Wind Resource Assessment Using SODAR at Cluttered Sites

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Abstract

The utility of SODAR is leading to its use in environments that challenge this tool's ability to collect accurate and representative wind resource data. One such challenging environment can be called a cluttered site. At a cluttered site, sources of extraneous echo can cause SODAR to collect faulty data that is not rejected by typical measures of data quality and can create a false impression of the site's wind resource. Site clutter can be very difficult to recognize and also to mitigate by simply re-siting the SODAR. This paper describes the RERL's efforts to improve the accuracy and representativeness of wind resource data collected via SODAR at cluttered sites. Of particular promise are new filtering methods based on the strength of the returned signal, as well as the use of a short pole-mounted anemometer for data validation.

Introduction

The Renewable Energy Research Laboratory of the University of Massachusetts at Amherst operates a wind data collection and analysis program over sites in the Northeast of the United States—primarily in Massachusetts. The nature of these sites varies considerably from flat coastal locations to complex, somewhat mountainous terrain. The majority of wind data collection is performed using in-situ anemometry and vanes mounted at various heights on meteorological towers—typically 10 m, 30 m, and 40 m. As a part of the wind resource assessment campaign, the RERL has also been using SODAR.

The following is a necessarily brief description of the relevant operational characteristics of SODAR, for more detail on the theory and operation of SODAR; the reader is referred to [1], [2], and [3] as modern examples of excellent literature on the subject. The UMass ART VT-1 SODAR measures wind speed and direction at multiple heights using the Doppler shift of an acoustic signal. For each transmit cycle, sound beam pulses are sent sequentially in three directions: once in the vertical (w-beam) and once each in two mutually orthogonal directions (u, v beams) in a plane slightly tilted (approximately 15 degrees) from vertical. Three sound beams are required to resolve the wind-speed data into its three-dimensional components. Because the three beams are transmitted from one location, the beams do not measure the exact same conical volume of air; instead, three distinct but nearly adjacent volumes are measured. A timer controls how long the SODAR waits to receive reflected signals. Since sound travels at a fairly constant speed, different heights above the SODAR can be sequentially scanned by setting the timer for different intervals. The atmosphere is sampled at a rate dependent primarily on both the maximum altitude scanned and the duration of the sound pulse used, but each range gate (i.e. measuring height) is sampled at about every 5 seconds. These 5 s samples are averaged over periods of approximately ten minutes to produce estimates of the mean wind-speed and wind-direction for each of the averaging periods.

The strength of the reflected signal decreases with height. Noise, whether naturally occurring acoustic noise in the environment or unwanted electrical noise that corrupts the signal that is measured, may overwhelm the reflected signal. When this occurs, the SODAR software does not use that sample of information. If too few samples in the 10 minute averaging period have a sufficient signal-to-noise ratio, the SODAR does not provide an average for that period. Thus, depending on the ambient noise levels, the SODAR may provide less data at higher elevations due to the weak signal.

The RERL's use of SODAR in wind resource assessment is due to the often-stated advantages that SODAR possesses versus in-situ measurements, namely: reduced permitting and installation costs, increased information about wind conditions both at more and higher heights, and increased flexibility and mobility in the site selection and deployment process. Firstly, the RERL is interested in SODAR as simply a tool for furthering wind resource assessment; and secondly, is interested in improving SODAR in order to facilitate its use in wind resource assessment.

This second interest in improving SODAR has arisen due to some of the complications that have occurred as a result of using SODAR in environments that challenge its ability to resolve accurate and representative data. Studies regarding SODAR use in complex terrain have been performed, and the effect of echo has been observed. However, beyond simply physically removing the SODAR from a location with echo interference (in effect re-siting it), what else can be done to mitigate echo's deleterious effect on SODAR performance—particularly when it may be impossible to re-site the SODAR? Often in the compact and complex New England environment the minimum physical distance (from clutter) necessary to prevent echo interference may be unclear and/or impossible to achieve.

A Short History of SODAR at the RERL

The RERL received its first ART VT-1 SODAR at the end of August 2001. After a few days of training at a nearby complex terrain site, a short comparison trial (versus a 40 m met tower) was run on a small, flat island in the Boston Harbor area [4]. This trial yielded results consistent with published findings [1] (e.g. a SODAR bias vs. anemometry of –0.5 m/s). At the next comparison trial in March of 2002, ten hours at another complex terrain site in Western Massachusetts (Northfield Mountain 1), Rogers, et al note that the SODAR performs better at higher heights—presumably this means that data collection improves, because reported mean wind speeds again are consistent with SODAR's typically reported bias of –0.5 m/s. After confirming that the SODAR was operating as expected, the RERL began to use SODAR as a stand-alone measurement tool. In April through March of 2002 another complex terrain site (Northfield Mountain 2) showed a reasonable mean wind speed (4.67 m/s at 60 m). From July 2003 until December 2003 stand-alone SODAR data was taken at two locations on Deer Island, MA—another small island in Boston Harbor. These trials were troubled with operational issues (e.g. battery swap-out) as well as high noise in the SODAR signal that was traced to faulty SODAR component pc-boards. The SODAR was then brought back to the RERL and repaired and outfitted with an AC electrical power supply. From the end of February 2004 until the end of July 2004 SODAR measurements were taken at a forested complex terrain site on the island of Vinalhaven, ME, approximately one mile from an existing meteorological tower. The SODAR indicated very high shear especially in the lower range gates, and this data was used to question the validity of current shear models for forested terrain [5]. In October 2004 SODAR data was taken with the SODAR placed on top of a concrete and steel water tower at Paxton, MA. Very little data resulted from this trial due to high noise levels, the cause of which is still unclear; however, the valid data that was taken was consistent with nearby anemometry. From November 2004 until March 2005 SODAR data was taken at a complex terrain site at Hull, MA. Again high levels of shear were reported, as well as speed-up effects from a nearby capped landfill. High levels of noise at this site were attributed primarily to a failing power supply; a replacement power supply helped to correct the noise problem. At about this time, Windfinders LLC gave the RERL data including intercomparison tests from two sites in the Arizona desert—Two Guns, AZ and Sunshine, AZ.

