Investigating Humidity Gradient Detection Using Bragg Scatter

B.L Crawford[1], A.D Byrd[2], and J.E Ruyle[2]

[1]*East Central University, Ada, OK*
[2]*Advanced Radar Research Center, University of Oklahoma, Norman, OK*

ABSTRACT

In real time and within a volume of space, humidity weather data is not readily available to all parts of the globe. Radar has the potential to provide such data. The ability to identify sharp changes in the refractive index is a first step in solving the larger issue of humidity. Using real weather data outputs from a large-eddy simulator (LES), a code was created to convert the data outputs into inputs for a passive multistatic radar simulator in an attempt to identify where fluctuations in the refractive index occur. The LES to radar simulator conversion code, used for identification of refractive index, and potential for the success of the simulation are investigated and discussed.

INTRODUCTION

Humidity weather data is not accessible to every place in the world. Not everyone around the globe has access to the technology and instruments used to collect such data. Vertical humidity profiles can currently be measured with instruments such as weather balloons, but they have to manually be sent up into the atmosphere. Using radars to take the vertical profile reduces the number of instrumentation necessary to collect measurements. Radars allow for less instrumentation and have the potential to be used globally.

Another problem that occurs from refractive index gradients is a phenomenon called atmospheric ducting. Ducting can take place when a channel is created between two sharp refractive index gradients. If the radar beam finds its way into the channel, it can propagate down the channel. This can result in the beam traveling a much larger distance that anticipated, which is problematic when precise locations of objects are trying to be identified. Beams traveling larger distances through ducts can be exploited. Ducting, if used strategically, has the potential to increase the range of radar systems.

One way to detect areas of turbulence and refractive index within the atmosphere lies in analysis of Bragg scattering. Bragg scatter echoes can be measured in the atmosphere to determine where fluctuation exists. This experiment is designed to take advantage of Bragg scatter data to display fluctuations in the atmosphere, ultimately determining absolute humidity.

Knowledge of the existence of these fluctuations and where they are occurring allows for identifying changes in the refractive index gradients to show where a possible duct may exist. Identification of refractive index gradients is a step towards being able to take real time and within a volume of space measurements of the humidity and being able to take vertical profiles of the humidity without manually sending out instrumentation.

Pre-existing free and shear weather data was used by a large-eddy simulator (LES). Free weather data corresponds to a clear boundary layer without wind shear. The shear data was a clear boundary layer with wind shear. Large-eddy simulation outputs were manipulated to be inputs for a bistatic radar simulator. Large-eddy simulations are a numerical tool used to compute large scale motions of turbulent flow[1]. Outputs from the LES underwent many mathematical conversions to become viable inputs for the passive multistatic radar simulator.

The following sections describe the data and methods behind the conversions along with the final results and conclusions.

DATA AND METHODS

Pre-existing weather data was run through a large eddy simulation. The outputs (u, v, w, E, q, Θ) correspond to the zonal wind field, meridional wind field, vertical wind field, subgrid TKE, specific humidity, and potential temperature, respectively [2]. Outputs were used to determine the refractive index, n. Equations (1-5) [2] were used once it was assumed that the background atmospheric pressure profile was in hydrostatic balance where the buoyancy force was equivalent to the downward force of gravity.

$$N = \frac{77.6}{T}\left(P + 4811\frac{e}{T}\right) \tag{1}$$

$$dlnP = -\frac{g}{RT}dz \tag{2}$$

$$T = \Theta\left(\frac{P}{P_o}\right)^{0.286} \tag{3}$$

$$e = \frac{qP}{0.622 + q} \tag{4}$$

$$n = 1 + N * 10^{-6} \tag{5}$$

The gas constant for dry air, (R), gravitational acceleration, (g), and initial pressure at z=0 (P_o) were the known variables. To find the refractivity, N, which was used to find (n), total atmospheric pressure (P), absolute temperature (T), and the partial pressure of water vapor (e) needed to be solved for. Total atmospheric pressure was solved for by manipulating equation (2) and equation (3) to obtain equation (6).

$$P = \left[\frac{1.714}{c}\left(z + \frac{c_o}{1.714}\,{P_o}^{1.714}\right)\right]^{\frac{1}{1.714}} \tag{6}$$

where z is the altitude at each measured point and c is equivalent to

$$c = \frac{-\Theta\,(R)}{g\,{P_o}^{0.286}} \tag{7}$$

Unlike Scipión, the radar simulator setup used for this research is not monostatic and pointed straight up in the air. The radar simulator for this particular research is a passive bistatic set up. Instead of applying the equation outlined by Scipión to find the structure parameter of refractive index to a line (beam), the angle at which the bistatic radars are setup must be accounted for. For this case, we cannot simply apply it to a direct line to the center of each subgrid as done by Scipión.

