Army Research Laboratory

Investigation of Atmospheric Laser Optics Test bed (A_LOT) Optical Turbulence Intensity for Free-Space Laser Communications

by Arnold Tunick, Mark Grobaker,
and Ronald Meyers

ARL-MR-0657 December 2006

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14. ABSTRACT
In this report, we examine optical turbulence intensity measured at the U.S. Army Research Laboratory's (ARL) Atmospheric Laser Optics Test bed (A_LOT). Our goal is to better understand the physics relationships between refractive index structure and micro-climatological moments (since these can significantly affect free-space laser communications). Optical scintillometer data are collected over a nearly horizontal (2.33 km) propagation path and compared with *in situ* (rooftop) measurements of temperature variance. Regression analysis of time-averaged data from these different sensor systems suggests that (occasionally) optical turbulence information for an extended propagation path can be derived via point sensors, which are less costly to install and easier to maintain than scintillometer-based methods. Nevertheless, a key factor to consider is the extent of homogeneity of the optical turbulence and micro-climatological conditions along the A_LOT optical path. Additional research is recommended to further explore optical turbulence and microphysical influences on (laser) light propagation in complex areas.

15. SUBJECT TERMS
Refractive index structure, statistical analysis, correlation coefficient, temperature moments

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1. Introduction

Optical turbulence is an important atmospheric effect that acts on the propagation of light waves to distort optical propagation paths and intensity. It is brought about by fluctuations in the refractive index in air, i.e., air density, which affects the speed at which light wave fronts propagate. Atmospheric refractions of electro-magnetic energy can cause spatial and temporal (intensity) variations in transmitted signals (Chiba, 1971; Fried et al., 1967; Ishimaru, 1978; Parry, 1981). In turn, these effects can significantly degrade (blur, shimmer, and distort) infrared images or increase transmission bit error rates in terrestrial free-space laser and ground-to-satellite communication systems.

The U.S. Army Research Laboratory's (ARL) Atmospheric Laser Optics Test bed (A_LOT) is a unique experimental facility with which to measure optical turbulence intensity (*Cn2*) and its effects on free-space laser propagation. ARL's A_LOT facility supports novel research and development for a wide range of laser communication, atmospheric optics, beam control, and imaging programs (Vorontsov et al., 2003). Within the A_LOT, a nearly horizontal, 2.33-km optical path extends from the top of a tall water tower to the Intelligent Optics Laboratory (IOL) rooftop at ARL (figures 1 and 2). Boundary layer scintillometers at the A_LOT measure continuous, path-averaged optical turbulence data along this line of sight (LOS). Scintillometers are ground-based, remote sensing instruments designed to measure optical turbulence intensity along an LOS path established between a transmitter and a down-range receiver. Scintillometer operation is based on the principle that scintillations (i.e., light intensity variations) occur as fluctuations in air density create refraction effects in propagating electromagnetic waves (Clifford et al., 1974). The refractive index structure parameter, *Cn*2, is related to the intensity of these refraction effects (also see Optical Scientific, 2003).

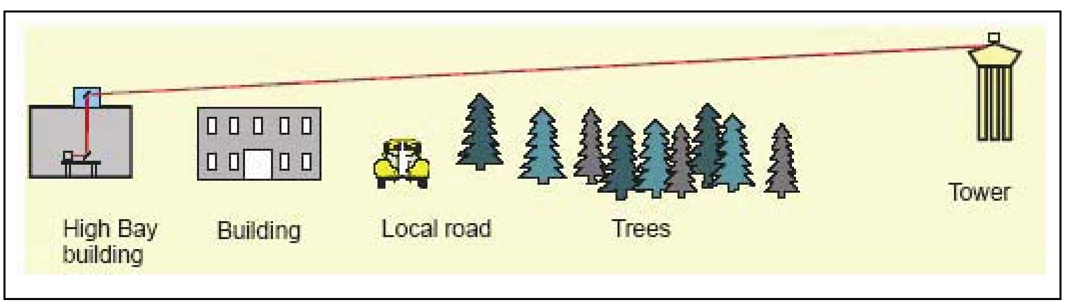

Figure 1. A schematic of the ARL A_LOT optical path.

Figure 2. An aerial photo of the A_LOT propagation path (data from terrafly.com).

In addition, micro-climatological sensors collect *in situ* (point) data on a tripod (~2.0 m) above the IOL rooftop. Measured microphysical data include mean temperature, wind speed (small three-cup anemometer), barometric pressure, relative humidity, and rainfall amount. We have also integrated a single three-axis sonic anemometer (R.M. Young Company[1], Model 81000) alongside the rooftop weather station. The sonic sensor provides quite a lot of useful data for optical turbulence characterization and modeling research (e.g., mean wind velocities, wind flow turbulent statistics, and mean and fluctuating temperature data). Basically, a sonic anemometer determines wind speed and wind direction by measuring the change in the velocity of sound waves traveling between a pair of sensors (as the wind accelerates or decelerates them). These measurements are made by short pulses of ultrasonic sound in three different directions. In this way, a three-dimensional view of the wind can be determined. In contrast, recorded temperature data are determined directly from measured sound speed (c), where the speed of sound in air can be expressed as $c = \sqrt{\gamma_s R T_v / M}$. Here, T_v is (virtual) air temperature in Kelvin, $R = 8314.32\ \ J\ \ mol^{-1} K^{-1}$ is the universal gas constant, and M is molecular mass, $\gamma_s = c_p / c_v$ is the ratio of specific heats. (For more details about sonic anemometry, see appendix 6.1, Principle of the Sonic Anemometer and Thermometer, in Kaimal and Finnigan, 1994.) In addition, fluctuation temperature data (T') and temperature variance data (T'^2) can be derived from the sonic anemometer, based on the Reynolds convention, as discussed in Lumley and Panofsky (1964), i.e., $T = \overline{T} + T'$, where $\overline{T}$ is the 15-minutes mean value, for example.

Note that the average (mid-point) elevation between the water tower and the IOL rooftop is approximately 40 m above ground level. As a result, several interesting challenges remain to obtain much desired *Cn*2 (and cross-wind) profile information along the optical path, particularly since it traverses a fairly complex and non-uniform landscape. The A_LOT optical path

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[1]The use of commercial or company names with regard to electronic products does not constitute an endorsement by the U.S. Army.

traverses an open sand lot, a fairly continuous forest stand, several local roads, and various building arrays. Naturally, complex microphysical influences may (at times) affect the A_LOT measured data and research applications. Some microclimate influences may be due to irregular wind flow patterns around the IOL and the water tower. Other effects may be due to varying wind shears, temperature gradients, and moisture changes across the top of nearby (and underlying) buildings and forest canopies. To this end, computer simulation models may provide some meaningful results, even though all the pertinent landscape or canopy data along the optical path may not yet be known or available (e.g., Tunick, 2006). At the same time, detailed data analysis and interpretation (using the A_LOT sensors server network) may help us to better understand the physics relationships between refractive index structure and micro-climatological moments, since these can significantly affect free-space laser communications.

Thus, in this report, we present regression analyses of time-averaged scintillometer (*Cn2*) data in comparison to time-averaged temperature variance data (T'^2). We derive 21 selected case studies from winter, spring, and summer months. Correlation statistics are also derived to help quantify our results. We anticipate that this research will provide new (and potentially useful) information with which to better predict optical turbulence conditions along the A_LOT optical path.

2. Data Analysis

In this section, we present a few graphs to illustrate the kinds of data that were analyzed for the 21 case studies previously mentioned. A complete set of data graphs for the study is provided in the appendix. As an example, figures 3 through 6 present data for 07 February, 06 April, 04 June, and 16 June 2006, respectively. Each graph contains six subplots. In the top row of each graph are the 1-minute average values for *Cn2* and T'. In the middle row are the 30-minute average values for *Cn2* and the 1-minute average values for the variance T'^2. On the bottom row is a linear regression and scatter plot of 30-minute average values of *Cn2* and T'^2 as well as the 30-minute average values for T'^2. Note that correlation statistics (R-values) are annotated within the linear regression subplots. The R-values indicate the extent of correlation; 1 is a perfect positive correlation, 0 is no correlation, and –1 is a perfect negative correlation. In figures 3 through 6, $R > 0.93$ for 07 February and 06 June, whereas $R = 0.35$ on 04 June and $R = 0.04$ on 16 June. Nevertheless, correlations were $R > 0.80$ for 8 of 21 cases studied (see figure 7). Within this group, five cases had correlations $R > 0.85$. Several of these "high" correlation cases are plotted concurrently and are shown in figure 8. Interestingly, some of the regression lines shown in figure 8 appear to be grouped by season. This raises the question why maximum values for *Cn2* are greater in February and April than in June. A possible explanation may be that there was quite a lot of rain in June this year. Higher rainfall amounts would affect the microclimate (temperature and humidity) gradients along the A_LOT optical path, particularly within and above the large (underlying) forest patch (see figure 2). Here, stronger than usual evapo-transpiration processes may have taken place. Recall that *Cn2* is a function of refractive index fluctuations, which in turn are influenced by density (microclimate) gradients. Nevertheless, it is not clear from our analyses what brings about higher versus lower correlation statistics. Perhaps a key factor to consider is the extent of homogeneity (or non-homogeneity) of the turbulence and microclimate conditions along the A_LOT optical path. This is discussed in the following section.

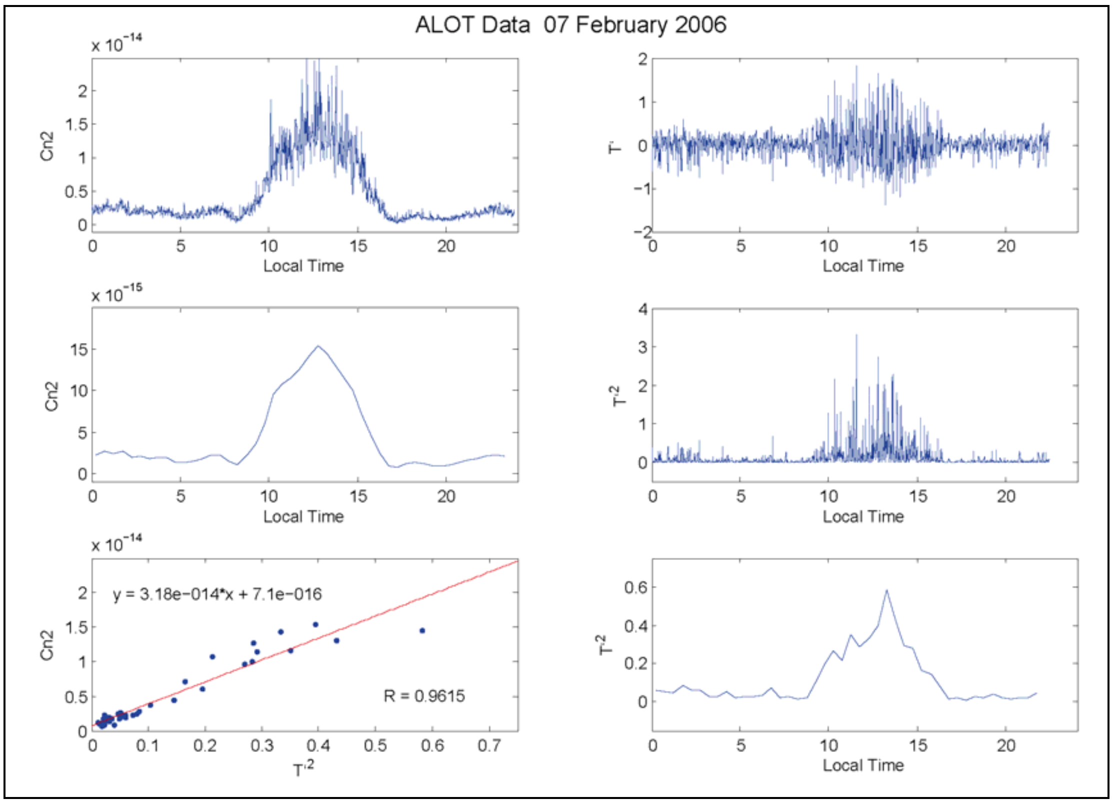

Figure 3. A_LOT data and regression analysis for 07 February 2006. (In the top row of subplots are the 1-min. avg. values for *Cn2* and T'. In the middle row are the 30-min. avg. values for *Cn2* and the 1-min. avg. values for the variance T'^2. On the bottom row is the linear regression of 30 min. avg. values of *Cn2* and T'^2 and the 30-min. avg. values for T'^2. Note that correlation statistic [R-value] is annotated within the linear regression subplot.)

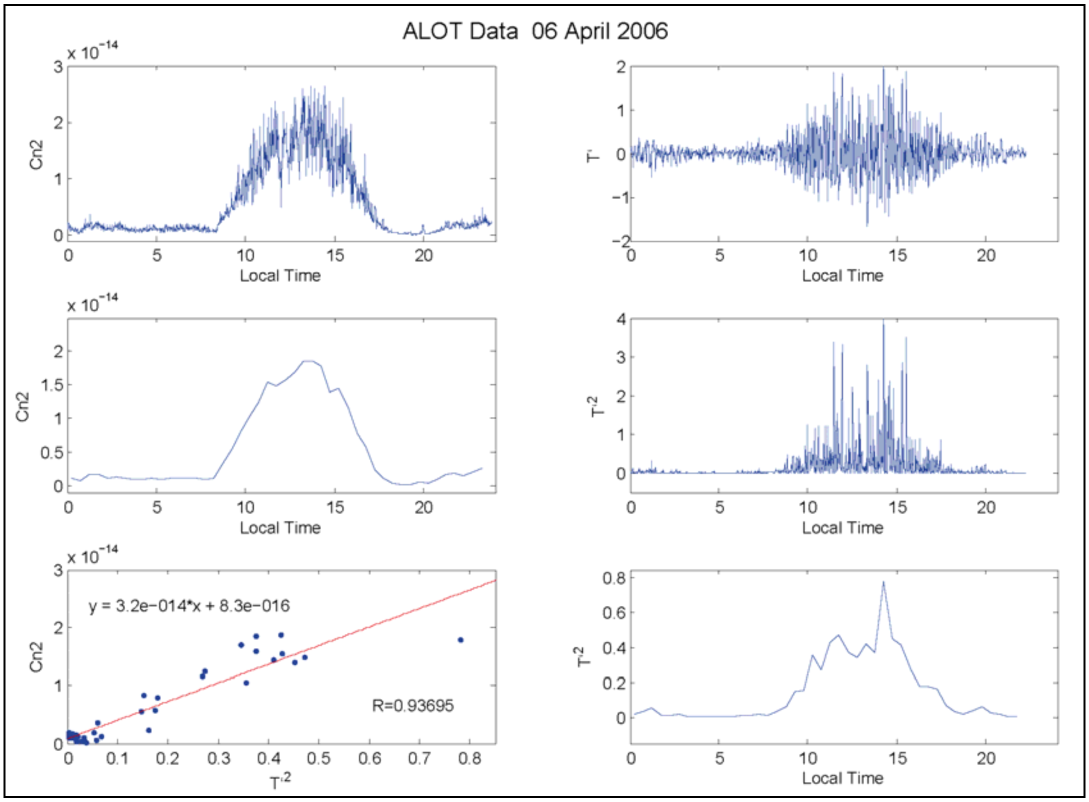

Figure 4. Same as figure 3 except for 06 April 2006.