At the end of March 2004, the RERL also received its second ART VT-1 SODAR (dubbed SODAR #2) as a trailerized unit. SODAR #2 was immediately taken to Orleans, MA, another forested complex terrain site. Again, high levels of shear were observed. The findings at this site initiated an investigation into clutter effects. Up until this point, both SODARs were operated in a "set and forget" type mode where data collection and parameter adjustment could only occur in conjunction with site visits (e.g. when the SODAR was moved to the next scheduled site); from this point forward, remote control and collection capability were added to both SODARs. This remote control and collection capability has proven essential in problem identification and correction. In April 2005 SODAR #1 was deployed again on a small island in Boston Harbor—Long Island, MA—where the utility of a short pole-mounted anemometer was discovered. After the Orleans, MA trial, SODAR #2 was taken to Falmouth, MA—a coastal site with some trees—for another anemometer intercomparison trial. Again differences were found between SODAR and tower anemometry, but due to the remote data collection capability, the problem was caught early enough in the schedule to allow for favorable re-siting of the SODAR at this location. At this site SODAR #2 was also outfitted with a short pole-mounted anemometer. In July 2005 SODAR #2 was taken to Nantucket, MA for intercomparison with a tall FM radio tower outfitted with anemometry. Although the trial at Nantucket was plagued with RF interference issues due to the SODAR's proximity to the high output FM radio transmitter, results at higher heights were consistent with anemometry. During this time SODAR #1 was placed on a small offshore observatory tower near Martha's Vineyard, MA to participate in a SODAR comparison experiment with Woods Hole Oceanographic Institute (WHOI). During this experiment the RERL ART VT-1 SODAR performed well, but inter-SODAR comparison was impossible because of the operational difficulties that WHOI experienced with their Scintec SODAR.

Site Clutter

A cluttered site is a site that possesses passive reflectors that interfere with correct SODAR operation by echoing the SODAR's own acoustic pulses. A cluttered site may have, for example, hills, trees, and low buildings near enough to the SODAR to affect it. Clutter does not seem to produce the same "hard surface" type of echo that commonly is detected by echo rejection algorithms. Though the exact variation of the effect of clutter as a function of height is unknown, clutter has more effect on SODAR measured data at lower range gates. One of the particularly damaging aspects of clutter-contamination is that it typically biases the observed average wind-speeds to lower than actual values. In fact, this low-biasing has been observed to be a signature of inappropriately accepted data collected at cluttered sites. Since clutter affects lower range gate data more strongly, there may also be inaccurate reporting of site wind shear. As shown in Figure 1, SODAR reported wind-speed plotted versus in-situ reported wind-speed should result in a tight grouping around a line. Ideally, this line should be one-to-one; however, as reported, SODAR may possess a bias compared to in-situ measurements. Therefore, this line commonly possesses a slope of less than one.

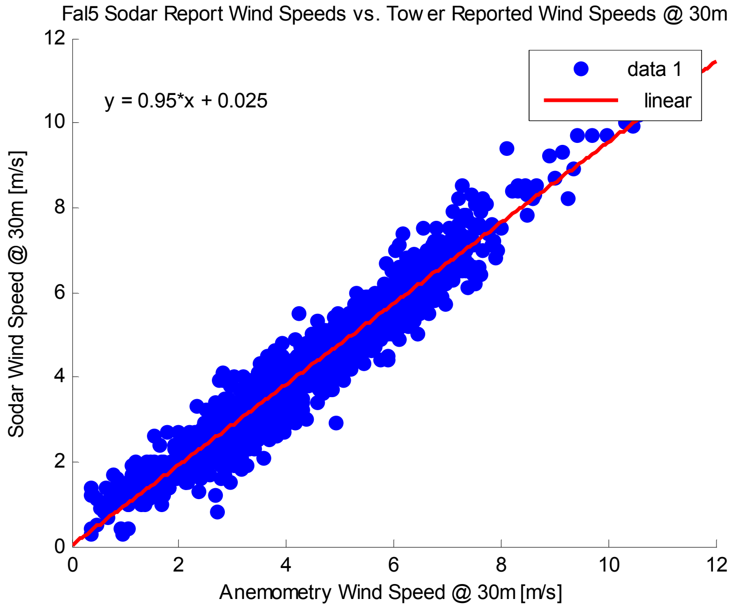

Figure 1

Figure 2 shows a particularly egregious example of the cluttered site signature—from the Orleans, MA site.

