous data.

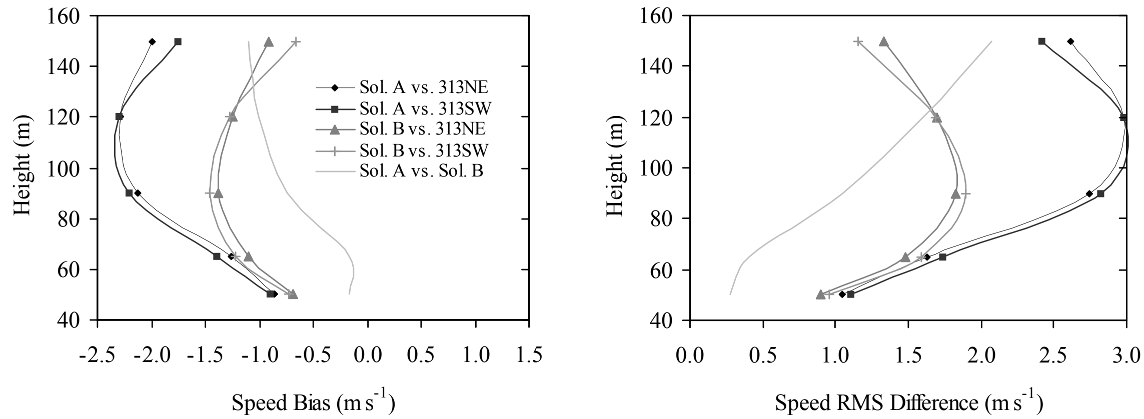


Figure 8. Wind speed bias (m s^{-1}) and RMS difference (m s^{-1}) versus height (m) for sodar data collected from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999. Comparisons are shown for both sodar wind solution A (Sol. A) and solution B (Sol. B).

2.2.4 Wind Direction Bias and RMS Differences

The direction biases for wind solution B range from -4^{o} to nearly –31^{o} and are largest at the lower gates (Fig. 9). It is interesting to note that differences in wind direction between sodar wind solution B and tower 313 at 50 m are on the order of 20 – 30^{o} for most of time between 2250:00 – 2340:00 UTC 17 March (Fig. A6). This result suggests that much of the bias in wind direction at the lower levels is likely due to the misalignment of the sodar. However, the bias is not constant with height, therefore variability in wind between the sodar and tower 313 sites is also contributing to the direction biases. The magnitude of the bias decreases significantly at the upper sodar gates indicating that there may be less wind variability between the sodar and tower 313 above 95 m.

The biases for wind solution A are similar to solution B at and below 95 m but increase to nearly 45^{o} above 95 m. Similar patterns are shown for the RMS differences which increase to more than 60^{o} for solution B and the solution A/solution B comparison above 95 m (Fig. 9). The rapid increase of wind direction bias and RMS differences above 95 m is primarily a consequence of the erroneous solution A winds discussed in Section 2.2.1 and shown in Figs. A9 – A10.

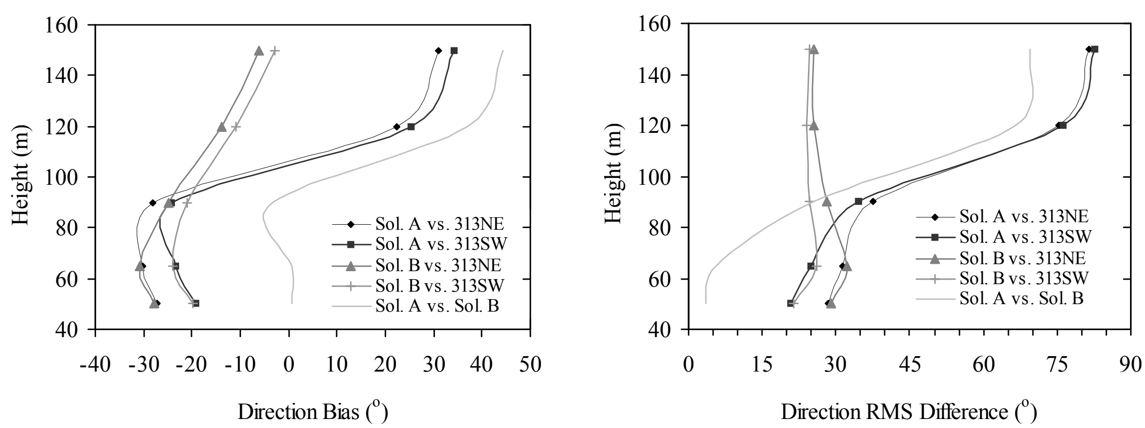


Figure 9. Wind direction bias (degrees) and RMS differences (degrees) versus height (m) for sodar data collected from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999.

2.3 Five-minute data: 2250:00 UTC 2 November – 0405:00 UTC 3 November 1999

This period was chosen because it contained the highest average wind speeds in comparison with the two periods from 17-18 March 1999. For 2 – 3 November, there is only one sodar solution for wind speed and direction. As mentioned in Section 1.4, the file already contains missing values instead of the SNR and Q flags indicating that some type of pre-processing was performed by the vendor.

2.3.1 Average Speed and Direction

Average wind speed and direction versus height from the sodar and tower 313 for the period 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998 are shown in Fig. 10. The average wind speed and direction for the sodar are calculated using all wind samples for the entire time period at heights of 50, 75, 100, 125, and 150 m. The time series of wind speed and direction for the sodar and tower 313 at each level are shown in Figs. A11 – A15.

The average wind speeds from tower 313 increase from 4.8 m s^{-1} at 50 m to 7.3 m s^{-1} at 150 m (Fig. 10). The average wind speeds from the sodar also increase with height but are smaller than those at tower 313 by as much as 1.8 m s^{-1} at 125 m. For comparison, the difference in average wind speed at 16.5 m between tower 412 adjacent to the sodar and tower 313 is 0.2 m s^{-1}. In contrast to the 17 – 18 March data comparisons, the average wind directions for 2 – 3 November differ by less than 4^{o} (Fig. 10).

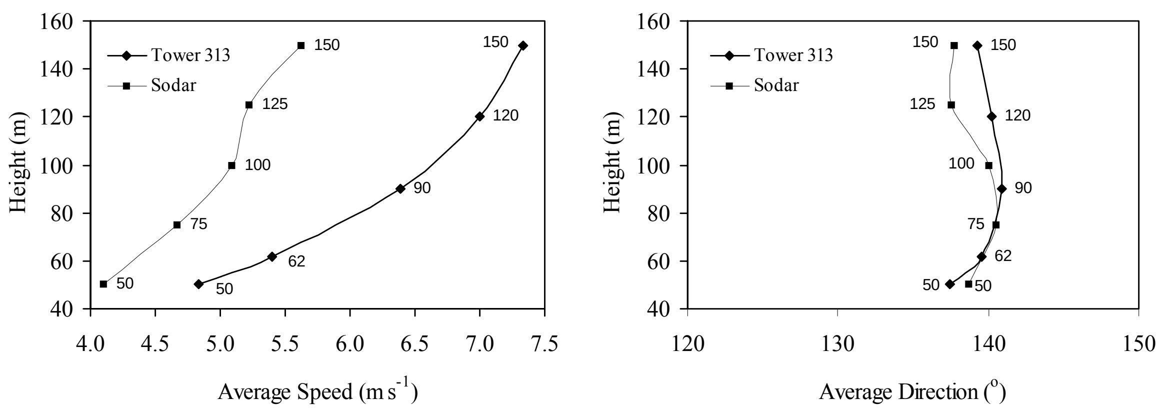


Figure 10. Average wind speed (m s^{-1}) and direction (degrees) versus height for the period 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998. The heights for tower 313 sensors and sodar gates are shown adjacent to the lines in each panel.

2.3.2 Sodar Data Availability

For the period 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998, there is one set of sodar data at 11 discrete heights and 64 discrete 5-minute time samples. Data availability for 2 – 3 November 1998 is 100% at and below 125 m and decreases to less than 50% above 220 m (Fig. 11). This result is consistent with the data availability statistics from the 1999 sampling period.

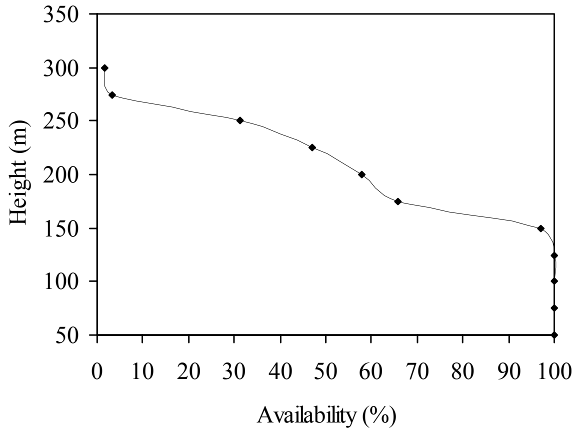


Figure 11. Sodar data availability (%) versus height (m) for sodar data collected from period 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998.

2.3.3 Wind Speed Bias and RMS Differences

The number of samples for the bias and RMS differences varies by height with a maximum of 64 corresponding to all available 5-minute times between period 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998, inclusive. For heights at 50, 75, 100, 125, and 150 m, the sodar had 64, 64, 64, 64, and 62 valid data samples, respectively.

The wind speed bias for the sodar is less than 1.0 m s^{-1} at lower gates but increases to more than 1.5 m s^{-1} at upper gates (Fig. 12). A similar trend appears in the RMS differences that increase to 2.0 m s^{-1} at 125 m (Fig. 12). Except for wind solution A from 17 – 18 March 1999 (Section 2.2.2), the differences are larger than for any other collection period shown in previous sections. These larger differences are related to a decrease in sodar-observed wind speed around 0250:00 UTC at the lower gates (50 – 100 m) and 0225:00 UTC at the higher gates (125 – 150 m) as shown in Figs. A11 – A15. In contrast, the wind speed at tower 313 does not decrease at any level after 0225:00 UTC 3 November (Figs. A11 – A15). The observations at 16.5 m on tower 412 (not shown) indicate a decrease in wind speed on the order of 1.5 m s^{-1} between 0200:00 – 0400:00 UTC 3 November. This result suggests that the wind speed bias and RMS differences for 2 – 3 November 1998 are more likely due to the spatial separation between the sensors rather than errors in the sodar-measured winds.

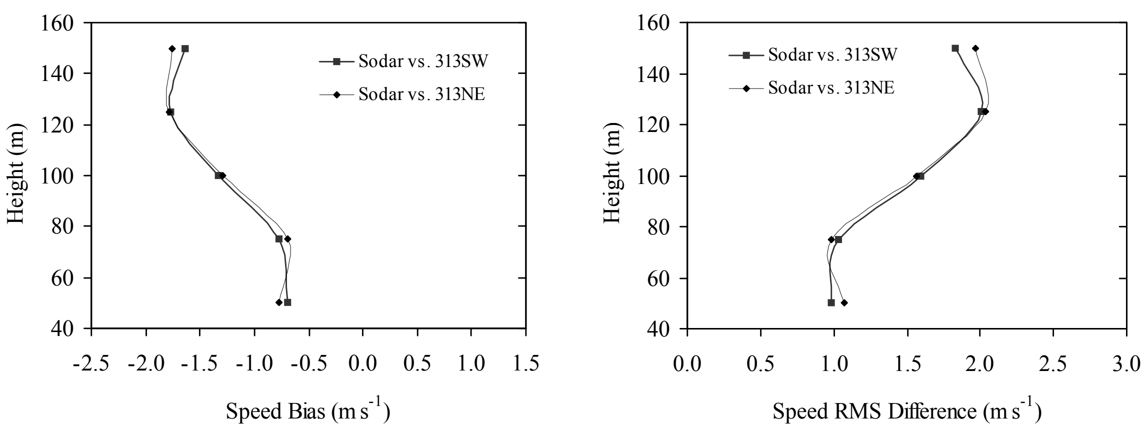


Figure 12. Wind speed bias (m s^{-1}) and RMS differences (m s^{-1}) versus height (m) for sodar data collected from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998.

2.3.4 Wind Direction Bias and RMS Differences

The magnitude of the wind direction bias for 2 – 3 November 1998 is less than 6^o for the lower sodar gates in comparison with the sensors on tower 313 (Fig. 13). The time series of wind direction from tower 313 shows that the NE and SW sensors differ by ~9^o at 50 m throughout the period and the differences decrease to ~2^o at 120 m (Figs. A11 – A14). At 150 m, the NE and SW sensors on tower 313 report nearly the same wind direction from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998 (Fig. A15). The changes in the sign of the wind direction bias (Fig. 13) occur because the sodar wind directions at the lower gates generally lie between the measurements from the NE and SW sensors on tower 313 (Figs. A11 – A14).