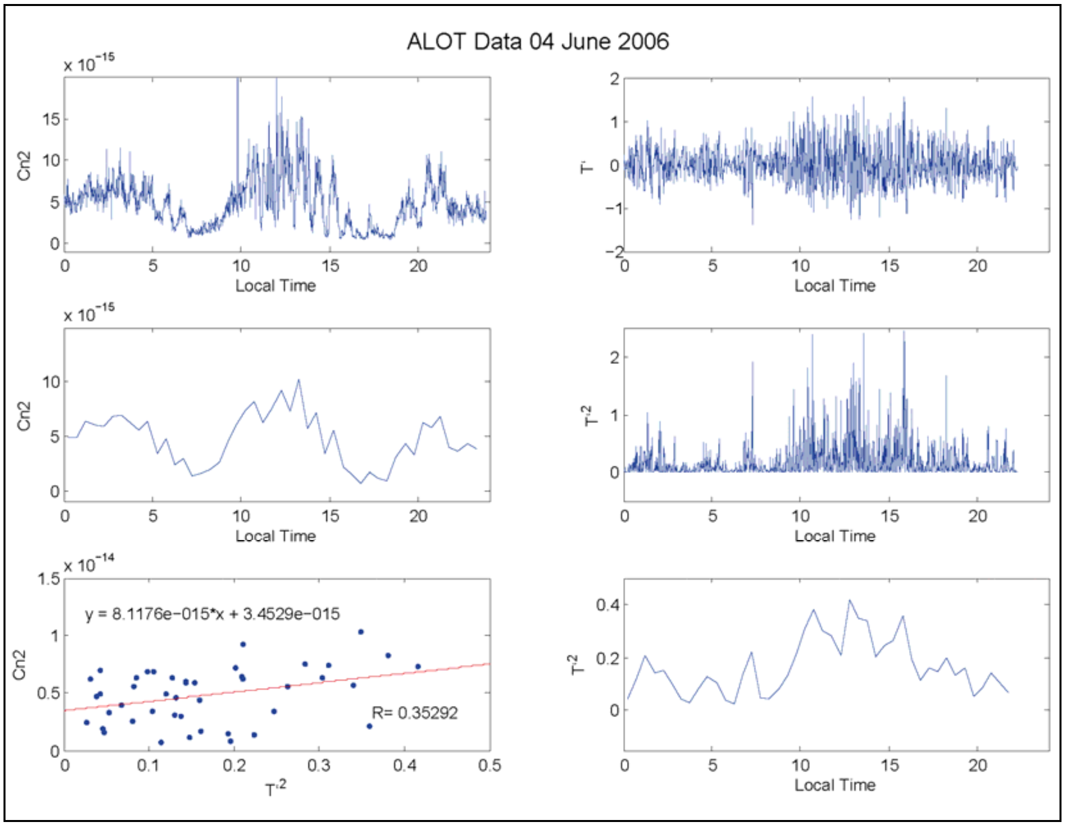

Figure 5. Same as figure 3 except for 04 June 2006.

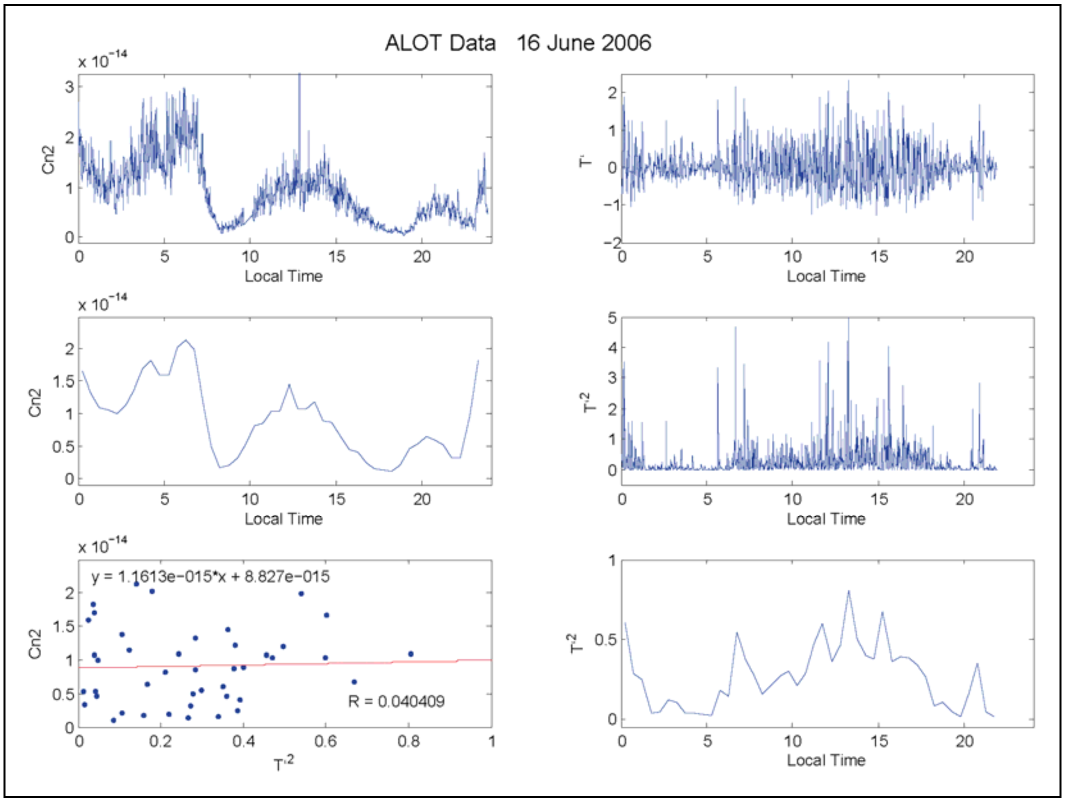

Figure 6. Same as figure 3 except for 16 June 2006.

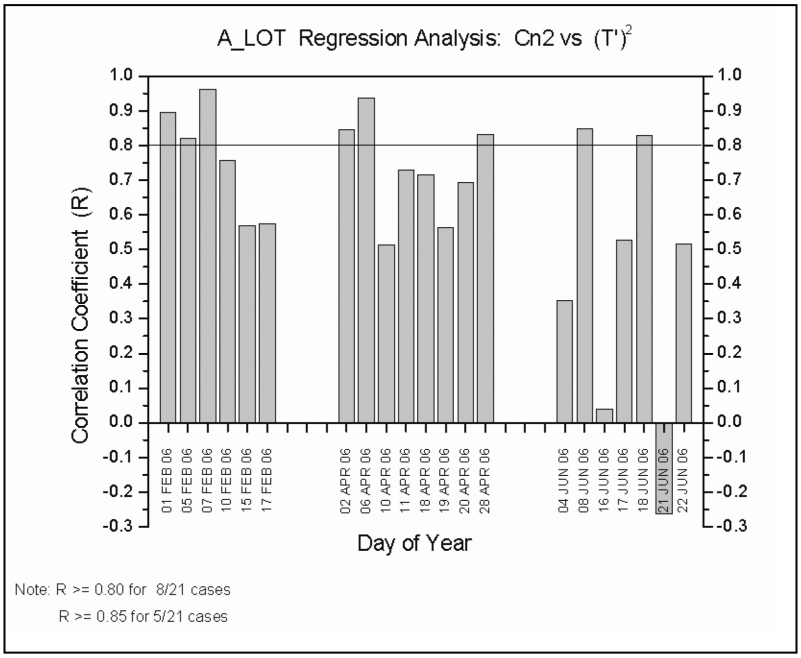

Figure 7. Summary of A_LOT regression analyses. (Note that R ≥ 0.80 for 8 of 21 cases where R ≥ 0.85 for five cases within this group.)

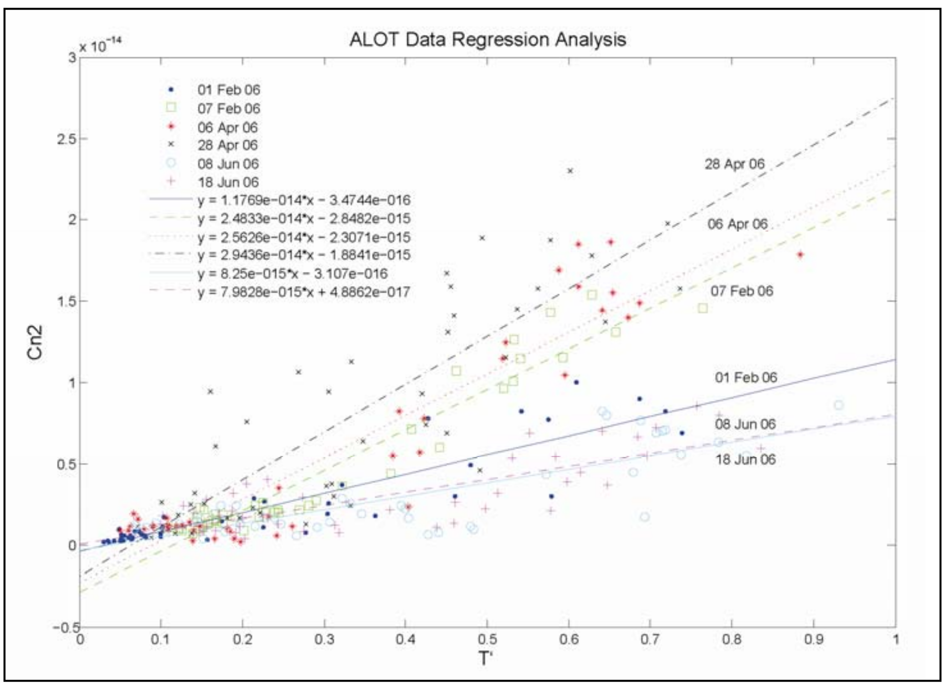

Figure 8. Several data sets with R ≥ 0.80 plotted concurrently.

3. Discussion

Our study focuses on data recorded via two different kinds of instruments. The A_LOT scintillometer is an optical device that provides path-averaged measurements of refractive index structure. In contrast, the A_LOT sonic anemometer is a point sensor, which provides local rooftop measurements of temperature moments. Therefore, we ask whether a point sensor, located at one end of the A_LOT optical path, can characterize average optical turbulence conditions along the entire LOS. We say "average" conditions, not "instantaneous" conditions, because predicting very short-time interval optical turbulence information is nearly an impossibility. Nevertheless, we propose that in order for the *in situ* data to correlate well with the path-averaged data, a certain degree of homogeneity must exist with regard to optical turbulence conditions along the A_LOT optical path. What evidence, then, confirms (or rejects) this notion of homogeneity for the 21 cases discussed.

To begin to address this question, we conducted an analysis of the (IOL rooftop) vector wind field. Results from the analysis (so far) are presented in figures 9 through 11 for data collected in February, April, and June, respectively. Each graph is divided into four subplots. Correlation R-values are annotated on each subplot. At first, it appears that higher wind velocities ($\geq$ 2.0 ms^{-1}) and wind direction from the southeast result in higher R-values, e.g., as confirmed by data on 01 February, 07 February, 02 April, and 06 April 2006. This link may be due to increased horizontal and vertical mixing of air parcels along the optical path. In addition, a relatively unobstructed upwind fetch exists southeast of the IOL building (see figure 2), which may provide wind flow patterns that more closely resemble the mean (path-averaged) wind field. In contrast, wind flow from other compass directions goes past adjacent buildings or forests that border the installation. While minimum wind velocity and preferred wind direction appear reasonable as a key factor for large R-values, it is (nevertheless) rejected by the data for 17 February, 19 April, and 18 June 2006. In addition, to complicate matters further, the *Cn2* and T'^2 data for 08 June (with low wind velocities) and 18 June 2006 (with winds from the northeast) were highly correlated. Thus, additional research is recommended to explore alternate factors, such as Richardson number stability (Stull, 1988), nighttime and daytime differences in *Cn2*, and/or clear sky and cloud cover effects on the measured *Cn2* data and derived R-values (e.g., Curley et al., 2006). Also, it may be helpful to install an additional sonic sensor on the A_LOT water tower. At that time, we can implement more complex, multi-parameter regression analyses to augment our research.