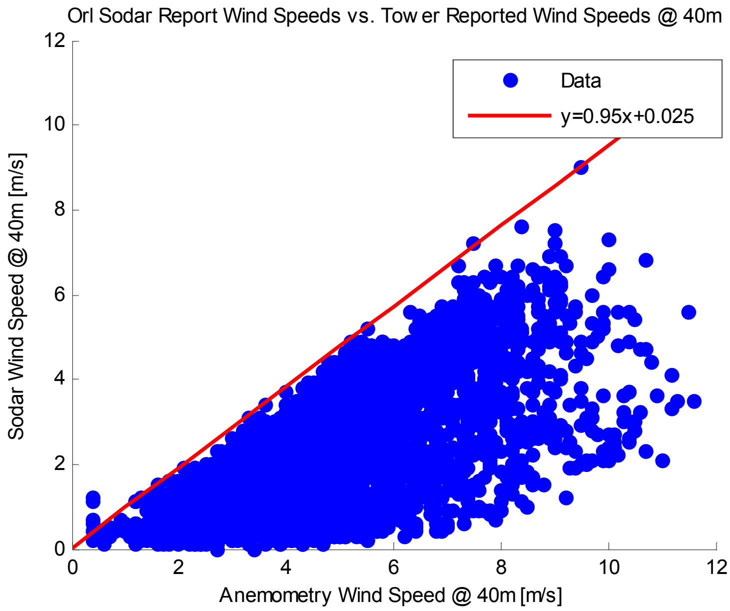

Figure 2

Without another source of accurate data for comparison (i.e. an instrumented tower) this faulty data can easily be taken as representative of the site's wind regime. The question to be answered is: How is it possible to assure that SODAR collected data is indeed representative of the true conditions without the use of in-situ anemometry and the inconvenience this extra equipment imposes? The RERL has been investigating the use of SODAR in complex terrain (as previously mentioned) and at cluttered sites and is in the process of developing an experimental method for determining the validity of SODAR collected data in these environments that does not require wind-monitoring towers. The problem can be broken into two parts, which shall be addressed here: 1) is it possible to recognize this clutter-affected data—without in-situ anemometry, and 2) can this clutter-affected data be salvaged somehow?

Overall Identification of Clutter Effects

As a first step in attempting to solve the problem of identifying cluttered data, an additional piece of hardware has been added—a short (approx. 5 m) pole-mounted anemometer. This short anemometer (or "shortie") can then be used for comparisons with the SODAR. The next step takes the form of a simple logical proposition: SODAR-measured wind-speeds across the range gates should cross-correlate more closely with any other range gate measured by the SODAR than these range gates should cross-correlate with the shortie-measured wind-speed. The reasoning of this proposition is two-fold: 1) correlation of wind speeds will decrease with increasing separation distance (i.e. height) and 2) measurements made by instruments based on entirely different operating principles should correspond less than the measurements of each instrument within its own dataset. Figure 3 shows data from the Hull, MA site that shows the expected relationship following from the logical proposition where the red crossed line corresponding to the SODAR 30 m vs. SODAR correlation is at all range gates greater than the blue line corresponding to the shortie vs. SODAR correlation.

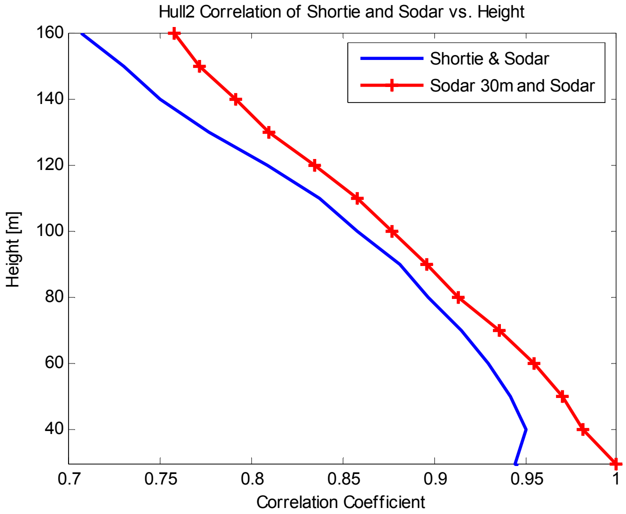

Figure 3

This proposition's use in recognizing clutter-affected data was first tested in April 2005 at the Long Island, MA site. Figure 4 shows the cross-correlation coefficient between the two data sets—shortie-measured wind-speed versus SODAR-measured wind-speeds at all range gates, and SODAR-measured wind-speed at 30 m (its lowest range gate) versus SODAR-measured wind-speeds at all other range gates.

