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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

INVESTIGATION OF OUTER LENGTH SCALE IN OPTICAL TURBULENCE USING AN ACOUSTIC SOUNDER

by

Jeffrey T. Douds

September 2004

Thesis Advisor:	D.L. Walters
Co-Advisor:	R.C. Olsen

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13. ABSTRACT (maximum 200 words)

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The data sampled at 2 and 5-minute intervals emphasized features within an individual thermal plume. The mean correlation distances found for 2 and 5-minute intervals were 81 meters ± 70 meters and 89 meters ± 72 meters, respectively. Their medians were 61 meters and 69 meters; and their modes were 41 meters and 50 meters, respectively.

The 10-minute time interval statistics used a low pass filter to emphasize larger scale features. The mean correlation length was 494 meters ± 373 meters, the median was 391 meters and the mode was 316 meters. These distances represent the distance between the center of a plume and the center of a quiet region adjacent to that plume.

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INVESTIGATION OF OUTER LENGTH SCALE
IN OPTICAL TURBULENCE USING AN ACOUSTIC SOUNDER

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MASTER OF SCIENCE IN SPACE SYSTEM OPERATIONS

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I would like to thank my wife, Solly, and my children, Tachiana and Ashley. Without their love, support, and companionship, this work would not have been possible. You’re what it’s all about.

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I. INTRODUCTION

A. OBJECTIVE

Light propagation through the atmosphere is affected by atmospheric absorption, scattering and turbulence. Velocity fluctuations in the atmosphere mix regions of the air with different temperatures producing local changes in the refractive index. This optical turbulence induces phase and amplitude fluctuations in electromagnetic waves that propagate through the air. These fluctuations smear the ability to see detail in imaging systems or spread and induce scintillation in laser beams. The atmospheric optical fluctuations are not distributed uniformly in the atmosphere, but are concentrated in local convective regions during the day. Understanding the spatial scale of these regions is part of the process of mitigating their effects.

This thesis focused on measuring an atmospheric outer scale length known as the horizontal convective scale by computing the autocorrelation length of the acoustic sounder and anemometer data in order to estimate the lateral dimensions of the turbulent, detrimental events. The data analyzed in this thesis were generated by an acoustic sounder that was directed vertically into the atmosphere to collect turbulent atmospheric data and by an anemometer used to measure wind speed. These instruments were located at the Starfire Optical Range, New Mexico.

B. BACKGROUND

1. The Acoustic Sounder

An acoustic sounder is a device designed to emit acoustic radiation and detect returns of that energy. This device has also been called a sodar (sonic detection and ranging). It is much like sonar, which detects objects underwater, except that sodar detects and measures properties of the air. One of the primary things that an acoustic sounder is good at is detecting and characterizing turbulence in the air since the signal that the sounder emits is scattered back by turbulence.

Acoustic sounders are available commercially. An example of a commercial acoustic sounder is the Model VT-1 sodar developed by Atmospheric Research & Technology (ART) (Neal 2004). This unit is a self-contained, portable system and includes a phased-array acoustic transmitter and receiver with supporting electronics, a notebook computer and software for system configuration, operation and data storage. Figure 1 shows this sodar.

Figure 1. Model VT-1 phased-array doppler sodar system.

The acoustic sounder used to gather the data presented in this thesis was designed and built by Professor Donald Walters, Ph.D., professor of physics at the Naval Postgraduate School, Monterey, CA. Figure 2 shows a picture of this acoustic sounder. Acoustic sounders are not good at retrieving reliable data during rain and their internal components can be damaged by inclement weather. Notice the lid on the acoustic sounder which can be lowered during rain.

Figure 2. Acoustic sounder designed and built by Professor Donald Walters and Jay Adeff at the Naval Postgraduate School.

2. Convective Turbulence

Thermal convective cells, or plumes, are formed in the atmospheric boundary layer (the layer of air bounded by the surface of the earth and about 1-2 kilometers above the surface) during the day as the sun warms the earth.

These convective cells consist of heated, turbulent air and they concentrate the optical path degradation into near vertical columns. These plumes are, however, separated by regions of relatively low turbulence where the optical path is relatively quiescent. Measuring the size of these plumes of turbulent air, and the quiet regions between them, is a component of an atmospheric compensation design. In order to understand and use an acoustic sounder for turbulence measurements, the structure of turbulence and the interaction with optical and acoustic radiation is essential.

The following section, from equations 1 to 10, follows that done by Lim (2003).

> To deal with the randomness of atmospheric turbulence, Kolmogorov used a statistical approach that relies on dimensional analysis to handle the spatial and temporal fluctuations (Max 2003). By assuming homogeneity and isotropy at least in a local volume, and if the random processes have slowly varying means, structure functions represent the intensity of the fluctuations of $f(r_1,r_2)$ over a distance between r_1 and r_2. Using the mean square differences, the structure function of $f(r_1,r_2)$ is:
>
> $$D_f(\overline{r}_1,\overline{r}_2) = \left\langle \left[f(\overline{r}_1) - f(\overline{r}_2) \right]^2 \right\rangle . \qquad (1)$$
>
> According to Kolmogorov's turbulence theory, turbulent eddies range in size from macroscale to microscale, forming a continuum of decreasing eddy sizes. Energy from convection and wind shear is first added to the system at the outer scale L_0 (10's - 100's of meters) before it cascades to a smaller scale l_0 (~ 1cm) where viscosity converts the energy to heat (Andrews 2001). By dimensional arguments and assuming an incompressible isotropic, homogeneous medium, Kolmogorov showed that the longitudinal structure function of the velocity is:
>
> $$D_v(r) = C_v^2 r^{2/3}, \qquad l_0 < r < L_0 . \qquad (2)$$
>
> The $r^{2/3}$ proportionality of the structure function in the inertial range ($l_0 < r < L_0$) applies to other structure functions such as temperature and refractive index. The refractive index structure function is:

$$D_n(r) = C_n^2 r^{2/3}, \tag{3}$$

where C_n^2 is the refractive index structure parameter, or the optical turbulence parameter ($m^{-2/3}$). Comparing equations (1) and (3), the refractive index structure parameter has the form:

$$C_n^2 = \frac{\left\langle (n_1 - n_2)^2 \right\rangle}{r^{2/3}}. \tag{4}$$

While C_n^2 is the critical parameter that describes optical turbulence, it is extremely difficult to measure C_n^2 directly using standard techniques since the index of refraction of the atmosphere is influenced by the atmosphere's temperature, pressure, moisture and the wavelength of the electromagnetic wave. However, C_n^2 depends on the temperature structure parameter, C_T^2 which can be measured directly. C_T^2 has a mathematical form similar to C_n^2:

$$C_T^2 = \frac{\left\langle (T_1 - T_2)^2 \right\rangle}{r^{2/3}}. \tag{5}$$

Though the refractive index depends on the dry-air wavelength, it is typical to ignore the wavelength dependence and assume a wavelength of 0.5µm (Beland 1996). The index of refraction is

$$n = 1 + 79 \times 10^{-6} P/T\ . \tag{6}$$

Taking the partial derivative of the air density with respect to the temperature and assuming isobaric density fluctuations, the optical turbulence parameter C_n^2 relates to the temperature structure parameter C_T^2 by

$$C_n^2 = \left(\frac{\partial n}{\partial T}\right)^2 C_T^2 = \left(79 \times 10^{-6} \frac{P}{T^2}\right)^2 C_T^2, \tag{7}$$

where C_n^2 is the optical turbulence parameter in $m^{-2/3}$, C_T^2 is the temperature structure parameter in $K^2m^{-2/3}$, P is the air pressure in mbar and T is the air temperature in Kelvin.

3. Acoustic Sounder Measurement

The acoustic sounder uses acoustic waves scattered by temperature and velocity fluctuations to measure changes in the refractive index of the atmosphere. It transmits an acoustic signal into the atmosphere and, for energy backscattered at 180 degrees, detects variations in the thermal structure parameter C_T^2 (Tatarski 1971). Once C_T^2 is found, equation (7) provides the optical turbulence parameter C_n^2.