In order to accomplish this, the bistatic bisector was accounted for. The bistatic bisector was found using equation (8) where u corresponds to the vector between transmitter and target, v is the vector between the target and receiver, and a is the bistatic bisector[3].

$$a = ||u||v + ||v||u \tag{8}$$

Dividing a by the norm of a allowed for calculation of the bistatic bisector unit vector. Interpolation along the bistatic bisector unit vector found the bistatic bisector gradient. Once the bistatic bisector was accounted for, the structure parameter of refractive index can be solved for using equation (9).

$$C_n^2 = \frac{\left\langle [n(r+\delta) - n(r)]^2 \right\rangle_r}{|\delta|^{\frac{2}{3}}} \tag{9}$$

The structure function parameter of refractive index allows for a way to statistically describe how the small scale turbulent fluctuations of the refractive index affect the propagation of electromagnetic waves.

After the structure function parameter of refractive index was calculated for, the radar simulator was modified to include the new calculations. The new structure function parameter was included in the code making it possible to run the radar simulation with the new code. Once the radar was able to simulate the turbulence using the structure function parameter of refractive index, the refractive index gradient could be observed to find any ducts within the atmosphere.

RESULTS

After calculating equations (1-9) the structure function parameter of refractive index could be plotted and analyzed for both the free and shear data sets. Figure [1] and Figure [2] show results for the structure function parameter of refractive index for the free LES weather

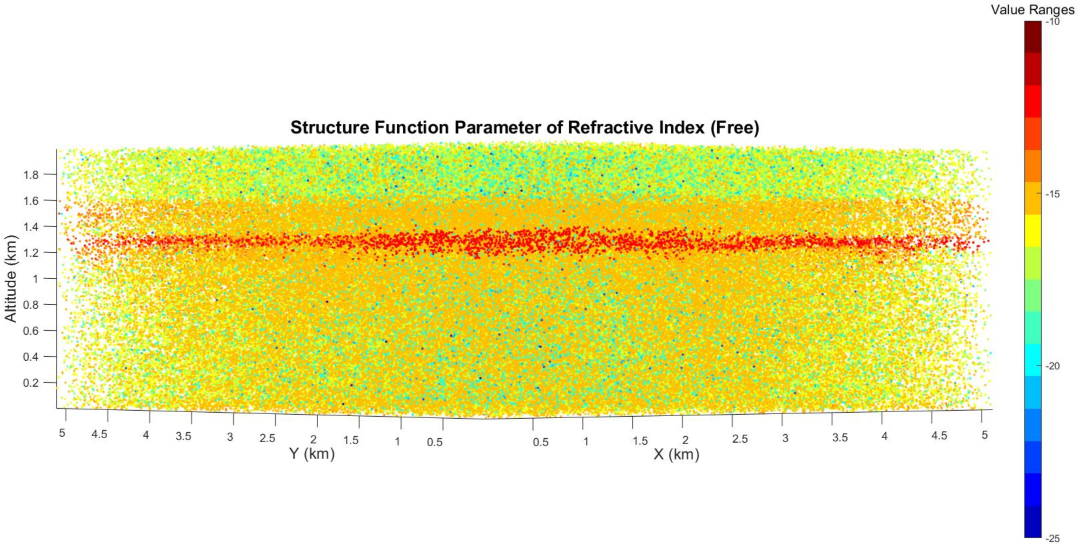

Fig. 1. Structure function parameter of refractive index from LES free data.