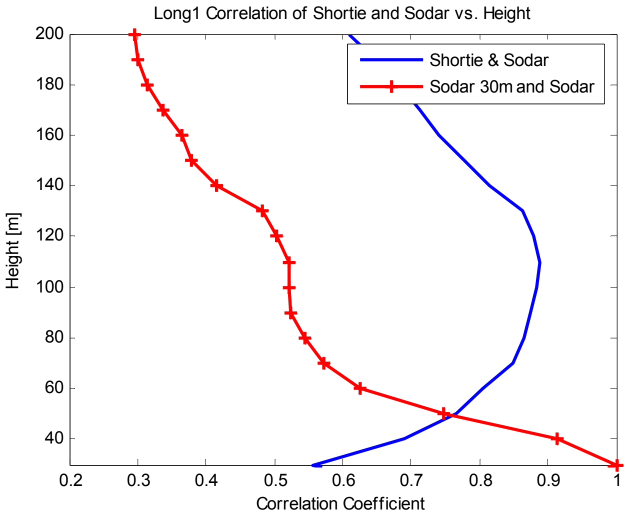

Figure 4

As can be seen in Figure 4, as the elevation increases the cross-correlation between the shortie and the SODAR is greater (blue line) than between the SODAR at 30 meters and all of the other range gates (red crossed line) with the exception of the 40 meter range gate. Obviously, something is affecting SODAR performance—it is believed that this something is echo from ground clutter. At the site, the SODAR was placed on the ground approximately 10 m from a large, low metal building, and trees with a maximum height of 7 m; these obstacles were well below a recommended 45° horizon. The SODAR was oriented with its beams pointing tangentially to a nearby small containerized lab, because, due to site constraints, its angular elevation (with respect to the SODAR) was 60°. Because of the care in siting, it was thought that the SODAR would be relatively unaffected by clutter at this site. Experience has shown that ground clutter issues in compact environments are often difficult to mitigate by siting alone. The shortie-correlation method has since successfully been used at a handful of sites for detecting clutter-affected data.

A natural question that follows is: How much data is required for this analysis? The answer varies because the wind regime at the site, as well as the placement of the shortie, will naturally affect the results. Approximately two weeks' worth of contiguous data (approximately 2000 ten-minute samples) has sufficed in the datasets so far studied. One could speculate that acquiring enough data to capture the underlying essence of the Van der Hoven spectrum is the cause for the required duration.

Identification and Removal of Clutter-affected Data

Another direction in the solution to clutter-contaminated data comes from attempts at recognizing flawed data within a larger dataset. The goal of this solution would be to identify and excise "bad" portions of the dataset instead of classifying a whole dataset as "bad". This search for identifiers has been greatly facilitated by the use of plotting routines that help in visualization of the large volume of data that the SODAR produces.

In fact, one of the complications of SODAR collected data is that there can be so much data, that it becomes difficult not only to process the data, but also to use the data provided in a useful manner. Conventional anemometry is usually limited to a handful of observation heights (i.e. mounting positions) that report only a few quantities of interest (e.g. mean and standard deviation of wind speed and direction); this limits the amount of data to be processed and reported to, for example, kilobytes of data over a month's measurements; however, SODAR can produce up to Megabytes of data per hour of measurement. This huge change in measured quantities results in fundamental questions about how to present the data in order to facilitate comprehension and analysis. Figure 5 is one typical ten-minute average output of the ART VT-1 SODAR. Each range gate entry displays statistics regarding vector averaged wind speed and direction, vector components wind speeds, component standard deviations, number of valid samples, reliability indicators, noise, returned signal amplitudes, and other quantities.