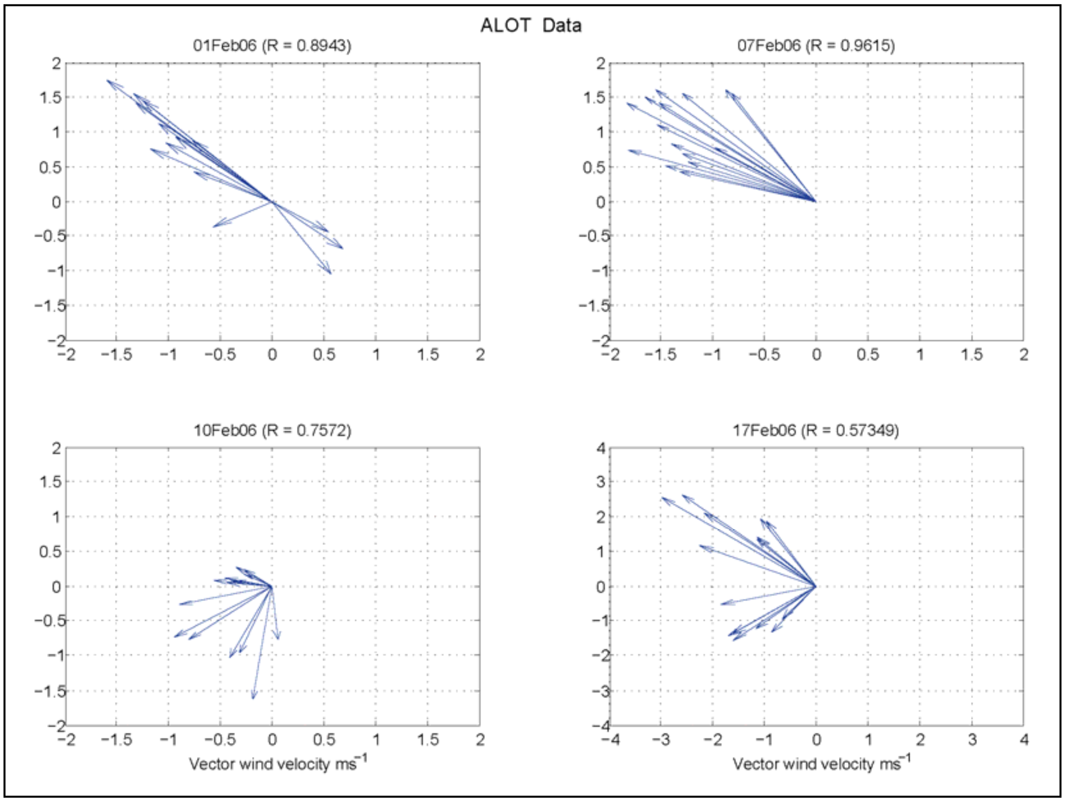

Figure 9. Vector wind field analysis for selected case studies in February 2006.

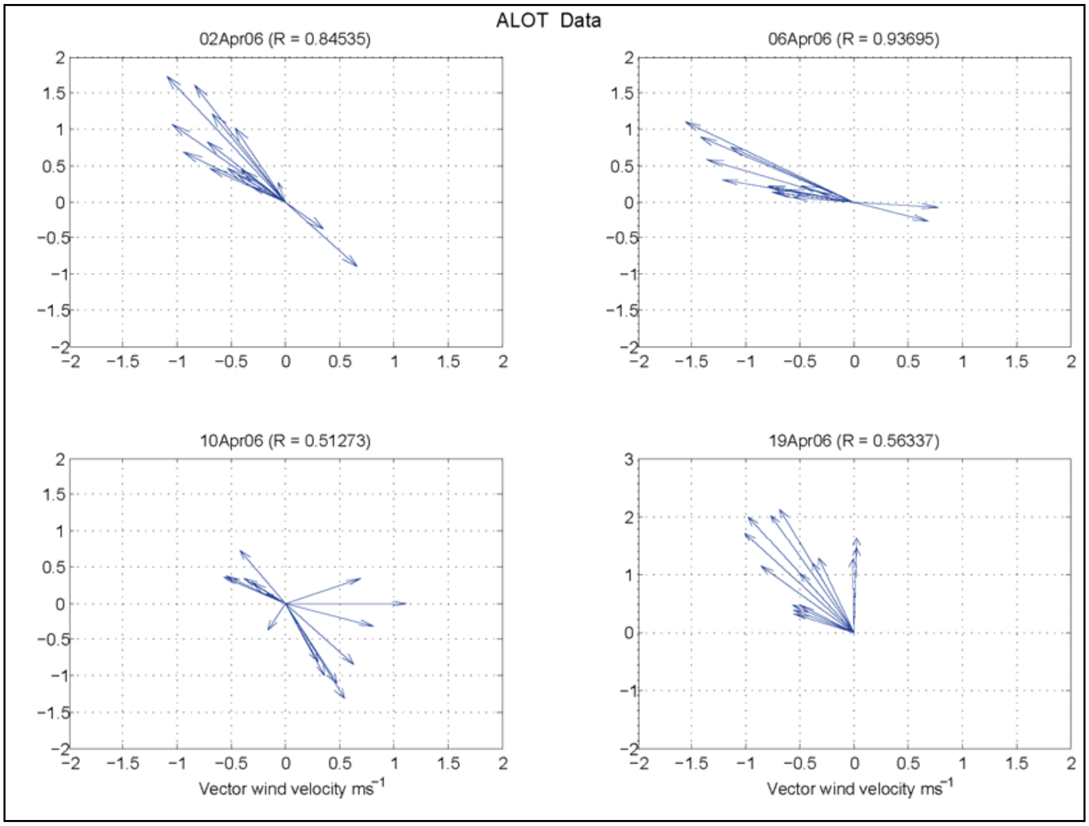

Figure 10. Same as figure 9 except for April 2006.

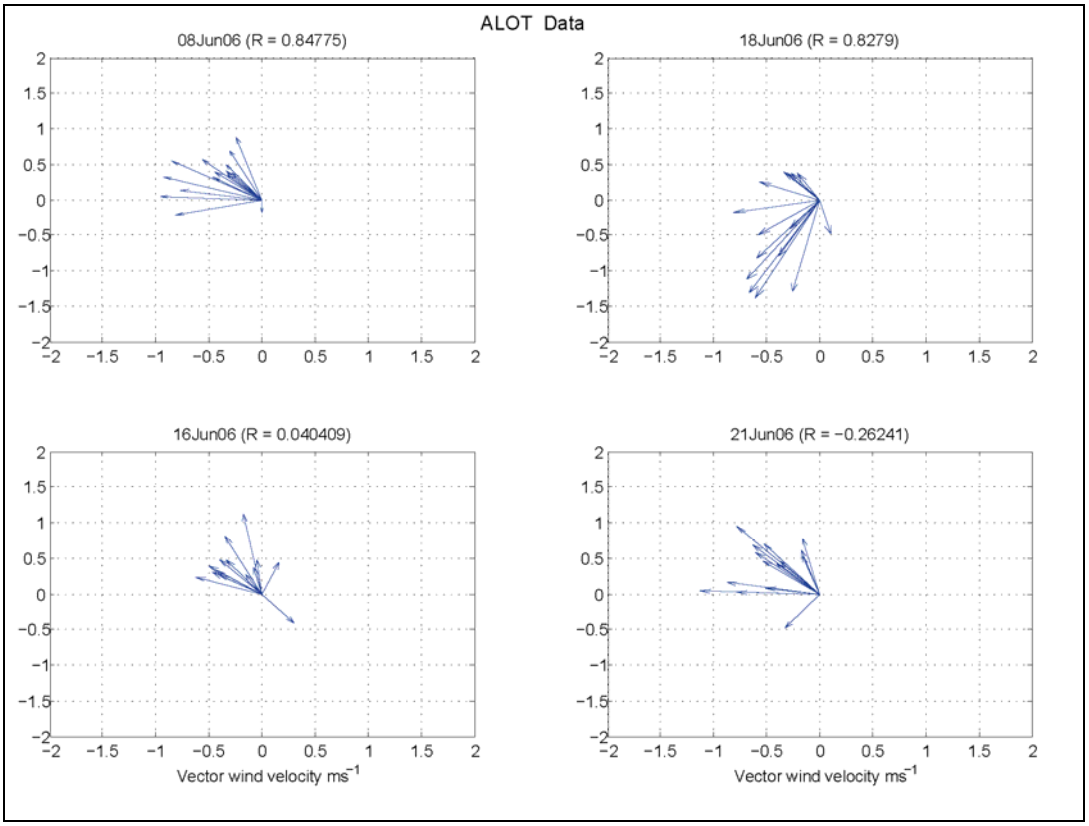

Figure 11. Same as figure 9 except for June 2006.

4. Summary and Conclusions

A_LOT sensor network data analysis was conducted to investigate physics relationships between *Cn2* and T'^{2}. We found 8 of 21 cases with fairly high (i.e., R ≥ 0.80) correlations. However, it is not yet clear what distinguishes between high versus low R-values. We suggested that homogeneity of the optical turbulence conditions along the A_LOT propagation path may be a key factor in determining correlation strength. So far, we investigated wind velocity and wind direction for several cases to support our hypothesis, but our findings were inconclusive. Nevertheless, a possible seasonal trend was detected in the regression analysis data, which can be explored in future works. In conclusion, we recommend that additional multi-parameter regression analyses be performed to better describe optical turbulence conditions at ARL's A_LOT. Multi-parameter regressions may be quite useful, particularly if an additional sonic instrument can be installed on the A_LOT water tower. As a result, new theoretical expressions can be developed to support Research and Development (and performance assessment) of advanced laser optics communications systems, including those that incorporate adaptive optics technologies.

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Appendix A. Regression Analyses

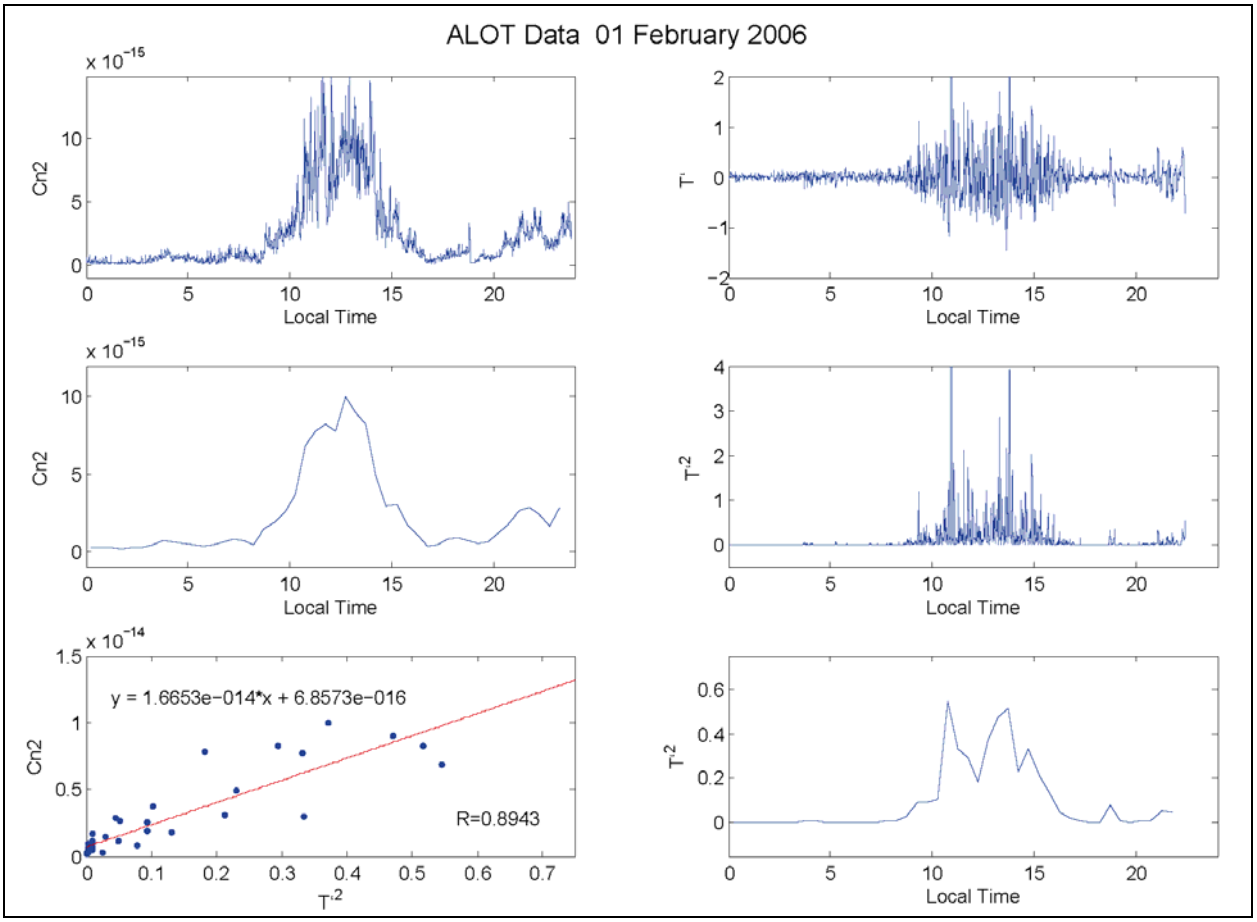
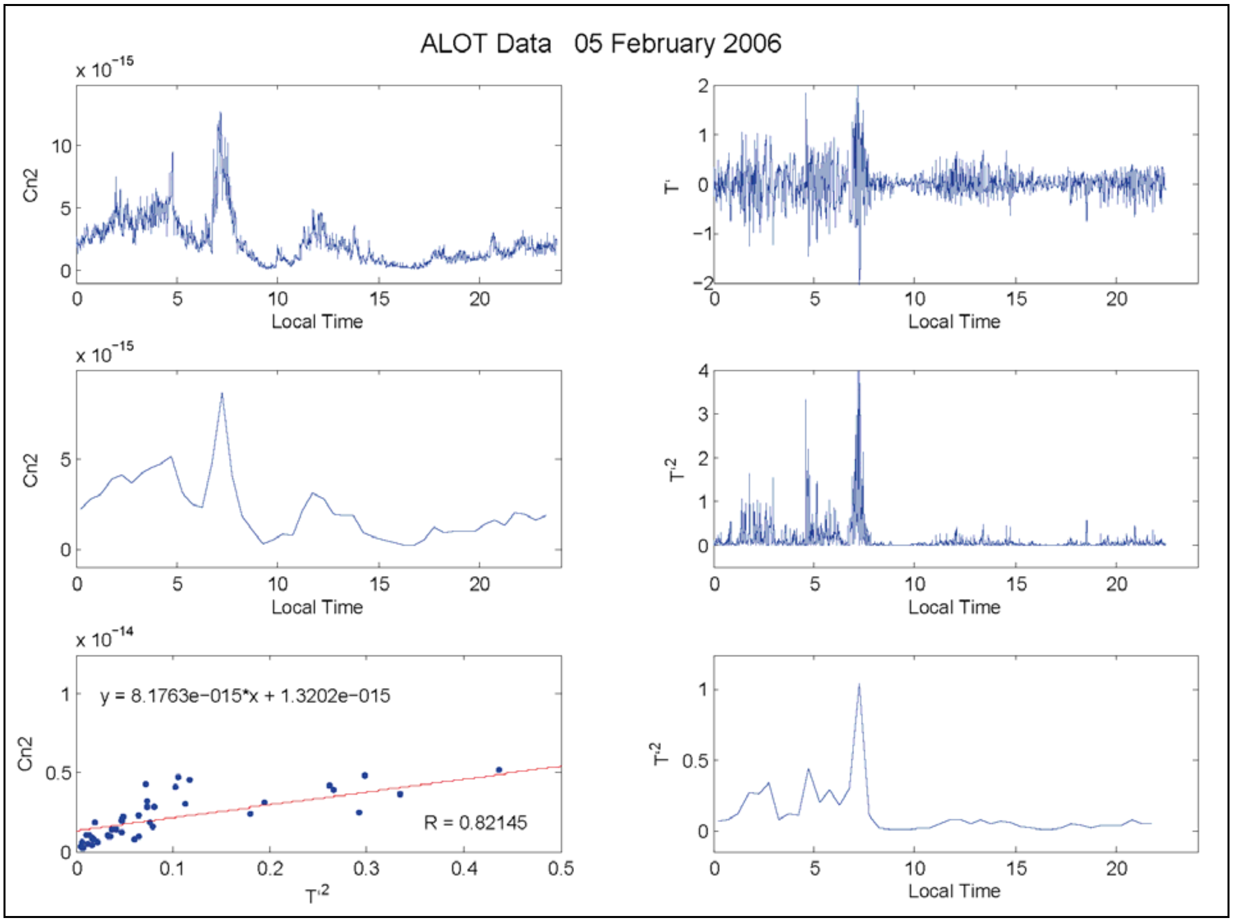


Figure A-1. A_LOT data and regression analysis for 01 February 2006. (In the top row of subplots are the 1 min. avg. values for *Cn2* and T'. In the middle row are the 30 min. avg. values for *Cn2* and the 1 min. avg. values for the variance T'^2. On the bottom row is the linear regression of 30 min. avg. values of *Cn2* and T'^2 and the 30 min. avg. values for T'^2. Note that correlation statistic [R-value] is annotated within the linear regression subplot.)