The power returned from the atmosphere was summarized by Neff (1975)

$$\frac{P_r}{E_r} = \left[P_t E_t\right]\left[e^{-2\alpha R}\right]\left[\sigma_0\left(\frac{c\tau}{2}\right)\left(\frac{A}{R^2}G\right)\right], \tag{8}$$

where $\frac{P_r}{E_r}$ is the received power (P_r is the measured electrical power and E_r is the efficiency of conversion from received acoustic power). $P_t E_t$ is the transmitted power (P_t is the electrical power applied to the transducer, E_t is the efficiency of conversion to radiated acoustic power). $e^{-2\alpha R}$ is the round trip loss of power resulting from attenuation by air where α is the average extinction coefficient (m^{-1}) to the scattering volume at range R(m). σ_0 is the backscatter cross section per unit volume and $\frac{c\tau}{2}$ is the maximum effective scattering volume thickness where c is the local speed of sound (ms^{-1}) and τ is the acoustic pulse length (s). $\frac{A}{R^2}G$ is the solid angle subtended by the antenna aperture A (m^2) at range R (m) from the scattering volume, modified by the factor G that accounts for the non-uniform antenna illumination.

Tatarskii (1971) expressed the backscatter cross section σ_0 at 180° as

$$\sigma_0 = \frac{\pi}{2} k^4 \frac{\Phi_T\left(2k\right)}{T_0^2}, \tag{9}$$

where $k = 2\pi/\lambda$ is the incident wavenumber, T_0 is the mean temperature, and $\Phi_T\left(2k\right)$ is the 3-D spectrum of turbulence. The cross section σ_0 represents the in-phase addition of backscattered waves from temperature inhomogeneities spaced $\lambda/2$ apart along the radial propagation direction. The temperature inhomogeneities can be represented by the temperature structure parameter C_T^2 Neff (1975) and the volume backscatter cross section for 180° returns becomes

$$\sigma_V = 0.0039 \quad k^{1/3} \frac{C_T^2}{T^2}. \tag{10}$$

The acoustic volume scattering cross section is proportional to the temperature structure parameter and the acoustic wavenumber. This provides the optical structure parameter C_n^2 indirectly with high spatial and temporal resolution.

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II. OBSERVATIONS

The acoustic sounder was directed vertically into the atmosphere to collect atmospheric data from 1 March 2001 until 12 August 2002 at the Starfire Optical Range in Kirtland Air Force Base, New Mexico. It was located near the top, but on the south side of a 70 m hill. Operating with a 4 KHz, 10-millisecond acoustic pulse, the acoustic sounder sampled the temperature structure parameter C_T^2 between 5 and 150 meters (in height) every second. The optical structure parameter C_n^2 was later calculated from the measured C_T^2 values. The Doppler frequencies of the returned signals were also captured. An anemometer located 15m above the ground measured the wind speeds.

The raw data from the acoustic sounder and the anemometer were saved as data files. Computing the autocorrelation of the mean C_n^2 values between 20-50 meters versus time and multiplying by the wind speed gave an autocorrelation function versus distance. The acoustic sounder data consisted of C_n^2 profiles collected once a second between 20 and 150 meters above the ground with a range resolution of 1.7 meters. After computing a single mean C_n^2 value for the data between 20-50 meters, the autocorrelation function of these values for 2, 5 and 10-minute segments of data gave the autocorrelation function versus time. The distance between the peak and the first minimum was computed by searching for the change in slope, after applying a 5th order, low-pass, Butterworth filter to the smooth the irregularities in the autocorrelation function. The distance between the peak and the first minimum in the auto correlation function, versus time, multiplied by the wind speed gave the thermal autocorrelation length. This distance is physically represented as the distance between the center of an area of strong thermal activity and the center of the area of relatively little thermal activity adjacent to it. Using a Matlab program (Appendix A) the data from 1000-1600 (local time) was analyzed. This time interval was chosen because this is when convection is intense. The data from other times would exhibit different scales and would not represent the strong turbulence situations.

The acoustic sounder data was a continuous, 24-hour stream and had to be organized into subsets in order to measure the convective scale lengths. The size of the subset chosen affects the measured scale length. For instance, a larger time scale would emphasize the distance between individual thermal plumes. A time scale of 10 minutes was chosen to measure this length. Smaller time scales would reveal features within a thermal plume. Time scales of 2 and 5 minutes were chosen to look for these features. The Matlab program displays this data in a color plot that depicts, in some sense, the plumes themselves. The program also uses an autocorrelation function in order to measure the time interval between the center of one plume and the center of the quiet region between it and the next plume.

A. RESULTS

As a representative sample of some of the data, the C_T^2 and Doppler frequencies measured over a 5-minute or 600-second interval (1 July 2001 from 1350-1355 hours, MST) are plotted in Figure 3 below. This figure shows a plot of the magnitude of C_T^2 represented in terms of intensity with the radial Doppler frequencies of $\pm$ 4 m/s as color for a 600 second interval. In general, red regions are plumes of air (similar to convective cells) moving upwards, green regions have little vertical motion, and blue regions are moving downwards. The speckled area mostly above 50 meters in range in Figure 3 represents noise. This noise degrades the calculation of the correlation time. Further, the data between 0-20 meters was not valid (and is not depicted in the plot because of this). For these reasons, the data analyzed were restricted to lie between 20-50 meters in range.

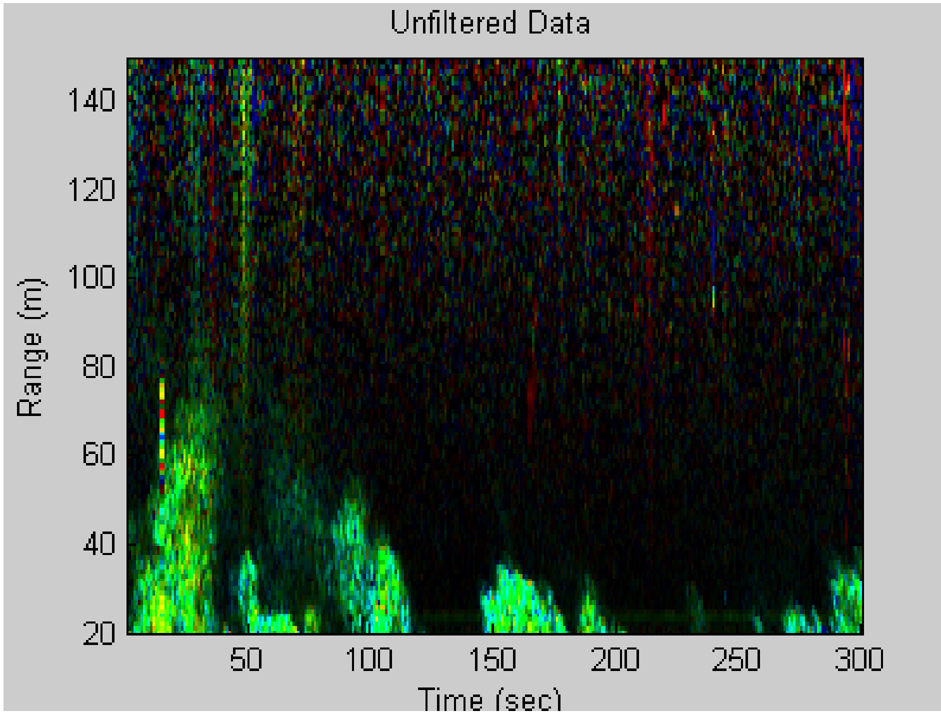


Figure 3. Plot of C_T^2 represented as intensity and vertical velocity as color between 20 and 150 meters over a 300 second interval (1 July 2001, from 1350 –1355 MST).

A technique was devised in the Matlab code to effectively filter out a vast majority of the noise in the plots produced. Some noise remained in many cases, however, so even with this filtering method being employed, the data was still restricted to lie between the limits of 20-50 meters in range. Figure 4 shows the same data as Figure 3, but with some of the noise filtered out. Figure 4 also shows graphically what the correlation time represents. For this particular case, the Matlab program calculated a correlation time of 29 seconds. Only two areas are shown in the picture (for clarity) but the autocorrelation function actually produced a correlation time based upon the entire 300-second interval.