The wind direction RMS differences range from 4 – 7^o depending on the vertical level and the comparison with NE or SW sensor on tower 313. More importantly, the RMS differences for this period are substantially lower than those from 17 – 18 March 1998. This result is consistent with the average direction differences shown in Fig. 10 and suggests that there may have been less variability in wind between the sodar and tower 313 for the 2 – 3 November data collection period.

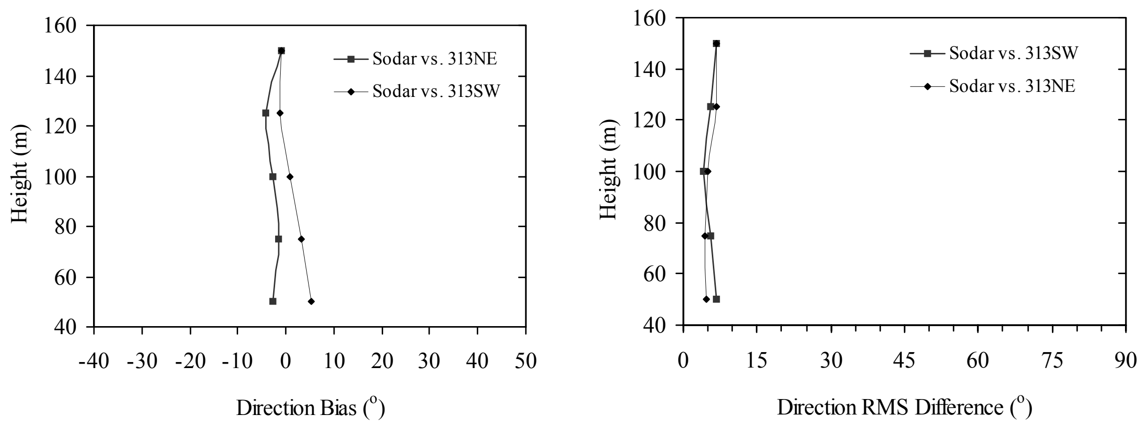


Figure 13. Wind direction bias (degrees) and RMS differences (degrees) versus height (m) for sodar data collected from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1998.

2.4 Summary of Bias and RMS Difference Statistics

The bias, RMS differences, and standard deviations in wind speed and direction from sodar wind solution B and tower 313 NE sensor are summarized in Table 2. Sodar wind solution B is chosen because it does not contain the erroneous estimates of wind speed and direction identified in sections 2.2.3 and 2.2.4. The bias, RMS differences, and standard deviations computed from the sodar and tower observations at White Sands Missile Range (WSMR) are included in Table 3. These data were collected by the vendor during selected periods from 22 – 30 September 1998. It is important to note that the sodar was aligned with north during that time and separated from the WSMR tower by a distance of 450 m. The statistics from WSMR are included here for comparison with those derived from sodar and tower 313 observations. There are three essential points that must be considered in comparing statistics shown in Tables 2 and 3.

- The bias, RMS differences, and standard deviations from the KSC data set are based on 5-minute averaged sodar data while those from WSMR are based on 10-minute averaged data.

- The wind direction statistics from the KSC data sets contain a systematic bias because no attempt was made to align the instrument with true north.

- At KSC, the sodar was located ~3.5 km from tower 313 whereas at WSMR, it was located 450 m from the tower. In addition, the potential for noise to contaminate the sodar wind estimates is greater at KSC than at WSMR.

The wind speed and direction biases at WSMR and KSC include a contribution due to the distance between the sodar and towers. The biases due to sensor separation at KSC are estimated by computing differences in wind measurements between tower 412 adjacent to the sodar and tower 313 at 16.5 m (Table 4). In comparing the WSMR and KSC statistics shown in Tables 2 – 4, it is assumed that wind variability generally decreases with height. Therefore, tower 412 and 313 comparisons at 16.5 m represent an upper bound on the magnitude of wind speed and direction differences due to spatial separation. Furthermore, biases at WSMR are assumed to result primarily from instrument error and not spatial separation, thereby providing an upper limit on instrument error. It is not possible to quantify further the magnitude and vertical profile of biases due to sensor separation from the data available at either KSC or WSMR.

If the estimated speed biases due to spatial separation (Table 4) are used to modify the values shown in Table 3, the resulting speed biases at KSC range from about -2 – 0.6 m s^{-1}. In comparison, the speed biases at WSMR range from -0.38 – 0.34 m s^{-1} (Table 3). During the three data collection periods examined for this evaluation, the KSC sensor separation-adjusted speed biases at certain times and levels are comparable to those from WSMR. However, at other times and levels, the adjusted speed biases at KSC exceed those at WSMR by more than 1.0 m s^{-1} suggesting that results at KSC are not entirely consistent with those from WSMR. A similar conclusion is apparent when analyzing the wind direction biases at KSC and WSMR given that there is also an alignment bias at KSC.

It is interesting to note that during 2 – 3 November 1998, the wind speed bias and RMS differences are largest while the wind direction bias and RMS differences are smallest in comparison with other statistics shown in Table 2. Although sodar alignment can explain a portion of these differences, wind regime is also a likely cause. Average wind speeds from 2 – 3 November are larger compared with all other collection periods at KSC. Under these conditions, wind direction variability is likely to be smaller than during weaker wind regimes. On the other hand, wind speed variability would be greater due to frictional effects and distance from the coast. For the 2 - 3 November 1998 data collection period, the average wind direction of ~135 – 140^{o} has a significant onshore component (Fig. 10). Therefore, average wind speeds would tend to be greater at tower 313 closer to the coast than further inland at the sodar site. In fact, the average wind speed plots for 2 – 3 November (Fig. 10) support this statement and suggest that spatial separation between the sodar and tower 313 could account for the larger wind speed bias and RMS differences.

Table 2. Summary of bias, RMS differences, and standard deviations from sodar and tower 313 NE sensor comparisons for periods listed below. Summary statistics from 17 – 18 March 1999 are from only sodar wind solution B. Standard deviations are computed as $(\mathrm{RMS}^2 - \mathrm{Bias}^2)^{1/2}$.

	5-Minute Sodar Data (1715:00 – 2055:00 UTC 17 March 1999)						
	Wind Speed			Wind Direction			Number of Samples
Height (m)	Bias (m s^{-1})	RMS Difference (m s^{-1})	Standard Deviation (m s^{-1})	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	
50	-0.37	0.78	0.69	-17.0	19.5	9.6	45
65	-0.52	0.83	0.65	-17.9	20.3	9.6	45
95	-0.05	0.80	0.80	-16.7	19.2	9.5	45
125	0.04	0.65	0.65	-13.3	16.8	10.3	43
155	0.36	0.79	0.70	-11.3	13.9	8.1	39
	5-Minute Sodar Data (2140:00 UTC 17 March – 0420:00 UTC 18 March 1999)						
	Wind Speed			Wind Direction			Number of Samples
Height (m)	Bias (m s^{-1})	RMS Difference (m s^{-1})	Standard Deviation (m s^{-1})	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	
50	-0.68	0.90	0.59	-27.8	29.0	8.3	81
65	-1.10	1.48	0.99	-30.8	32.3	9.7	81
95	-1.37	1.83	1.21	-24.8	28.1	13.2	78
125	-1.25	1.70	1.15	-13.8	25.4	21.3	63
155	-0.91	1.33	0.97	-6.2	25.4	24.6	51
	5-Minute Sodar Data (2250:00 UTC 2 November – 0405:00 UTC 3 November 1998)						
	Wind Speed			Wind Direction			Number of Samples
Height (m)	Bias (m s^{-1})	RMS Difference (m s^{-1})	Standard Deviation (m s^{-1})	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	
50	-0.77	1.07	0.74	-2.7	4.5	3.6	64
75	-0.70	0.98	0.69	-1.5	4.5	4.2	64
100	-1.29	1.57	0.89	-2.6	4.8	4.0	64
125	-1.79	2.04	0.98	-4.2	6.8	5.4	64
150	-1.76	1.97	0.89	-0.9	6.8	6.7	62

Table 3. Summary of bias, RMS differences, and standard deviations from the sodar and tower measurements at White Sands Missile Range. Standard deviations are computed as $(RMS^2 – Bias^2)^{1/2}$. These statistics are used with permission from Dr. P. Chintawongvanich (Sensor Technology Research, Inc.) and adapted from his NASA SBIR Phase II final report briefing given on 21 April 1999.

	10-Minute Sodar Data (22 – 30 September 1998)							
	Wind Speed				Wind Direction			
Height (m)	Bias ($m\ s^{-1}$)	RMS Difference ($m\ s^{-1}$)	Standard Deviation ($m\ s^{-1}$)	Number of Samples	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	Number of Samples
50	0.19	0.61	0.58	219	-2.1	10.5	10.3	209
75	-0.12	0.49	0.48	226	-3.1	10.2	9.7	211
100	-0.34	0.62	0.51	224	-1.0	10.9	10.8	214
125	-0.38	0.69	0.58	223	2.9	11.4	10.9	212
150	0.34	0.64	0.54	216	-2.5	12.0	11.7	213

Table 4. Summary of bias and RMS differences from tower 412 and tower 313 NE at 16.5 m for periods listed below. Standard deviations are computed as $(RMS^2 – Bias^2)^{1/2}$.

	5-Minute Tower Data (1715:00 – 2055:00 UTC 17 March 1999)						
	Wind Speed			Wind Direction			Number of Samples
Height (m)	Bias ($m\ s^{-1}$)	RMS Difference ($m\ s^{-1}$)	Standard Deviation ($m\ s^{-1}$)	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	
16.5	-0.21	0.66	0.63	-17.9	21.9	12.6	45
	5-Minute Tower Data (2140:00 UTC 17 March – 0420:00 UTC 18 March 1999)						
	Wind Speed			Wind Direction			Number of Samples
Height (m)	Bias ($m\ s^{-1}$)	RMS Difference ($m\ s^{-1}$)	Standard Deviation ($m\ s^{-1}$)	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	
16.5	-0.68	0.90	0.59	-2.5	7.8	7.4	51
	5-Minute Tower Data (2250:00 UTC 2 November – 0405:00 UTC 3 November 1998)						
	Wind Speed			Wind Direction			Number of Samples
Height (m)	Bias ($m\ s^{-1}$)	RMS Difference ($m\ s^{-1}$)	Standard Deviation ($m\ s^{-1}$)	Bias (degrees)	RMS Difference (degrees)	Standard Deviation (degrees)	
16.5	0.20	0.54	0.50	-3.9	5.3	3.6	62

2.5 Spectral Analysis

This section describes the spectral analysis of the 1-second sodar data collected using Method B from 1832:07 – 1902:49 UTC 16 March 1999 and Method C from 1904:56 – 1937:40 UTC 16 March 1999. The spectral analysis is designed to indicate the true temporal resolution of the data as a function of height by differentiating between the noise and wind signals in the observations. Both data files contain the SNR and Q flags and two wind solutions (A and B). In addition, Method B and Method C are missing two 22-second periods of data.

Calculations of the spectra were repeated with different cubic spline routines, windowing functions, and a subset of the time series that are not missing the 22-second data periods. The spectra generated by varying the interpolation and windowing routines, and length of data record are not shown because they are very similar to those presented in the following graphs.

2.5.1 Sodar Data Availability

The 1-second, sodar data availability for wind solutions A and B is shown in Table 5. These statistics are computed for the data sets collected using Method B and Method C on 16 March 1999. The data availability as a function of height is greater than 98% primarily because these data sets have no gates available above 100 m. The results are consistent with those shown for the 5-minute data in previous sections where data availability is close to 100% at and below 100 m.

Table 5. Sodar data availability as a function of height for 1-second sodar data collected from 1832:07 – 2002:49 UTC (Method B) and 2002:56 – 2037:40 UTC 16 March 1999 (Method C).

	Data Availability (%)			
	Method B		Method C	
Height (m)	Solution A	Solution B	Solution A	Solution B
50	99.6	99.8	100.0	100.0
75	99.1	99.4	99.9	100.0
100	98.3	98.5	99.9	99.8

2.5.2 Spectral Response

The spectral analyses at all three levels suggest that the sodar is able to resolve features down to the Nyquist frequency which is 0.5 Hz (2-second period) for the data sets shown in Figs. 14 – 19. Although the results from Method B and C are similar, it appears that Method B performs better than Method C in most instances based on the fact that Method B power spectra generally display less departure from the –5/3 slope at higher frequencies.