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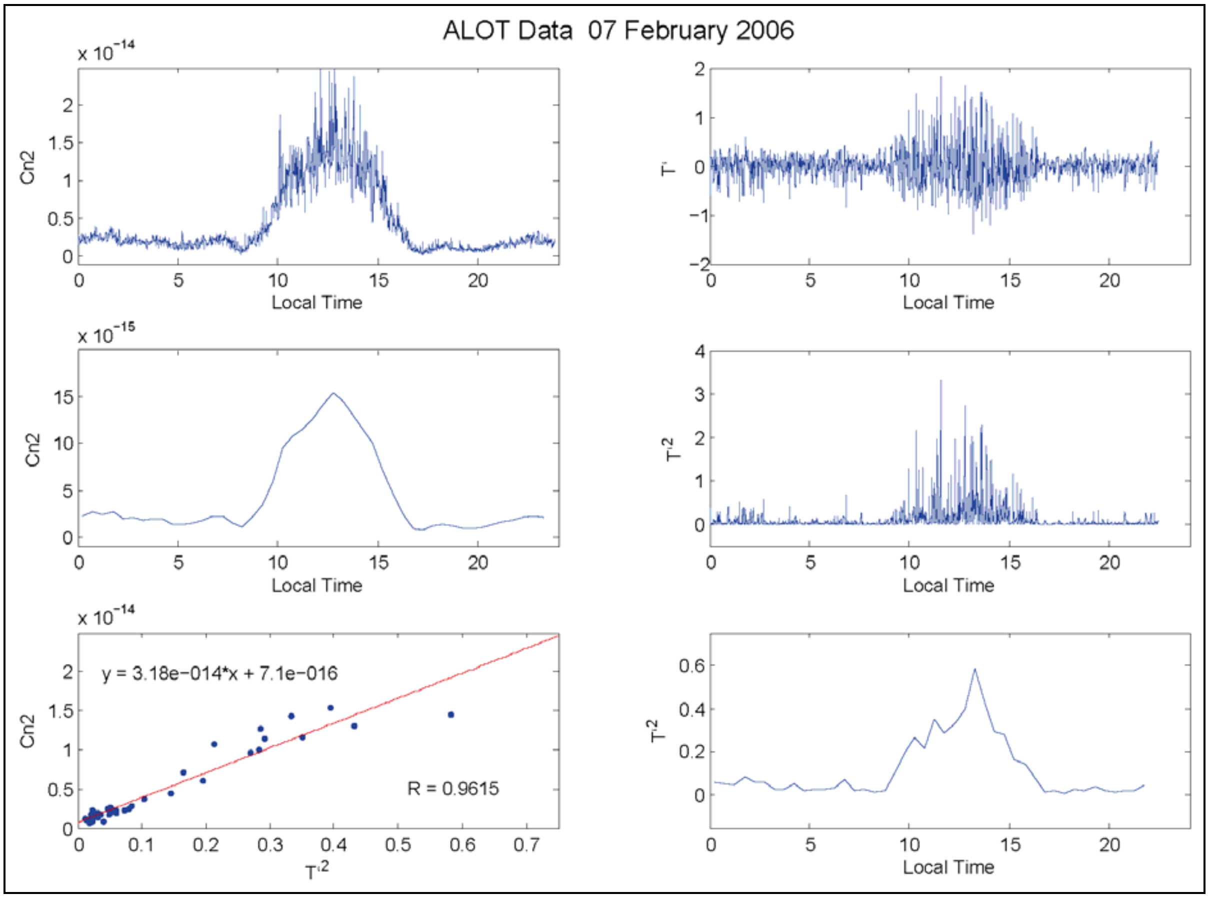

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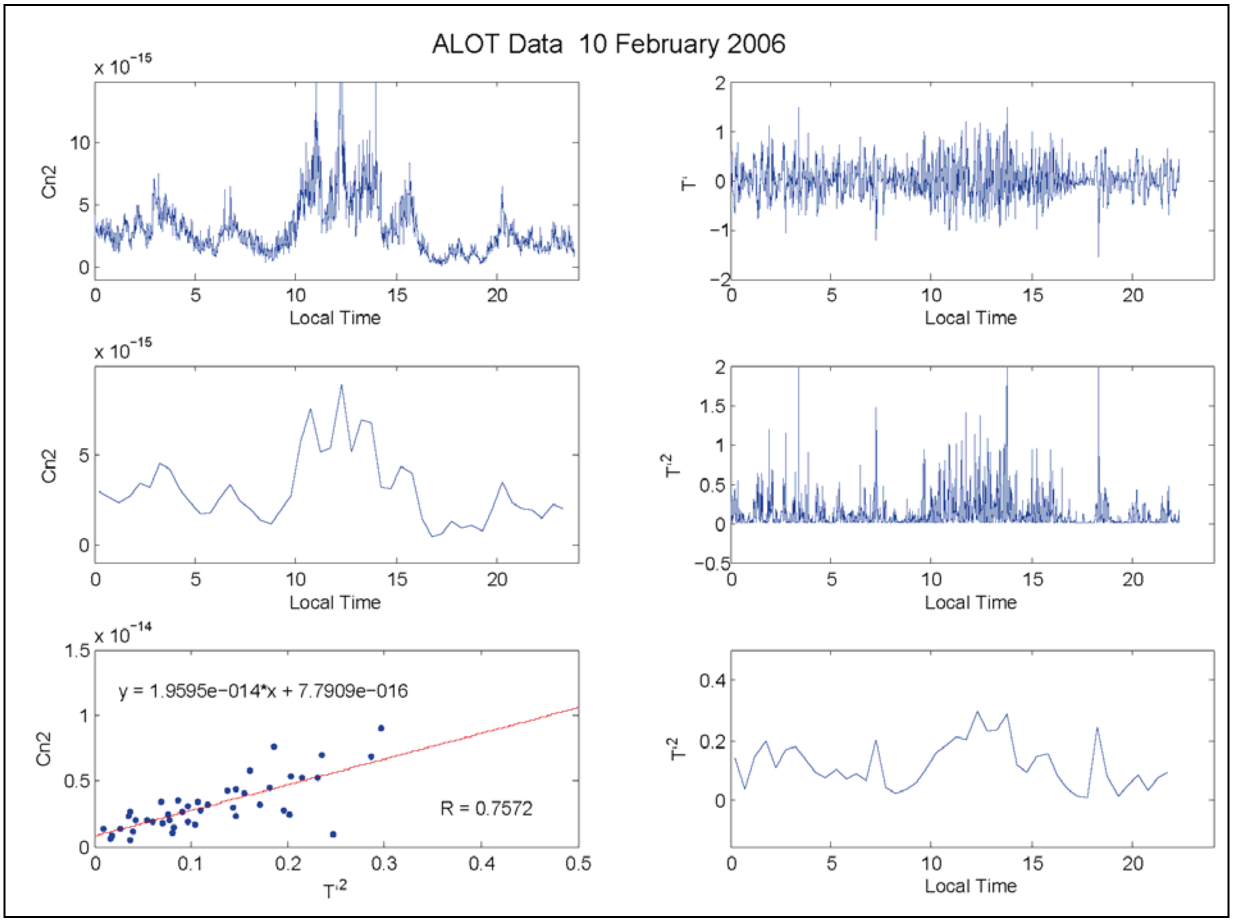

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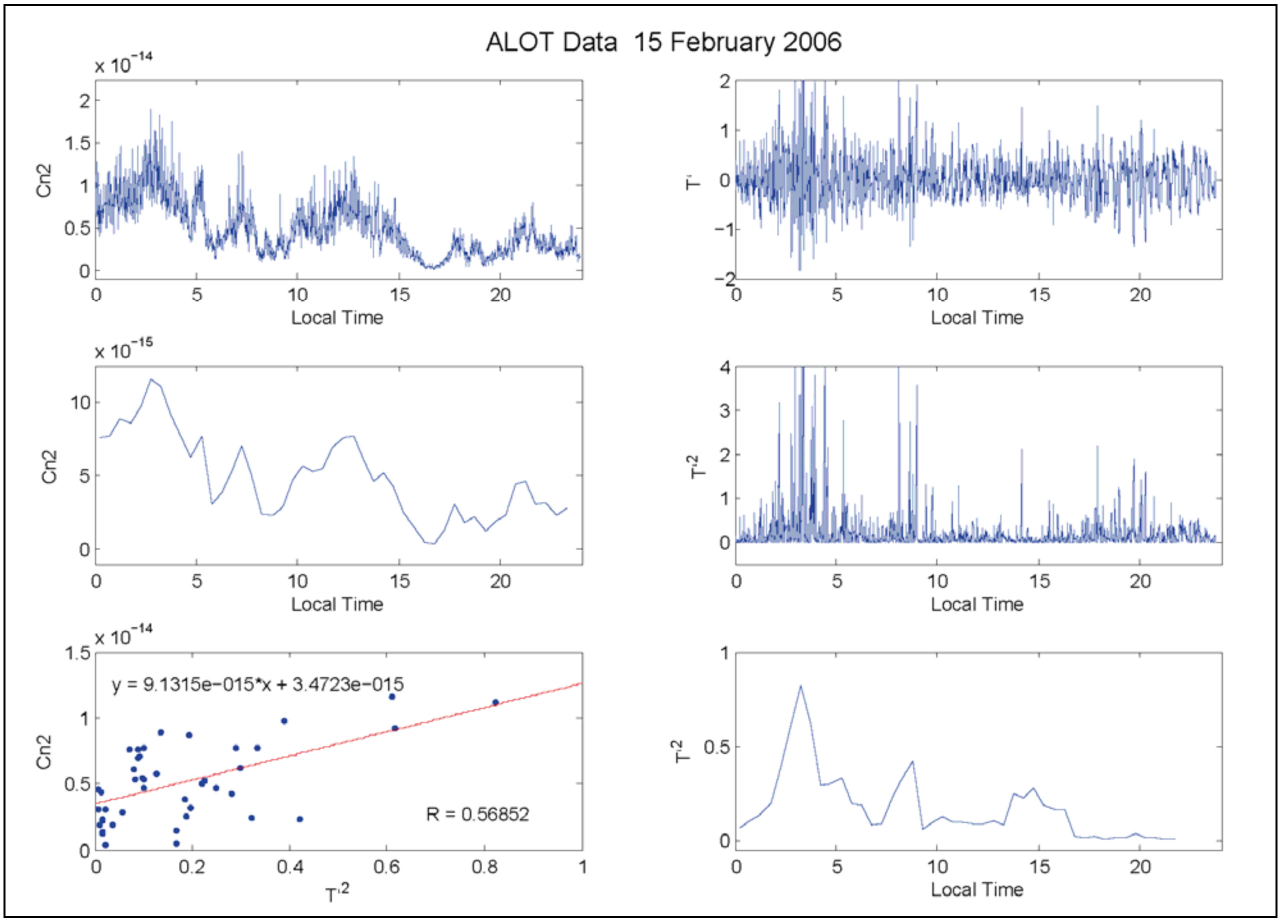