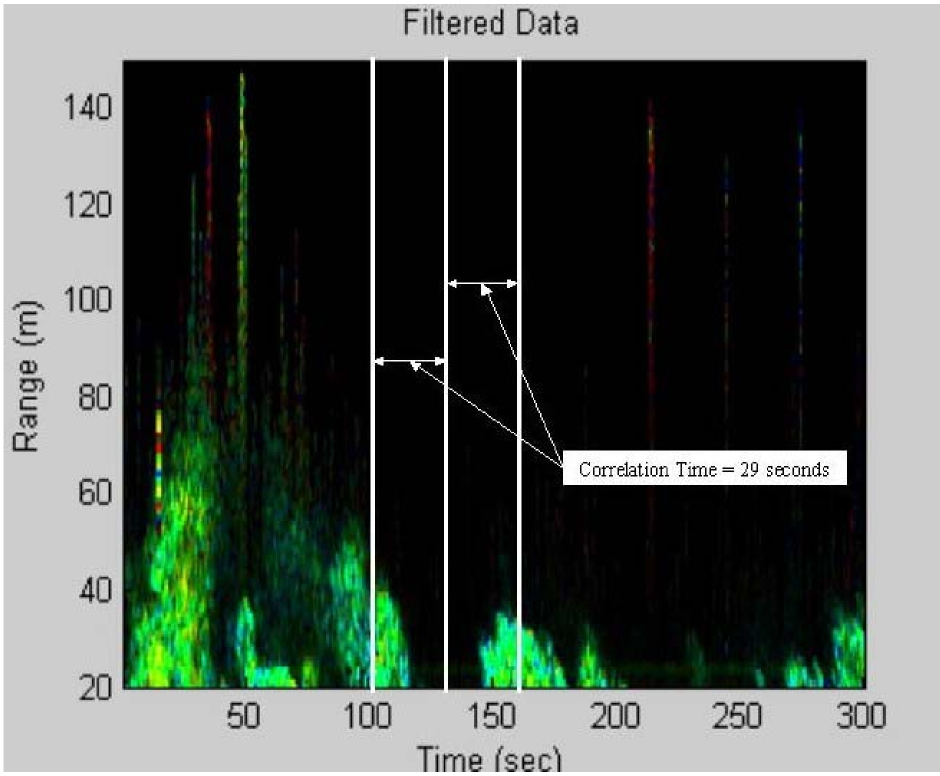


Figure 4. Figure 3 with the noise somewhat filtered out. The correlation time can be graphically seen as the distance between the center of a plume and the center of the quiet, adjacent area.

Figure 5 shows a plot of the autocorrelation function over the 300-second time interval. The Matlab program used this function to determine the correlation time. The program found the peak of the curve plotted below, found the first minimum to either side of the peak, and found the time between the peak and the first minimum. This time is the correlation time and corresponds to the area marked off in Figure 4.

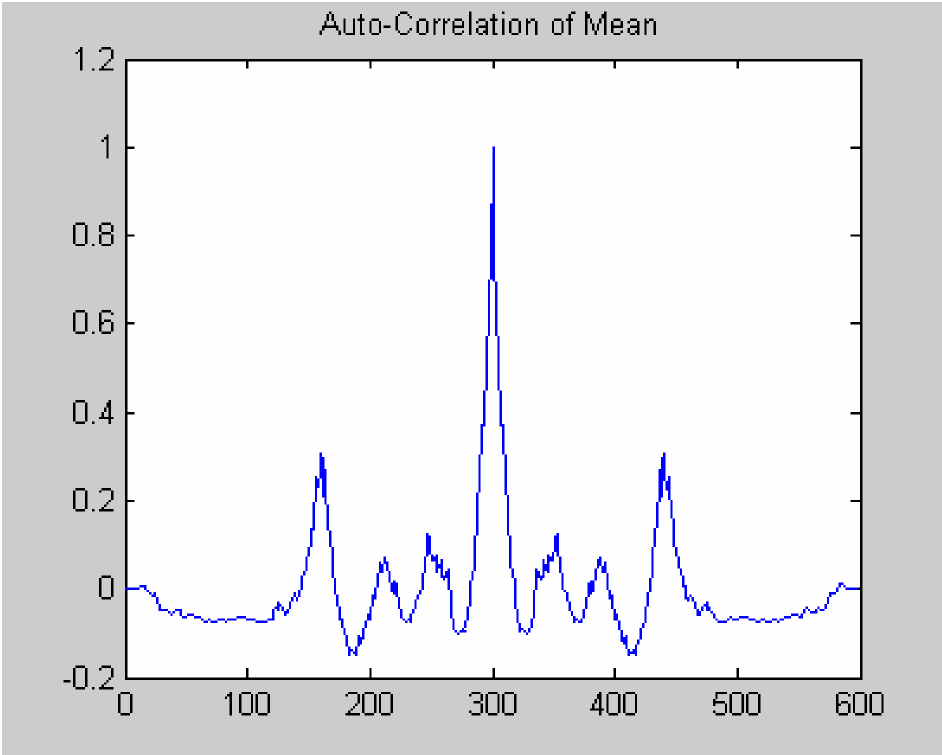


Figure 5. Autocorrelation plot of C_n^2 mean (1 July 2001, from 1350 –1355 MST).

Although it is not so evident in the particular case depicted in Figure 5, often the autocorrelation plot would contain too much fine detail and needed to be smoothed out in order to find a consistent minimum. A 5th order Butterworth filter with a cutoff of W_n = 0.2 of the Nyquist frequency was used to accomplish this. Figure 6 shows the same plot as Figure 5, but with this Butterworth filter applied to it. The plot also depicts the correlation time for this case of 29 seconds.

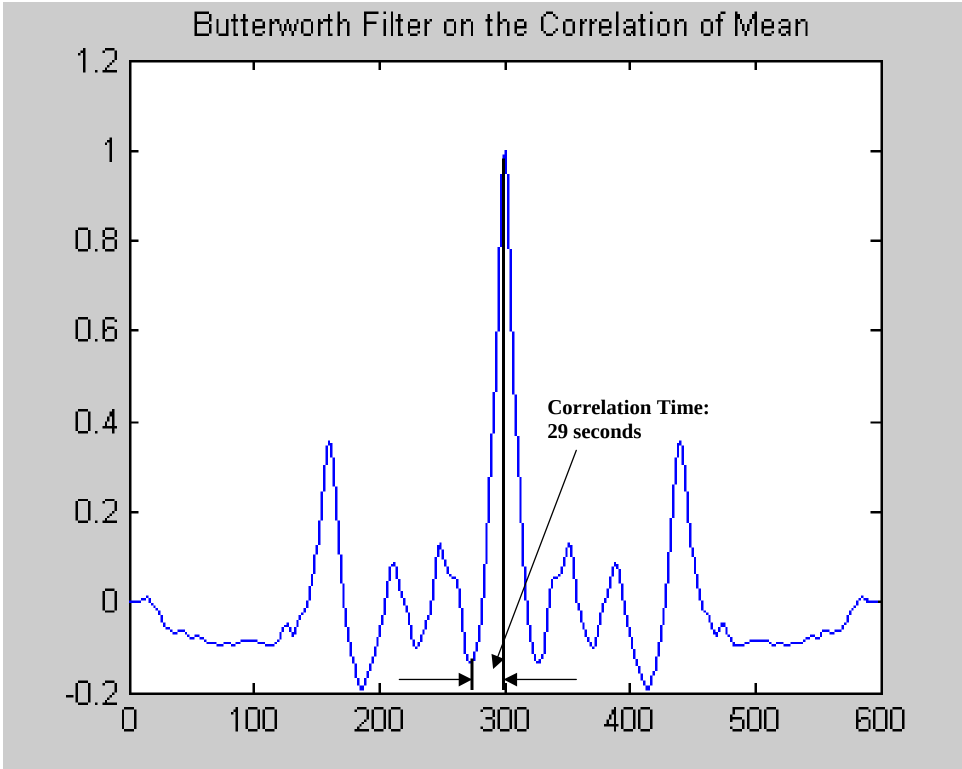


Figure 6. 5th order Butterworth filter of with $W_n = 0.2$ applied to the autocorrelation plot of C_n^2 mean (1 July 2001, from 1350 –1355 MST).

Depending upon the length of the data sample used to compute a function and the strength of the low pass Butterworth filter applied to the autocorrelation function, different values for the correlation time were found. Small time samples are sensitive to finer features of individual thermal plumes. One can visualize this by observing Figure 4 and realizing that as the sample time (the x-axis) becomes smaller, the number of distinct plumes in the sample will decrease and the individual features of any one plume will become more prominent. Conversely, for larger time samples, the correlation time between the plumes, or organized clusters, becomes evident. Also, reducing the bandwidth of the low pass Butterworth filter, by decreasing W_n, smoothes out the autocorrelation function thus emphasizing larger scale functions.