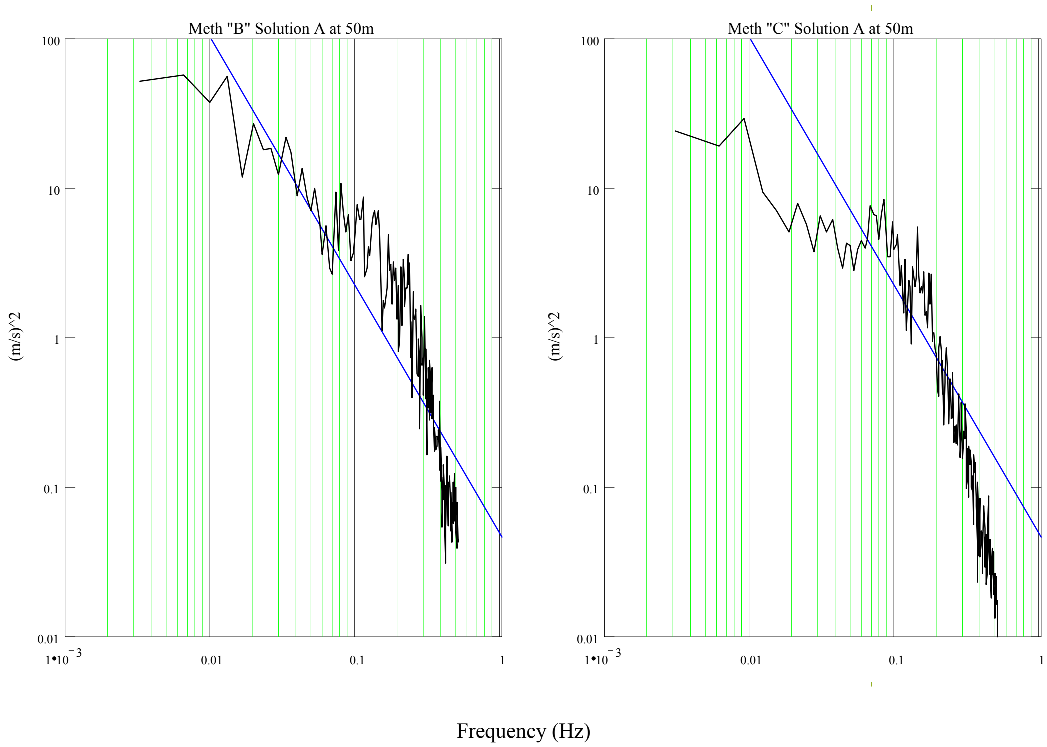


Figure 14. Spectral density versus frequency for 1-second sodar data (solution A) at 50 m using Method B (left panel) and Method C (right panel). A -5/3 reference line is also plotted in both panels.

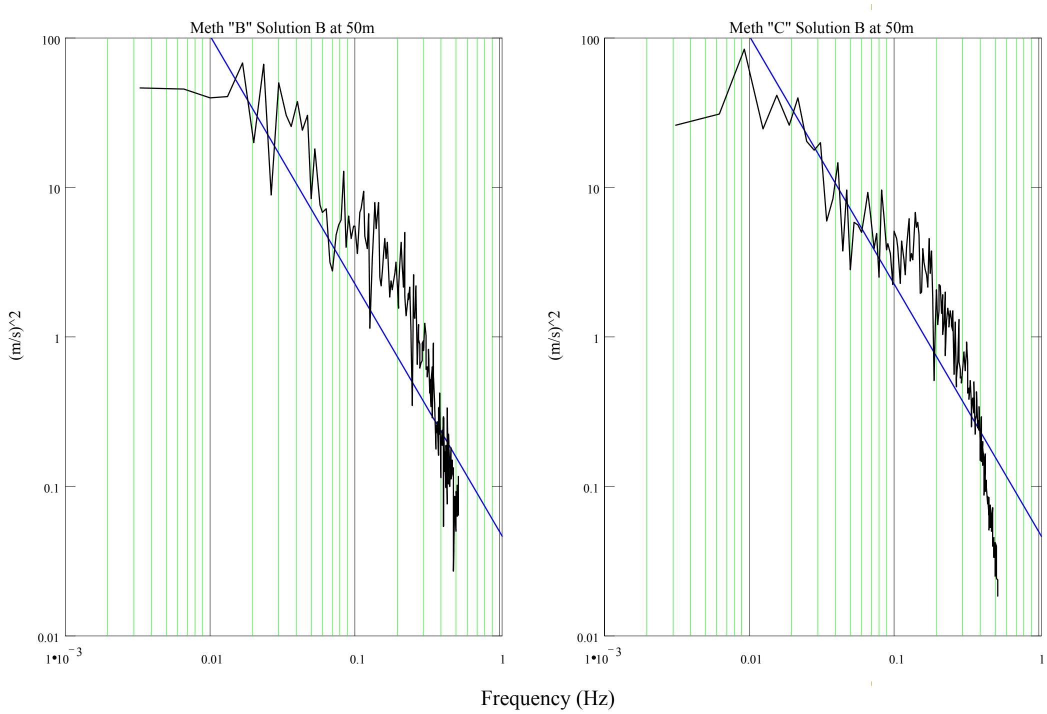


Figure 15. Spectral density versus frequency for 1-second sodar data (solution B) at 50 m using Method B (left panel) and Method C (right panel). A -5/3 reference line is also plotted in both panels.

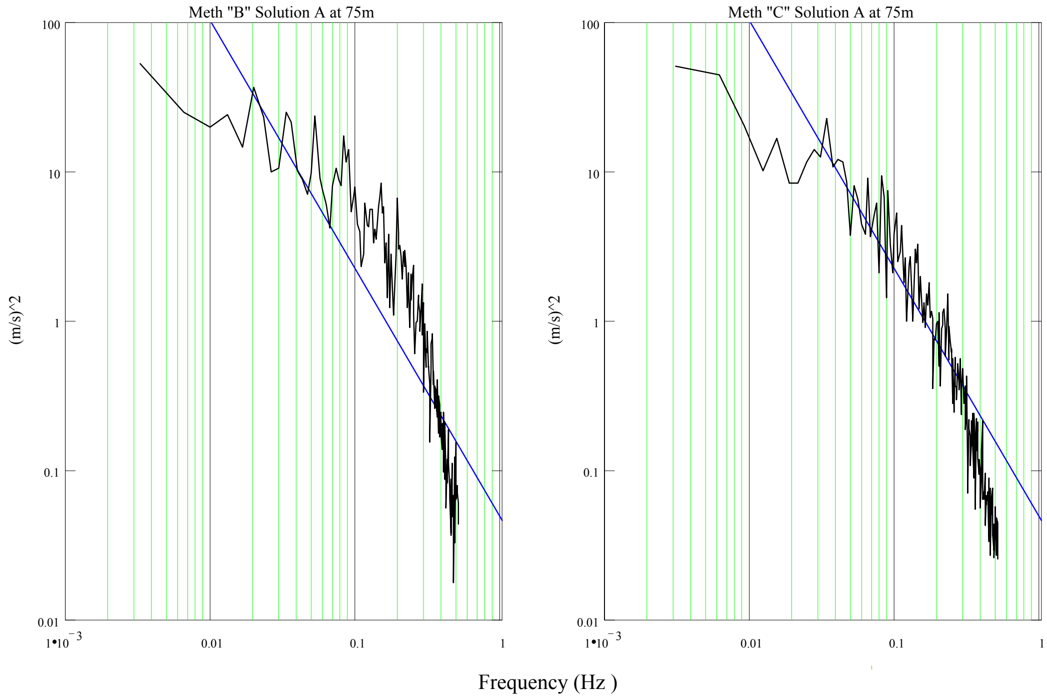


Figure 16. Spectral density versus frequency for 1-second sodar data (solution A) at 75 m using Method B (right panel) and Method C (left panel). A -5/3 reference line is also plotted in both panels.

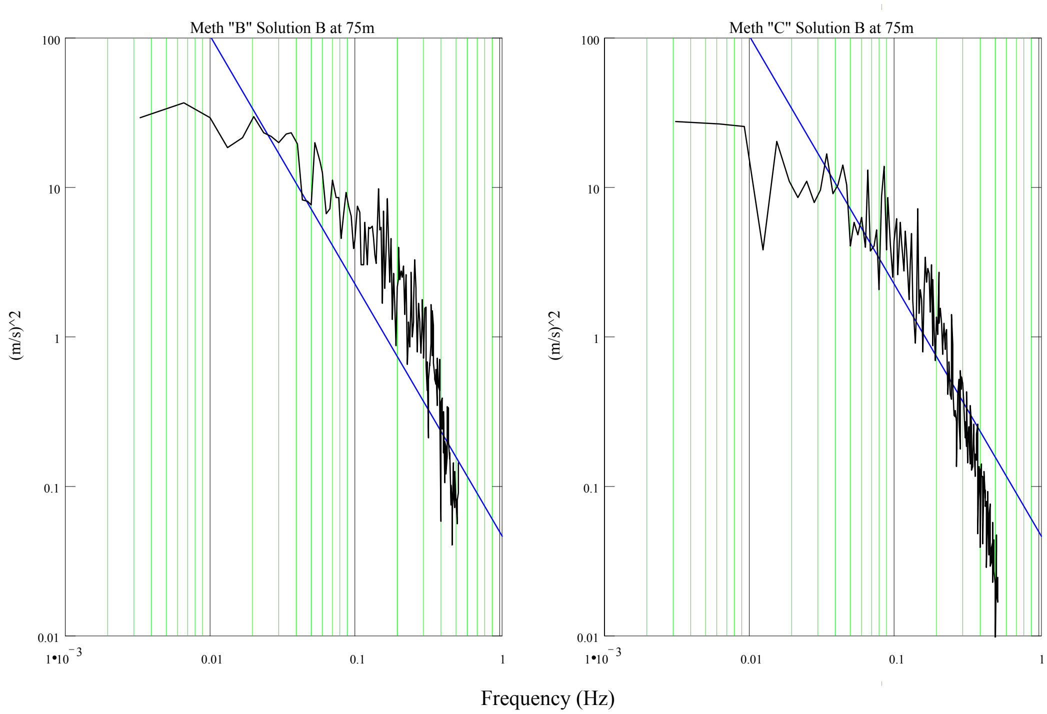


Figure 17. Spectral density versus frequency for 1-second sodar data (solution B) at 75 m using Method B (left panel) and Method C (right panel). A -5/3 reference line is also plotted in both panels.

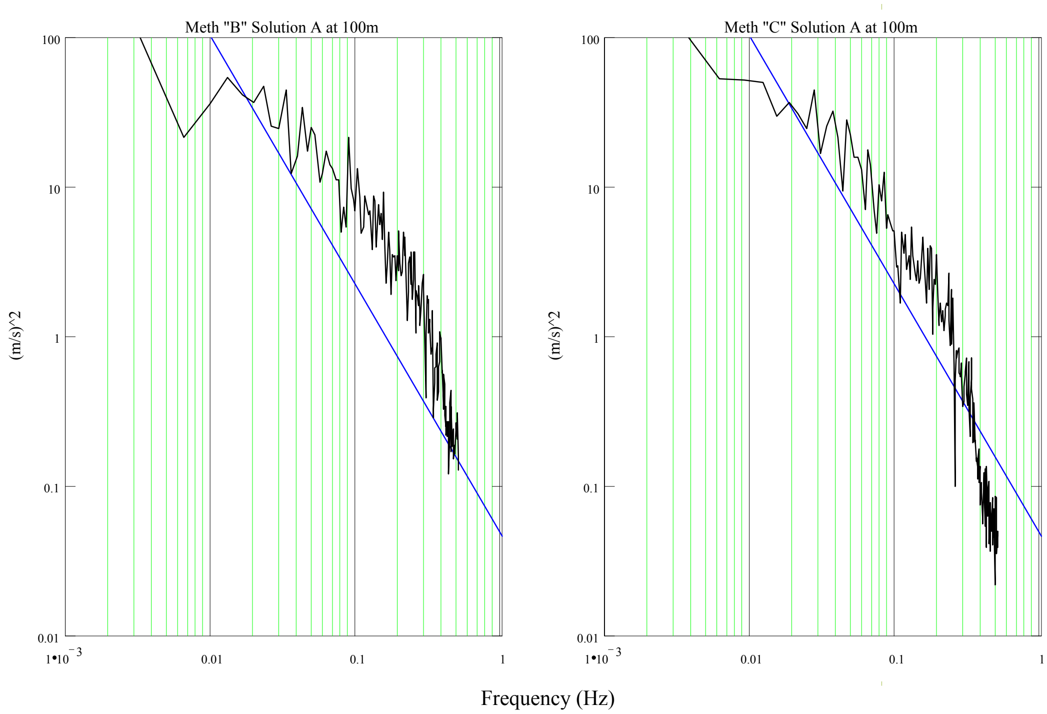


Figure 18. Spectral density versus frequency for 1-second sodar data (solution A) at 100 m using Method B (left panel) and Method C (right panel). A -5/3 reference line is also plotted in both panels.