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30,4.4,266,9,.27,9,145,.42,1444,161,19.2,145,-4.1,9,145,2.3,1544,180,18.4,145,1.4,9,145,1.5,1306,151,18.6,145
40,4.7,257,9,.16,9,145,.48,1030,111,19.3,145,-4.2,9,145,2.3,1140,130,18.7,145,2.2,9,145,1.4,856,100,18.5,145
50,5.4,260,9,.15,9,145,.51,831,87,19.1,145,-4.9,9,145,2.1,833,97,18.4,145,2.3,9,145,1.6,719,83,18.2,145
60,5.8,263,9,.15,9,145,.45,680,74,18.5,145,-5.4,9,145,1.9,737,88,18.2,145,2.2,9,145,1.4,613,71,18.3,145
70,6.3,265,9,.19,9,145,.43,577,66,18.2,145,-5.9,9,145,1.8,618,75,17.7,145,2.2,9,145,1.5,487,63,17.5,145
80,6.6,262,9,.14,9,145,.44,522,58,18.4,145,-6.1,9,145,1.8,535,69,17.3,145,2.5,9,145,1.3,432,54,17.6,144
90,6.9,262,9,.14,9,145,.39,430,52,17.8,145,-6.4,9,145,1.8,446,59,17,144,2.6,9,145,1.3,350,46,16.9,145
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110,7.8,267,9,.19,9,145,.42,284,39,16.7,144,-7.4,9,145,1.5,300,44,15.9,145,2.4,9,145,1.3,237,38,15,140
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130,8.4,272,9,.22,9,145,.35,182,31,14.4,140,-8.2,9,145,1.4,180,36,13.1,136,1.9,9,145,1.2,147,33,12.1,132
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150,9.1,275,9,.2,9,145,.32,112,27,10.9,109,-8.9,9,145,1.3,118,32,9.9,91,1.6,9,145,1.1,110,30,10.1,105
160,9.3,276,9,.22,9,145,.34,89,26,9.6,96,-9.2,9,145,1.3,105,31,9.2,90,1.5,9,145,1,85,29,8.4,74
3.4,0,3.4,0,-99.9
8.77
0
88
12.7
```


Figure 5

Of course, most interesting to wind resource assessment are the wind speeds and directions at all range gates; but the other data can provide valuable insight into the operation of the SODAR and/or the characteristics of the site. The following are examples of some of the visualizations that can be performed using the data from the ART VT-1 SODAR. Figure 6 shows plots for data collected during the Orleans, MA trial in which the magnitude and direction of the data points are plotted on a compass rose. By adding a third dimension, height, the range gates of each of the data points can be shown (color is also used in the Figure to segregate range gate height). This type of plot allows for patterns that change according to height to be visualized (e.g. on the right, as expected, returned signal amplitude decreases with height).

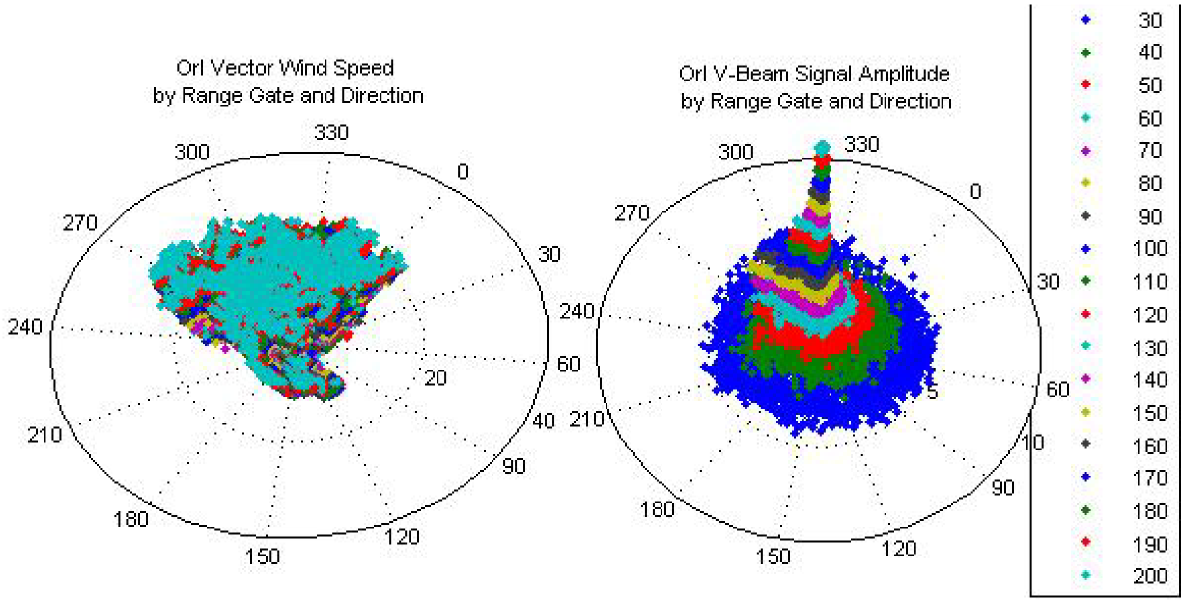

Figure 6