Because the correlation time can vary depending upon the sample time and the strength of the Butterworth filter choices, three sample lengths of 2 minutes, 5 minutes and 10 minutes were analyzed. The Butterworth filter for the

2 and 5 minute samples was set at $W_n = 0.2$ to maintain full scale structure and W_n was 0.02 for the 10-minute samples to reveal the major structures.

Multiplying the correlation time by the wind speed gave the correlation distance (the distance between thermal plumes for large time samples, or the distance between features of an individual plume for smaller time samples). As stated previously, an anemometer provided the wind speed data simultaneously with the sounder data. The output from the Matlab program was a list of correlation lengths for each day between the hours of 1000 and 1600 MST at intervals of 2,5, and 10 minutes. These lists of correlation lengths were then statistically analyzed and the results are presented in the following tables and figures.

There are three different standard statistical measures used to analyze a collection of data such as these: the mean, the median and the mode. Tables 1,2 and 3 present the mean, standard deviation, median and mode of the correlation distances as found by month for the three different time intervals measured.

Correlation Distance 2 Minute Summary ($W_n = 0.2$)					
Date	**Mean**	**Std Dev**	**Median**	**Mode**	**# Samples**
Mar 01	92	70	74	50	2446
Apr 01	78	63	62	50	2913
Jun 01	71	58	53	45	3043
Jul 01	81	65	60	45	4522
Aug 01	73	62	56	35	4124
Sep 01	70	59	51	35	3358
Oct 01	88	88	61	38	4110
Nov 01	69	57	50	35	2717
Dec 01	62	67	45	30	3111
Jan 02	70	60	54	35	3114
Feb 02	84	77	62	45	3320
Mar 02	91	72	69	45	3750
Apr 02	99	77	76	68	3619
May 02	92	74	68	45	3463
Jun 02	82	70	61	35	2230
Jul 02	84	69	64	35	2840
Aug 02	95	97	67	30	779
Entire Period	81	70	61	41	3145

Table 1. Statistical summary of correlation distances for 2-minute interval length and $W_n = 0.2$.

Correlation Distance 5 Minute Summary ($W_n = 0.2$)					
Date	Mean	Std Dev	Median	Mode	# Samples
Mar 01	99	76	79	70	985
Apr 01	84	64	67	50	1168
Jun 01	72	52	55	45	1222
Jul 01	88	59	72	50	1814
Aug 01	83	63	67	45	1650
Sep 01	79	69	58	45	1350
Oct 01	103	109	69	50	1649
Nov 01	80	65	62	45	1093
Dec 01	69	65	50	45	1252
Jan 02	80	63	64	45	1253
Feb 02	89	71	67	50	1333
Mar 02	99	73	76	50	1486
Apr 02	101	73	78	53	1452
May 02	101	78	78	45	1373
Jun 02	92	68	71	50	896
Jul 02	92	67	76	45	1133
Aug 02	109	106	82	60	311
Entire Period	89	72	69	50	1260

Table 2. Statistical summary of correlation distances for 5-minute interval length and $W_n = 0.2$.

Correlation Distance 10 Minute Summary ($W_n = 0.02$)					
Date	Mean	Std Dev	Median	Mode	# Samples
Mar 01	723	680	531	350	498
Apr 01	490	391	405	350	588
Jun 01	481	347	391	325	615
Jul 01	452	268	380	298	913
Aug 01	374	265	297	225	807
Sep 01	477	355	364	338	679
Oct 01	599	518	446	350	796
Nov 01	442	348	341	263	553
Dec 01	374	394	249	188	632
Jan 02	401	307	324	250	633
Feb 02	501	406	419	263	671
Mar 02	524	369	417	350	756
Apr 02	592	387	494	375	728
May 02	552	317	463	450	689
Jun 02	487	341	391	350	451
Jul 02	458	307	363	350	565
Aug 02	473	345	366	303	156
Entire Period	494	373	391	316	631

Table 3. Statistical summary of correlation distances for 10-minute interval length and $W_n = 0.02$.

Figure 7 presents histograms of the mean correlation lengths (from Tables 1-3).

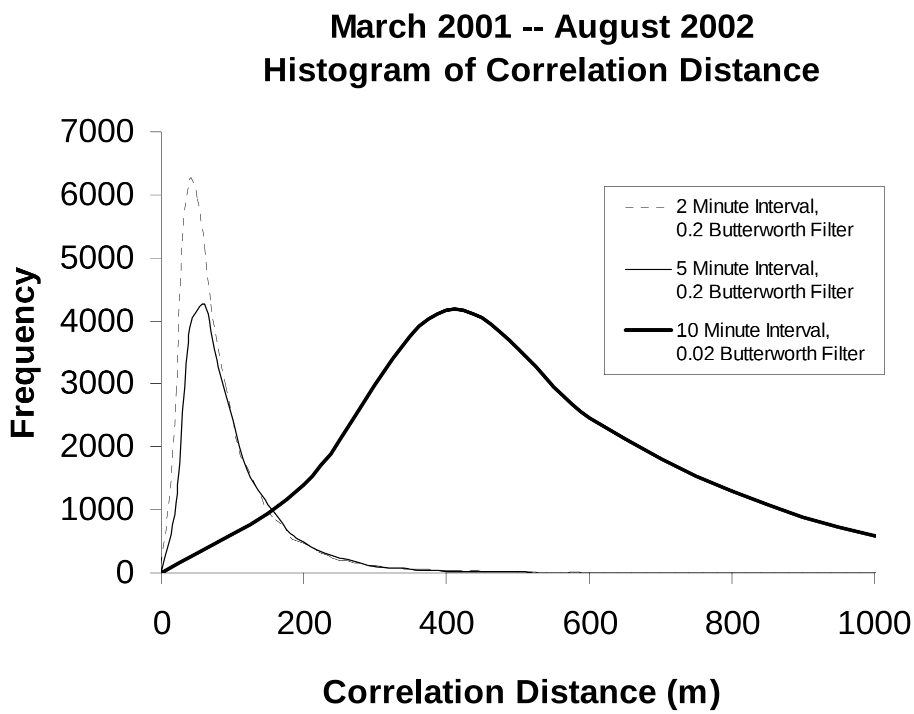


Figure 7. Histogram of 2,5, and 10 minute sampled correlation distances for March 2001 to August 2002.

Because of the wide separation in Figure 7 between the peak of the 10-minute interval histogram with the other two it is difficult to see where the peaks of the two and five minute histograms lie. Figure 8 plots just the two and five minute histograms.

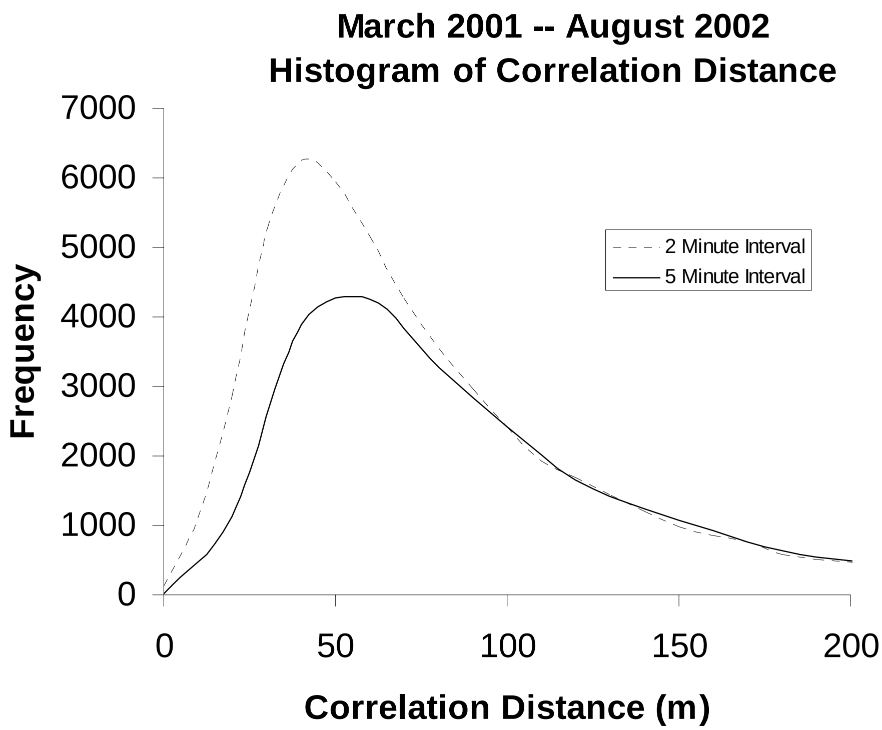


Figure 8. Histogram of 2-minute and 5-minute sampled correlation distances.