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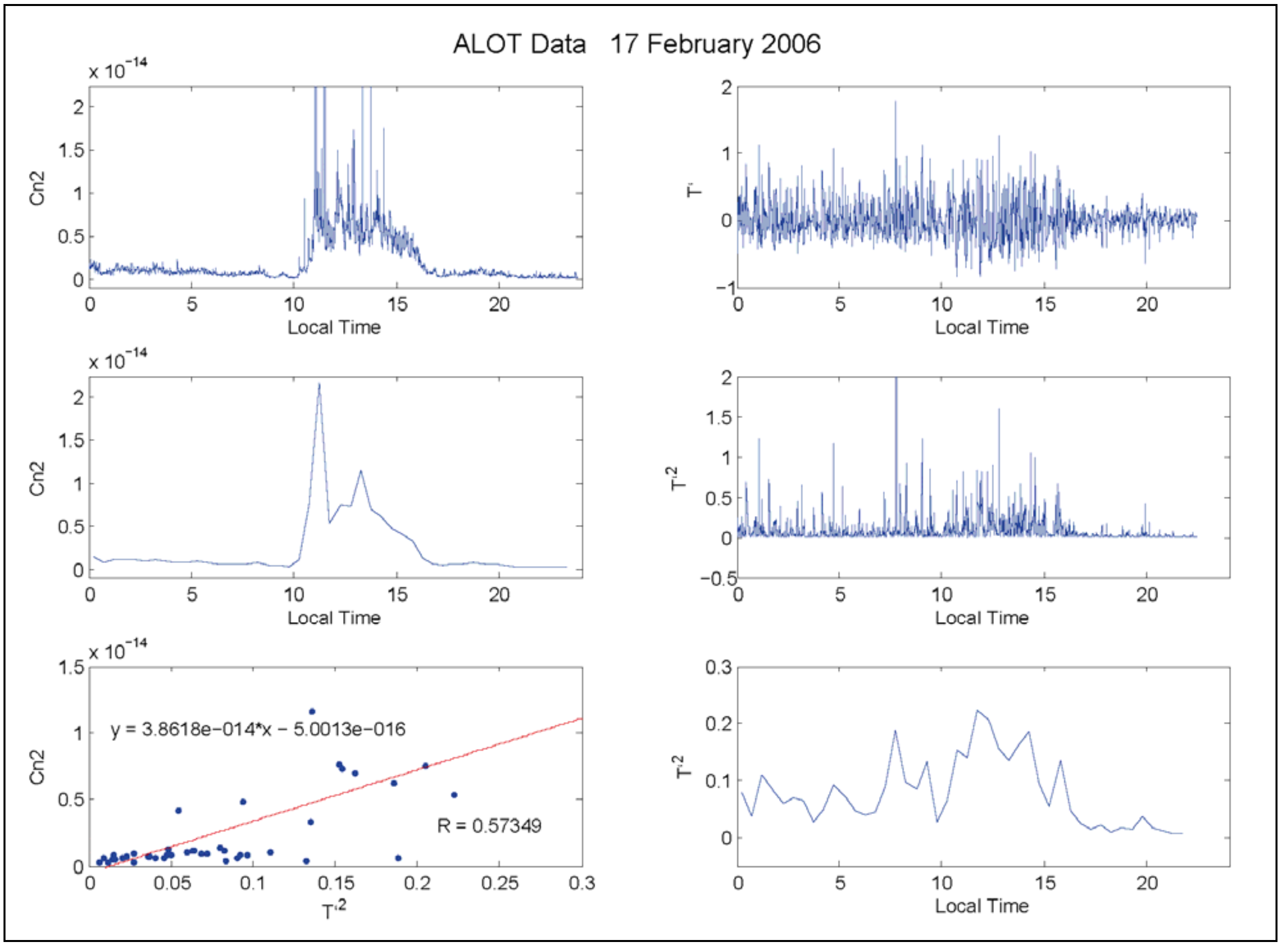

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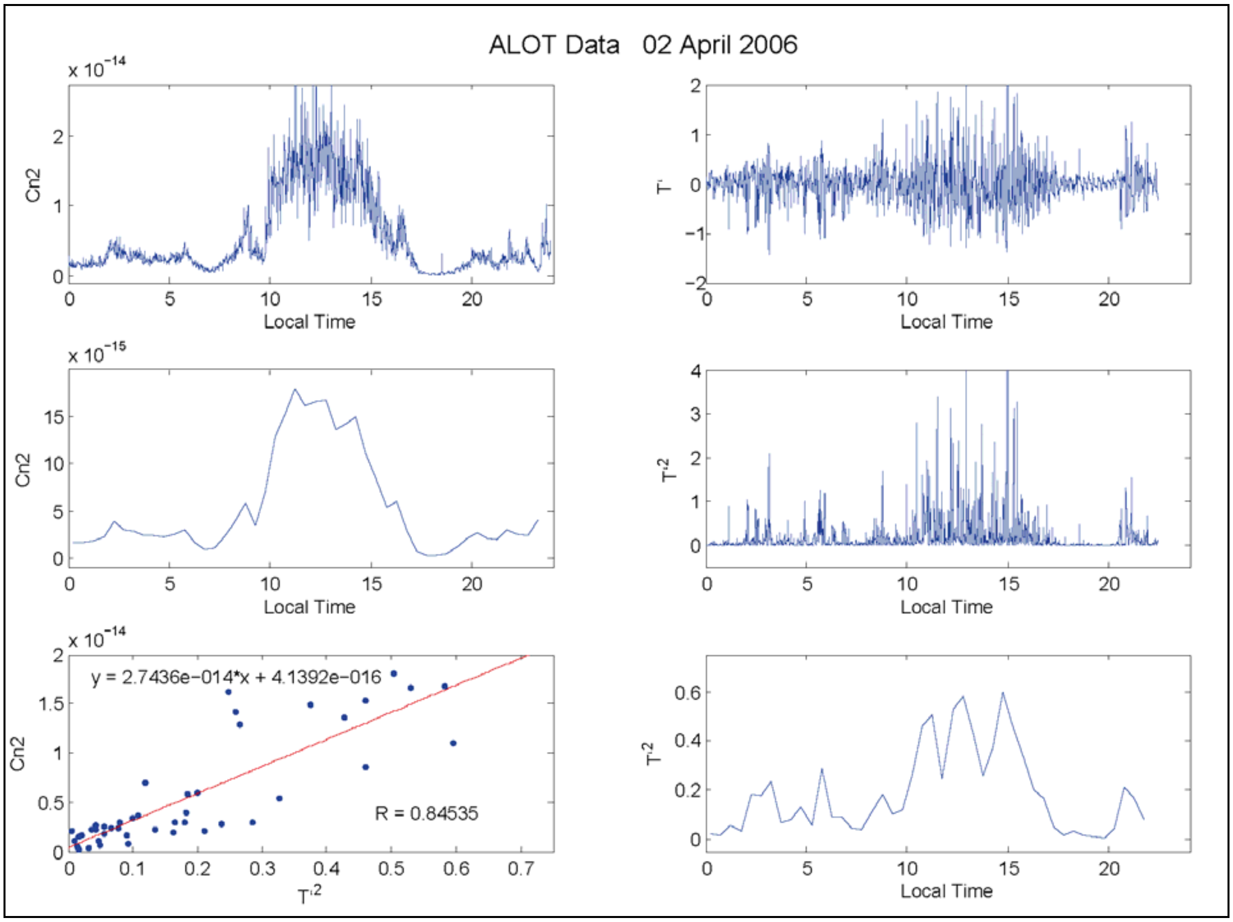

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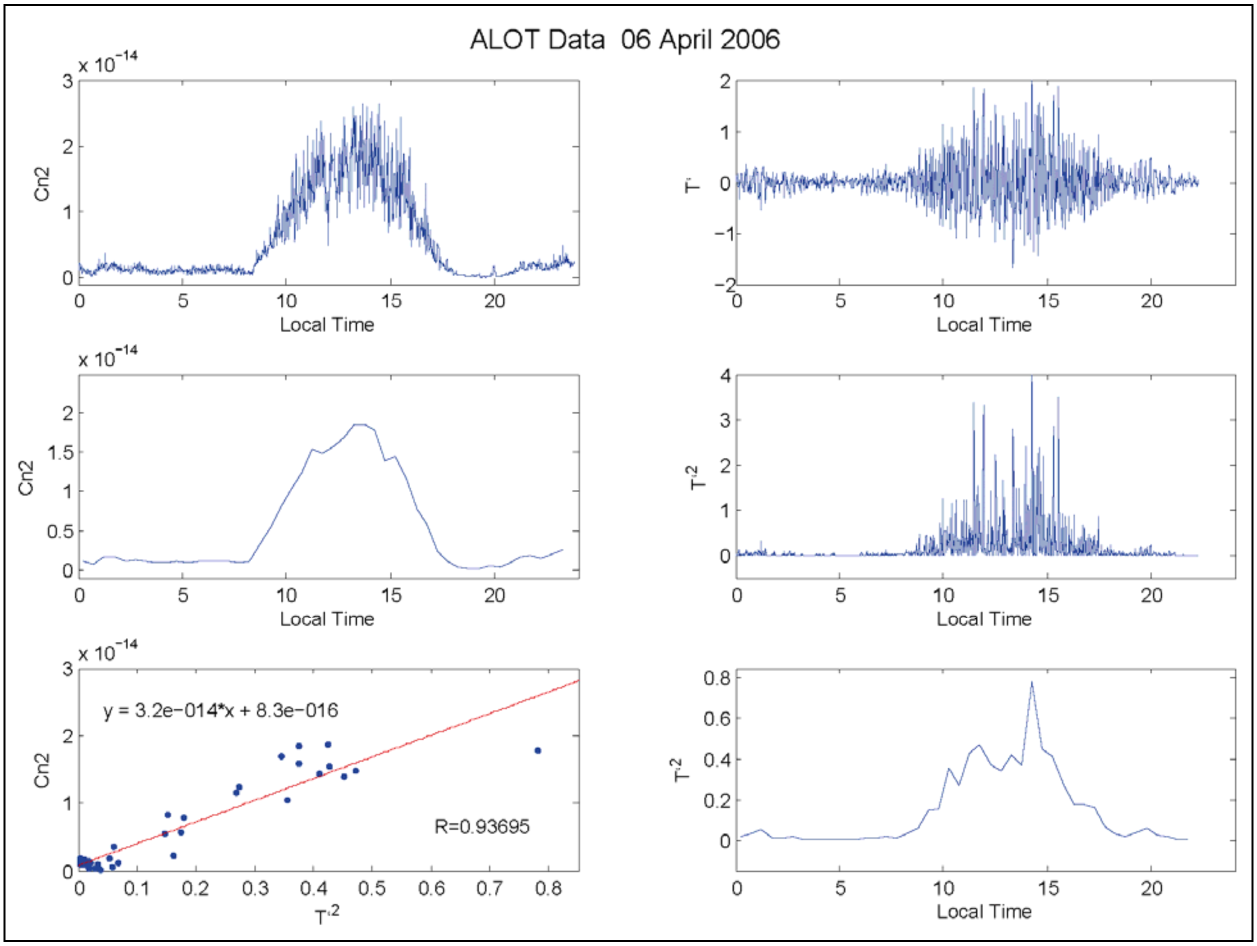

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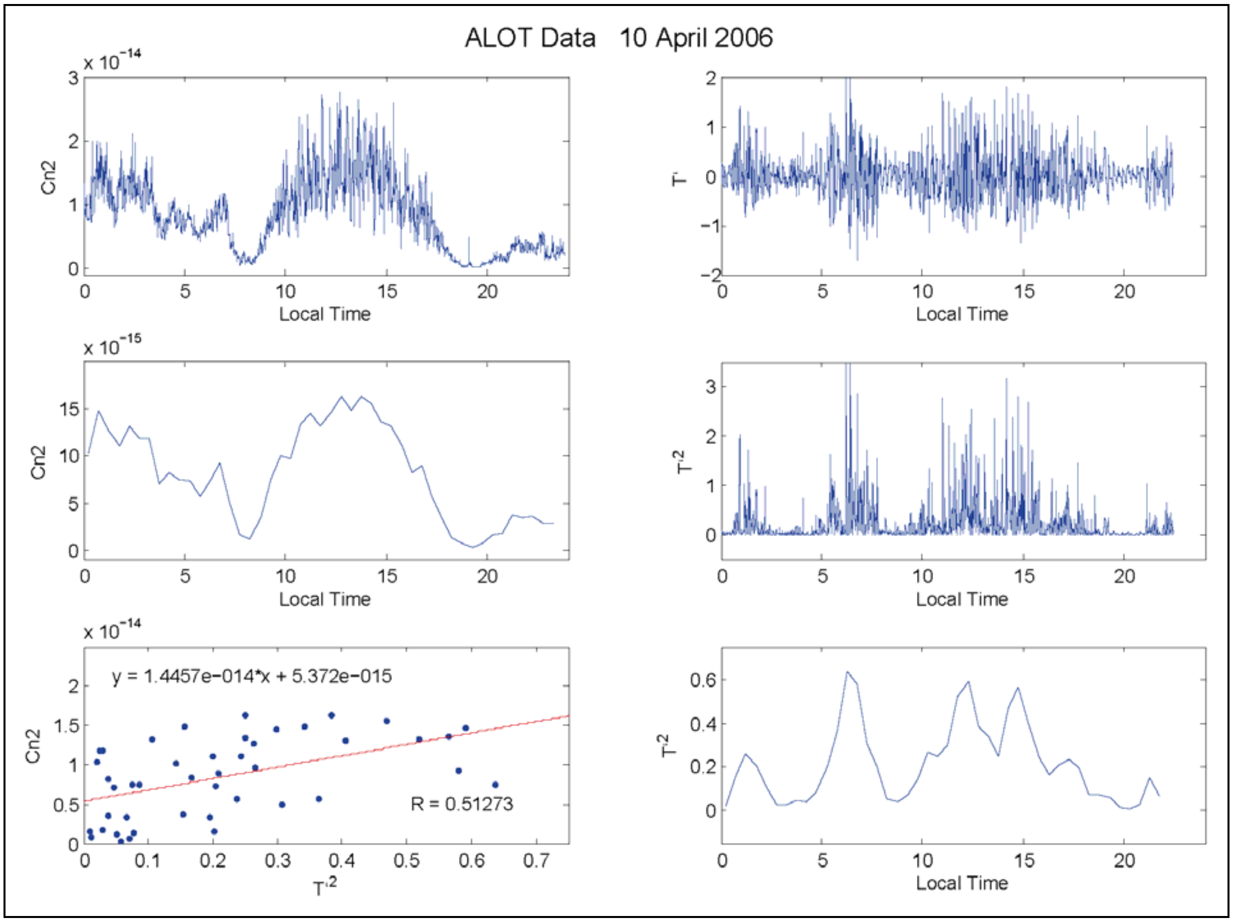