This amount of information can also overwhelm pattern recognition. To avoid this, the data can be binned into the familiar rose-type plot, as is shown in Figure 7. In this plot the width of the sector is proportional to the number of data points collected and the wind-speed has been normalized per range gate. This allows information about the quantity and quality of data to be visualized. For example, in Figure 7 it can be seen that at the lower range gates, increasing wind speed (shown on the right) does not necessarily correspond to high v-beam signal amplitude (shown on the left); this is one indication of possible clutter.

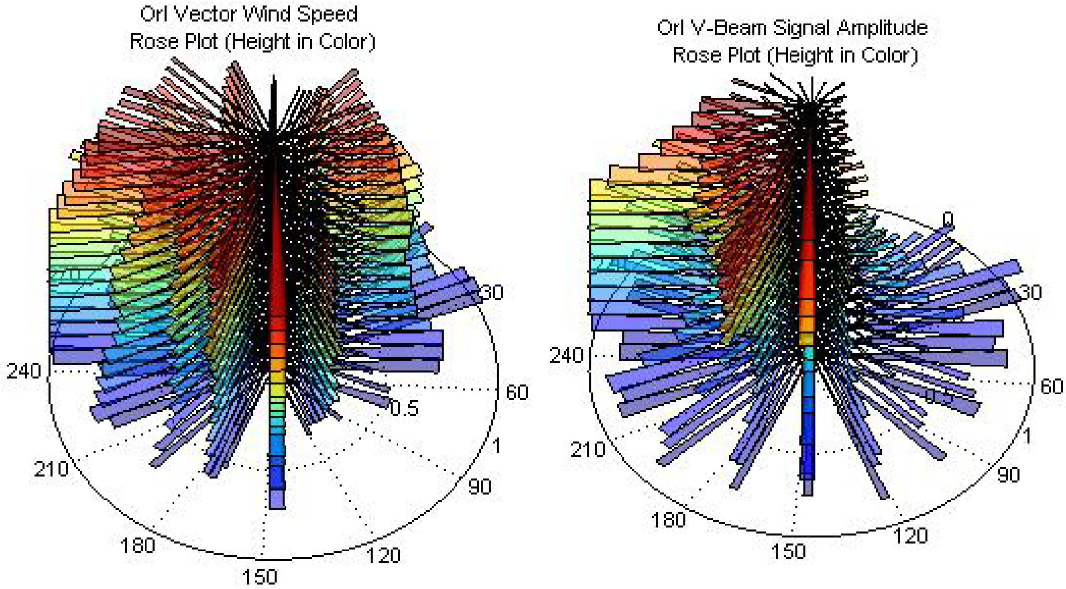

Figure 7

Figure 8 shows another type of plot that has been used to formulate a possible criterion for clutter-rejection. At higher wind-speeds (as measured by the in-situ anemometry), there is far less spread in the ratio of SODAR reported wind-speeds to in-situ reported wind-speeds. In effect, the SODAR is confused less by clutter echoes because the Doppler shift is stronger at higher wind-speeds which leads to stronger differentiation between signal (sound signal Doppler-shifted by wind-speed) and noise (clutter-affected zero Doppler-shift signal).

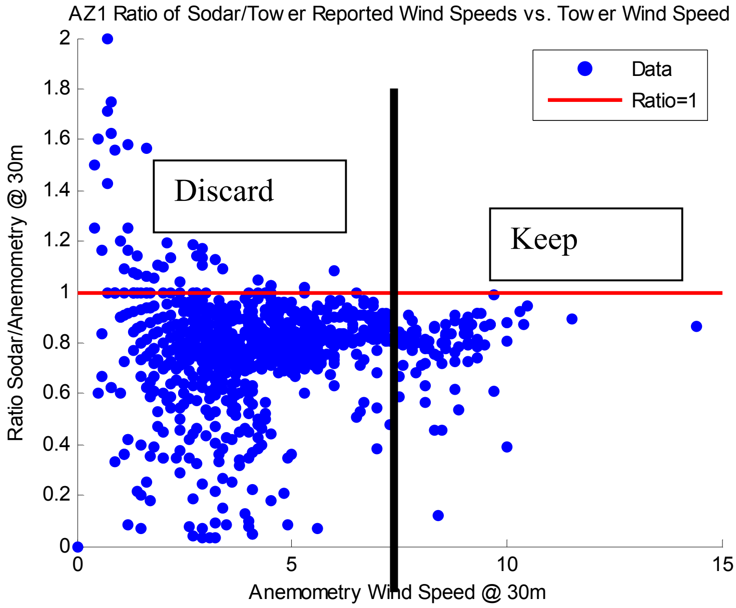

Figure 8

The logic behind Figure 8 leads to a criterion that accepts wind-speeds above a certain level and rejects those that fall below this level. Because this criterion rejects low wind-speed data it requires the use of some sort of measure correlate predict (MCP) analysis in order to make accurate predictions about a site's wind regime.

Figure 9 is the familiar SODAR-anemometry scatter plot with additional information presented by color-scale. The main portion of clutter–affected data has been circled. This plot has been used to formulate an alternate acceptance criterion.

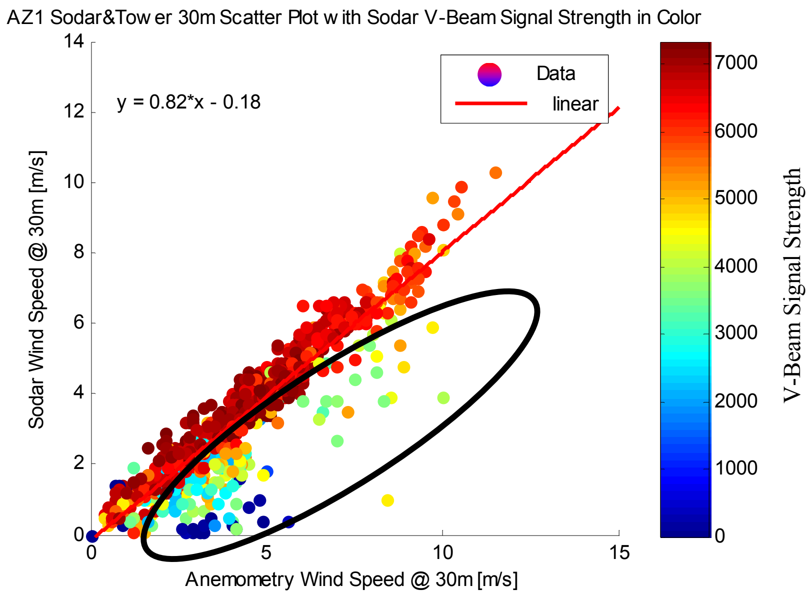

Figure 9

It is evident from Figure 9 that the clutter-affected data has a commonality in that the returned signal from the SODAR v-beam from this data is much lower than that of the clutter-free data. When the criterion requiring a certain minimum signal strength is applied, the clutter affected data is filtered out, as is shown in Figure 10.

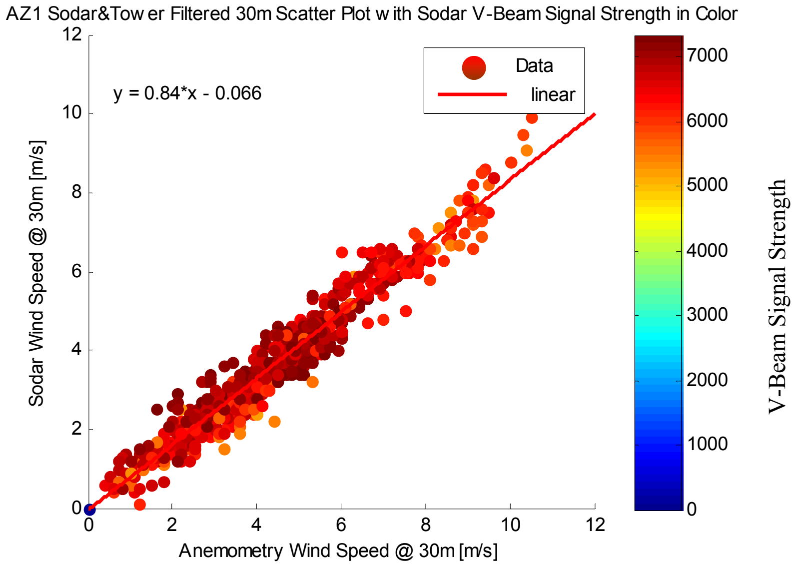

Figure 10