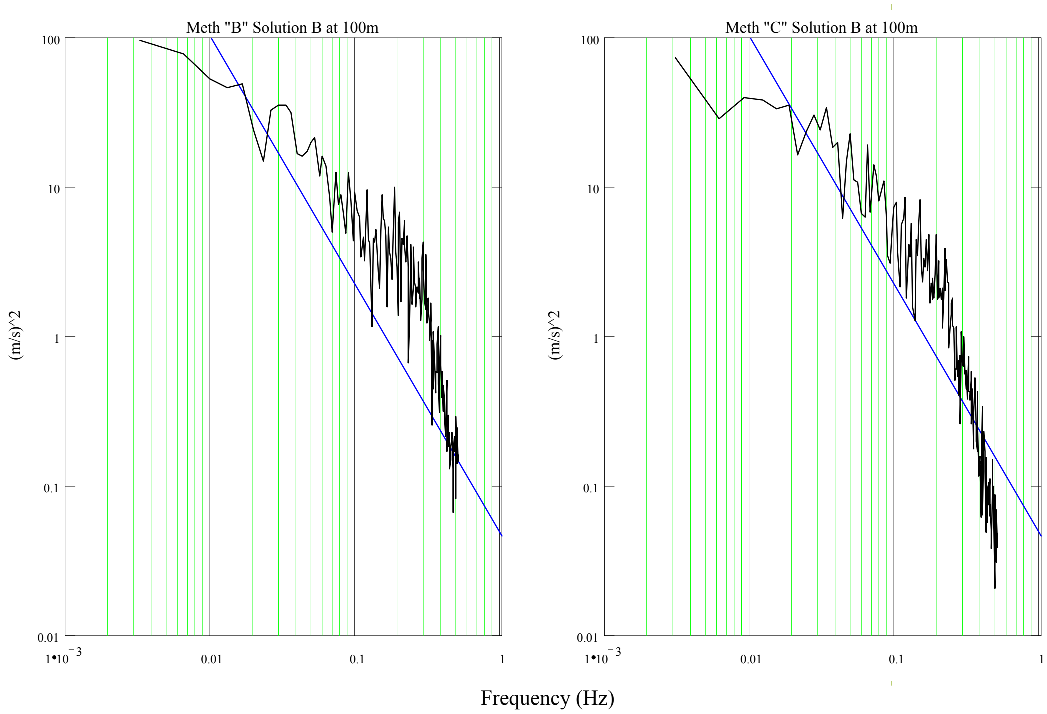


Figure 19. Spectral density versus frequency for 1-second sodar data (solution B) at 100 m using Method B (left panel) and Method C (right panel). A -5/3 reference line is also plotted in both panels.

3.0 Summary and Conclusions

This report presents the AMU evaluation of a hypersodar wind profiler located on KSC adjacent to tower 412. The sodar data used for this evaluation were collected during two different periods in March 1999 and November 1998. The sodar orientation and position were changed twice during the data sampling periods considered in this study. In neither case was any attempt made to align quantitatively the sodar with true north. Therefore, it is not possible to account for (and remove) any systematic alignment bias from total instrument bias.

The evaluation is performed by calculating sodar data availability as a function of height and bias and RMS differences versus height using 5-minute averaged sodar data and observations from tower 313. The bias and RMS differences are compared with those obtained by the vendor using 10-minute averaged sodar and tower data collected at WSMR. Finally, a spectral analysis of 1-second sodar data is performed to highlight the true temporal resolution of the data by differentiating between the noise and wind signals in the observations.

Direct comparisons of sodar and tower 412 data are not useful because the lowest sodar gate at 50 m is above the highest sensor at 16.5 m on tower 412. Therefore, tower 313 is used for the bias and RMS difference computations because it provides wind speed and direction measurements up to 150 m. As shown in Fig. 1, tower 313 is located ~3.5 km to the north-northeast of the sodar site. Comparisons of sodar and 915-MHz boundary layer wind profiler data are also not shown for the following reasons.

- The closest profiler is more than 4 km from the sodar.
- Only the highest gates of the sodar overlap with the lowest two gates of the 915-MHz profilers.
- Data are often flagged by QC checks and are least reliable at the highest sodar gates.

The following conclusions can be drawn from the evaluation described in this report:

- Using the SNR and Q checks or missing value flags, sodar data availability is generally near 100% below 100 m but decreases rapidly above 100 m and is typically less than 50% above 200 m. Signal processing and QC methods not solely dependent on the SNR may improve the data availability statistics as well as ensure data which pass the vendor QC checks are not contaminated.
- The wind speed biases between tower 313 and wind solution B vary by height and time period and range from -1.79 – 0.36 m s^{-1}. The standard deviations in wind speed for solution B at all time periods and heights range from 0.59 – 1.15 m s^{-1}. The RMS differences in wind speed for solution B at all time periods and heights range from 0.65 – 2.04 m s^{-1}. Note that RMS differences are not bias-corrected.
- The wind direction biases between tower 313 and sodar solution B for all time periods and heights are negative and range from -30.8 – -0.9°. The standard deviations in wind direction for solution B at all time periods and heights range from 3.6° – 24.6°. The RMS differences in wind direction range from 4.5 – 32.3°. Note that RMS differences are not bias-corrected.
- For the second 5-minute sodar data set collected during 17 – 18 March 1998, solution A produces wind estimates that are inconsistent with those from solution B or tower 313 observations. The SNR and Q checks did not flag these winds therefore some other form of quality control is needed to identify erroneous data that may have acceptable SNR.

- Overall, the differences between tower 313 and sodar wind observations for the limited samples examined in this evaluation are due to misalignment of the sodar, variability in wind over the 3.5-km distance separating the two instruments, and instrument error. It is not possible to identify accurately the systematic errors due to alignment and spatial separation given the available data collected at KSC.

- Spectral response at all levels suggests that the sodar is able to resolve features down to the Nyquist frequency which is 0.5 Hz (2-second period) for the data sets examined in this evaluation.

The RMS differences in wind speed and wind direction from sodar wind solution B at KSC range from 0.65 m s^{-1} – 2.04 m s^{-1} and 4.5 – 32.3°, respectively. Note that these RMS differences are not bias-corrected. The vendor claims that the accuracy of the wind measurements from the sodar is better than 0.5 m s^{-1} in speed and 10° in direction (Sensor Technology Research, Inc. NASA SBIR phase II final report briefing). The results of the evaluation described here suggest that such accuracy may be attainable though the data available for this comparison made it impossible to confirm the vendor's claims. The sodar was not aligned with true north and was separated by a distance of 3.5 km from tower 313 used for comparisons in this study.

During the three data collection periods examined for this evaluation, the KSC sensor separation-adjusted wind speed and direction biases at certain times and levels are comparable to those from WSMR. However, at other times and levels, the adjusted speed biases at KSC exceed those at WSMR by more than 1.0 m s^{-1}. These statistics suggest that results at KSC are not entirely consistent with those from WSMR given the differences in spatial separation between the sodar and tower at each site.

4.0 References

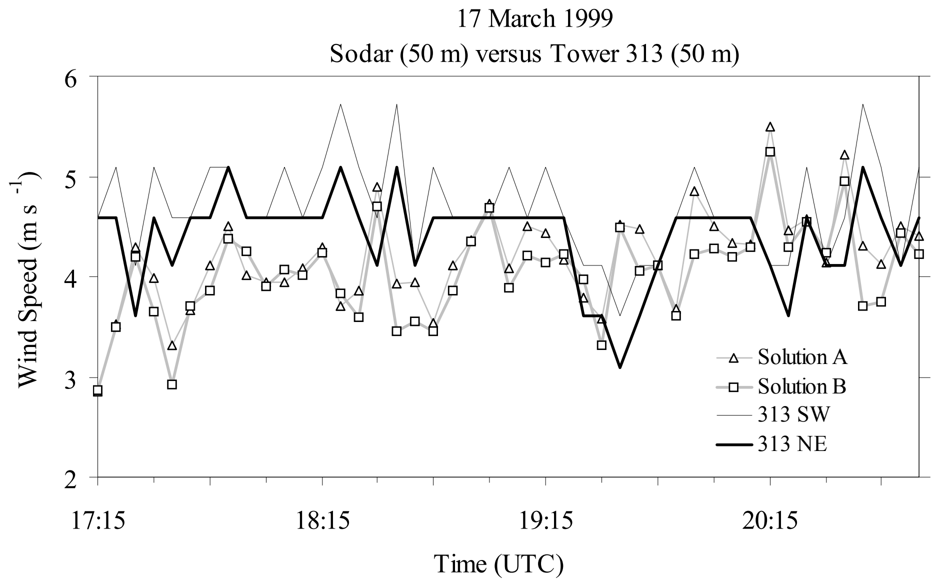
Lambert, W. L., and G. E. Taylor, 1998: Data quality assessment methods for the Eastern Range 915-MHz profiler network. NASA Contractor Rep. CR-1998-207906, 49 pp.

Merceret, Francis J., 1995: The effect of sensor sheltering and averaging techniques on wind measurements at the Shuttle Landing Facility. NASA TM-111262, 42 pp.

Appendix

Time Series Plots

The appendix includes time series plots of wind speed (m s^{-1}) and direction (degrees) from the sodar and tower 313 at each height. The time series cover the verification periods discussed in section 2.1 (1715:00 - 2055:00 UTC 17 March 1999), section 2.2 (2140:00 UTC 17 March – 0420:00 UTC 18 March 1999), and section 2.3 (2250:00 UTC 2 November – 0405:00 UTC 3 November 1999).



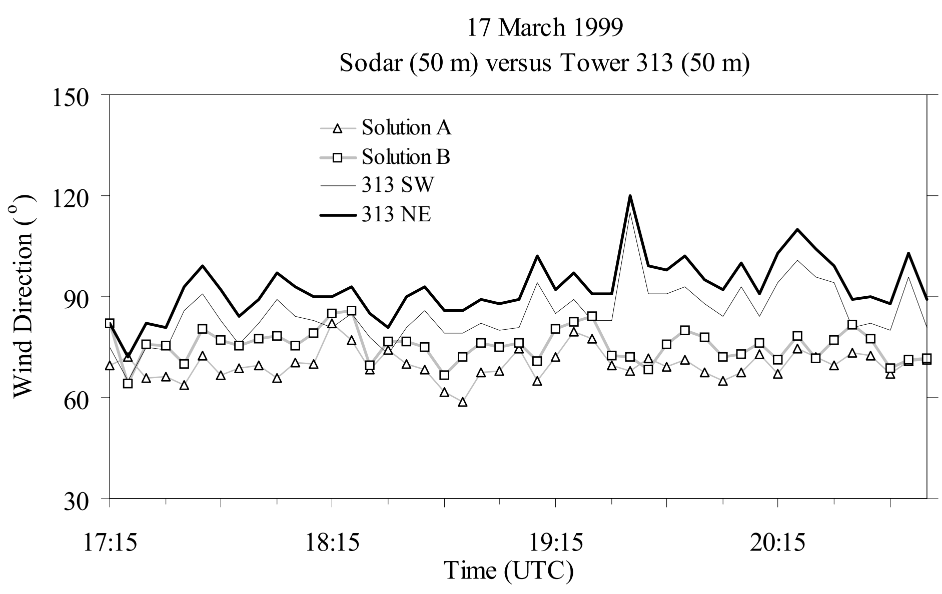
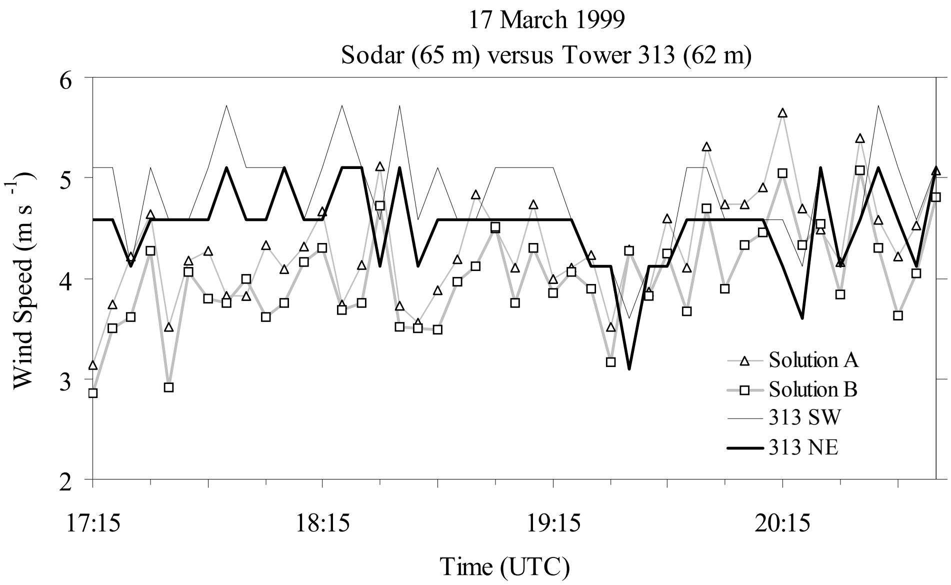


Figure A1. Time series of wind speed (m s^{-1}) and direction (degrees) from 1715:00 – 2055:00 UTC 17 March 1999 for sodar wind solutions A and B at 50 m and tower 313 NE and SW sensors at 50 m.



