The illustrations that follow outline several of the principal aspects of STARS performance for vertically-pointing profiler application. Sections 1 and 2 report on simulations of STARS operation. Section 3 summarizes results obtained through use of actual profiler field data. In each case, the transmit frequency is 915 MHz and a Cartesian coordinate system is assumed ($x$ and $y$ axes horizontal, $z$ axis along the vertical).

1. Simulated Measurements of Mean Wind Speed in Three Dimensions

Simulation of received signals for a ground-based wind profiler yielded an illustration of STARS recovery of three-dimensional winds. The simulations were based on the nine-panel antenna array shown schematically in Fig. 1. To maximize transmitted signal strength, all nine panels were used to transmit each pulse. Returned signals were received by four overlapping sub-arrays supporting four independent receivers. Each antenna sub-array was comprised of four adjacent antenna panels as shown in Fig. 1. The pulse repetition frequency (PRF) was 1,000 Hz, the range resolution was 60 m, and the center-height of measurements was 300 m. To obtain the radial velocity component, each antenna/receiver obtained and processed the signals from two overlapping range gates centered at 291 and 309 m respectively.

Fig. 2 shows encouraging results for the recovery of horizontal mean speed components $U_x$ and $U_y$. Velocities retrieved by STARS (green diamonds) are seen to closely track the time-varying “actual” or input wind velocities (red solid lines).

**Figure 1.** The nine-panel antenna array and configuration of four sub-arrays supporting receivers 1-4.

**Figure 2.** Comparison of STARS simulated retrieval of horizontal wind components (green diamonds) with time-varying input “actual” wind components (red line).
STARS retrieval utilized an averaging time of 10 sec. The simulation test included the effects of turbulence intensities (taken as 0.7 m/s, 0.5 m/s, and 0.3 m/s in $x$, $y$, and $z$ directions, respectively). No noise signal was superimposed on input values in this case.

Fig. 3 provides similar results for the recovery of vertical air motion ($U_z$), and illustrates STARS’ immunity to the velocity aliasing or folding found in velocity estimators that rely upon Doppler shift effects. As in the previous example, STARS $U_z$ estimates (green diamonds) compare favorably with the time-varying input velocity (red solid line) across the full range of input velocities. In contrast, velocity estimates retrieved from the peak of the Doppler spectrum (blue asterisks) show folding at $\pm 82$ m/s, which corresponds to the maximum unambiguous Doppler velocity. Details of the Doppler spectrum and the associated folding of mean velocity estimates at times $t_1$, $t_2$ and $t_3$ are shown in Fig. 4.

The preceding simulation illustrates STARS’ promising performance as an estimator of three-dimensional mean velocities under realistic conditions that include superimposed turbulence and time-varying velocity structure. We see clear evidence of a significant advantage of the STARS non-coherent scatter approach – namely immunity from the troublesome velocity folding or aliasing that is characteristic of coherent Doppler techniques. We believe this immunity yields especially attractive potential for application of STARS to velocity estimation tasks where complex velocity folding is a significant problem, e.g., atmospheric or other motion structures containing regions of strong radial velocity gradients.

**Figure 3.** Comparison of STARS simulated retrieval of vertical wind component (green diamonds), "actual" vertical wind (red line), and estimates of vertical wind derived from the Doppler spectrum (blue asterisks). Folding of Doppler estimates is seen at $\pm 82$ m/s (blue line).

**Figure 4.** The Doppler spectrum at times $t_1$, $t_2$ and $t_3$ (marked in Fig. 3) illustrating velocity folding at $\pm 82$ m/s.
2. Simulated Measurements of Horizontal Winds in the Presence of Strong Clutter

A second simulation exercise sought to examine the response of STARS processing to the presence of an interfering “clutter” signal of non-zero velocity. Superimposed turbulence affected both “pure” signal and clutter signal. The simulation parameters were equivalent to those above - with the following exceptions: (i) Imposed simulated turbulence intensities were 1.0 m/s, 0.75 m/s, and 0.5 m/s in the x, y, and z directions, respectively; (ii) Received signals were simulated for 300 m altitude only. Thus, no retrieval of the mean vertical wind component was carried out.

Retrieval of the horizontal wind components under clutter-free conditions and utilizing a 20-sec averaging period is shown in Fig. 5. As in the earlier simulation results (Fig. 2), retrieval of the average, time-varying horizontal wind was quite successful. The input or “actual” vertical wind component is also shown in Fig. 5, although this component was not retrieved.

The simulation of a clutter signal that interferes strongly with the “atmospheric” signal shown in Fig. 5 was carried out by introducing 50 scattering particles into a region of 20 m$^3$ at the center of the radar sample volume. Each clutter particle bore a randomly prescribed reflectivity and moved with constant mean speed components of $U_x = 5$ m/s, $U_y = 3$ m/s and $U_z = 0$. Each particle was also subject to turbulence intensities of 1.25 m/s in each dimension. Of particular importance to simulation of the STARS technique, the clutter particles were assigned a temporal correlation scale of 0.2 sec, which is typical of problematic, non-stationary clutter targets such as birds, fluttering tree leaves or ocean surface waves. Quasi-stationary clutter targets such as towers, buildings or terrain features are associated with a much longer temporal correlation scale.