This approach accepts data over the range of wind-speeds making it more suitable for direct calculation of mean wind-speeds, as well as providing more information for MCP analysis which should shorten the required dataset length for estimation of long-term mean wind speeds. When the v-beam amplitude is shown using the Orleans, MA dataset of Figure 2, the value of this information can be appreciated (see Figure 11). Unfortunately at this site, the data has been so heavily influenced by clutter-induced echoes that there is little data left after a strong filter has been applied.

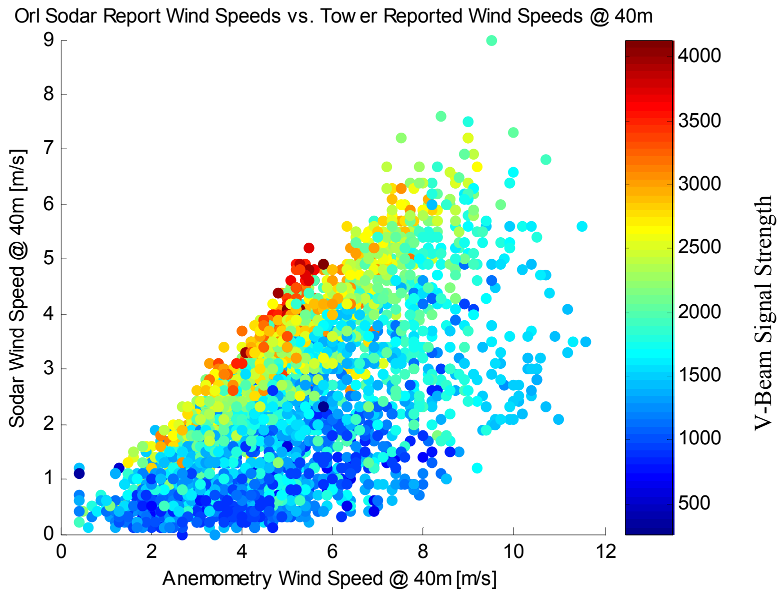

Figure 11

The question yet to be resolved is: What level should this filter be set at so as to maximize the size of the viable dataset while also maximizing correspondence to what would be measured by in-situ instruments? The intercomparison datasets studied so far indicate that at clutter-affected sites there is some correlation between the v-beam ("vamp") returned signal amplitude and two SODAR-tower error indices, while at clutter-free sites there is almost no correlation between them. The next Figures attempt to address this issue. The top portion of Figure 12 plots the cross-correlation coefficients of the two measures of the error between SODAR and anemometry and the v-beam returned-signal amplitude as the strength of the applied filter is increased. For example, the blue dashed line ("vamp & sodar-tower") corresponds to the correlation between v-beam returned-signal and the difference between SODAR and anemometry measured wind-speeds, while the red dash-dotted line indicates the number of filter-accepted samples. The bottom portion of the figure plots the cross-correlation coefficients between the SODAR reported wind-speed at 30 m and 1) anemometry reported wind-speed, 2) shortie reported wind-speed, and 3)

SODAR reported wind-speed at 100 m (presumably less affected by clutter; however, possibly in a different localized wind regime—especially in complex terrain).

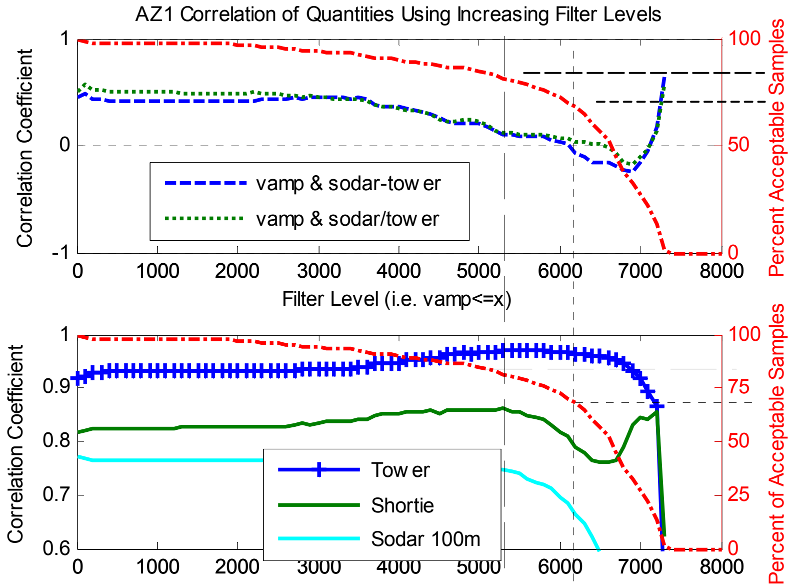

Figure 12

As can be seen from Figure 12 (indicated by a black thin, vertical, dashed line), the correlation of the shortie and the SODAR (green solid line) improves until approximately 80 percent of the dataset remains at which point it reaches a local maximum. The cross-correlation of the SODAR reported wind-speeds and the anemometry reported wind speeds (blue crossed line) also reaches a local maximum at about the same point. This is also near the point where the cross-correlation between the error indices and the v-beam returned signal strength approaches zero (indicated by the black thin, vertical, dotted line).