The statistical mean, median and the mode varied in a consistent manner. The shape of the histograms shows why this is so. The histograms all have very long tails. This fact skews the median, and especially the mean to the right of the most likely value, the mode. The mode is the most likely value to occur and as such is deemed the most significant for potential applications of this thesis. Figure 9 shows one example of a histogram with the mean, median and mode plotted on it. The tail of this histogram is actually much longer than shown – it extends to 1140 meters. It has been truncated in this plot in order to better show the difference between the mean, median and mode.

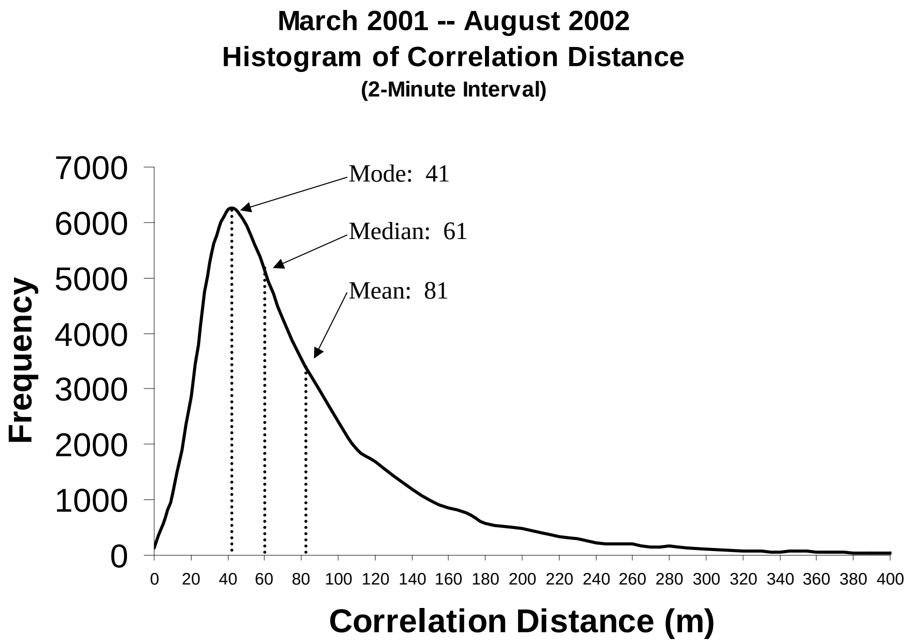
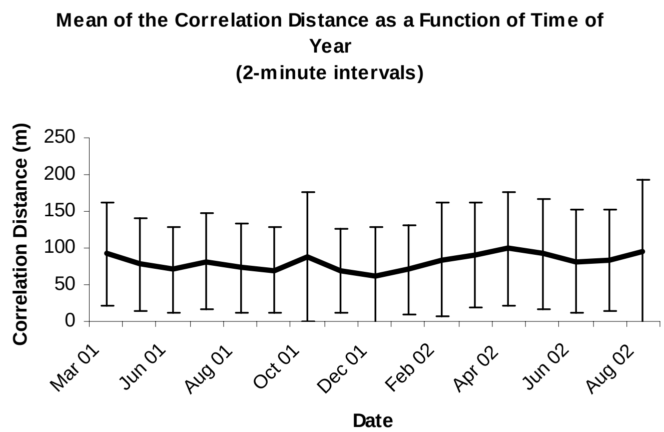
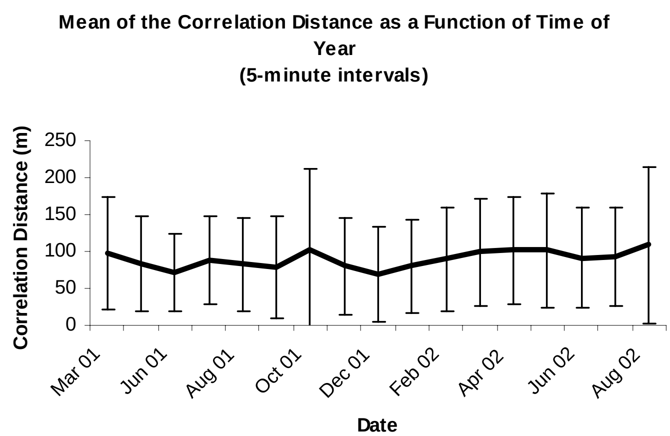


Figure 9. Histogram of 2-minute sampled correlation distance with mean, median and mode plotted.

Figure 10 displays the mean correlation length, with error bars of plus and minus one standard deviation of the data set, for each of the time intervals, by month.





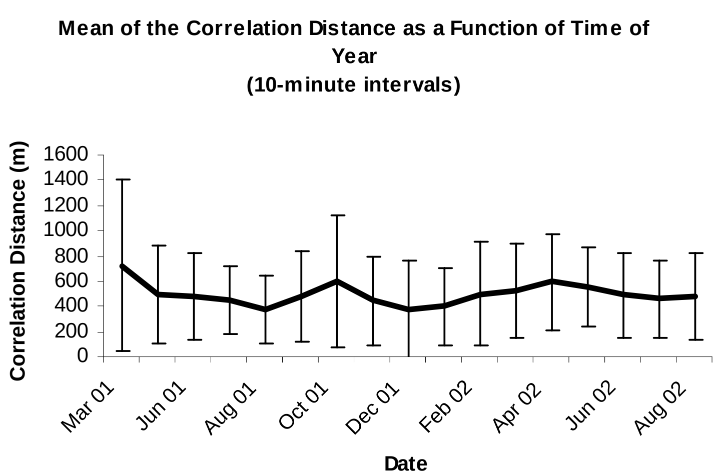


Figure 10. Histogram of 2, 5 and 10-minute mean correlation distances.

Figure 11 compares the mean, median and mode for the 2, 5 and 10 minute intervals. Note that the most likely value, the mode, is also the lowest value.

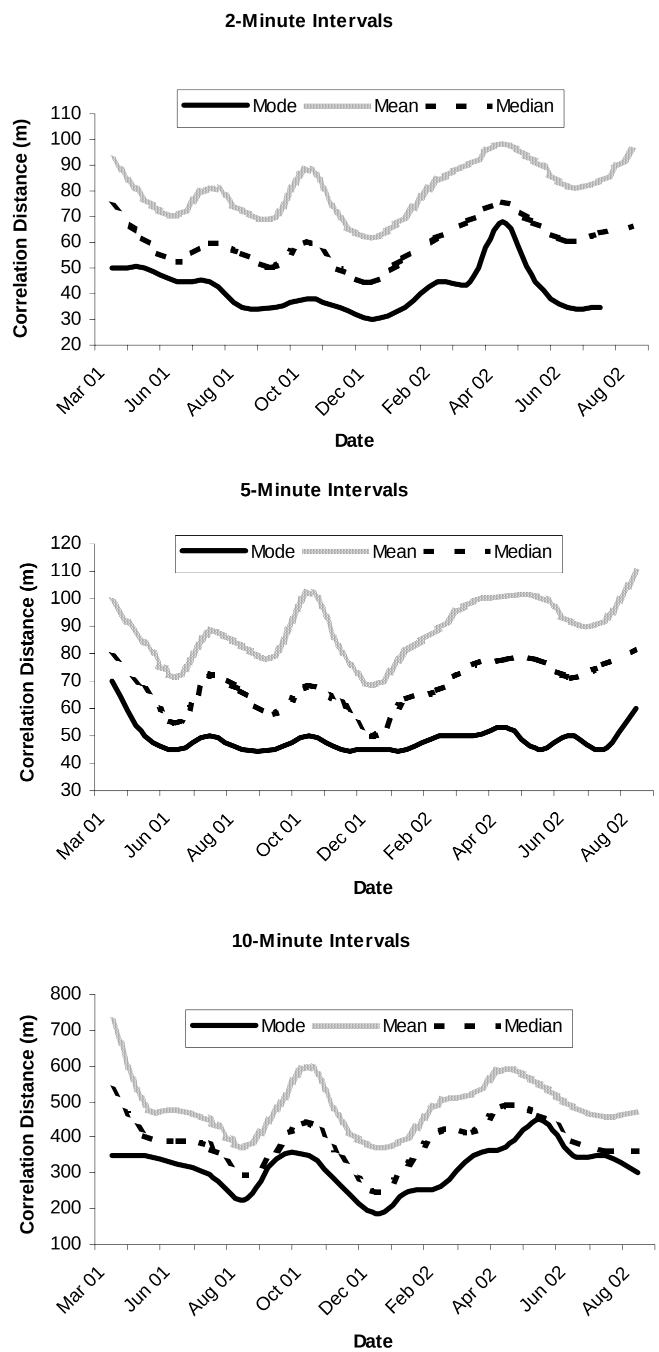


Figure 11. Comparison of the mean, median and mode for the 2, 5 and 10 minute intervals.