Simulation of joint returns from atmospheric signal and clutter were carried out by summing atmospheric and clutter returns independently for each pulse. To evaluate STARS sensitivity to the strength of clutter returns, a series of simulations were carried out over a range of signal-to-clutter ratio (SCR) values. The results of these simulations are shown in Figs. 6-8, which correspond to SCR values of –10, –15 and –20 dB, respectively.

![Figure 5. Simulated STARS retrieval of horizontal wind components in clutter-free conditions. STARS data shown as green dots overlying time-varying input “actual” wind components shown as red line. Retrieval of vertical component (Uz) was not carried out.](image-url)
The simulation results in Figs. 6-8 demonstrate that the variance of retrieved velocity components increases noticeably as the SCR decreases from −10 to −20 dB. At SCR values of −10 and −15 dB, the standard deviation of the error in $U_x$ and $U_y$ components remained less than 1 m/s. At SCR values of −20 dB, however, the standard deviations of the error in both components exceeded 1 m/s, and we judge that at this SCR value the retrieval method failed to produce acceptable results for typical atmospheric profiling applications. It is interesting to note the importance of the clutter temporal scale on the degradation of STARS velocity estimates. As its temporal scale increases from 0.2 sec, clutter has diminishing effect on STARS results. We found that when the clutter temporal scale is 0.5 sec, the standard deviation of STARS $U_x$ and $U_y$ error components remained less than 1 m/s for SCR values as low as −25 dB.

Figure 6. Simulated STARS retrieval of horizontal wind components in the presence of clutter. SCR value is −10 dB. STARS data shown as green dots overlying time-varying input or "actual" wind components shown as red line.

Figure 7. As in Fig. 6, but for SCR value of −15 dB.

Figure 8. As in Fig. 6, but for SCR value of −20 dB. Note increased scatter in STARS estimates due to lower SCR value.
3. Measurements of Horizontal Winds and Turbulent Kinetic Energy with the NCAR MAPR

In this example we demonstrate the application of STARS to the retrieval of wind parameters using actual field data collected by the NCAR Multiple Antenna Profiling Radar (MAPR). This ground-based 915 MHz profiler utilizes a 2 m by 2 m flat plate antenna array comprised of four individual antenna panels approximately 1 m square. On transmit, the four antenna panels operate as a unified system. On receive, each panel acts as an independent antenna supporting a dedicated receiver. A detailed description of NCAR’s MAPR system is given by Cohn et al. (1997) in Radio Sci., 32, 1279 - 1296.

For this test, MAPR was installed approximately 600 m from the instrumented tower at the National Oceanic and Atmospheric Administration’s Boulder Atmospheric Observatory. A sonic anemometer atop the tower (at 300 m agl) collected continuous wind measurements for comparison with STARS retrievals at the same height. STARS processing was applied to MAPR data averaged over a 30-sec period. Resulting wind component estimates were further averaged over 5 min to match the averaging period of the sonic anemometer data. STARS 5-min average wind estimates were output every 30 sec.

Test results shown in Fig. 9 indicate that the horizontal winds derived from STARS processing (green line) compare very well with the simultaneous measurements made by the sonic anemometer (red line). This comparison utilizes field data collected on 16 November 1998 in clear conditions with moderate winds. It is interesting to note that no editing or quality control was applied to the MAPR data prior to STARS processing, and no editing or quality control was applied to the STARS wind estimates shown. This test demonstrates an important characteristic of STARS processing – that the processing itself does not introduce significant variance or noise in the output products. Of course, subsequent simulation and field testing is needed to better characterize the impact of input noise on STARS results.

Figure 9. Actual STARS retrieval of horizontal wind components (in green) using MAPR field data in moderate winds on 16 November 98. Simultaneous measurements from sonic anemometer shown in red.
A second test using the same field instrumentation was applied to field data collected in strong gusty winds in clear conditions over a 6-hr period on 23 November 1998. In this case we compared estimates of turbulent kinetic energy (E) from STARS processing of MAPR data with values of E derived from simultaneous anemometer measurements. Test results shown in Fig. 10 again illustrate promising agreement between the STARS estimates (in green) and the anemometer results (in red). As before, no editing or quality control was applied to the data presented in Fig. 10.

**Figure 10.** As in Fig. 9, but for retrieval of turbulent kinetic energy (E) in gusty conditions on 23 November 1998.

Overall, these field test results demonstrate excellent agreement between STARS products and measurements from the sonic anemometer. We are particularly encouraged by the absence of outliers in the STARS estimates. Further tests and simulations will explore the impacts of input noise over varying signal-to-noise ratios, clutter sources (such ground features, birds and heavy rainfall) over varying SCR values, and other factors relevant to field application of STARS.