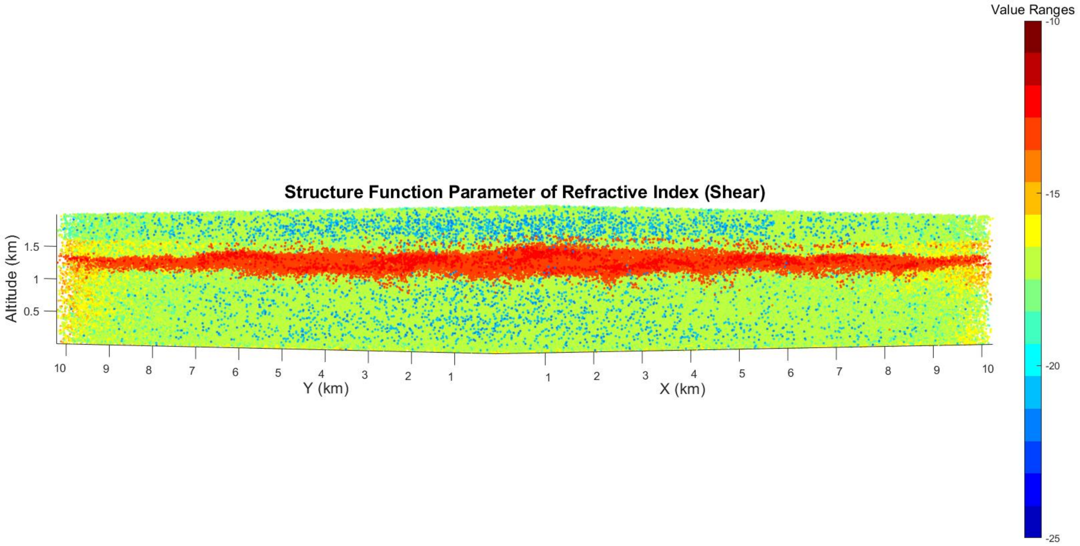

Fig. 2. Structure function parameter of refractive index from LES shear data.

data and shear LES weather data, respectively. To make the data easier to visualize, the logarithm of the structure function parameter was taken. The data was depicted in a 3D-plot to show if there was uniformity in the layers or if the values were completely scattered. As Figure [1] and Figure [2] show, the values were uniform within the layers and show change as they go higher in the atmosphere.

Something interesting to notice is the thin change in the structure function parameter of refractive index you can see between the layers in the atmosphere on both plots. This change was viewed in all of the plots made from the LES data. It was determined that this change was a common shift in values that should be seen in all of the variables calculated during this research. The plot shows how gradients for free and shear LES data have small magnitudes until it reached the level of turbulence and the gradient magnitude gets larger. Once it passes that layer, the magnitude decreases again. This sharp increase in structure function parameter of refractive index values shows us that there is indeed turbulence and a gradient in refractive index occurring at that area in the atmosphere. The physical nature of the change is further discussed in [2].

Figure [3], Figure [4], and Figure [5], located on the following pages, depicts the results after running the simulator with the new structure function parameters of the refractive index through the radar simulator. The simulator is set up to have three receivers making up the multistatic radar. Due to three different receivers surrounding the weather, each receiver sees a different angle of the weather. These specific views of the weather correlate to getting clearer results in the SNR for either forward scatter, back scatter, or perpendicular scatter.

Figure [3] visually represents the received power from the change in the refractivity. More specifically, it shows the power received that can be seen from the forward scatter. Utilizing the Bragg scatter allowed for the change in refractivity to be seen. Since our simulator simulated the results seen by three receivers, each receiver allows us for either the forward scatter, back scatter, or perpendicular scatter signal to noise ratio. Figure [4] and Figure [5] depict the SNR measured by the receivers from the

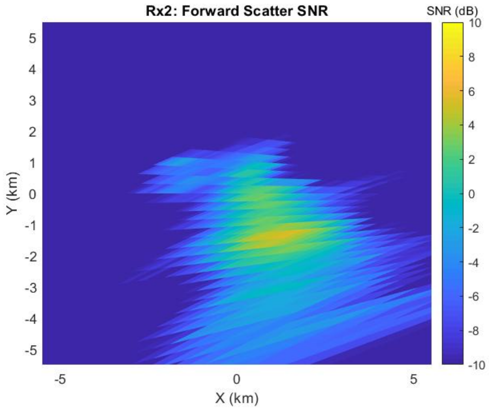

Fig. 3. Forward scatter signal to noise ratio plot from LES weather data ran through radar simulation

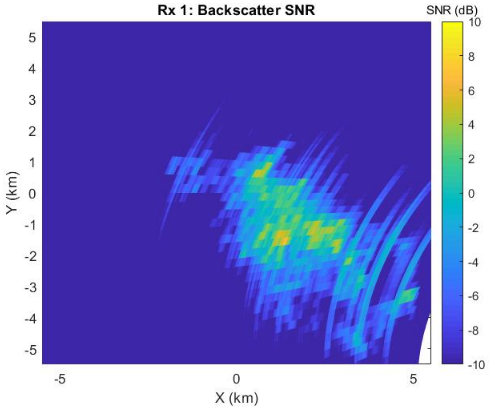

Fig. 4. Back scatter signal to noise ratio plot from LES weather data ran through radar simulation