Another way to compare the data is examine the means as a group (for the three time intervals), the medians as a group and the modes as a group. Figure 12 depicts this.

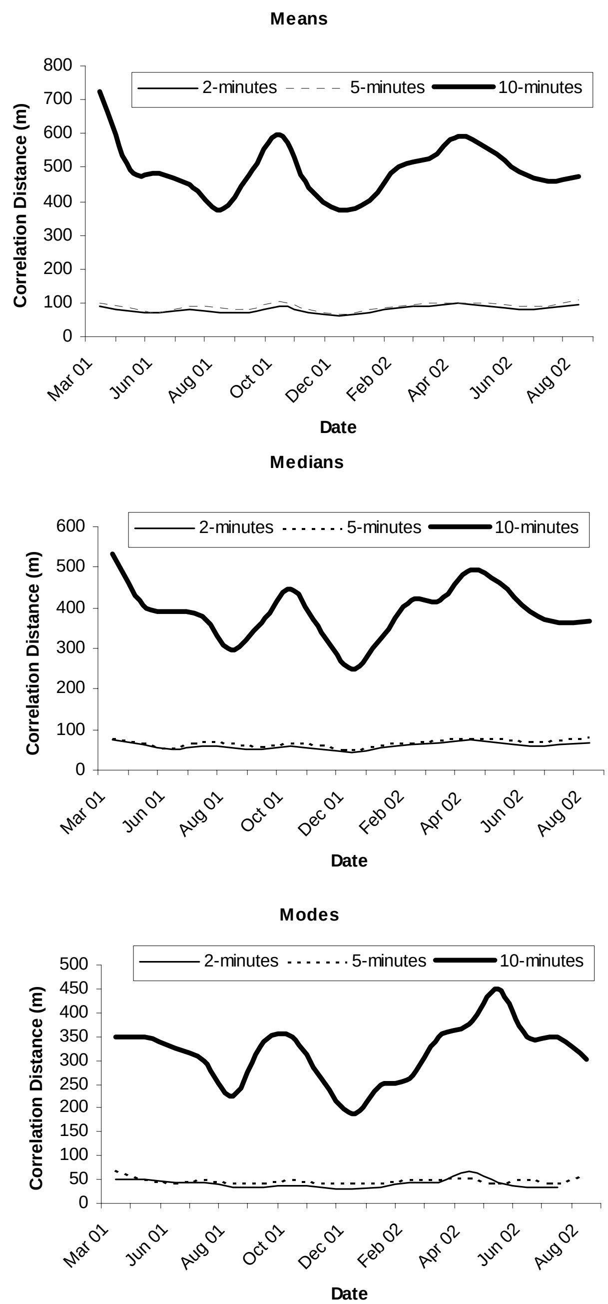


Figure 12. Comparison of the means as a group, medians as a group and modes as a group for the 2, 5 and 10 minute intervals.

It was also of interest to see how the correlation length vaired hourly over the course of the day, from 1000 to 1600 MST. The data for the 5-minute interval was chosen as a representative sample and the correlation lengths were calculated for each hour, by month. Then the months were grouped together into seasons: Winter = December, January, February; Spring = March, April, May; Summer = June, July, August; and Fall = September, October, November. The hourly changes in correlation length were then plotted for each season as well as a composite of all the data. This is presented in Figure 13.

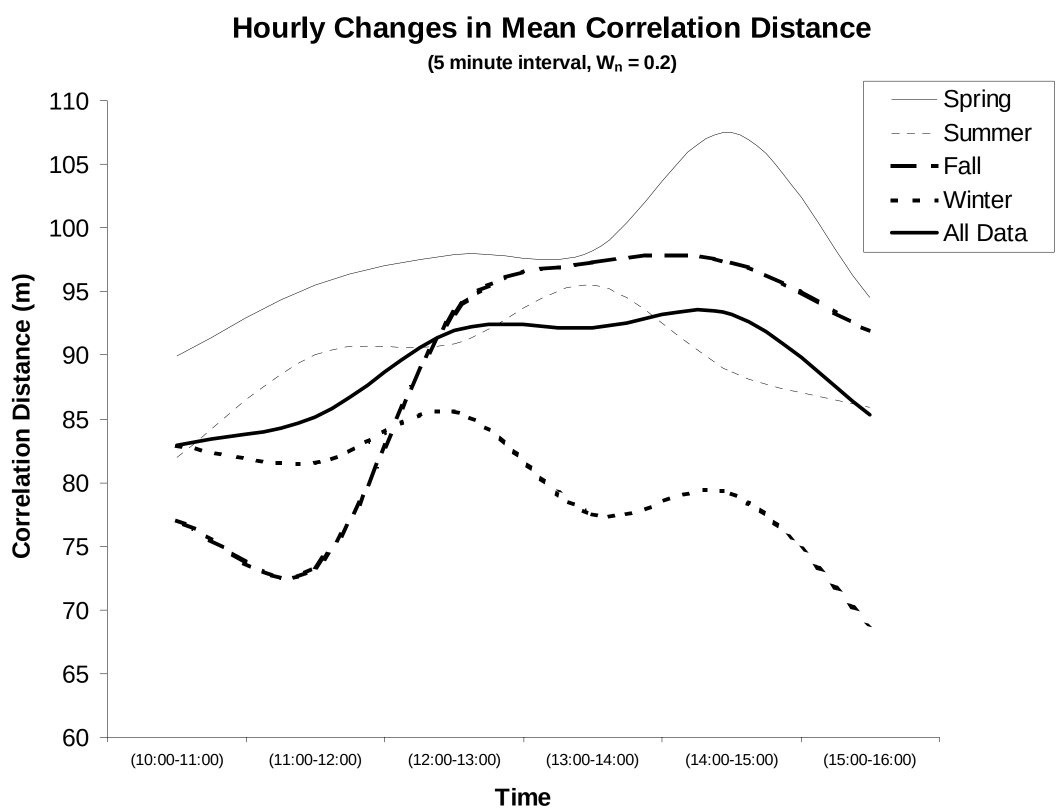


Figure 13. Average correlation distance of the seasons, by hour, between the hours of 1000 and 1600 MST.

B. DISCUSSION

The mean, standard deviation, median and mode were calculated for the autocorrelation lengths of the average C_n^2 values for 20-50 meter vertical segments of acoustic sounder data grouped in 2, 5 and 10 minute time intervals.

These three statistical measures varied from each other because of the long tail shape of the histogram illustrated in Figure 9. While each statistical measure has value, the mode, which represents the most likely value, is the most representative value of the distance between a plume and an adjacent minimum.

As Figure 12 shows, the mean, median and mode of the 2 and 5 minute intervals match up quite well with each other while the 10-minute interval's statistical values are much higher. This is most likely due to two factors. The first, and most dominant, reason for the discrepancy is that the bandwidth of the low pass Butterworth filter applied to the autocorrelation plot was much narrower for the 10-minute case. This was done to suppress the fine scale structure seen within a single plume and to reveal the separation between the plumes. This longer correlation time, of course, implies a longer correlation distance. The second reason that the correlation distance was found to be higher in the 10-minute sample was that for longer sample times, larger scale features of the thermal plumes were being correlated. A 10-minute segment was long enough to include several plumes, while for the 2 and 5-minute intervals, individual features within a plume were more prevalent.