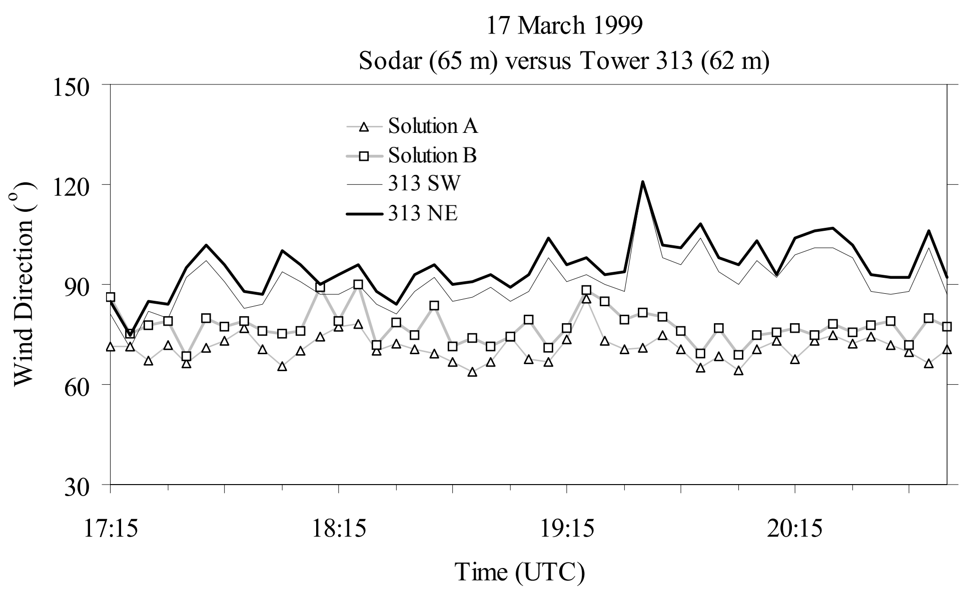
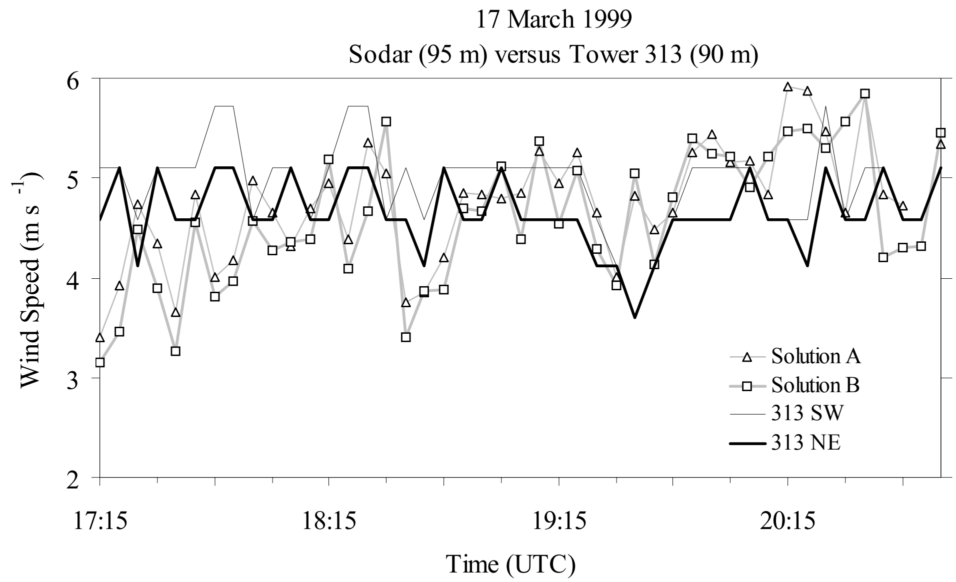


Figure A2. Time series of wind speed (m s^{-1}) and direction (degrees) from 1715:00 – 2055:00 UTC 17 March 1999 for sodar wind solutions A and B at 65 m and tower 313 NE and SW sensors at 62 m.



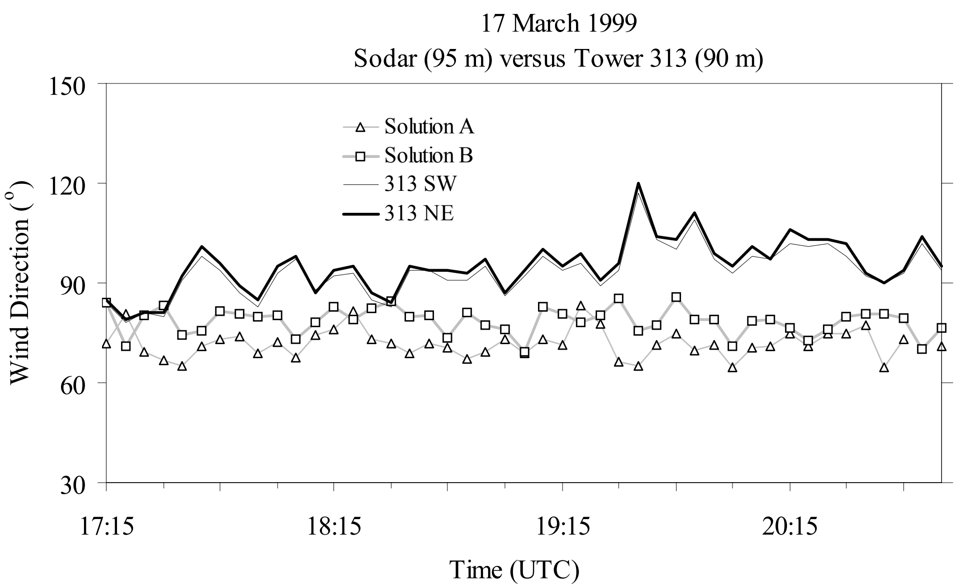
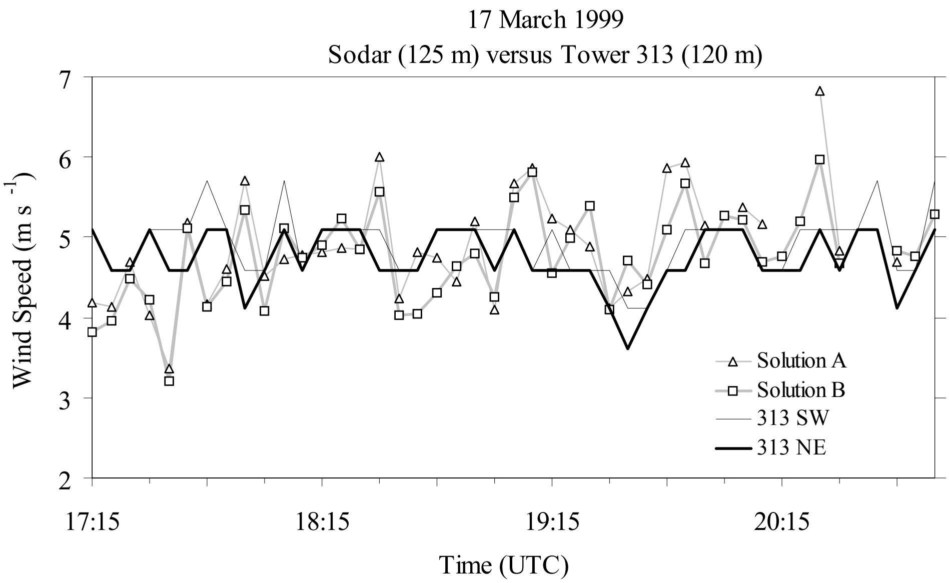


Figure A3. Time series of wind speed (m s^{-1}) and direction (degrees) from 1715:00 – 2055:00 UTC 17 March 1999 for sodar wind solutions A and B at 95 m and tower 313 NE and SW sensors at 90 m.



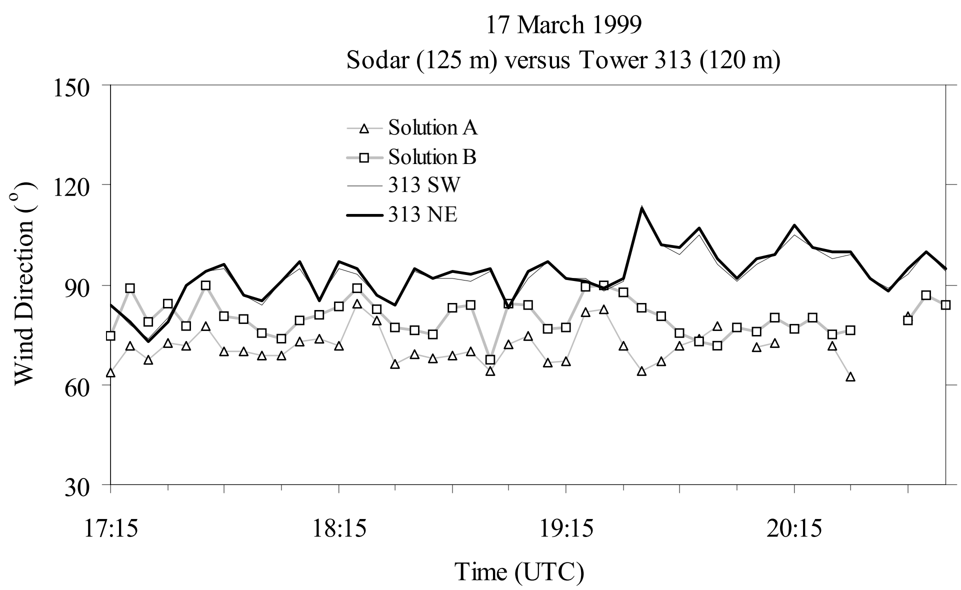
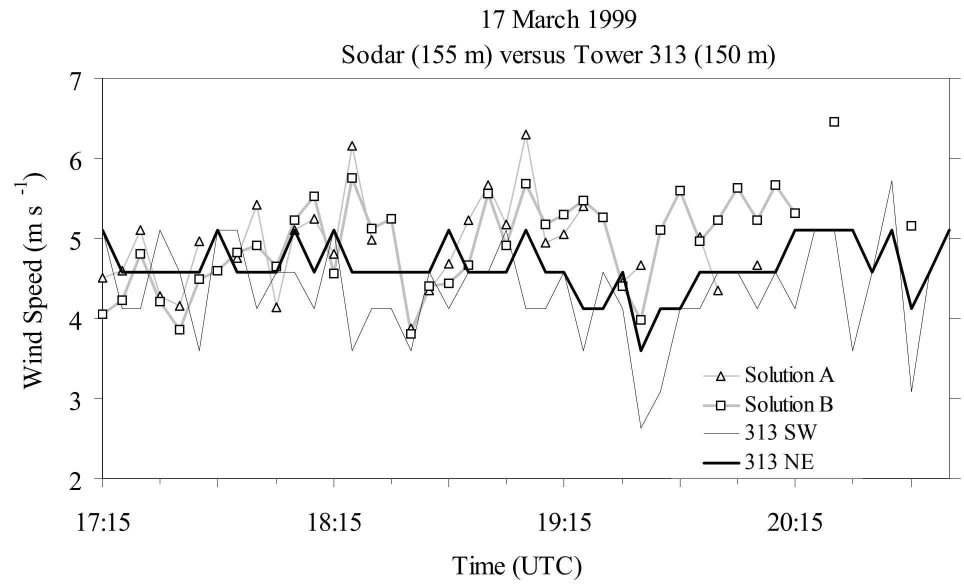


Figure A4. Time series of wind speed (m s^{-1}) and direction (degrees) from 1715:00 – 2055:00 UTC 17 March 1999 for sodar wind solutions A and B at 125 m and tower 313 NE and SW sensors at 120 m.