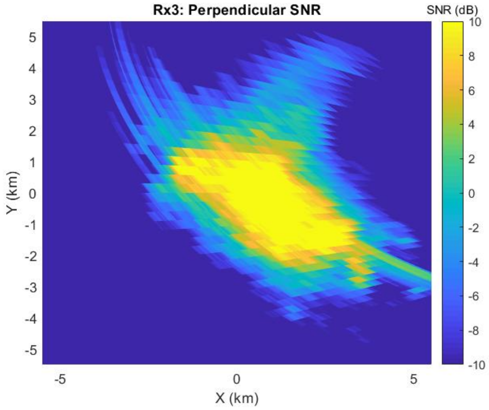

Fig. 5. Perpendicular signal to noise ratio plot from LES weather data ran through radar simulation

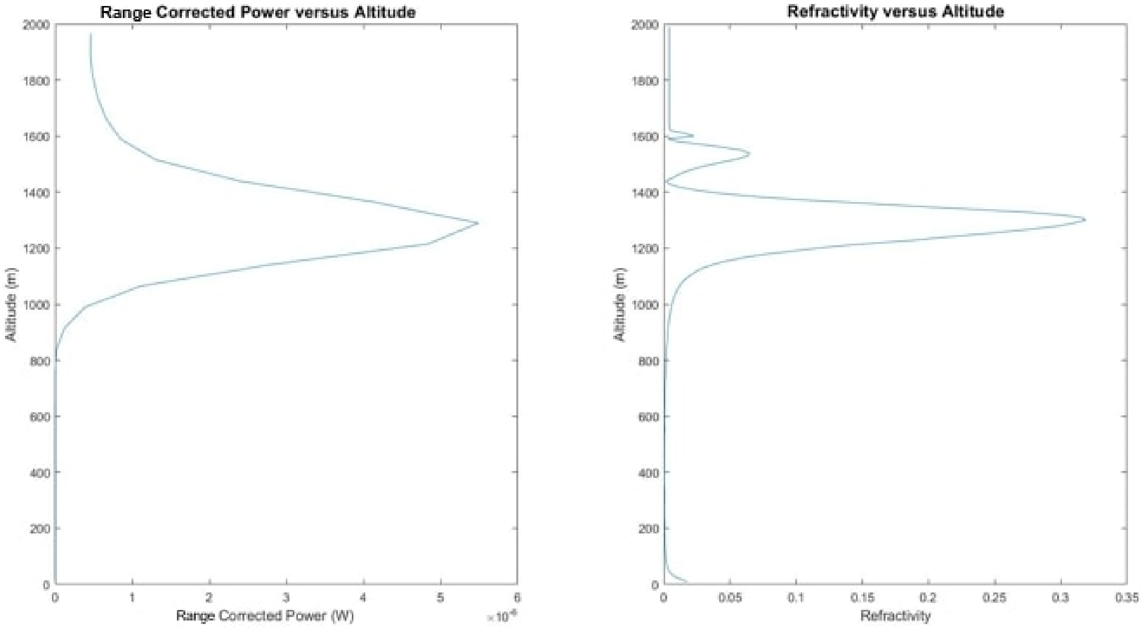

Fig. 6. Comparison of range corrected power versus altitude and refractivity versus altitude. Plots observe the altitude at which peak corrected power and refractivity were recorded.

back scatter and perpendicular scatter, respectively.

Figure [8] is a set of two graphs, from ground level to 2000 meters, showing the power being received from in the atmosphere and where the sharp change in refractive index is located. Range corrected power is the information about the amount of power reflected by a specific volume. Initially, the power received depended on both the amount of power reflected and how far away from the volume the receivers are. Multiplying by the range squared, (r^2), removes the effect of the distance so that the result only reflects power reflected per unit volume. As you can see, both graphs peak close to 1300 meters high in the atmosphere. This suggests that the most power is being recorded at the same altitude as the sharp change in the refractive index. If one can locate the sharp change in refractive index with the peak in power shown by the radar, one could potentially locate atmospheric ducts.

DISCUSSION

Many assumptions about the weather data were made throughout the experiment. In order to use equation (9), it was assumed that that the turbulence was isotropic and in the inertial subrange, along with the radar resolution volume being uniformly filled throughout with turbulence [2]. To make equations (1-4) true, it was assumed that the background atmospheric pressure profile was in hydrostatic balance [2]. Since Scipión made such assumptions in his earlier experiments using similar LES weather data, we believed the same assumptions could be made for our experiment. If the weather data used does not follow the assumptions made, different methods of calculating the structure function parameter of refractive index would be necessary.