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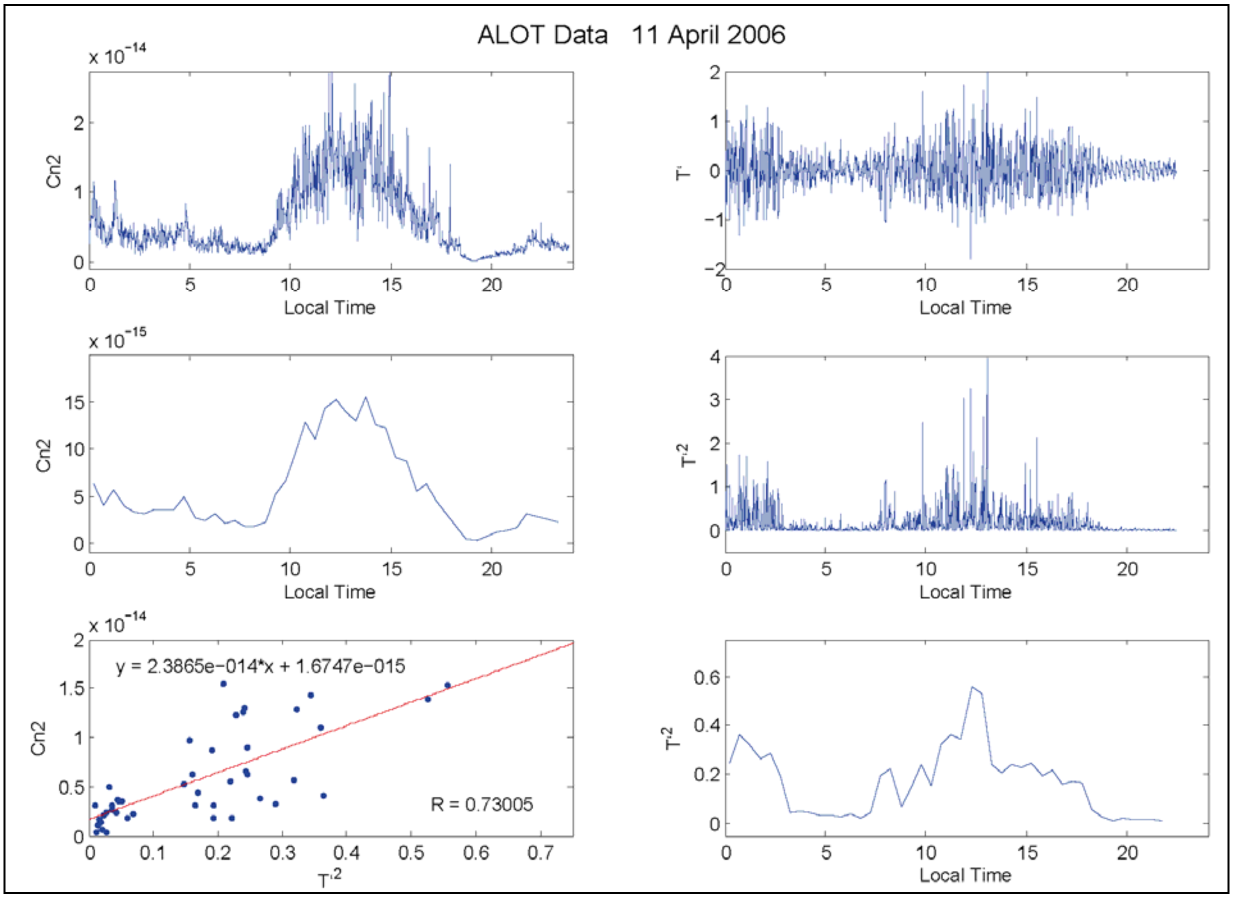

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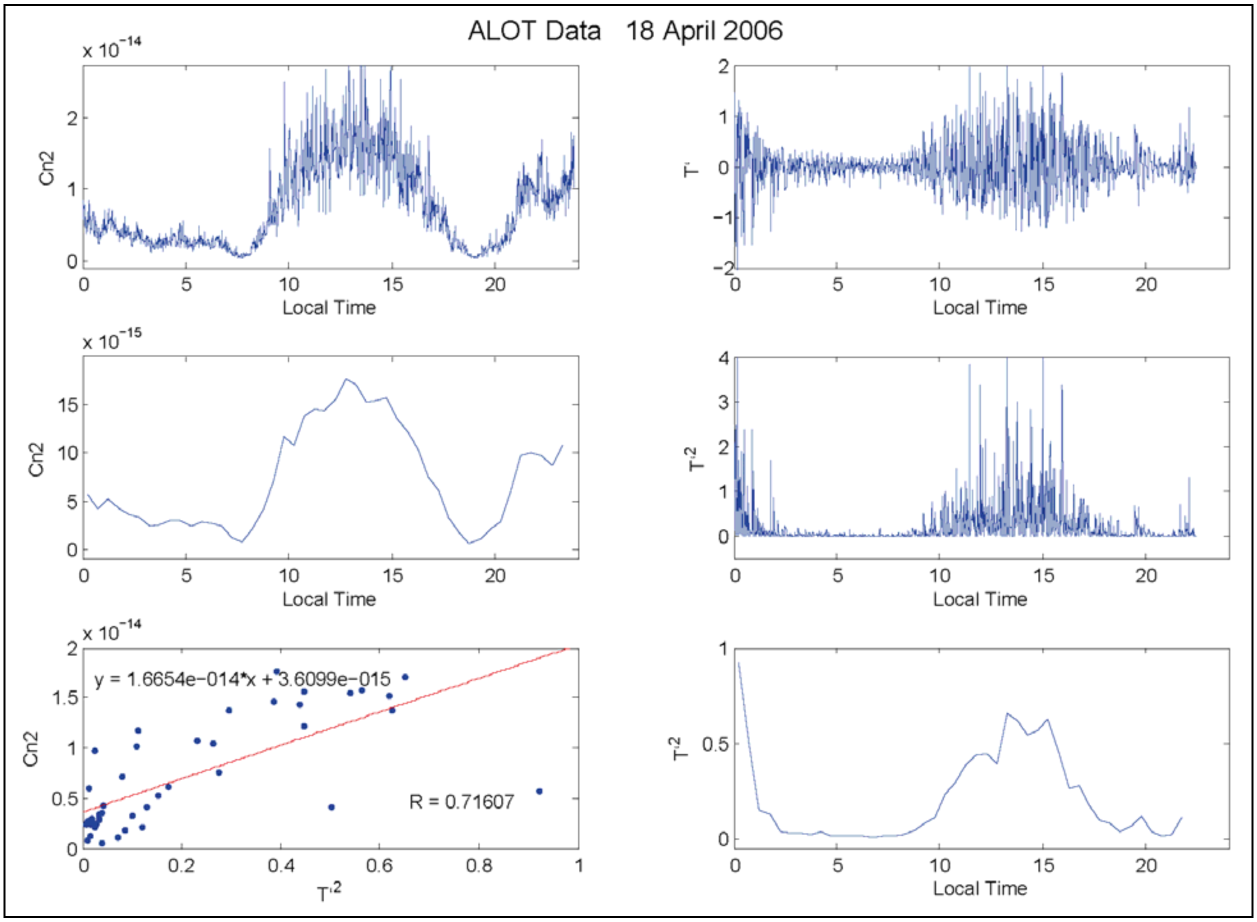

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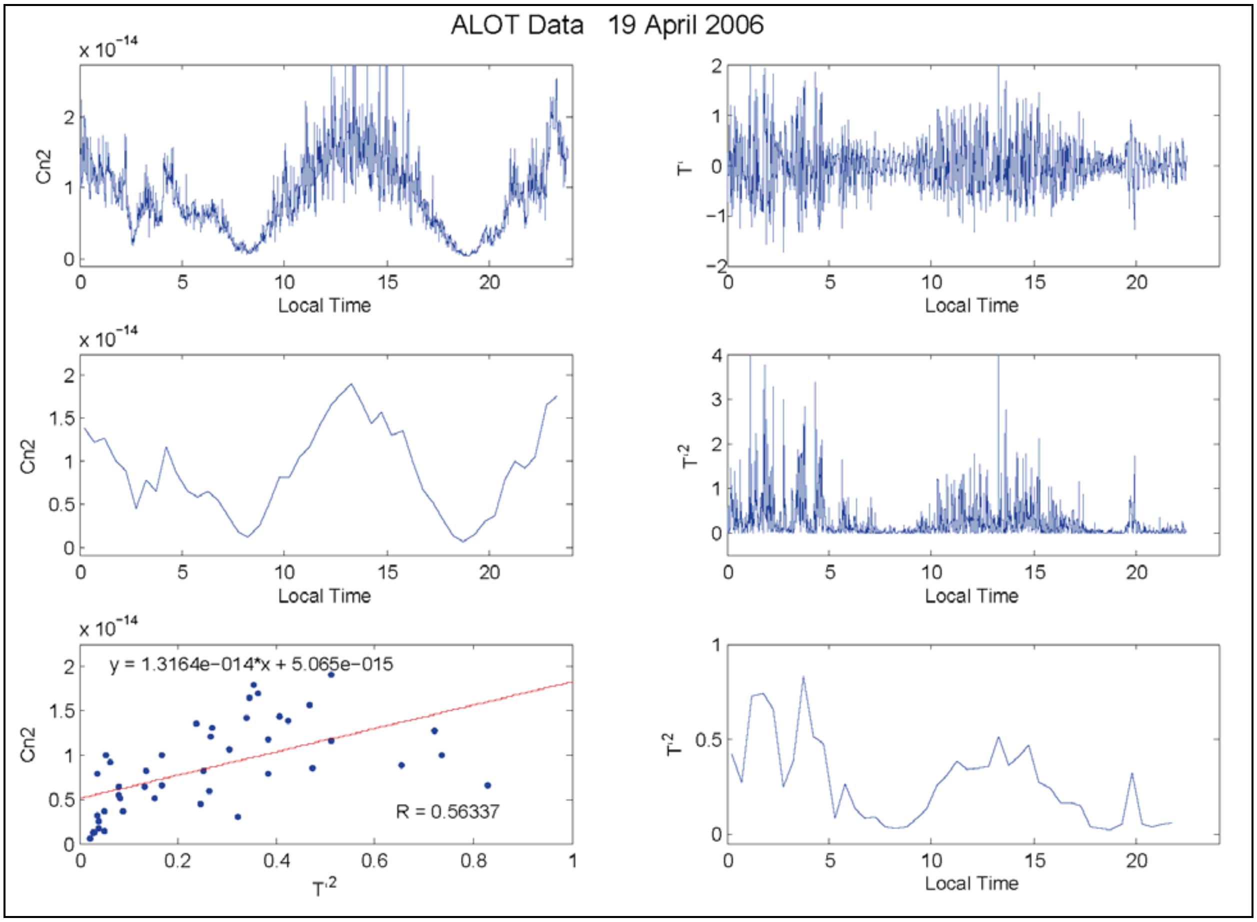

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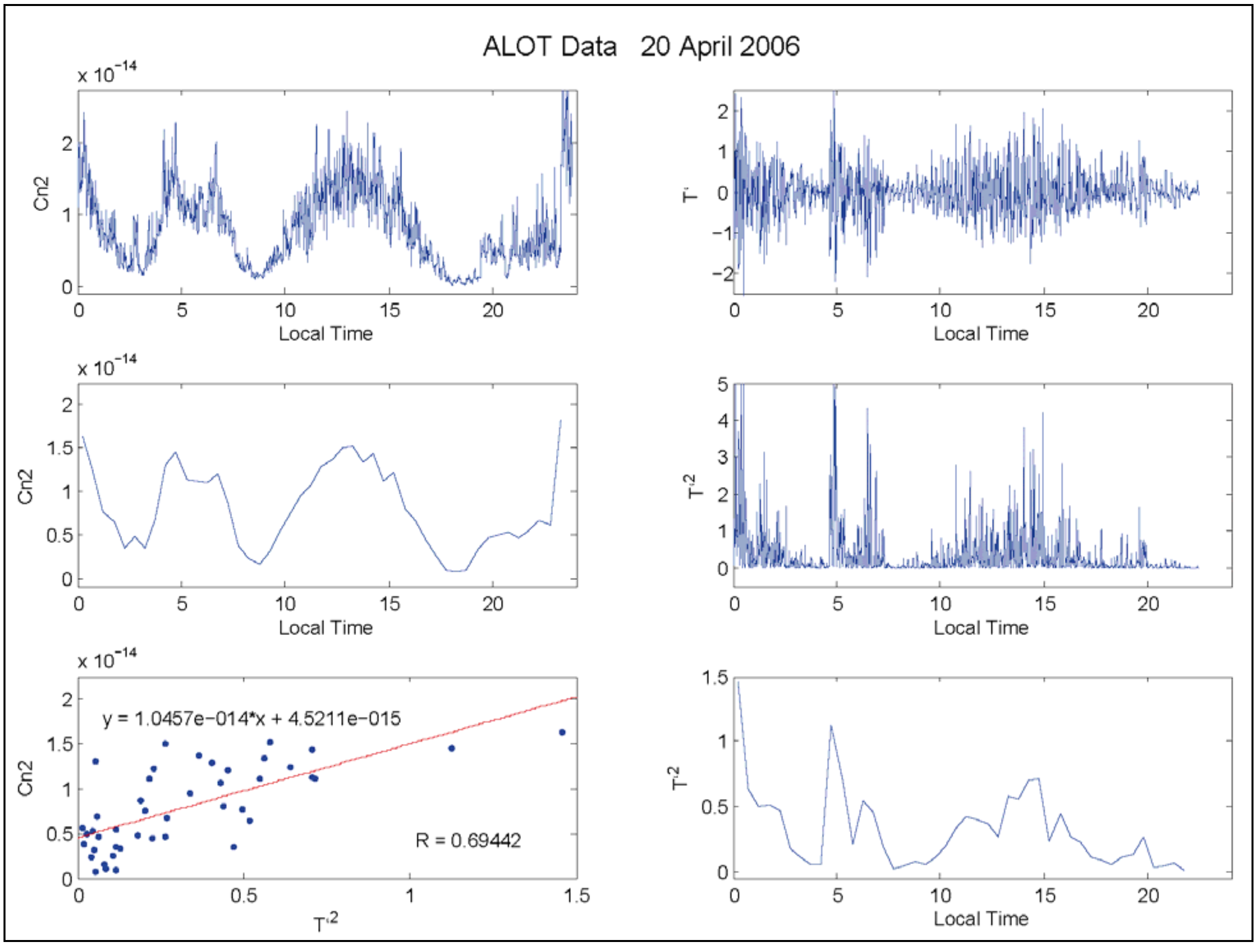