Figure 13, which presents the average correlation lengths of the seasons, organized by hour, displays several interesting features. The overall trend of the data is that the distance tends to increase from approximately 1000 hours to 1500 hours and then goes down. In the morning as the sun rises higher in the sky, the ground warms up producing thermal plumes. These plumes grow in height and lateral extent as they carry more heat up into the boundary layer. The length decreases after 1500 hours as the solar radiation abates and the ground begins to cool. Spring has the highest correlation distances, which should be expected since the average wind speeds in the spring are higher than in the other seasons. Fall shows the steepest increase in correlation distance, while winter shows a slight decrease.

III. CONCLUSIONS AND RECOMMENDATIONS

The horizontal separation between convective thermal plumes, and features within a thermal plume, were determined from acoustic sounder profiles with the corresponding anemometer wind speeds and extensive data analysis. The mean, standard deviation, median and mode were calculated for the computed correlation lengths. The acoustic sounder produced a vertical C_n^2 profile once a second that was represented as a single C_n^2 average for the 20-50m altitude range. These averages were grouped into 2, 5 and 10 minute long sequences to compute an autocorrelation function. The times between the autocorrelation maxima and the first minima were found and multiplied by the average wind speed over that interval. The data sampled at 2 and 5-minute intervals most likely revealed features within an individual thermal plume. The 2 and 5-minute time interval statistics correlated very strongly with each other, and the mean correlation distance was 81 meters $\pm$ 70 meters and 89 meters $\pm$ 72 meters, respectively. Their medians were 61 meters and 69 meters; and their modes were 41 meters and 50 meters, respectively. These two time intervals also used the same strength Butterworth low pass filter in the Matlab program to determine the correlation time, which provided just enough smoothing to find a robust minimum in the autocorrelation function.

The 10-minute time interval statistics were significantly larger than the 2 and 5-minute cases. The mean correlation length was 494 meters $\pm$ 373 meters, the median was 391 meters and the mode was 316 meters. This was the result of using a narrower bandwidth Butterworth filter to smooth the autocorrelation function. This stronger filter was designed to filter out the smaller features within an individual plume and, therefore, find the distance between the center of a plume and the center of the quiet region adjacent to that plume (effectively finding the distance between thermal plumes). Another factor involved in the higher values for the 10-minute interval was the fact that the time interval was longer: 10 minutes versus 2 or 5 minutes. This longer time interval allowed several thermal plumes to be correlated in the same data set.

The validity of this study should be verified using optical methods to determine the correlation lengths between and within thermal plumes. This would be important to do before any major applications utilizing the results obtained here were begun. If the results agree, then this acoustic sounder method could be a cost effective way to study thermal characteristics, and the resulting degradation in the optical environment, at other locations.