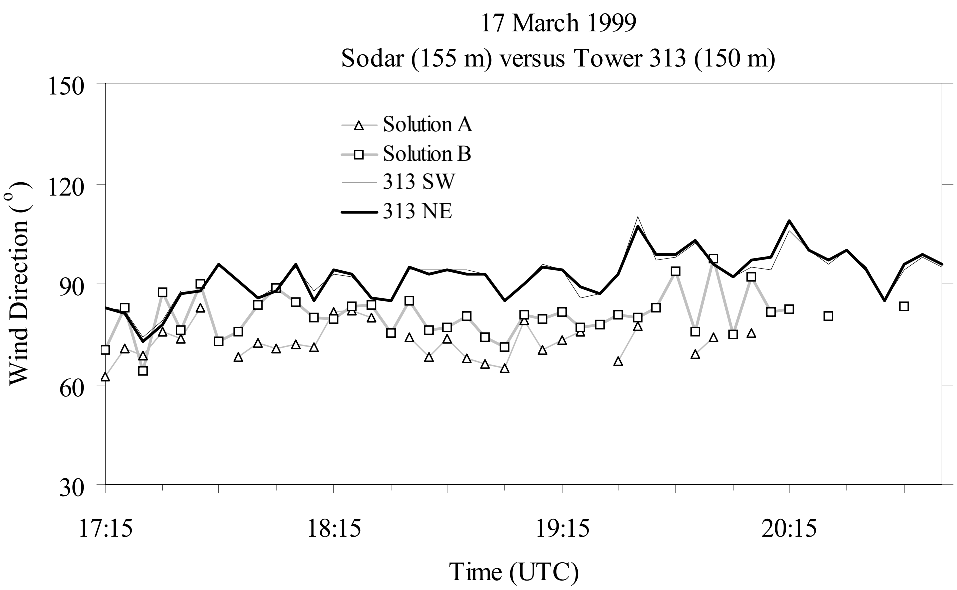
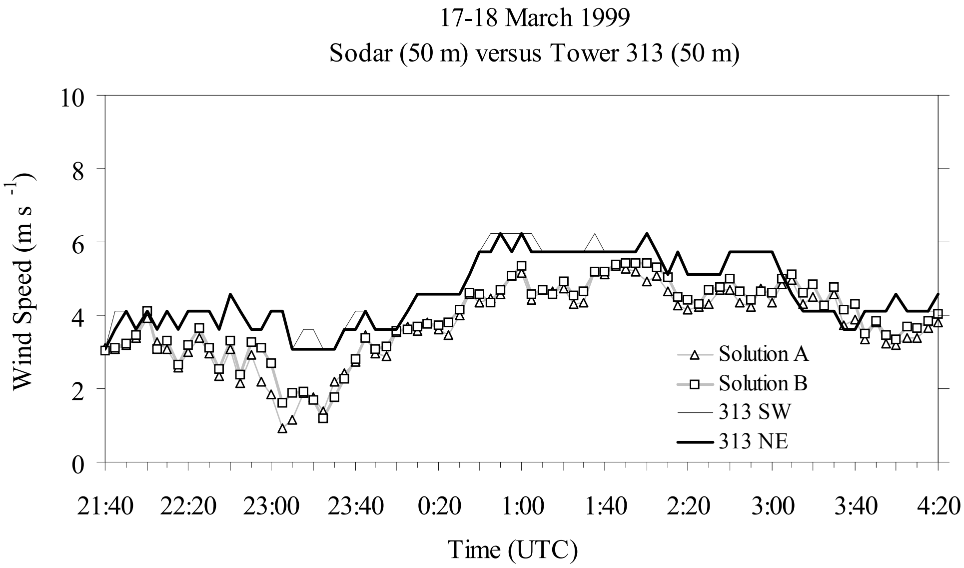


Figure A5. Time series of wind speed (m s^{-1}) and direction (degrees) from 1715:00 – 2055:00 UTC 17 March 1999 for sodar wind solutions A and B at 155 m and tower 313 NE and SW sensors at 150 m.



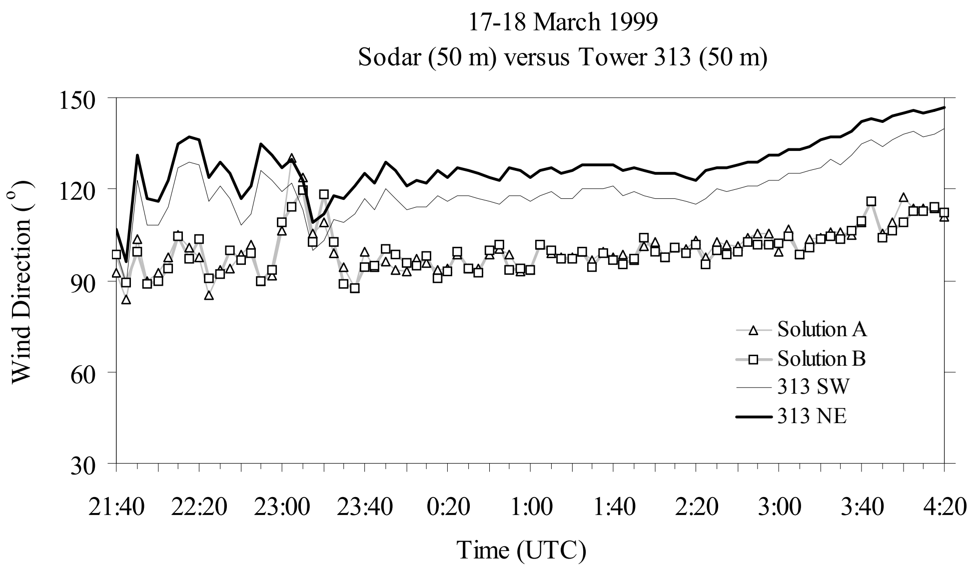
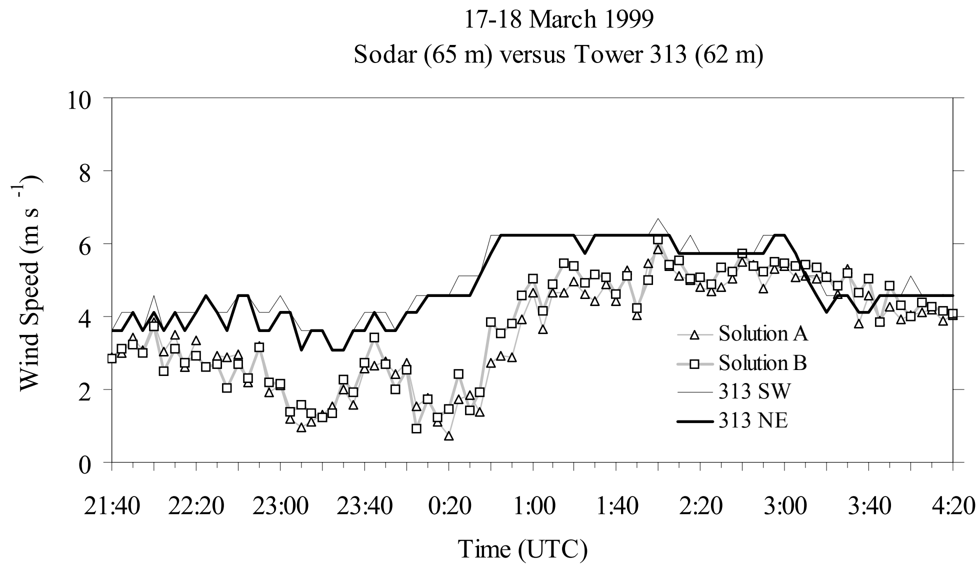


Figure A6. Time series of wind speed (m s^{-1}) and direction (degrees) from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 for sodar wind solutions A and B at 50 m and tower 313 NE and SW sensors at 50 m.



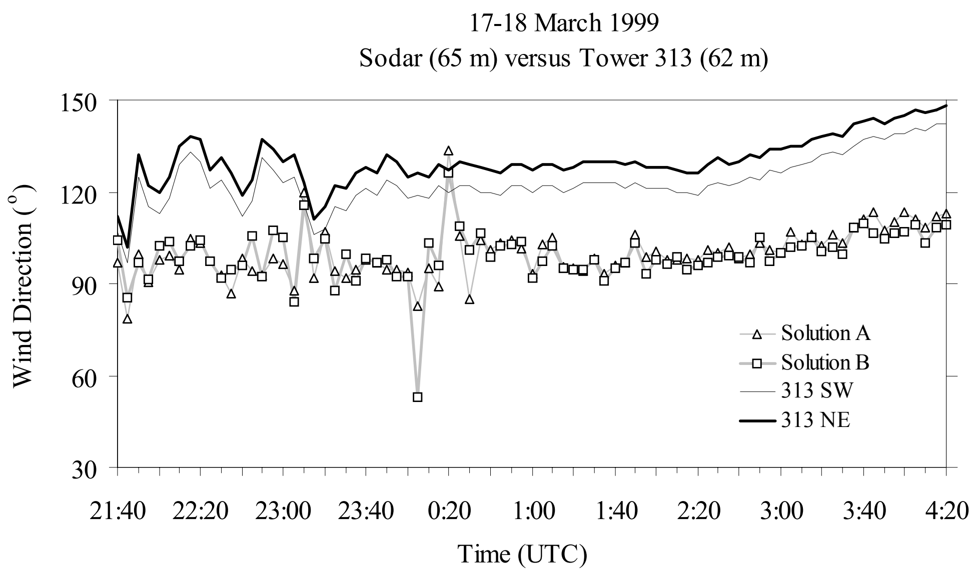
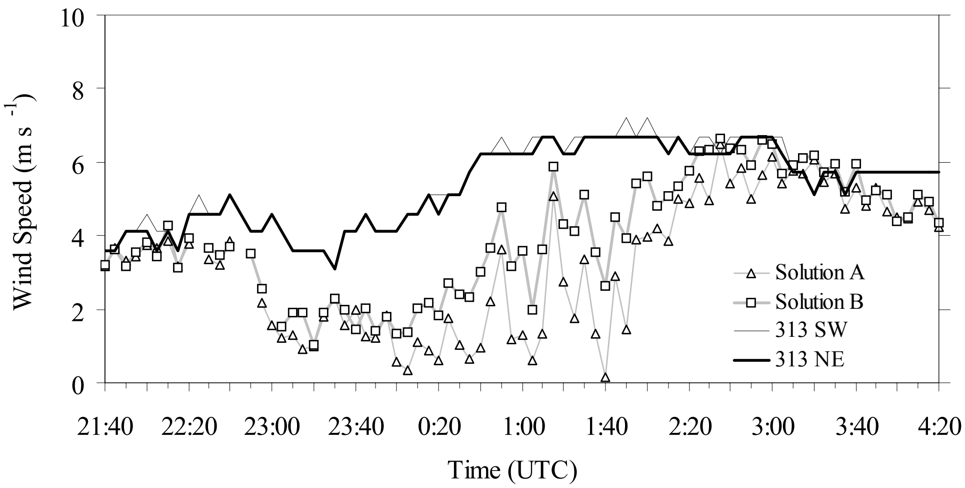


Figure A7. Time series of wind speed (m s^{-1}) and direction (degrees) from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 for sodar wind solutions A and B at 65 m and tower 313 NE and SW sensors at 62 m.

17-18 March 1999
Sodar (95 m) versus Tower 313 (90 m)



17-18 March 1999
Sodar (95 m) versus Tower 313 (90 m)

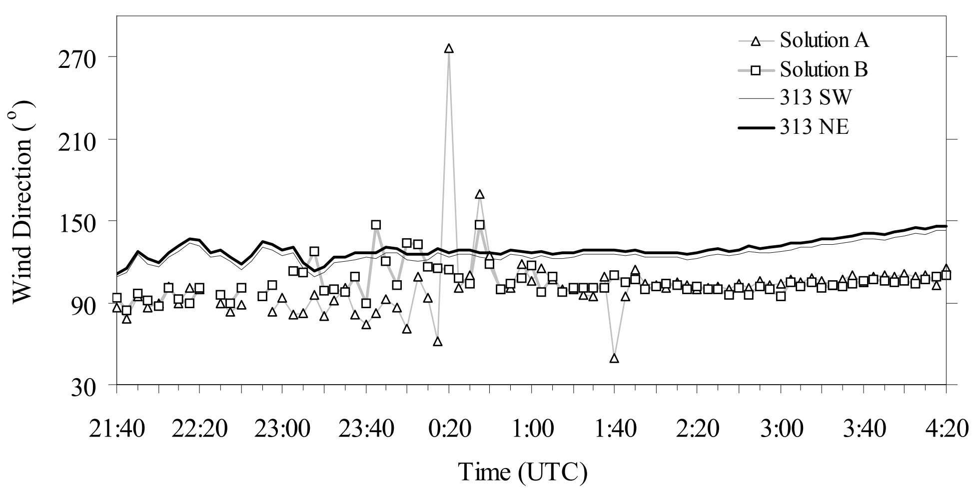
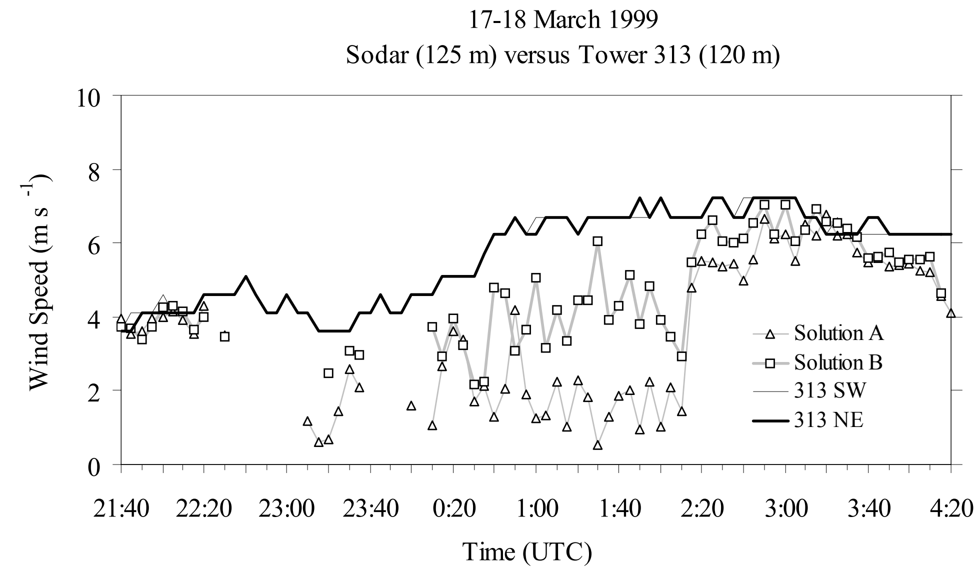


Figure A8. Time series of wind speed (m s^{-1}) and direction (degrees) from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 for sodar wind solutions A and B at 95 m and tower 313 NE and SW sensors at 90 m.