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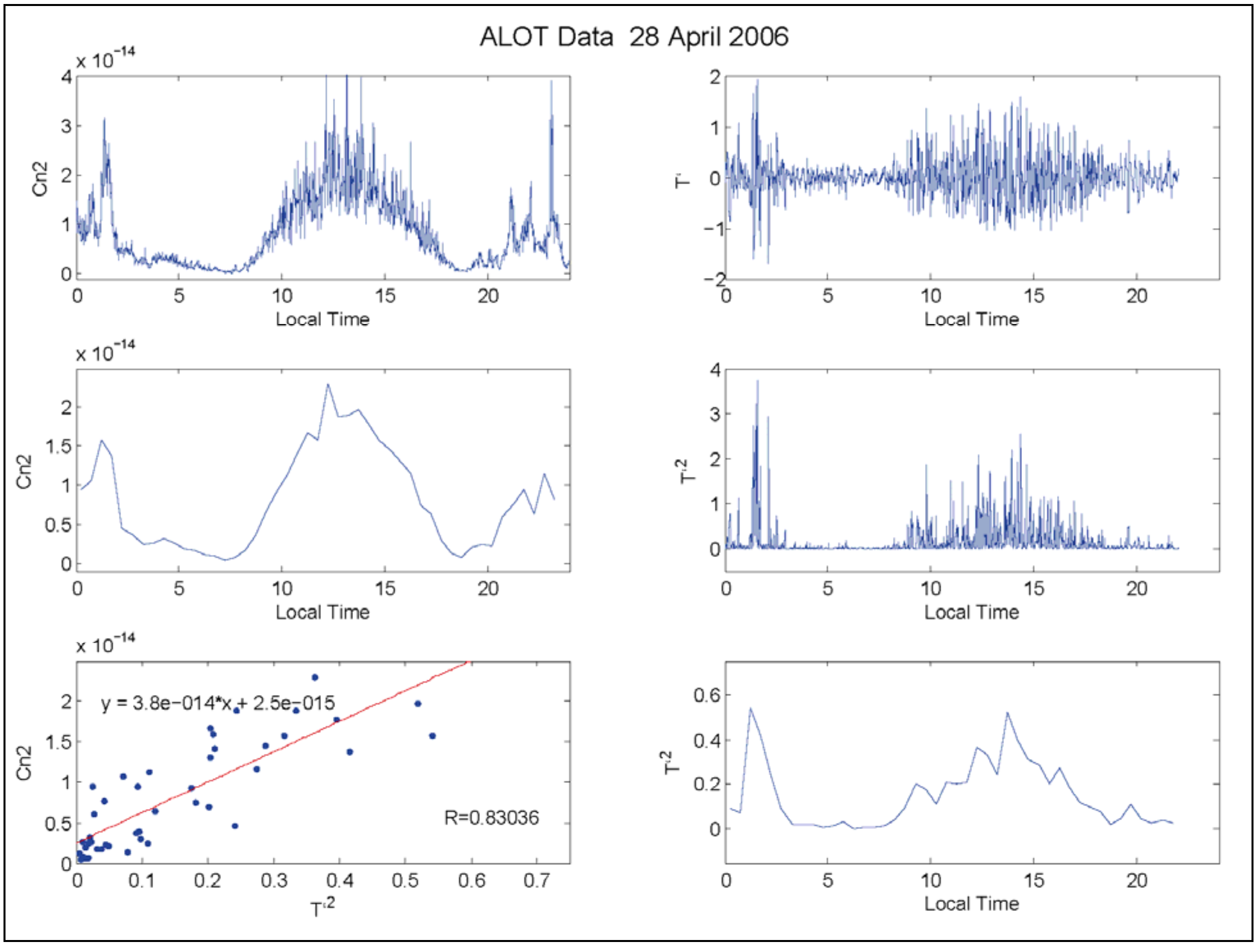

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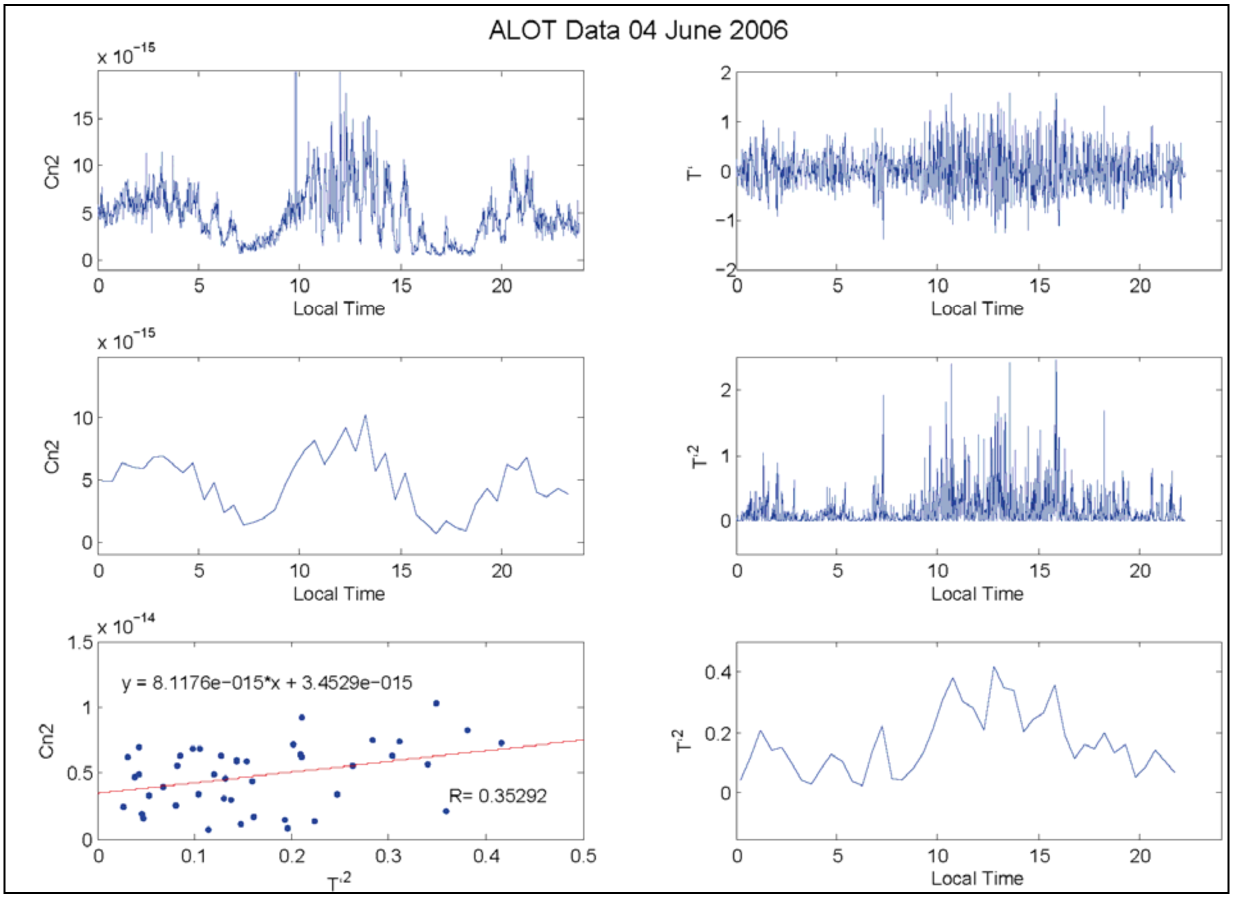

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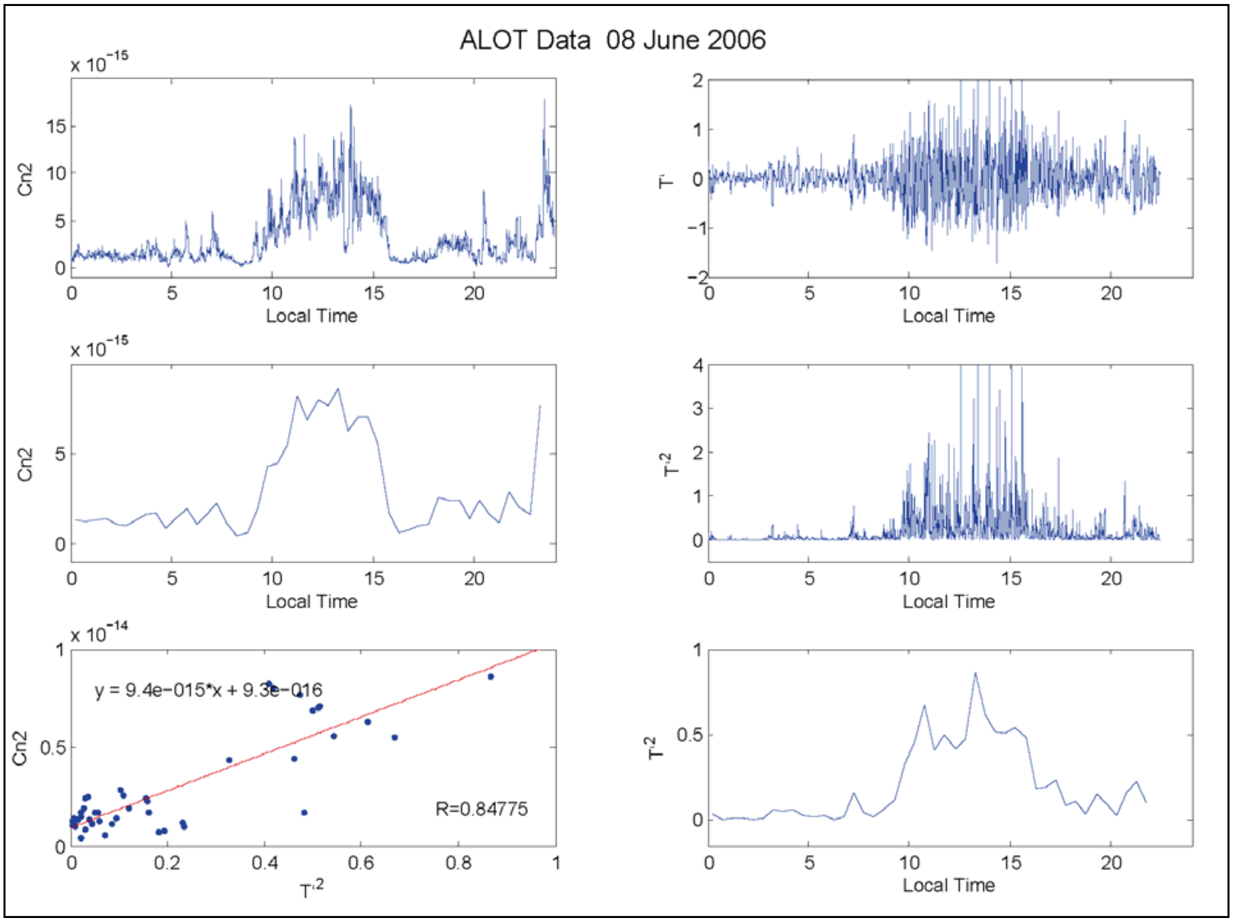

Figure A-16. Same as figure A-1 except for 08 June 2006.

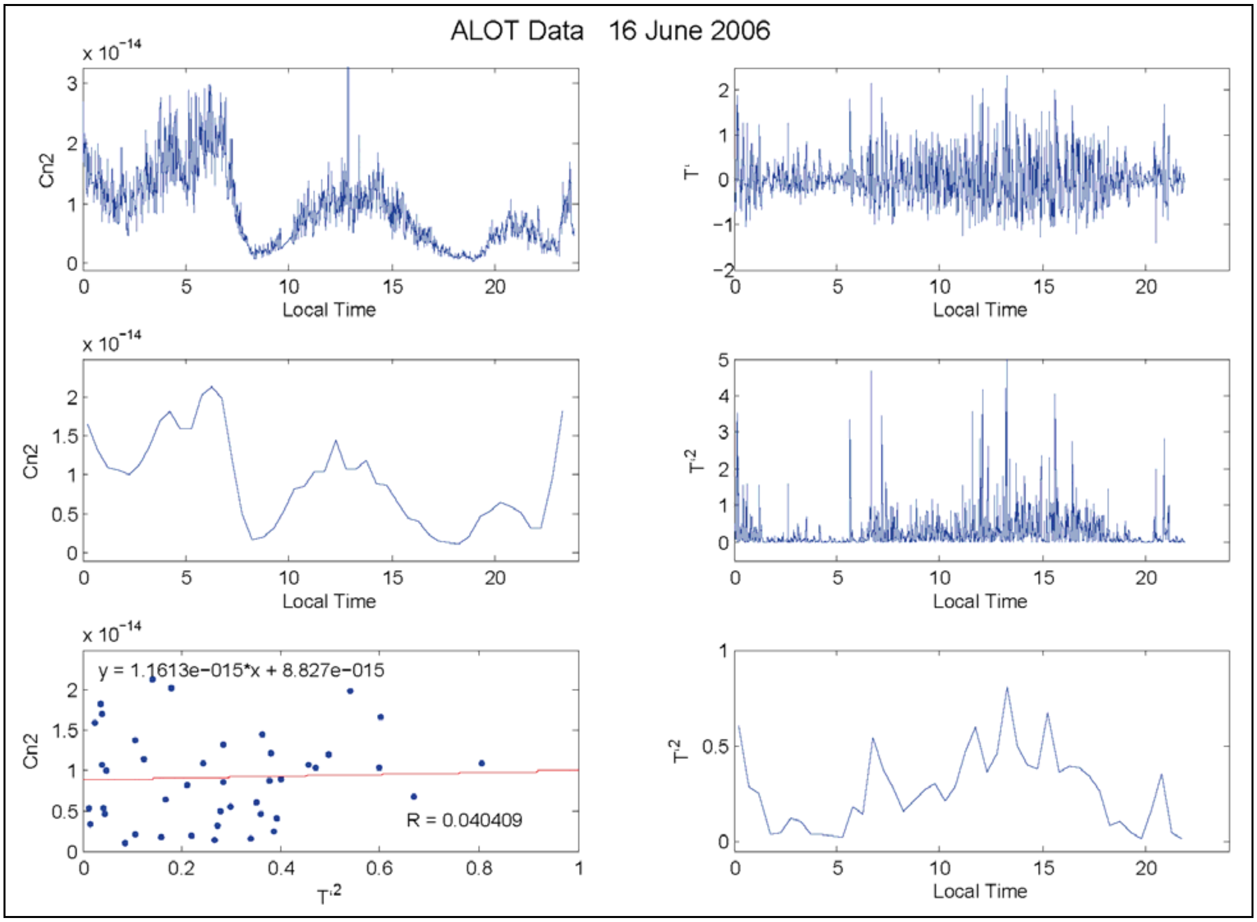

Figure A-17. Same as figure A-1 except for 16 June 2006.