APPENDIX MATLAB CODE

The following program is the code used to generate the data analyzed in this thesis.

```
% This program reads in acoustic sounder data and
% meteorological data collected at the Starfire Optical
% Range (SOR) and produces an output listing in successive columns:

% year of sample
% month of sample
% day of sample
% time of sample
% correlation time (unfiltered),
% correlation time (filtered)
% average windspeed (for time of sample)
% correlation distance (max to first min)
% correlation distance (max to global min)

% The video display mode must be set for 24 bits or more
% 25 Feb 98; 24 Oct 97, DLW

%*******************************************************
% This file modified Aug/Sep 2004 by Jeff Douds *
%*******************************************************

%*************************************************************************************
% SOR VARIABLES ON DATA FILES (included for reference)                *
%   fdat(1)=floor(now); % days                                        *
%   fdat(2)=rem(now,1);          % fraction of day                    *
%   fdat(3)=Pres;                                                     *
%   fdat(4)=Temp;                                                     *
%   fdat(5)=Rel;                                                      *
%   fdat(6)=atten2;                                                   *
%   fdat(7)=Ct_cal;                                                   *
%   fdat(8)=Pltrng;                                                   *
%   fdat(9)=dt;                                                       *
%   fdat(10)=Cn_sensor;                                               *
%   fdat(11:Pltrng+10)= CT^2 array in K^2 m^-2/3                      *
%   fdat(Pltrng+11:2*Pltrng+10)= Radial Doppler wind speed in m/s     *
%                                                                     *
% METEOROLOGICAL DATA VARIABLES (in txt files)                        *
%   col 1 = ABD temp (deg C)                                          *
%   col 2 = ABD dew point temp (deg C)                                *
%   col 3 = ABD wind direction (deg)                                  *
%   col 4 = ABD wind speed (mph)                                      *
%   col 5 = ABD pressure (mb)                                         *
%   col 6 = ABD pyranmometer                                          *
```

```
%   col 7 = 3.5m wind speed (mph)                                    *
%   col 8 = 3.5m temp (deg C)                                        *
%   col 9 = 3.5m dew point temp (deg C)                              *
%   col 10 = 3.5m wind direction (deg)                               *
%   col 11 = time (hhmmss.00) (increases in 1 minute increments)     *
%*******************************************************************************

clear all;
close all;
clc;

% Set Constants
color_scale=1/3/4;      % (1/3)/5  For full scale of 5 m/
Ct_cor=1;               % Empirical constant (use 2.3 before Feb 10 98)
lambda_o=0.5e-6;        % Optical wavelength
romin=15;               % ro minimum array index altitude (ie 5 = 4m)
ro_Pltrng=200;          % ro plot maximum range
scale=2000;             % colormap CT^2 scale factor

% User Inputs
time_samp=input('\nEnter sampling time in min = ');
nscans= time_samp*60;% max # of pulses displayed on plot
tstart=input('Enter time to start (use UTC, in whole hours, e.g. 17)');
tend=input('Enter time to end (use UTC, in whole hours, e.g. 23) ');

% Derived Constants
nscan1=nscans-1;
ro_const=1000*2.1*(1.46*(2*pi/lambda_o)^2)^-0.6;

for j=1:12 %select the month (run through them all sequentially)
   switch j
      case 1
         month='Jan';
      case 2
         month='Feb';
      case 3
         month='Mar';
      case 4
         month='Apr';
      case 5
         month='May';
      case 6
         month='Jun';
      case 7
         month='Jul';
      case 8
         month='Aug';
      case 9
         month='Sep';
      case 10
         month='Oct';
      case 11
```

```
        month='Nov';
    case 12
        month='Dec';
end

% loop to read in a month at a time day by day
for count=1:31
    if count<10
        count=(['0',int2str(count)]);
    else
        count=([int2str(count)]);
    end

    %assign names to the input files
    sounder_file=(['c:\SOR FOLDER\SOR DATA FILES\',month,' 2002\',count,'-',month,'-2002.bin']);
    met_file1=(['c:\SOR FOLDER\S2002\',month,'02\',count,month,'02data.txt']);

    %open the input files
    fid=fopen(sounder_file,'r');
    met_file=load(met_file1);

    %open the output file
    outputfile=(['c:\SOR FOLDER\Output\',month,'_2002_10_min_intervals_no_douds_filter.txt']);
    fid2 = fopen(outputfile,'a');

    %check for valid data files
    ValidData=1; % 1 = yes, valid data; 0 = no, not valid data
    if size(met_file)==[0,0] | fid==-1
        fprintf('The file %s does not exist.\n',sounder_file); %output to data file
        ValidData=0; %flag for invalid data
    end

    if ValidData==1     %only enter this loop if two valid data files have been read

        % read input parameters
                fdat=zeros([10 1]);
                fdat=fread(fid,10,'float32');
                Pltrng=fdat(8);      % get vector length
                fsize=2*Pltrng+10;     % actual file size
                frewind(fid);
                fdat=zeros([fsize 1]);  % Output file data buffer
                fdat=fread(fid,fsize,'float32');

        % Set Arrays
                i0=0:Pltrng-1;
                i1=1:Pltrng;
                n2=1:nscans;
                avg=zeros(size(i1));
                Cn2=avg';
                Cn2_row=zeros(Pltrng,nscans,1);
                Cn2_norm=zeros(Pltrng,nscans,1);
                color=avg;
```

```
            img=uint8(zeros(Pltrng,nscans,3));  % plot array with 1m range bins
img2=uint8(zeros(Pltrng,nscans,3));  % plot array with 1m range bins (for 2nd color plot)
            inten=avg';
            ravg=avg';                % Cn^2 running average
            rgb=zeros(Pltrng,3);  % Current data array
rgb2=zeros(Pltrng,3); % for second color plot
            vavg=avg;
            vdop=avg;
            roi=zeros(1,nscans);

% Initialize first plot
            close('all','hidden')
            figure('Position',[430 50 400 300]);
            colormap(hsv);
            m=colormap;
            h1=image(img,'Erasemode','none');
            axis xy;  % set plot for Cartesian coordinates
xlabel('Time (sec)');
            ylabel('Range (m)');
title('Filtered Data');
YLim([20 150]); %don't display the bottom 20 meters since this data is not being used anyway

%Initialize second plot
figure(2)
set(2,'Position',[20 50 400 300]);
            colormap(hsv);
            m2=colormap;
            h2=image(img,'Erasemode','none');
            axis xy;  % set plot for Cartesian coordinates
xlabel('Time (sec)');
            ylabel('Range (m)');
title('Unfiltered Data')
YLim([20 150]); %don't display the bottom 20 meters since this data is not being used anyway

% Queing loop: this loop queues the data to begin reading at the tstart input
            fdat(2)=0;
if size(fdat)==[fsize 1]  %only enter the following loop if data has been read each time
               while ValidData==1 & (tstart>24*fdat(2)),  %flag is to check that data has actually been read each time
      fdat=fread(fid,fsize,'float32');
      if size(fdat)==[fsize 1]

      else
         ValidData=0;
      end
               end
end

% Main Data Acquisition Loop (goes until tend is reached)
for time=tstart:time_samp/60:tend,

   % Loop for each frame that is printed out
   for k=1:nscans
```

```
        fdat=fread(fid,fsize,'float32');

if  ValidData==1 & size(fdat)==[fsize 1]  %only enter the following loop if data has been read each time
            Pres=fdat(3);
            Temp=fdat(4)+273.15;
            Cn_cal=Ct_cor*(79e-6*Pres/Temp^2)^2;
   avg=(fdat(11:Pltrng+10));
   inten=min(scale*sqrt(max(avg,0)),255);
   inten_unfiltered=inten;

   %the following for loop will black out the areas above where the avg
   %value was first <=0 and set the avg values above there to zero
   %the avg values at these points are already very close to
   %or less than zero
   flag=0;
   for counter=1:Pltrng
      if or((avg(counter)<0), (flag==1))
         inten(counter)=0;
         avg(counter)=0;
         flag=1;
      end
   end

   %the following algorithm will look for noise beginning in the upper
   %region and working its way down.  As it finds noise, it will set avg
   %and inten to zero
   noise=1;
   for j=150:-1:2 %look from the to of the column down to the bottom
      if noise==1;
         if avg(j)>0.002  %avg value too high ==> noise; set to zero
         avg(j)=0;
         inten(j)=0;
         elseif avg(j)==0 %%avg value=0 is inconclusive, so check the next pt down the column

         else
         noise=0;    %once avg value drops below threshold level, back out of the loop
                  %and stop changing avg and inten values.  This will preserve the valid
                  %high avg numbers at the bottom of the columns.
         end
      end
   end

            % Doppler processing
   vdop=transpose(fdat(Pltrng+11:2*Pltrng+10));
   color=max(min(color_scale*vdop+0.333,0.666),0); % Clip red & blue
   color=round(color*63+1);  % Color table index
   rgb(i1,:)=m(color(i1),:);
   for l=1:3,rgb(:,l)=inten.*rgb(:,l);end

            % Shift plot and display
   img(:,1:nscans-1,:)=img(:,2:nscans,:);
            img(:,nscans,:)=uint8(round(rgb));
```

```
      ravg=0.6*ravg+0.4*avg;
            Cn2=Cn_cal*avg;
      Cn2_row(:,1:nscans-1)=Cn2_row(:,2:nscans);
      Cn2_row(:,nscans)=Cn2(:);
      row_avg=mean(Cn2_row,2);
      for i_col=1:nscans,
        Cn2_norm(:,i_col)=Cn2_row(:,i_col)-row_avg(:);
      end

      %Produce data for 2nd color plot
      rgb2(i1,:)=m2(color(i1),:);
      for l=1:3,rgb2(:,l)=inten_unfiltered.*rgb2(:,l);end

            % Shift plot and display
      img2(:,1:nscans-1,:)=img2(:,2:nscans,:);
            img2(:,nscans,:)=uint8(round(rgb2));

    end  %if loop to check if fdat had data in it

end  % loop for each frame that is printed out

if size(fdat)==[fsize 1]  %only enter the following inner loop if data has been read each time

    % prepare the output for the color graph and draw it
    set(h1,'CData',img)
    drawnow

    % prepare the output for the color graph and draw it
    set(h2,'CData',img2)
    drawnow

          % find the correlation time between limits in array below
    Cn2_ab = mean(Cn2_norm(20:50,:));    %Find mean of Cn2 (finds the mean value of each column)
    cor_ht1 = xcorr(Cn2_ab);             %Find correlation time

    % Filter the data
    [b,a] = butter(5,0.02);      %5th order, Wn=0.2
    corfilt = filtfilt(b,a,cor_ht1);

    % Check for first min to max
    N=nscans;
    last=cor_ht1(nscans);
    while ((corfilt(N-1)<last) & (N>2)),
      last=corfilt(N-1);
      N=N-1;
    end
    time_0=nscans-N;

    % Check for global min
    [Y1,I1] = min(corfilt(1:nscans));
    time_1 = nscans-I1;
```

```
            % Find the corresponding time in the met data file
            met_tstart_1=time*10000; %decimal format (e.g. 17.8333)
            hours=double(int8(met_tstart_1/10000));
            met_tstart_2=met_tstart_1 - hours*10000; %leaves only the minutes and seconds, still in base 10 format
            minutes=double(int8(met_tstart_2/100)); %extracts the minutes
            minutes=double(int8(minutes*0.6)); %convert minutes to time format
            seconds=double(met_tstart_2 - (double(int8(met_tstart_2/100))*100)); %extracts the seconds and converts to time format
            seconds=double(int8(seconds*0.6)); %convert seconds to time format
            met_tstart=(hours*10000) + (minutes*100) + seconds;  %time in the correct format for the .txt met file
            J=min(find(met_file(:,11)>=met_tstart));  %finds the row in the met file where the time starts
            sum_wndspd=0;
            for i=J:J+(time_samp – 1)
               sum_wndspd=sum_wndspd + met_file(i,7);  %add the windspeeds over the sample to then calculate an average
            end
            avg_wndspd=sum_wndspd/time_samp;  %using the 3.5m windspeed, not the ABD windspeed

            % calculate the correlation distance
            cor_dist_first=0.44704*avg_wndspd*time_0; %0.44704 = conversion factor for mph to m/s; distance from max to first min
            cor_dist_global=0.44704*avg_wndspd*time_1;  %distance from max to global min

            figure(3);
            set(3,'Position',[20 430 400 320]);
            plot(cor_ht1);
            title('Auto-Correlation of Mean');

            figure(4);
            set(4,'Position',[430 430 400 320]);
            plot(corfilt);
            title('Butterworth Filter on the Correlation of Mean');

            Tm=datevec(fdat(1)+fdat(2)); % pulls out the year, month, day from the SOR data file

            % output to screen
            fprintf('\nYear\tMonth\tDay\t\tUTC Time\tCorr Time 1\t\tCorr Time 2\t\tAvg Wndspd\t\tCorr Dist 1\t\tCorr Dist 2');
            fprintf('\n%g\t %g\t\t %g\t\t %02.0f:%02.0f:%02.0f\t %4.0f\t\t\t %4.0f\t\t\t %8.2f\t\t %8.2f\t\t %8.2f\t\r\n',...
                  Tm(1),Tm(2),Tm(3),hours,minutes,seconds,time_0,time_1,avg_wndspd,cor_dist_first,cor_dist_global);

            if Tm(1)==2001 | Tm(1)==2002  %some bad data has the incorrect date, this will filter that data out by not printing it

               % output to data file
               fprintf(fid2,'%g\t %g\t %g\t %8.4f\t %02.0f:%02.0f:%02.0f\t %4.0f\t %4.0f\t %8.2f\t %8.2f\t %8.2f\t\r\n',...
                     Tm(1),Tm(2),Tm(3),time,hours,minutes,seconds,time_0,time_1,avg_wndspd,cor_dist_first,cor_dist_global);

            end

         end  %inner if loop to check if fdat had data in it
%                    pause;
      end % Main Data Acquisition Loop

      fclose(fid); % close current SOR file

   end %if statement for valid data obtained
```

```
    end % for loop to read in a day at time for the whole month

end  %for loop to select the month

fclose(fid2); % Close output file
```

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