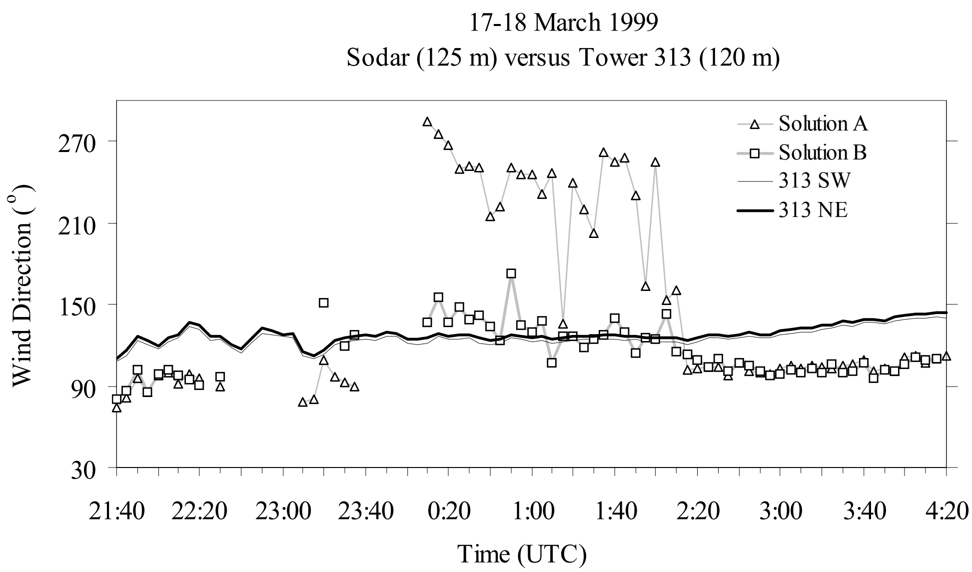
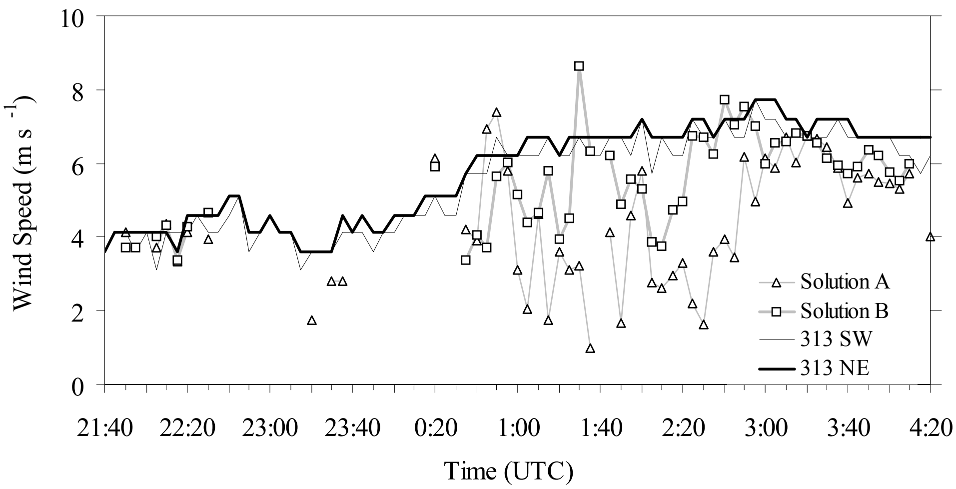


Figure A9. Time series of wind speed (m s^{-1}) and direction (degrees) from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 for sodar wind solutions A and B at 125 m and tower 313 NE and SW sensors at 120 m.

17-18 March 1999
Sodar (155 m) versus Tower 313 (150 m)



17-18 March 1999
Sodar (155 m) versus Tower 313 (150 m)

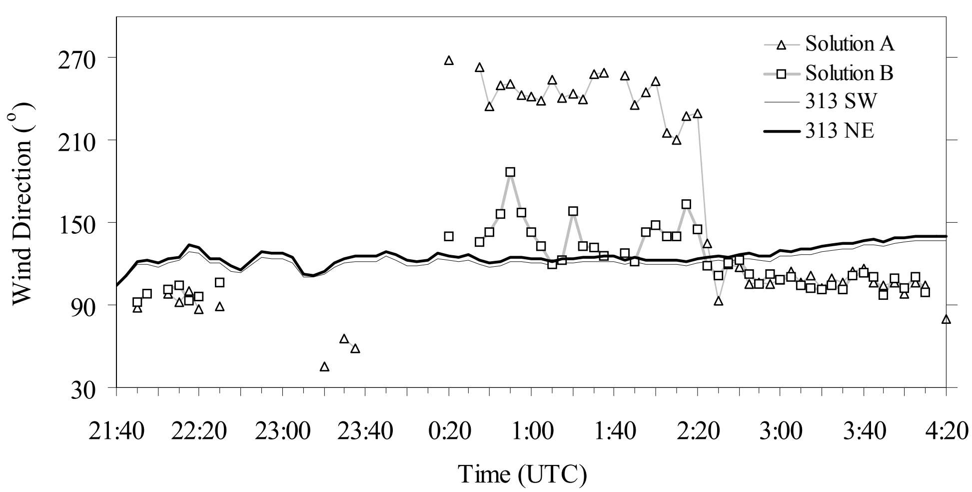
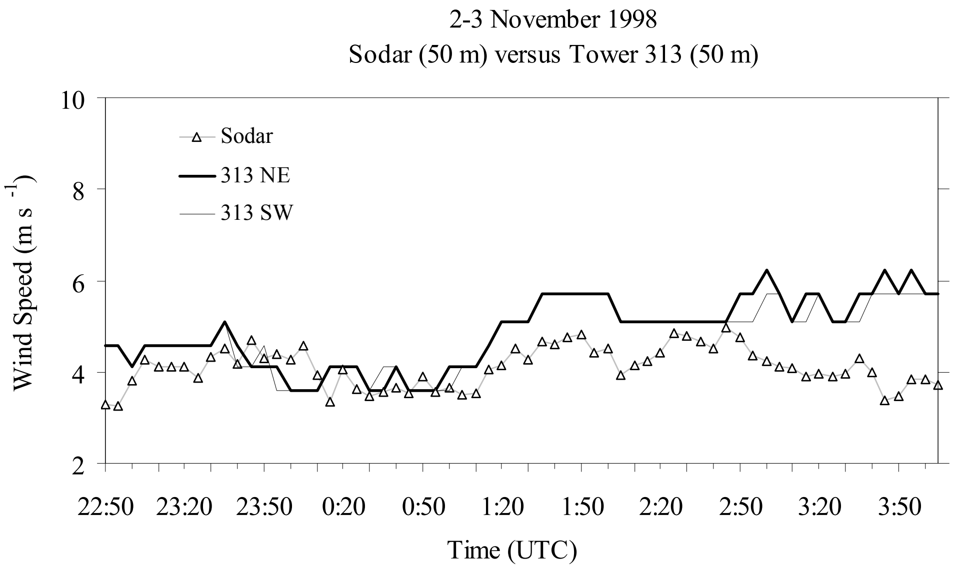


Figure A10. Time series of wind speed (m s^{-1}) and direction (degrees) from 2140:00 UTC 17 March – 0420:00 UTC 18 March 1999 for sodar wind solutions A and B at 155 m and tower 313 NE and SW sensors at 150 m.



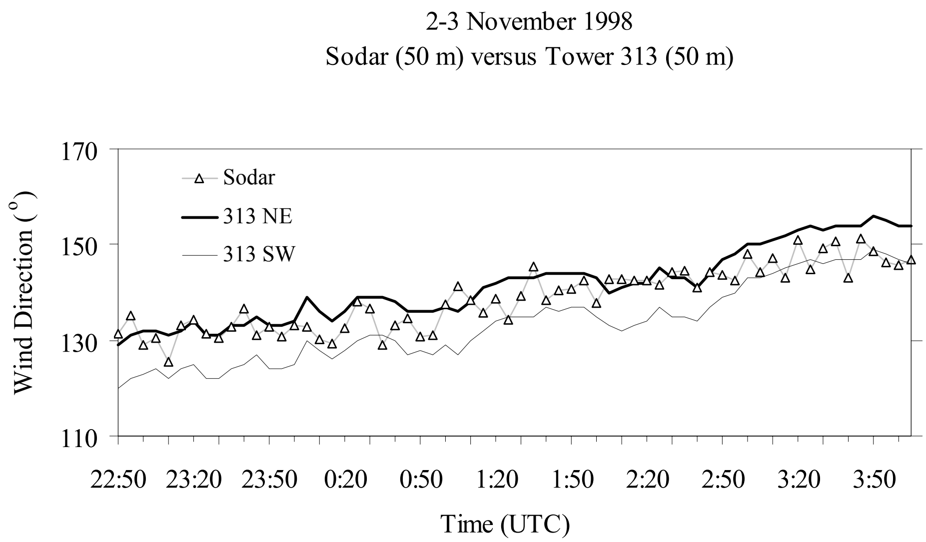
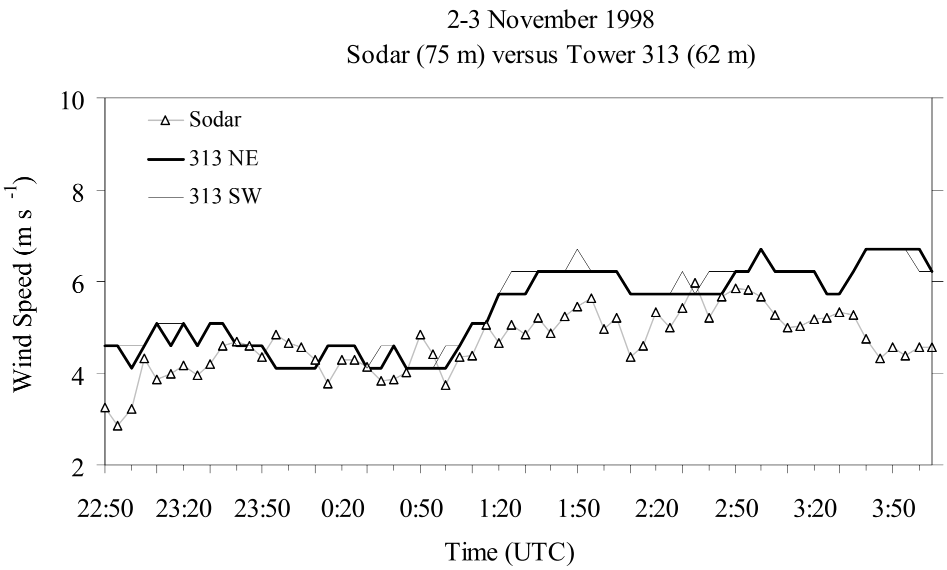


Figure A11. Time series of wind speed (m s^{-1}) and direction (degrees) from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1999 for the sodar at 50 m and tower 313 NE and SW sensors at 50 m.