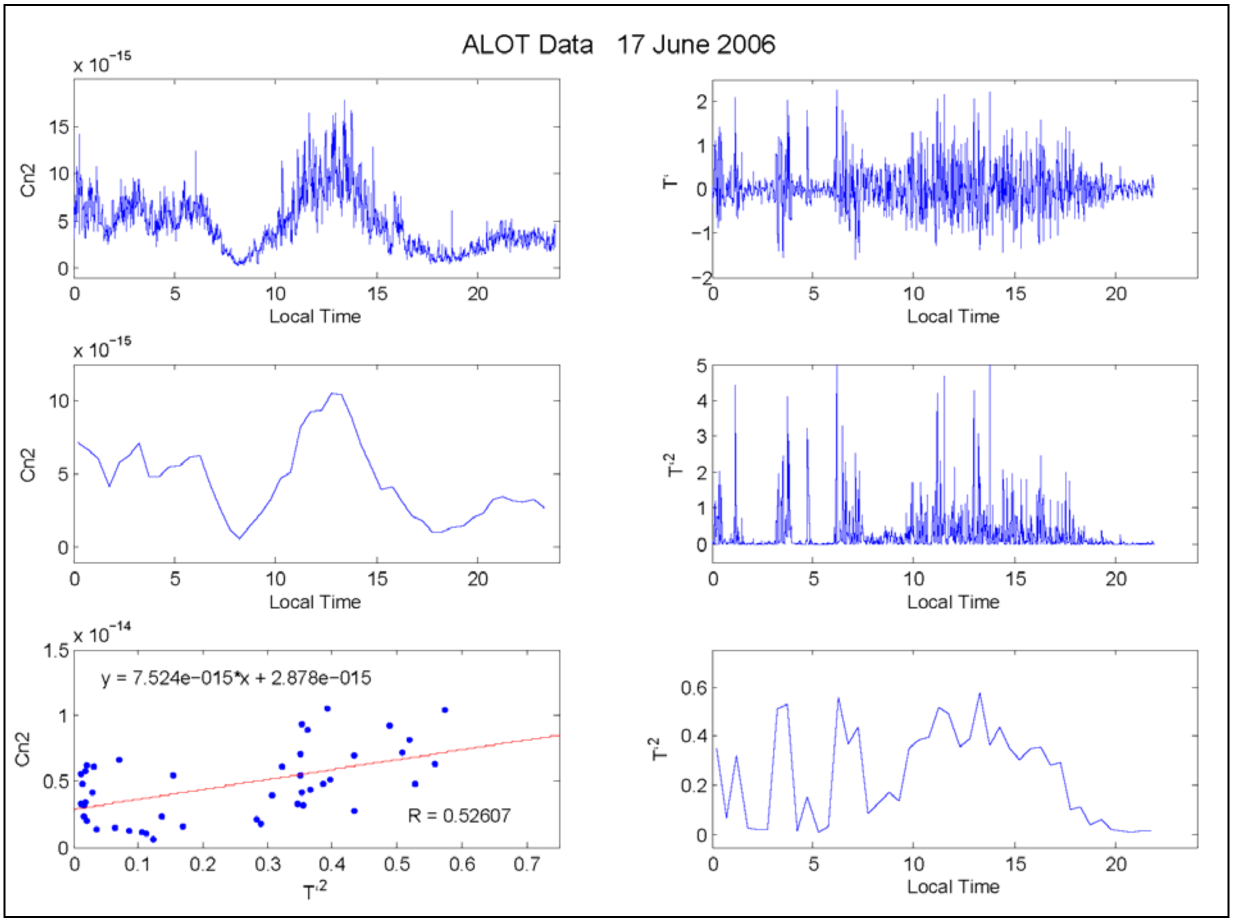

Figure A-18. Same as figure A-1 except for 17 June 2006.

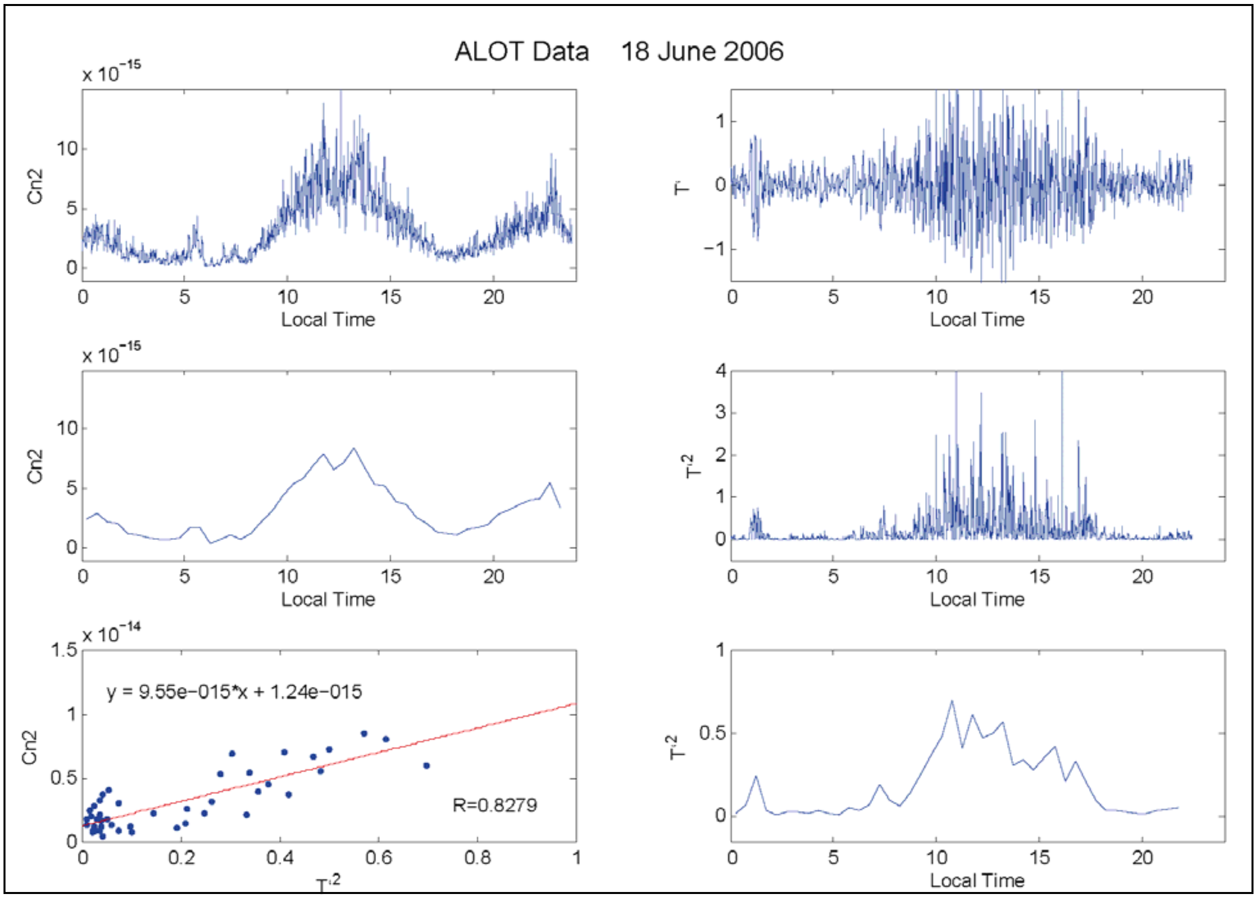

Figure A-19. Same as figure A-1 except for 18 June 2006.

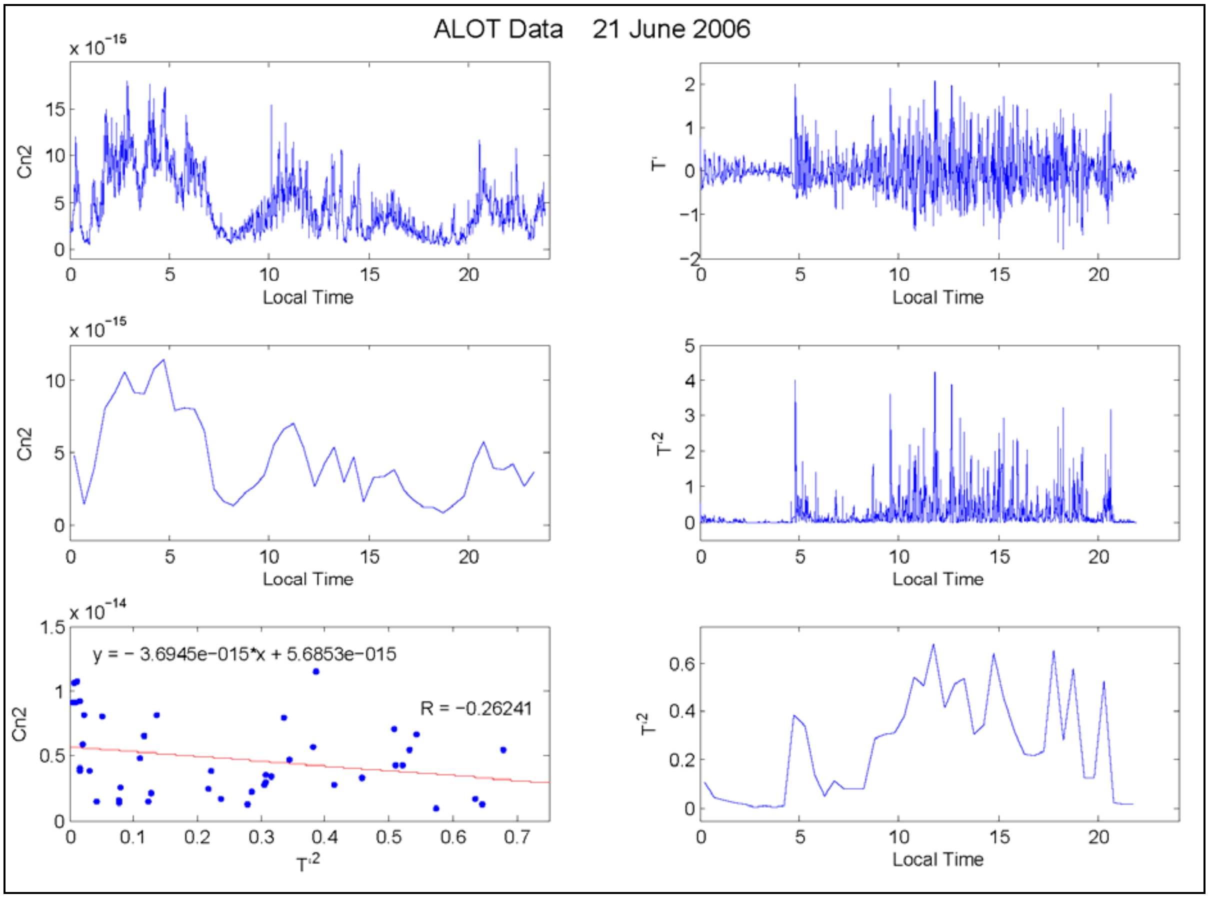

Figure A-20. Same as figure A-1 except for 21 June 2006.

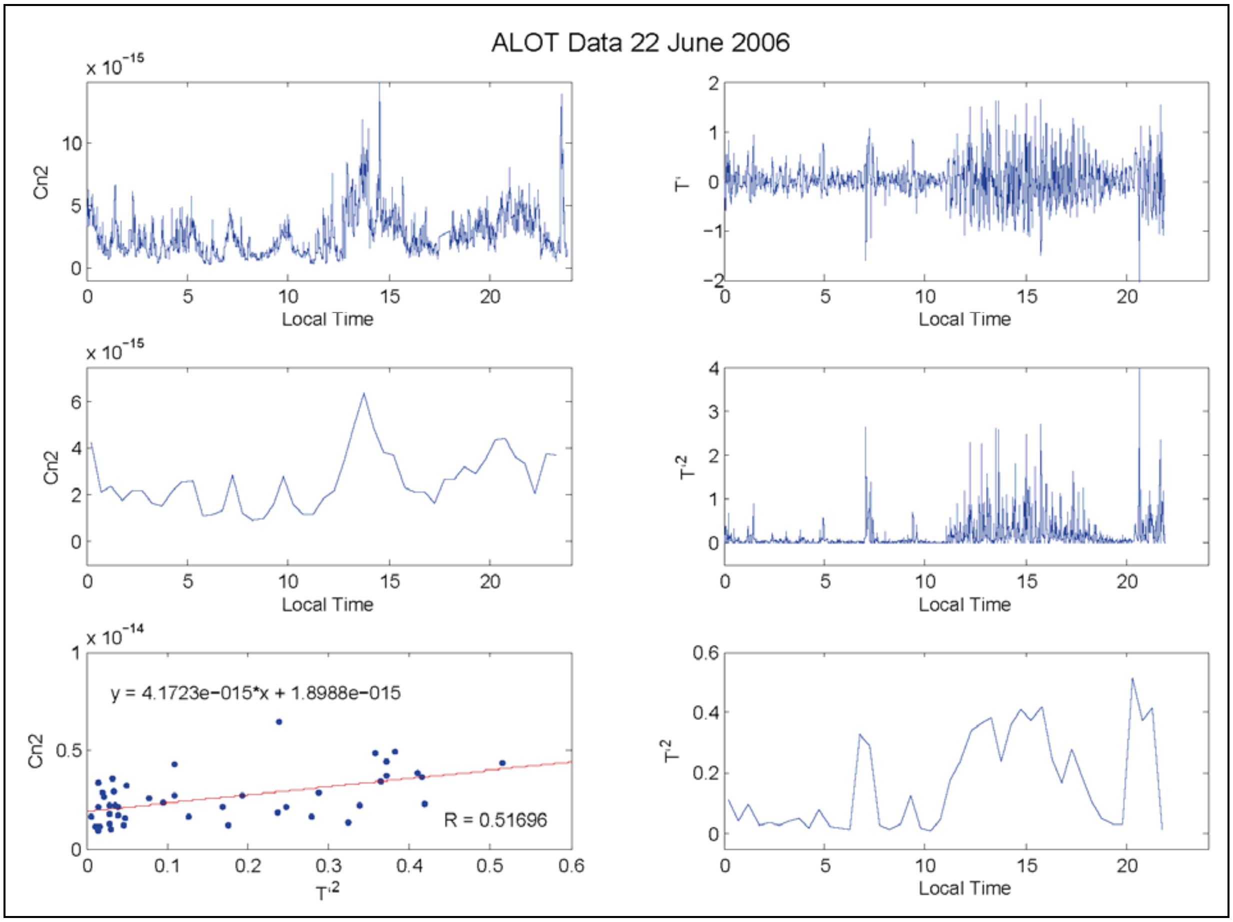

Figure A-21. Same as figure A-1 except for 22 June 2006.

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