The top portions of Figure 12 from the Falmouth, MA site and Figure 13 from the Sunshine, AZ site illustrate the independence of v-beam signal strength and SODAR vs. anemometry error. This is encouraging; however, the goal is to reduce the very dependence on meteorological towers that would allow evidence of this relationship. Returning to the bottom portions of Figures 12 and 13 and to the correlations between shortie and SODAR, and SODAR and anemometry, one finds another possible indicator of how to set the filter level. As evidenced in both Figures 12 and 13, the first local maximum in the correlation between shortie and SODAR corresponds to the maximum correlation between SODAR and anemometry. This relationship requires only the use of the shortie and SODAR.

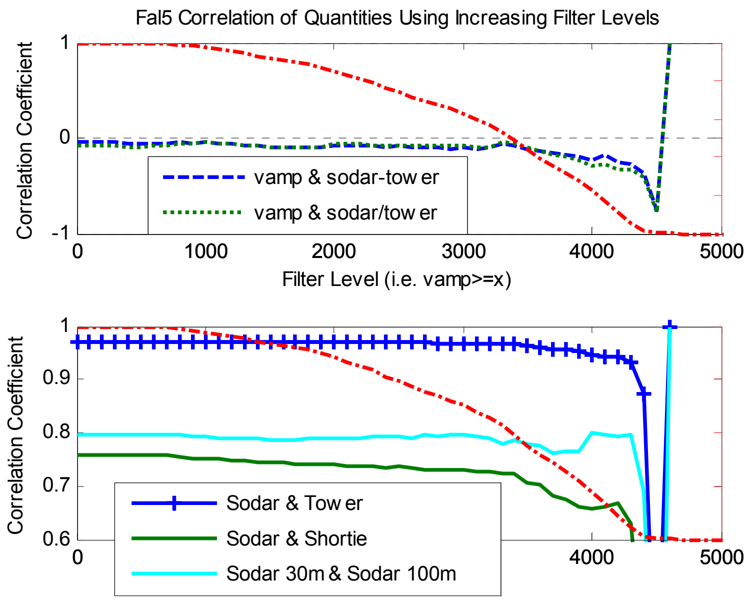

Figure 13

Conclusion

Cluttered sites can be problematic for SODAR wind-speed data collection. Without in-situ anemometry it may be difficult to detect that data has indeed been corrupted. This paper presents some of the experimental work that the RERL is performing in order to recognize clutter-induced echoes and mitigate their effects in SODAR data. The main findings of this research experience have been 1) remote control and data collection capability is essential to finding and correcting problems as soon as they occur; 2) much clutter-affected data can be salvaged by the use of appropriate filtering; 3) a short anemometer can be extremely useful in validating SODAR collected data and setting filter levels; and 4) there is more work to be done in processing SODAR collected data, especially to remove clutter effects. As more data is gathered, there will be more opportunities for validation and refinement of these and other methods. The authors would like to acknowledge the assistance provided by Atmospheric Research and Technology LLC, and thank Windfinders, LLC for some of the data used in this research. This paper marks the end of the RERL investigation of the ART VT-1 SODAR as a "grey box" with only changes in user adjustable parameters and changes in post-processing of data, and marks the beginning of a new phase of investigation that may use changes in run-time processing and possible addition and modification of software and/or hardware, all with the goal of increasing the accuracy, reliability, and robustness of SODAR for use in resource assessment.

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