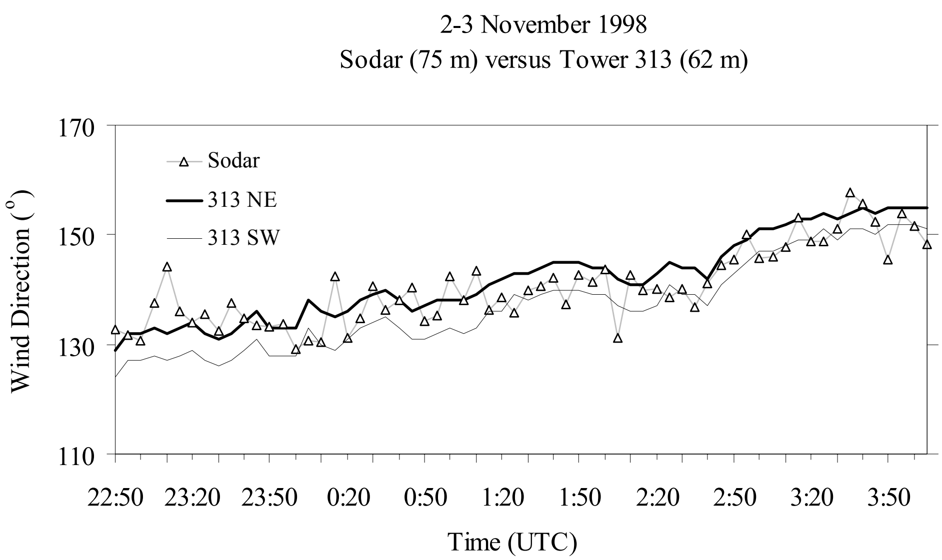
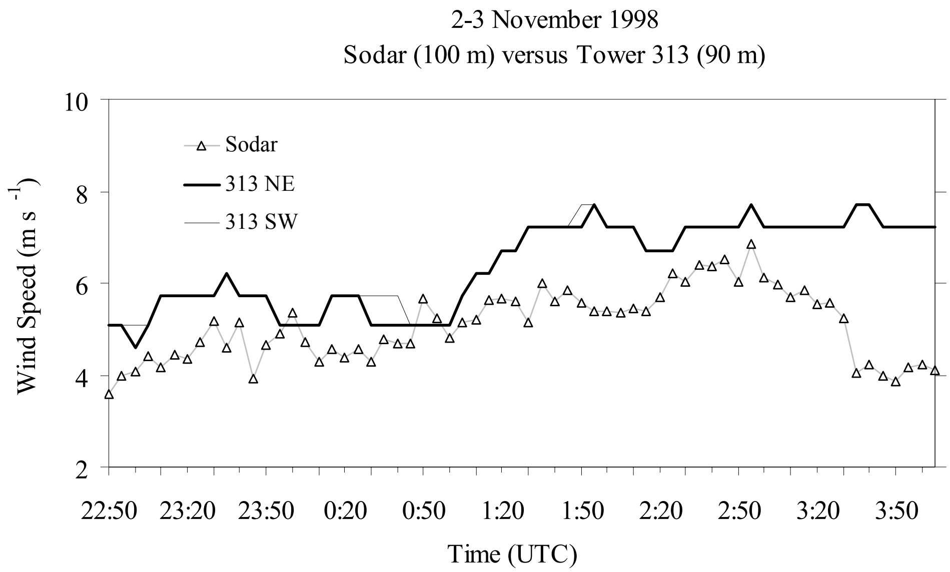


Figure A12. Time series of wind speed (m s^{-1}) and direction (degrees) from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1999 for the sodar at 75 m and tower 313 NE and SW sensors at 62 m.



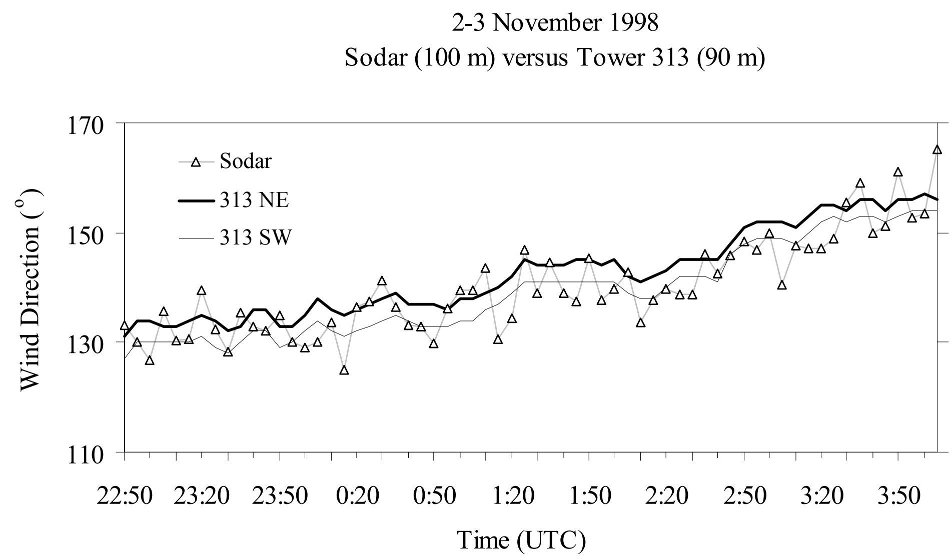
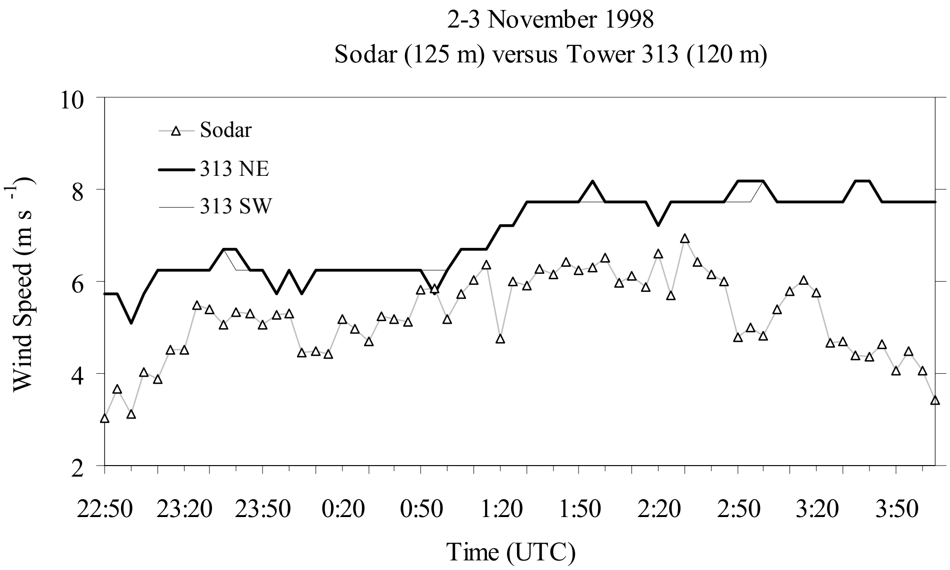


Figure A13. Time series of wind speed (m s^{-1}) and direction (degrees) from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1999 for the sodar at 100 m and tower 313 NE and SW sensors at 90 m.



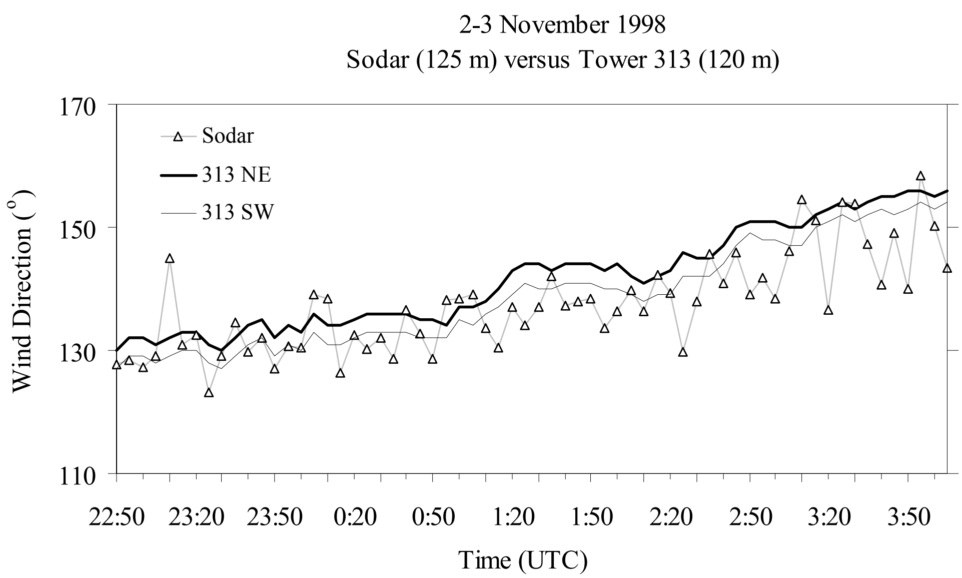
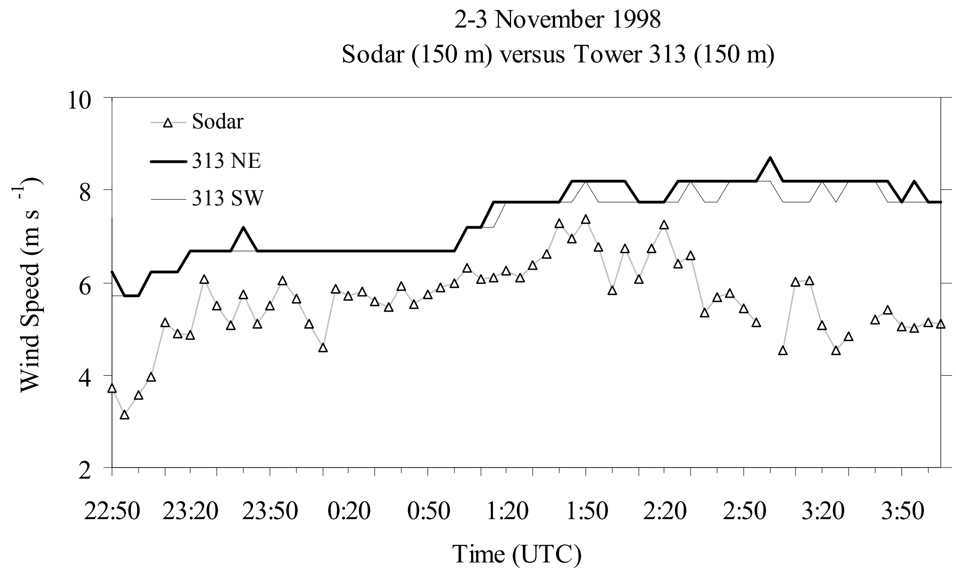


Figure A14. Time series of wind speed (m s^{-1}) and direction (degrees) from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1999 for the sodar at 125 m and tower 313 NE and SW sensors at 120 m.



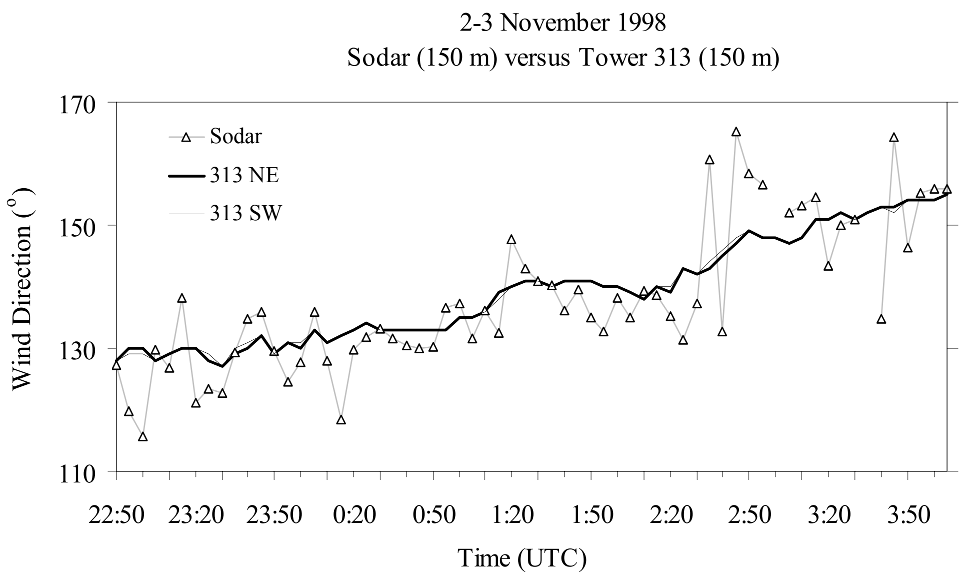


Figure A15. Time series of wind speed (m s^{-1}) and direction (degrees) from 2250:00 UTC 2 November – 0405:00 UTC 3 November 1999 for the sodar at 150 m and tower 313 NE and SW sensors at 150 m.

NOTICE