Azimuthal smears can be seen in figure 5-7 which could come be from various sources. Few points are being calculated to have structure function parameter values that are impossibly large. These are acting like strong point targets that are drowning out Bragg scatter signals and getting smeared out by the wide beam pattern of the receiver. A few sources of error can be looked at. One source of the error could be from calculating the gradient. When doing estimates on derivatives of noisy data, as done in the calculations of the gradient, issues with outlying values could occur. Another source of the error could come from numerical precision issues.

A simple solution to the problem would be throwing away outliers in the structure function parameter of the refractive index to eliminate the artifacts. Gradient issues could possibly be improved by using a higher order difference estimate that includes more points. The precision issue could possibly be improved by adding scaling factors, doing some calculations, and removing them at the end.

In this study, the refractive index gradient was calculated, but ultimately the humidity gradient is what needs to be found. Because the refractive index gradient and the humidity gradient act so similarly in the atmosphere, one can observe the refractive index gradient and have an idea of how the humidity gradient is working. Extracting the humidity gradient and humidity from the refractive index with require more calculations and known variables. Going from the the refractive index gradient to the humidity gradient is something that will be explored in further work.

CONCLUSIONS

Simulations indicate that passive multistatic radar can use Bragg scatter to detect changes in refractive index. Future work would include expanding on the refractive index information to be able to take real time and space, within a volume, measurements of the humidity. If the humidity could be found using radar, it could then be expanded to cover the globe.

ACKNOWLEDGMENTS

The author would like to thank Dr. Daphne LaDue, the Research Experience for Undergraduates program, and the Advanced Radar Research Center for the opportunity to conduct research. Thank you to the mentors, Dr. Jessica Ruyle and Dr. Hjalti Sigmarsson, for their guidance. Also, a special thanks to Andrew Byrd, Alexander Moreno, and Melanie Schroers for coding assistance and their willingness to share their knowledge.

The funding for this research was supported by the National Science Foundation under Grant NO. AGS-1560419.

REFERENCES

[1] Y. Zhiyin, “Large-eddy simulation: past, present and the future,” *Chinese Journal of Aeronautics*, vol. 28, no. 1, pp. 11–24, 2015.

[2] D. E. Scipión, P. B. Chilson, E. Fedorovich, and R. D. Palmer, “Evaluation of an les-based wind profiler simulator for observations of a daytime atmospheric convective boundary layer,” *Journal of Atmospheric and Oceanic Technology*, vol. 25, no. 8, pp. 1423–1436, 2008. [Online]. Available: https://doi.org/10.1175/2007JTECHA970.1

[3] “How to find the vector formula for the bisector of given two vectors?” Mathematics Stack Exchange, uRL:https://math.stackexchange.com/q/2285965 (version: 2017-05-18). [Online]. Available: https://math.stackexchange.com/q/2285965

[4] R. J. Conzemius and E. Fedorovich, “Dynamics of sheared convective boundary layer entrainment. part i: Methodological background and large-eddy simulations,” *Journal of the atmospheric sciences*, vol. 63, no. 4, pp. 1151–1178, 2006.

[5] A. Muschinski, P. Sullivan, D. Wuertz, R. Hill, S. Cohn, D. Lenschow, and R. Doviak, “First synthesis of wind-profiler signals on the basis of large-eddy simulation data,” *Radio Science*, vol. 34, no. 6, pp. 1437–1459, 1999.

[6] R. Kropfli, I. Katz, T. Konrad, and E. Dobson, “Simultaneous radar reflectivity measurements and refractive index spectra in the clear atmosphere,” *Radio Science*, vol. 3, no. 10, pp. 991–994, 1968.

[7] D. R. E. Rinehart, *Radar for Meteorologists: or You, Too, Can Be a Radar Meteorologist, Part iii*. Rinehart Publishing, 2010, vol. 5.

[8] C. T. A. R. Centre, “Ctarc photos of june 2017 meeting - 25 jun ’17.” [Online]. Available: http://zs1ct.blogspot.com/2017/06/ctarc-photos-of-june-2017-meeting-25.html

[9] D. Scipión, E. Fedorovich, R. Palmer, P. Chilson, and A. Botnick, “Turbulence kinetic energy and dissipation rate estimated from a virtual wind profiler and verified through large eddy simulations,” pp. 1–10, 01 2009.